Is Blockchain mining profitable in the long run?

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Abstract

Blockchain technologies are at the heart of digital innovation and are a harbinger of Industry 4.0. Consequently, popular press and academic researchers alike have focused on its importance. Yet blockchain technologies' most promising efforts, cryptocurrency and smart contracts, are underpinned by blockchain mining. The blockchain mining service is undergoing change, cryptocurrencies like Ethereum and others are nearing the end of their minting. Smart contracts are in their infancy. The financial impetus for providing the mining service has changed. Here, we add to the literature through a deep financial analysis of blockchain mining regarding its long-term financial viability. Our methods include a financial cost analysis and an analysis of the financial viability of cryptocurrency through focus on Ethereum. It is found that blockchain miners, despite initial profitability, cannot maintain sustainable financial viability without substantial fees. This work is important to those academics who focus on understanding how service technologies and products underpin Industry 4.0. Finally, this paper contributes to the practitioners' decision-making process to embrace blockchain mining as a technological entrepreneur.

Keywords: blockchain mining, cryptocurrency, Industry 4.0, Ethereum, smart contract, technological entrepreneurship

I. Introduction

Blockchain technology is an important element of the digital economic movement. Some authors (Jensen et al. 2019) suggest that digitization provides a broad technology solution where blockchain technology plays a key role while others (Yang 2019; Nguyen et al. 2016) have provided more specific examples of how digitization is assisting global logistics in purchasing contracts such as long-term loan agreements and smart contracts. Furthermore, blockchain is one of the technologies underpinning Industry 4.0 (I4.0) (Bodhke et al. 2020). For instance, Lin et al. (2018) discuss blockchain's role in underpinning smart factories and smart contracts, Viriyasitavat et al. (2018) state that blockchain is "The application …that underpins bitcoin" and Zhao et al. (2019) have proclaimed that blockchain technology is the new digital technology approach for I4.0.

I4.0 is the first industrial revolution based on not only physical technologies but also service technologies like blockchain (White et al .2020) and the Internet of Things (IoT) (Islam et al. 2018). As such, I4.0 provides new and greater opportunities for service-based products like smart contracts and cryptocurrencies. One of the key questions that arise in the course of the commercialization of an emerging technology is which product to develop (Walsh and Linton 2011). The focus of a new product is on solving problems that are important to societies and on generating financial viability. In this paper, we concentrate on the problem-solving ability and the financial viability of blockchain technology-based activities as well as address and answer the questions centered on blockchain technologies, such as that of who considers blockchain as a "technology in search of a problem" (Bull 2018).

It is appropriate to ask, what problems do blockchain solve? We will discuss the problem-solving abilities of blockchain mining, cryptocurrencies and smart contracts. The analysis of these three activities is initiated by an examination of the difference between service and physical products (Linton and Walsh 2003) in our literature review. We also discuss the problems that each of these service products solve. The 21st century problems that are addressed by blockchain technologies include the development of stateless currency, a manner to create smart contracts (Luu et al. 2016; Cong and He 2019) and a pathway to validate new transactions (Gaggioli 2018). I4.0 has challenged the validity of the product development strategies defined by Porter (1980); as a result, instead of Porter's four business models, which firms traditionally used to commercialize emerging technologies like blockchain, there are many other models (Groen and Walsh 2013; Harms et al. 2015; Westerlaud et al. 2014) that are being used for the same purpose. All business models seek value creation, stability, and financial viability in a variety of ways.

We provide a financial analysis of blockchain mining at the level of the miner. For example, Kroll et al. (2013) state that digital currency “Depends for its correctness and stability” on blockchain mining, which is centered on the mechanism used in the mining. They further investigated the economics of blockchain mining with the assumption that miners would behave according to the incentives. In our methodological effort, we focus on the long-term financial viability of blockchain mining using Ethereum. We also take advantage of the work of those who have analyzed the viability of cryptocurrencies (White et al. 2020) and smart contracts (Chang et al. 2019) to aid us in our purpose. We also benefit from the economic models of blockchain mining, which are often utilized by miners to determine what to mine, proceed by developing a mathematical model describing the economics of a mineable cryptocurrency and then specifically focus on the economics of Ethereum blockchain mining.

Our investigation on whether blockchain mining is financially viable in the long run found serious indicators that this process is moving toward financial unviability without the use of financial transfer fees. We find that high growth rates in the blockchain mining hash rate (which is proportional to the network’s total mining power), coupled with even a limited appreciation in cryptocurrency prices, make mining operations unprofitable in the long run. In the dynamic models of both cryptocurrency and the network hash rate, we find further evidence that maintaining operational profitability *in the long run* is only possible with additional investment. Finally, we also find increased investment by many miners in mining capability leads to increased network hash rate, further reducing profitability for miners.

Our work is relevant to those studying blockchain commercialization and development. We utilize scenarios to show that blockchain mining does not develop the sustainable economic profit that is needed for financial viability. This is further important for the blockchain technology product base since if blockchain mining is not financially profitable, then the underpinning of the premise of cryptocurrency as a stateless currency is called into question and the promise offered by smart contracts is unstable. We develop a blockchain profitability model and incorporate cryptocurrencies, smart contracts and blockchain mining into it.

II. Theoretical Background

Some state that the promise of cryptocurrency as a global stateless instrument of exchange—whether such an instrument was ever needed—should have been dashed by the spectacular rise and fall of the value of bitcoin (White et al. 2020). Yet the number of cryptocurrencies continues to increase, not decrease. Further, we acknowledge the drawbacks of cryptocurrencies (Islam et al. 2017, 2020). Blockchain-based smart contract products are now also heralded as ushering in a new era in supply chain transparency in finance (Du et al. 2020a), banking (Dozier and Montgomery 2019) and healthcare (Du et al. 2020 b). Blockchain miners solve the problem of verification for all blockchain-based final products (Li et al. 2019; Rifi et al. 2017). They are individual suppliers providing service products (McDermott et al. 2001; Linton and Walsh 2003) to the emerging blockchain-based industry (Qin et al. 2018).

One aspect of the relation between cryptocurrencies and blockchain mining is further discussed in this paper: the fact that buying a cryptocurrency is motivated by user intentions (Arias-Oliva 2019). There are a multitude of user intentions that direct the purchase of cryptocurrency including its ability to be "fraud-proof" (Kramps and Kleinburgh 2018), to lower the risk of identity theft (Kim and Lee 2018), to make you your own banker, to facilitate global settlement, to embrace a specific product (Al Shehhi et al. 2014) and many more. Moreover, investors obtain cryptocurrencies by buying the asset directly and mining the cryptocurrency.

There are two ways to mine cryptocurrency and they are dependent on the cryptocurrency you mine. When the first cryptocurrency, Bitcoin, was developed, a transaction verification process was required. The system created to verify Bitcoin was the Proof of Work[1] (PoW) system (Bentov et al. 2014). To mine cryptocurrencies, powerful computers are utilized to solve cryptographic puzzles (Duong et al. 2020; Xue et al. 2018). The solution forms part of a block, which are files that act as a transaction ledger functioning as the cornerstone of a blockchain. As a reward for mining the block,

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[1] See https://www.investopedia.com/terms/p/proof-work.asp

miners receive a distribution of cryptocurrency. This incentivizes further mining investment because the block reward is proportional to the computational power used.

Proof of Stake (PoS) is another verification method being utilized to overcome some of the shortcomings of PoW (Zhang et al. 2020; Saleh 2020). The PoS mining process was designed to alleviate excessive electricity use (Li et al. 2019) and increase the number of transactions that can be processed at the same time. PoS was first adopted by a cryptocurrency named Peercoin and Ethereum, the second largest cryptocurrency network, is now trying to adopt the process. In the last few years, many miners have coalesced into mining pools, distributing risk and reward across a large number of users.

A. Cryptocurrencies, Blockchain Mining and Smart Contracts

Given its status as an emerging asset class, academic research into cryptocurrency has generally been exploratory in nature. Operational frameworks have been established for Bitcoin (Nakamoto 2009) and Ethereum (Wood 2014), the two most widely traded cryptocurrencies. A sweeping introductory survey of the cryptocurrency product's technological paradigm has been provided by Narayanan et al. (2016). A critical approach towards the nascent cryptocurrency market has also been provided by Mukhopadhyay et al. (2016).

Further literature has focused on novel innovations in cryptocurrency, including Primecoin (King 2013), Spacecoin (Park et al. 2015), and somewhat ominously, Darkcoin (Duffied and Hagan 2014). The growth in blockchain mining has led to unforeseen demand (and consequences) for hardware and network providers. The Bitcoin-mining processor Goldstrike 1 was proposed to address some of the technical challenges that is evident in blockchain mining cryptocurrency (Barkatullah and Hanke 2015). In addition, legal and illegal Bitcoin solutions using non-customized hardware options have been discussed by Dev (2014).

Given the recent growth in the population of different systems, intra-cryptocurrency dynamics are important to consider. An analysis of intra-cryptocurrency competition, documenting Bitcoin's winner-take-all domination of the early cryptocurrency market, was performed by Gandal (2014). Arbitrage effects on blockchain mining operations, documenting how profitable miners of altcoins (non-Bitcoin cryptocurrencies) convert to Bitcoins to perform transactions with the real economy, was detailed by Hayes (2015). Dominant currencies like Bitcoin have been conceptualized as competitively coexisting with other cryptocurrencies in a dynamic ecosystem by Iwamara et al. (2014).

Research has also examined the critical link between the technological and financial characteristics of cryptocurrency. Sovbetov (2018) finds that cryptocurrency values are strongly influenced by the market beta, the trading volume, and volatility. Wei (2018) finds that the predictability of cryptocurrency returns is inversely related to market liquidity. Wang and Vergne (2017) find evidence that while cryptocurrencies do not behave like commodities, they remain fundamentally different from speculative assets. White et al. (2020) find that Bitcoin is similar to other I4.0 technology product paradigms that diffuse in a sigmoidal fashion (Marinakis et al. 2017a, b, c). This is not consistent with the adoption of a financial instrument.

Nakamoto's Bitcoin protocol design (2009) relies on a decentralized blockchain mining network. However, Eyal and Sirer (2014) propose that colluding pools of Bitcoin miners form an existential risk to Bitcoin, citing the possibility of manipulating the revenue structure in their favor and undermining the entire system. Consolidation of mining pools is a major problem; as Luu et al. (2017) point out, 95% of Bitcoin and 80% of Ethereum's mining power has less than ten mining pools. If a pool exceeds half of the cryptocurrency hash rate, a coordinated mining attack could effectively end the security of the system.[2] Velner et al. (2017) propose that smart contracts can effectively undermine the power of a mining consortium using little resources. In Lewenberg et al.'s study (2015), mining pools were seen as being better at coordinating miners and collecting rewards than individual miners. However, incentives exist for participations to 'switch' between pools to maximize

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[2] As described in Luu et. al (2017), the mining group *Dwarfpool* controlled over 50% of Ethereum's total mining capacity in 2016, but did not engage in a coordinated attack.

their cryptocurrency rewards. Scaling mining operations in this way is likely an economically rational response to challenges in the mining environment.

Developing a mining economics model requires an understanding of the dynamics between hardware demand and minable currency prices, the consolidation pressure faced by individual miners that result in their joining mining pools as well as the economic trade-off between treating the currency as both an investment and something directly mineable. Yet existing research into cryptocurrency is still nascent. Currencies possess value because enough economic agents believe it can (Kiyotaki 1989). The rapid growth of the cryptocurrency market makes its value self-evident, even as the existing framework for its economic success remains underdeveloped.

It was the introduction of blockchain technology into supply chain management that led to the creation of the concept of smart contracts. Smart contracts hold the promise of increasing the transparency of cargo flow, facilitating inspection, and reducing fraud (Chen et al. 2017, Xu et al. 2018, Fu and Zhu 2019). Information asymmetry between upstream producers and downstream retailers has resulted in unwieldy solutions such as just-in-time manufacturing and material requirements planning. Information asymmetry also increases the risk of extending credit. The transparency of the ledgers in blockchain technology leads to reduced information asymmetry (Fu and Zhu 2019). Much of the work on blockchain technology in supply chains focuses on permissioned or private blockchains (Caro et al. 2018, Li et al. 2018, Meng and Xian 2018, Xu et al. 2018), which some argue are not blockchains at all but only shared ledgers.

III. Methods

A. Financial Analysis

In order to develop a model, the equipment and the capital that are necessary to start a mining operation have to be described; we have done this in Section 3.1. Outside of the mining operation, the cryptocurrency network possesses its own unique characteristics, as described in Section 3.2, that force the establishment of viable assumptions (see Section 3.3). Finally, an integrated mining model is created (Section 3.4) that may be applied to a large number of PoW currencies. Due to its popularity, liquidity and ease of mining, Ethereum was selected as a case study for the application of the developed model.

B. Mining Operations

B.1 Equipment

The primary component of a mining operation is the mining rig. It is dependent on the on the algorithm used, the primary means of solving PoW or PoS cryptographic puzzles. Both are typically central processing unit (CPU)- or graphics processing unit (GPU)-based. The components of a rig are globally available at similar pricing, in both high-cost countries like the U.S. or low-cost ones like China and Russia where many miners are located. This study focuses on a GPU-based mining operation with an emphasis on understanding organic, long-term sustainable growth. Typical GPU mining equipment consists of a desktop computer with added PCI-E riser cables[3]. The PCI-E ports on the motherboard communicate with the GPU through the PCI-E riser cables. Motherboards with typically six (or more) PCI-E ports are used[4] for mining the major GPU coins (ETH, ZEC, XMR, BTG). The components of the computer used in this analysis and the prices thereof are shown in Table 1.

Table 1: Mining Rig Cost Estimation Framework

Component	**Description**	**Cost**
GPU	Graphics Processing Unit	$ 300.00
PSU	Power Supply Unit (2x)	$ 260.00
CPU	Central Processing Unit	$ 50.00
RAM	Random Access Memory	$ 60.00
Case	Secures Components	$ 20.00
Motherboard		$ 150.00
PCI-E Cables		$ 27.00
SSD/OS	Solid State Drive & Operating System	$ 40.00
	Total Cost for 1 GPU	$ 907.00

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[3] See https://cryptomining-blog.com/tag/pci-e-riser/ for more details.

[4] This allows for as many GPUs to be added to the motherboard as there are PCI-E ports.

Total Cost of 6 GPUs	$ 2,407.00

Since the mining rigs here are designed for GPU mining, cost savings are realized on other components of the rig. Cost-saving assumptions are seen in the CPU (Intel® Celeron®), the RAM (4 GB DDR4), and the case built from striped building studs. The operating system (ethOS) is a Linux operating system that was built for the purpose of GPU mining, which was selected in order to reduce the operational costs associated with buying a Microsoft Windows OS while allowing the typical miner to start and scale the operation more quickly than if they were to purchase a hard drive, install and modify a free Linux distribution.[5]

Higher costs are incurred with the motherboard, the power supply unit (PSU) and the GPU. The price of the motherboard is driven by demand and the need for six or more PCI-E ports. The price of the PSU (2x EVGA 750W 80 PLUS Gold G2) is driven by the need for highly efficient energy use (80 PLUS Gold) for the large power supply of the GPUs (160 W/GPU). The GPU selection is driven by a cost function that considers the maximum mining hash rate drawing the lowest amount of power (hash/$). For this model, we are using the AMD RX570 series. The GPU prices are driven by current demand due to increases in coin price (see Figure 1) and are chosen as a constant $300 for the first stage of the analysis. A setup with one GPU and expansion room for five additional GPUs costs above $900, whereas the total cost of a rig with all six GPUs is just under $2500. Higher cost savings are achieved using greater PCI-E ports per board, cutting the expenditure on the CPU, the RAM, the motherboard, the hard drive and the OS[6].

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[5] Small cost savings could be obtained by the purchase of a separate solid-state hard drive and personally modifying a free Linux distribution. This would scale linearly for large mining operations.

[6] Due to limited availability of 12-port PCI-E motherboards, we ignored this for our analysis.

Figure 1: Price Relationship between Ethereum and the AMD RX570 Graphics Card (X-axis: Date. Y-axis: Price in US dollars)

We compare the price of Ethereum to the RX570 GPU[7] (Fig. 1). Demand for cryptocurrency mining equipment causes increased demand for GPUs, raising GPU prices substantially.[8] The ordinary least squares (OLS) regressions performed on this relationship suggested that a 18.57-day lag exists between increases in Ethereum prices and the corresponding increases in GPU prices with determined by the equation:

$\text{Price}_{RX570} = 0.2\ \text{Price}_{ETHI} + \$234.5$ and a coefficient of determination of 79.6%

C. Network Hash Rate

Solving a cryptographic puzzle to mine a block is a random process, where the probability for success of any user is determined as the fractional portion of that miner's mining power to the total network mining power. *Mining power* is measured using several metrics that are dependent on the cryptographic algorithm. The most popular term for mining power and the process of mining are the *hash* and *hashing*, respectively.[9] Miners may increase the probability of solving a puzzle by increasing the number of GPUs that are utilized while mining as each GPU allows the business to test more random hashes during a given block period. Smaller mining operations often form collective

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[7] Historical GPU data was taken from https://pcpartpicker.com/trends/price/video-card/

[8] See https://motherboard.vice.com/en_us/article/zmemza/cryptocurrency-mining-fueling-a-gpu-shortage

[9] See Hayes (2017).

mining pools where profits are distributed according to the hashing power each miner provides.[10] By pooling resources, miners have a steady income to pay overhead costs, ensuring that miners do not need to run a full node that syncs with the blockchain as this requires greater technical knowhow.

Miners mine *blocks*, a file that stores records of transaction, information about the previous blocks, and the solution to the mathematical puzzle that was used to 'solve' the block. For mining blocks, the reward is cryptocurrency.[11] The greater a miner's individual hash rate[12] relative to the total hash rate of the network, the greater the likelihood of mining a block. We assume that a pool method of mining is used for this analysis to ensure income stability. To determine the coin generation rate, a miner must first determine the expected time to find a block using Equation (1).

$$Time\ to\ Find\ Block = \frac{Network\ Hash\ Rate}{User\ Hash\ Rate} \times Block\ Time \qquad (1)$$

As seen in Equation (1), the time taken to find a block is inversely proportional to the probability that the user finds a block (the probability being defined as normalizing the user's hash rate by the network hash rate). Typical cryptocurrencies have a defined, consistent *block time* which determines how often a block on the blockchain is completed and by extension, how often a coin is distributed.[13] Once the miner has determined the expected time to find a block, the coin generation rate may be determined based on the coin's block reward. The *block reward* is the cryptocurrency that is received for mining a block and is specific to each coin. The amount of coin generated each week is then determined by the block reward divided by the miner's time to find a block as given by Equation (2)[14]:

$$Coin\ Generation\ Rate = \frac{Block\ Reward}{Time\ to\ Find\ Block} \qquad (2)$$

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[10] Pool hosts often charge a 1% management fee.

[11] For a cryptocurrency such as Bitcoin, the original award of 50 coins per block was halved every 210,000 blocks (or roughly, every four years), ensuring a finite limit to the number of mined coins.

[12] The higher the GPU processing power, the greater the miners' hash rate.

[13] The block time for Ethereum is set to roughly 15 seconds, whereas Bitcoin is roughly 10 minutes. See also https://www.cryptocompare.com/coins/guides/why-is-Ethereum-different-to-bitcoin/

[14] This analysis ignores payments for 'uncle blocks' in Ethereum, which result from two different miners trying to generate a block at the same time. One of these blocks will be accepted and added to the 'blockchain', the other will be rejected. While these are comparable to Bitcoin's *orphan blocks*, Ethereum offers financial incentives for *uncle block* miners.

As the blockchain's block time and block reward are approximately constant, the two variables that affect the coin generation rate are the user and the network hash rate. As additional miners join a particular coin network, the network hash rate increases. If any miner does not increase hashing capabilities in proportion to the growth in the network hash rate, the entire operation will observe a decrease in the coin generation rate. The relationship between the individual miners and network hash rates is an important element in this study.

D. Organic Growth Model

The organic growth model utilizes an initial capital investment of $10,000. The strategy is to purchase as many mining rigs as possible with the initial investment: in this case, four rigs containing 24 GPUs, leaving $372 for future reinvestment. Based on the initial number of GPUs purchased, the miners' total hash rate can be determined as well as the amount of coin generated during the first week.

We assume that at the end of the first week, the miner will sell all coins in hand at the time at *zero* coin exchange rate to USD. The miner will then pay the power bill, which is set at 160 W/GPU plus 100 W/Rig. The electricity rate is set at a residential rate of 10 cents/kWh[15]. After paying the cost of electricity, the miner will invest in additional mining hardware with the remaining funds subject to the following two rules:

Rule 1: The miner must fill all free PCI-E ports on the motherboard before purchasing another rig.

Rule 2: To purchase a new rig, the miner must raise enough money to cover the costs of the components and one GPU.

Our first analysis assumes no lag time due to shipping or shortage of supplies when purchasing and that the prices of the components are constant (as given in Table 1). Rule 2 ensures that the maximum amount of money the miner can have at any time is $907: the price of a rig plus GPU.

E. Governing Equations

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[15] Data for March 2018 suggests average US electricity prices are about 10.37 cents/kWh across all sectors and 12.99 cents/kWh for residential users. See https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

Understanding the economics of an organic mining operation is essential to running one effectively. One distinct element of mining operations is the set of well-defined relationships that determine profitability. In Tables 2 and 3, we outline the lists of symbols and constants that we use to define these relationships:

Table 2: List of Symbols

Symbol	Value	Unit	Description
GPU	-	GPU	The total number of GPUs in the mining operation
Network HR	-	Hash/s	The total hash rate of the blockchain
User HR	-	Hash/s	The total hash rate of the business
t	-	Seconds	Time

Table 3: List of Constants

Symbol	Value	Unit	Description
AvgCostGPU	2407 / 6	$\frac{\$}{GPU}$	The average cost to add 1 GPU of mining power
blockTime	15	$\frac{s}{Block}$	blockchain target time to mine one block
blockReward	3	block ethereum	blockchain reward for mining one block
e^{-p} rice	0.1/3600	$\frac{\$}{KW * s}$	The cost of electricity
GPU HR	27		Hash rate per GPU
GPU Power	0.16	$\frac{\$}{KW}$	Power per GPU
$HR_{network}^{0}$	288133782*106	Hash/s	Time zero network Hash rate

In its simplest form, the profit from the business can be quantified using the difference between revenue and expense. Since mining is a continuous operation, it is useful to treat profit here as a profit rate or profit per unit time as shown in Equation (3) in the unit of $/s.

$$Profit = Revenue - Expense (3)$$

The interest of the present study is to understand an organic growth operation where the assumption is that all profit is reinvested in business growth. A mining business growth can be measured by its ability to produce more coin on the network. To increase the mining hash rate, the purchase and addition of GPUs to the business is required. We substitute the *rate of profit* for the *rate of GPU growth* and convert the revenue and expense model into units of GPU by multiplying using the average cost to add one GPU [AvgCostGPU]. The result is Equation (4) in unit of GPU/s.

$$\frac{\partial GPU}{\partial x} = \frac{1}{AvgCostGPU} * (revenue - expense) \quad (4)$$

The rate of revenue growth is related to the coin/time released by the blockchain multiplied by the fraction of network hash rate the user is contributing, multiplied by the current coin exchange rate. This relationship is shown in Equation (5):

$$Revenue = \frac{blockReward}{blockTime} * \frac{HR_{user}}{HR_{network}} * USDExchangeRate \qquad (5)$$

The mining operations expense is defined here as only including the cost for power as shown in Equation (6):

$$Expense = e^{-P}rice * userPower \qquad (6)$$

Substituting Equations (5) and (6) in Equation (4), we get Equation (7):

$$\frac{\partial GPU}{\partial t} = \frac{1}{AvgCostGPU} * \left(\frac{blockReward}{blockTime} * \frac{HR_{user}}{HR_{user}} * USDExchangeRate - e^{-P} * userPower\right) \qquad (7)$$

In Equation (7), both *HR*_{*user*} and *userPower* are functions of the miner’s GPU capacity, as defined below in Equations (8) and (9):

$$HR_{user} = GPU * HR_{GPU} \qquad (8)$$

$$userPower = GPU * Power_{GPU} \qquad (9)$$

Substituting these in Equation (7), we have a first order ordinary differential equation (ODE) describing a mining businesses growth.

$$\frac{\partial GPU}{\partial t} = \frac{GPU}{AvgCostGPU} * \left(\frac{blockReward}{blockTime} * \frac{HR_{GPU}}{HR_{network}} * USDExchangeRate - e^{-P}rice * Power_{GPU}\right)$$

(10)

Assuming all variables except the GPU are constant, we a have a separable ODE of the form given below:

$$\frac{dGPU}{dt} = GPU * \lambda$$

(11)

$$\lambda = \frac{1}{AvgCostGPU} * \left(\frac{blockReward}{blockTime} * \frac{HR_{GPU}}{HR_{network}} * USDExchangeRate - e^{-P} * Power_{GPU}\right) \qquad (12)$$

The separable ODE has the following solution:

$$\frac{dGPU}{dt} = GPU * \lambda \qquad (13)$$

$$\frac{dGPU}{GPU} = \lambda dt \qquad (14)$$

$$\int_0 (GPU) = \lambda t + c \qquad (15)$$

$$GPU(t) = c * exp \int_0 (\lambda t) \qquad (16)$$

$$GPU(0) = GPU_0 = c \qquad (17)$$

$$GPU(t) = GPU_0 * exp \int_0 (\lambda t) \quad (18)$$

Thus, we have our basic equation for the growth of a mining operation.

IV. Results and Discussion

A. Financial Analysis

Using historical data obtained from *EtherScan.io* for Ethereum (ETH), we examine the cryptocurrency over a fifty-two-week period after an initial $10,000 investment. Using our framework, we held Ethereum prices (at $400 per coin) as well as the network hash rate growth to be constant. Additions to the miner’s hash rate are not considered as increasing the network hash rate as the hash rate of the network is much greater than the hash rate of the user. In Figure 2, the results of the fifty-two-week mining simulation are detailed in four subplots. All subplots in Figure 2 have an abscissa representing time in weeks. The top left subplot in Figure 2 has an ordinate axis of coin (ETH) with the equivalent in USD shown on the opposing ordinate. The top right subplot of Figure 2 displays the coin generated per week and the equivalent in USD. This plot provides insight into the rate at which the miner is producing Ethereum. In the lower left subplot, the “bank” shows how much money the miner has each week after paying expenses (being only that of power in this case). The change in the number of rigs, PCI-E ports and total GPUs is shown in the bottom right subplot of Figure 2. All markers in the subplots are indicative of two-week intervals.

A.1 Case 1: Constant Ethereum Price, Constant Network Hash Rate

For this base case (Fig. 2), the miner manages to produce 1.17 more Ethereum by reinvesting the earnings in new equipment (see “Eth Generated”) than without reinvestment. In the coin generation plot in Figure 2, a stair-like behavioral pattern is observed with respect to the weeks. Each time a new “stair” is climbed, it is implied that a new GPU has been purchased for the mining operation, thereby increasing the rate at which the miner is able to generate Ethereum. This purchase of a new GPU can be viewed in the bottom left subplot of Figure 2 in the miner’s “bank”. In this case, the bank linearly increases in value each week until enough money has been generated to purchase a GPU (if free PCI-E ports exist) or a rig plus one GPU (if all PCI-E ports are full). This base case shows the initial purchase of one rig and then the next fifty-two weeks are spent filling the PCI-E ports of this new rig. In this case, the total number of GPUs are shown on the left ordinate while the free PCI-E ports and total rigs are shown on the right ordinate.

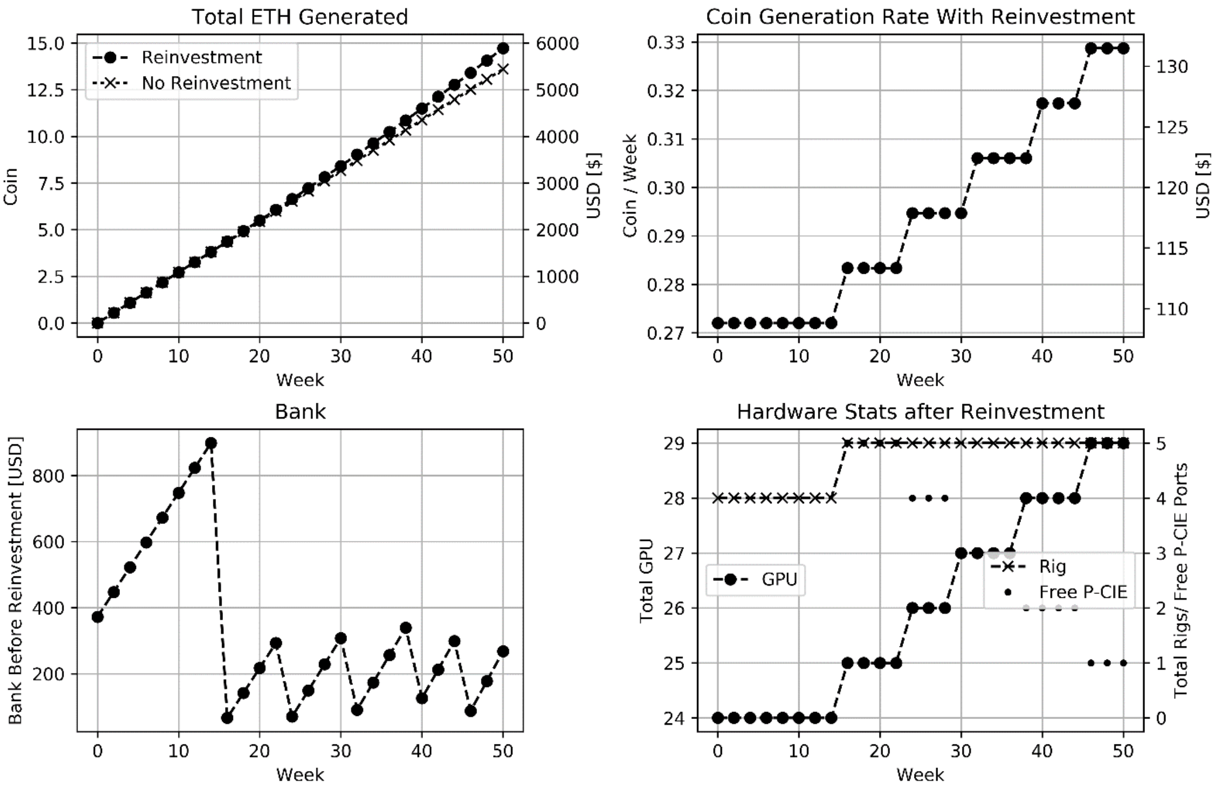

Figure 2. Organic Growth of an Ethereum Mining Operation: Fixed Price Model

This base case is an over-simplified version of the mining operation as it fails to consider \ changes in the price of Ethereum and those in the network hash rate. However, it provides the insight that with a $10,000 investment, even after fifty-two weeks, the miner has not made back the investment with or without reinvestment in the coin. Arguably, the miner has hardware that can be salvaged; this is ideally a net profit on investment of the pending sale of the rig components. In the coming sections, the model complexity will be increased to demonstrate what happens when considering additional changes, first in price and second in network hash rate. It is expected that for increasing or decreasing the price of the Ethereum, the right ordinate of each plot representing USD increases or decreases accordingly near the beginning of the simulation and because the Ethereum generated in the early months was worth more, reinvestment would become more profitable. In the next section, three price trends of Ethereum will be suggested based on the forecasting of historical data.

A.2 Case 2: Dynamic Ethereum Price, Constant Network Hash Rate

In the base model, we created at least one significant oversimplification: holding the price of the Ethereum constant. The high volatility associated with cryptocurrency since 2016[16] has made variability a hallmark of the entire market and has vastly increased the difficulty in making predictive assumptions on future prices. Since most pricing models use some measure of historical price growth and volatility data, many of the resulting models produced irrationally high values. In particular, Monte Carlo simulations were notably ineffective. Consequently, we settled on a reduced variance model (Fig. 4) to provide a more reasonable estimation range for Ethereum prices. The forecast was run as a Holt-Winters exponential smoothing on the historical price of Ethereum. As may be expected, due to the high volatility of Ethereum, the results shown in Figure 3 predicts that the price will gradually rise over the next year, with 90% confidence intervals bounded by zero and just above the peak that was observed in January 2018.

Figure 3. Predictive Model Used in Forecasting Ethereum Prices

We incorporate this revised estimation of future price growth into the next iteration of our Ethereum mining model. We sort our expectations into three simulations: A low forecast ETH price model, a mid-forecast ETH price model and a high forecast ETH price model. Predicting future price changes is uniquely challenging, but the broad range of estimates (i.e., heroic gains, moderate gains and absolute crash) incorporates most likely scenarios. We use these projections to inform a revised model (Fig. 4).

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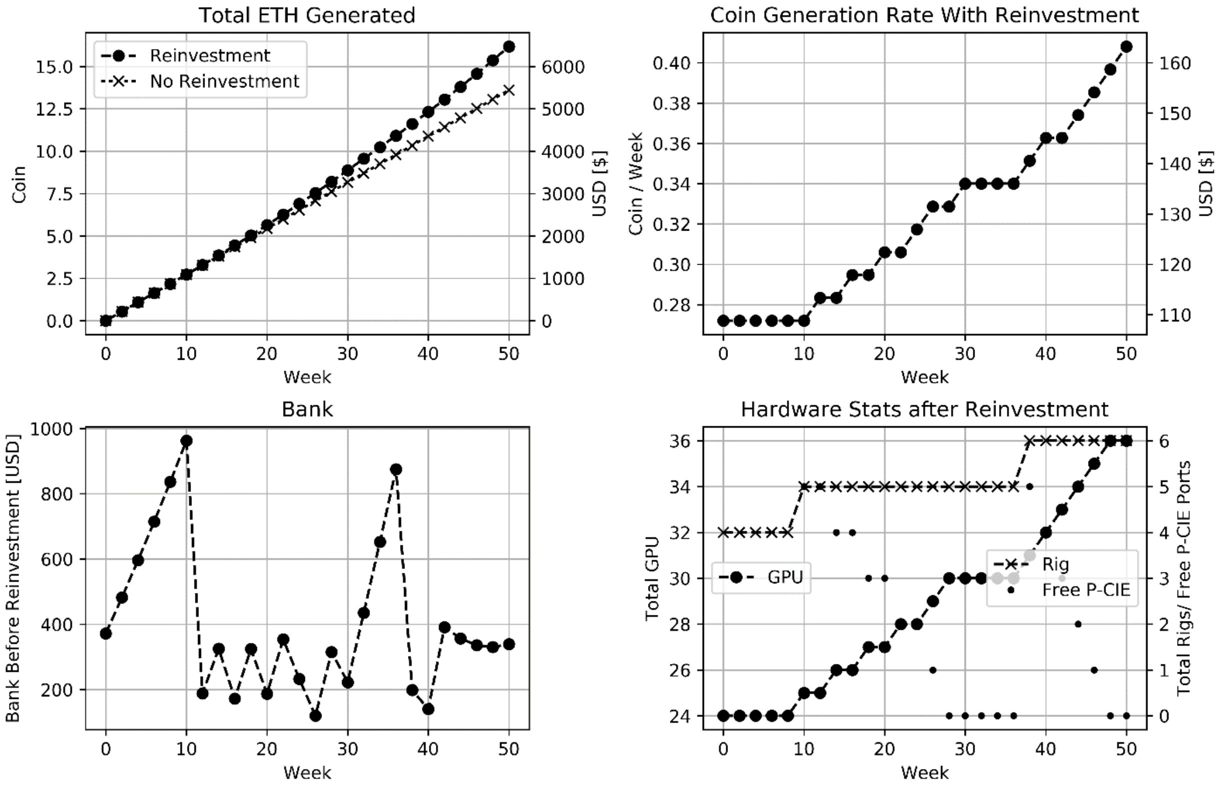
[16] One-year rolling betas for Bitcoin exceeded 10.0 at times, while three-year rolling Betas exceeded 7.0. (White et al. 2018)

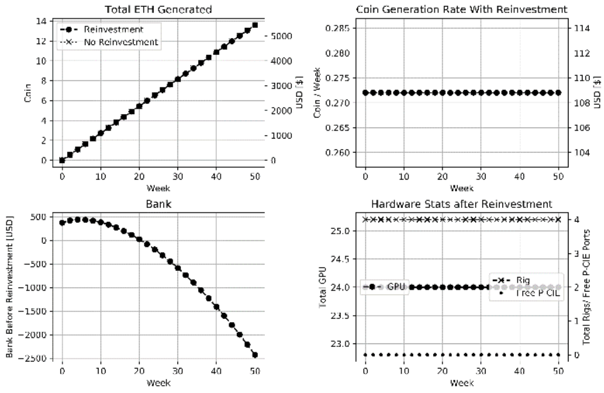
Figure 4 considers the consequences of the forecast model prices depicted in Figure 3 on the previously discussed mining operation. The forecast value (moderate price gains) is shown at the top of Figure 4, with the lower bound confidence interval (price crash) depicted in the bottom left and the upper bound confidence interval (heroic price gains) shown in the bottom right. This model does not consider an increase in the network hash rate with respect to time. The first-year increase in the forecast price leads to a slightly higher coin generation rate than in Figure 4 because the Ethereum generated is worth \$500 more than that generated in the case with the constant price. The higher price of Ethereum allows the business to grow more quickly as a new rig can be purchased in the thiry-sixth week.

In the bottom left of Figure 4, we show the model in the lower bound of the 90% confidence interval. In this case, Ethereum continually decreases to a \$0 price and the mining operation become unprofitable within the first ten weeks. The coin generation rate never increases past the first week because there is no money to reinvest. Lastly, we show the upper bound estimate in the bottom right of Figure 5. In this case, reinvestment is a clearly profitable strategy. The number of rigs has increased to twelve by the end of the first year and we are able to collectively generate over twenty Ethereum. The business change was measured using the following equation:

$$\left(GPU_{final} - GPU_{initial}\right)/GPU_{initial} * 52\,weeks \qquad (19)$$

It was calculated to be 3.7%, 0.96% and −34% per week for the high, expected and crash markets, respectively. For the price crash, measuring the change in GPU is not reflective of the loss as the simulation was not set up to sell equipment (this would introduce hardware salvaging uncertainty etc.). Therefore, the net loss was converted to number of GPUs at the purchase price. In the next section, we consider the historical network hash rate and integrate this into a dynamic price model.


Total ETH Generated
Reinvestment
No Reinvestment
Coin
USD [$]
Week
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
1000
2000
3000
4000
5000
6000
0
10
20
30
40
50
Coin Generation Rate With Reinvestment
Coin / Week
USD [$]
0.28
0.30
0.32
0.34
0.36
0.38
0.40
110
120
130
140
150
160
Week
Bank
Bank Before Reinvestment [USD]
200
400
600
800
1000
Week
Hardware Stats after Reinvestment
Total GPU
Total Rigs/ Free P-CIE Ports
GPU
Rig
Free P-CIE
24
26
28
30
32
34
36
0
1
2
3
4
5
6
Week


Total ETH Generated
Reinvestment
No Reinvestment
Coin
USD [$]
0
2
4
6
8
10
12
14
0
1000
2000
3000
4000
5000
Week
Coin Generation Rate With Reinvestment
Coin / Week
USD [$]
0.260
0.265
0.270
0.275
0.280
0.285
104
106
108
110
112
114
Week
Bank
Bank Before Reinvestment [USD]
500
0
−500
−1000
−1500
−2000
−2500
Week
Hardware Stats after Reinvestment
Total GPU
Total Rigs/ Free P-CIE Ports
GPU
Rig
Free P CIE
23.0
23.5
24.0
24.5
25.0
0
1
2
3
4
Week
0
10
20
30
40
50

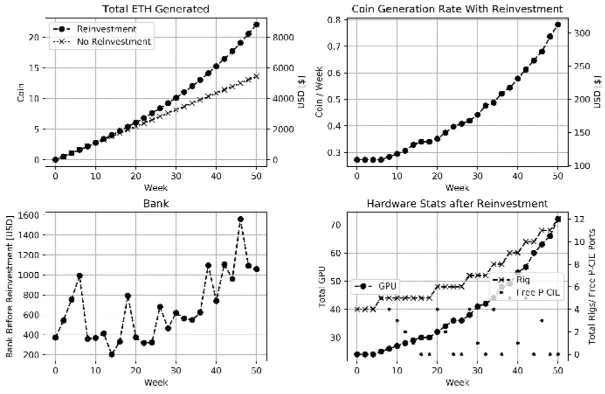

Total ETH Generated
Reinvestment
No Reinvestment
Coin
USD [$]
0
5
10
15
20
0
2000
4000
6000
8000
Week
Coin Generation Rate With Reinvestment
Coin / Week
USD [$]
0.3
0.4
0.5
0.6
0.7
0.8
100
150
200
250
300
Week
Bank
Bank Before Reinvestment [USD]
200
400
600
800
1000
1200
1400
1600
Week
Hardware Stats after Reinvestment
Total GPU
Total Rigs/ Free P-CIE Ports
GPU
Rig
Free P CIE
30
40
50
60
70
0
2
4
6
8
10
12
Week
0
10
20
30
40
50

Figure 4. Organic Growth of an Ethereum Mining Operation: Dynamic Price Model (Forecast)

A.3 Case 3: Dynamic Ethereum Price, Dynamic Network Hash Rate

The previous scenario depicts an ostensible view of an organic growth business which is driven solely by market demand forces. The high, moderate and low-price gains returned proportional business growths (3.7%, 0.96, −34%). However, as demonstrated in Equation (5), the revenue is calculated as a fraction of the total network hash rate or the supply (of hashing) market forces. Figure 5 demonstrates that the network hash rate growth coincides with Ethereum price increases in this case. The promise of large, speculative gains for passive work lures an increasing number of miners into the market. As the number of miners increases, the fractional revenue for any one miner decreases (as given in Equation 5). Figure 5 also shows that while increases in Ethereum's price lead to growth in the network hash rate, losses in price coincide with lower growth in the network hash rate.

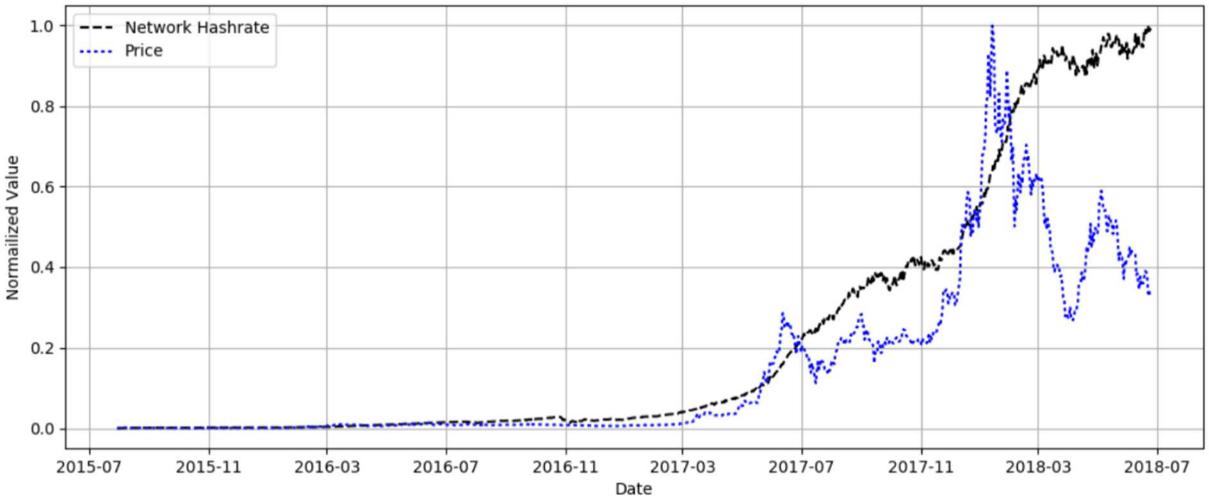


Figure 5. Normalized Network Hash Rate and Ethereum Price

To model the change in network hash rate, the data was smoothed by considering a 200-day moving average. Then, a historical weekly percent change was calculated (Fig. 6). The descriptive statistics of the historical network hash rate growth were found to be consistent regardless of the smoothing time, period of gain or specific time period considered (e.g., 2016, 2017). The data in Figure 6 has a mean of 5.3% and a standard deviation of 2.3%. The minimum and maximum are 1.5% and 10.4%, respectively. This weekly percentage growth in hash rate implies that for the model business to maintain its profitability, it would need to add 5% (on average) to its total hash rate every week.

This 5% growth value is prohibitively high for miners, as demonstrated in Section 4.1.2 and Figure 4. In the upper confidence interval of the no hash rate growth model, the business growth was only 3.7%/week. To inform our model, two price forecasts from Figure 4 are considered (moderate gains and heroic gains) with two hash rate weekly growths (minimum and mean).

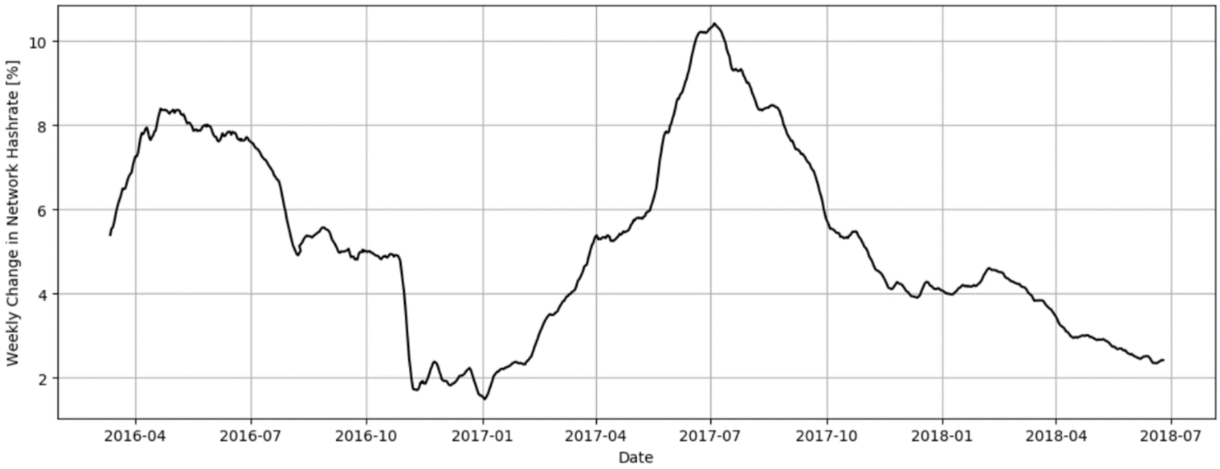
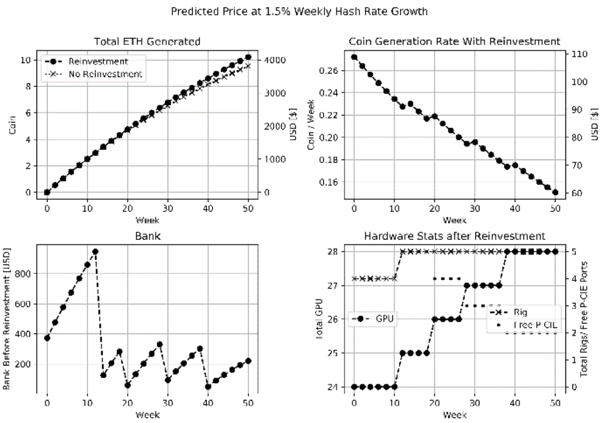
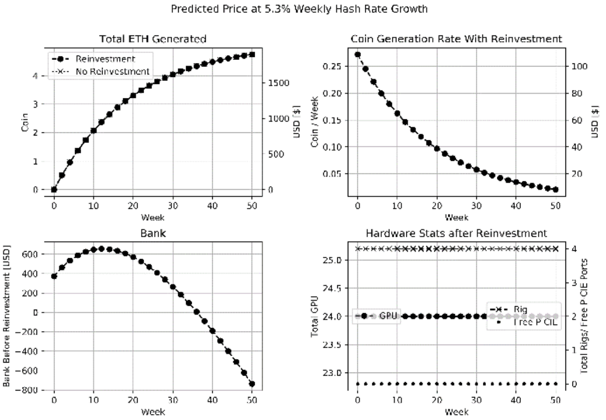
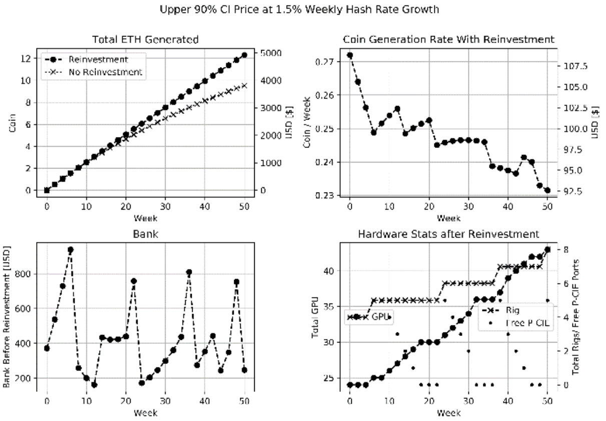


Figure 6. Weekly Percent Change of the 200-Day Moving Average of Network Hash Rate

The results of the four simulations are depicted in Figure 7. The columns in Figure 7 are the minimum hash rate growth (left) followed by the high hash rate growth (right). The rows reflect moderate price gains (top) and heroic price gains (bottom). The best case scenario for a miner would be the high price gains and low hash rate growth depicted in the bottom left of Figure 7. The business does not immediately go insolvent, but will eventually fail due to the inability to contend with hash rate growth. The most probable scenario incorporates moderate price gains and the high network hash rate growth, depicted in the top right of Figure 7. In this scenario, the coin generation rate deteriorates so substantially that the business quickly fails to cover weekly expenses. Organic mining growth is only profitable in the unlikely scenario of high price growth paired with low hash rate growth. In the colorful words of noted mining author T.A. Rickard, “An unprofitable mine is fit only for the sepulcher of a dead mule.”


Predicted Price at 1.5% Weekly Hash Rate Growth
Total ETH Generated
Reinvestment
No Reinvestment
Coin
USD [$]
Week
Coin Generation Rate With Reinvestment
Coin / Week
USD [$]
Week
Bank
Bank Before Reinvestment [USD]
Week
Hardware Stats after Reinvestment
GPU
Rig
Free P CIE
Total GPU
Total Rigs/ Free P CIE Ports
Week


Predicted Price at 5.3% Weekly Hash Rate Growth
Total ETH Generated
Reinvestment
No Reinvestment
Coin
USD [$]
Week
Coin Generation Rate With Reinvestment
Coin / Week
USD [$]
Week
Bank
Bank Before Reinvestment [USD]
Week
Hardware Stats after Reinvestment
GPU
Rig
Free P CIE
Total GPU
Total Rigs/ Free P CIE Ports
Week


Upper 90% CI Price at 1.5% Weekly Hash Rate Growth
Total ETH Generated
Reinvestment
No Reinvestment
Coin
USD [$]
Week
Coin Generation Rate With Reinvestment
Coin / Week
USD [$]
Week
Bank
Bank Before Reinvestment [USD]
Week
Hardware Stats after Reinvestment
GPU
Rig
Free P CIE
Total GPU
Total Rigs/ Free P CIE Ports
Week

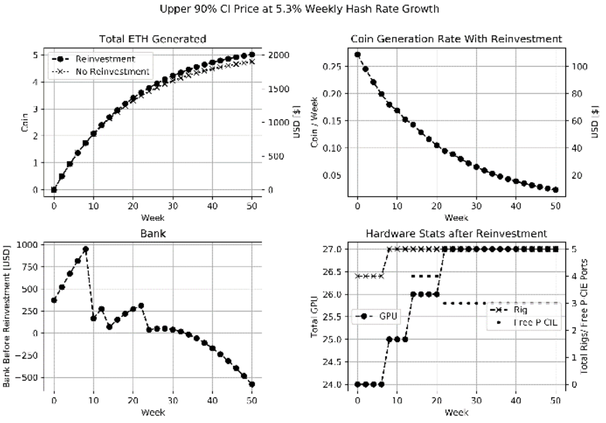

Upper 90% CI Price at 5.3% Weekly Hash Rate Growth
Total ETH Generated
Reinvestment
No Reinvestment
Coin
USD [$]
Week
Coin Generation Rate With Reinvestment
Coin / Week
USD [$]
Week
Bank
Bank Before Reinvestment [USD]
Week
Hardware Stats after Reinvestment
GPU
Rig
Free P CIE
Total GPU
Total Rigs/ Free P CIE Ports
Week

Figure 7. Organic Growth of an Ethereum Mining Operation: Dynamic Price Model & Dynamic Hash Rate

Although this research is the first to systematically address the dynamics of cryptocurrency mining, we believe the assumptions of the model have merit. As noted previously, there is a strong positive correlation between the price growth of Ethereum and the growth in hardware prices. Therefore, in the best-case scenario depicted in Figure 7, the decline in coin generation rate would be higher as the large gains in Ethereum price would, in turn, increase hardware demand, raising hardware prices. We also limit the scope of expenses in this analysis to only the price of power generation. Reasonable additional expenses include fixed costs of shelter and internet. While an initial investment of $10,000 was made, it is fairly irrelevant as the miner will never be able to keep up with the network hash rate growth. Figure 8 depicts a simulation with an initial 5000 GPUs ($2M plus), $0 in the bank and the price of electricity at $0.01/kWh for moderate price gains and an average hash rate growth.

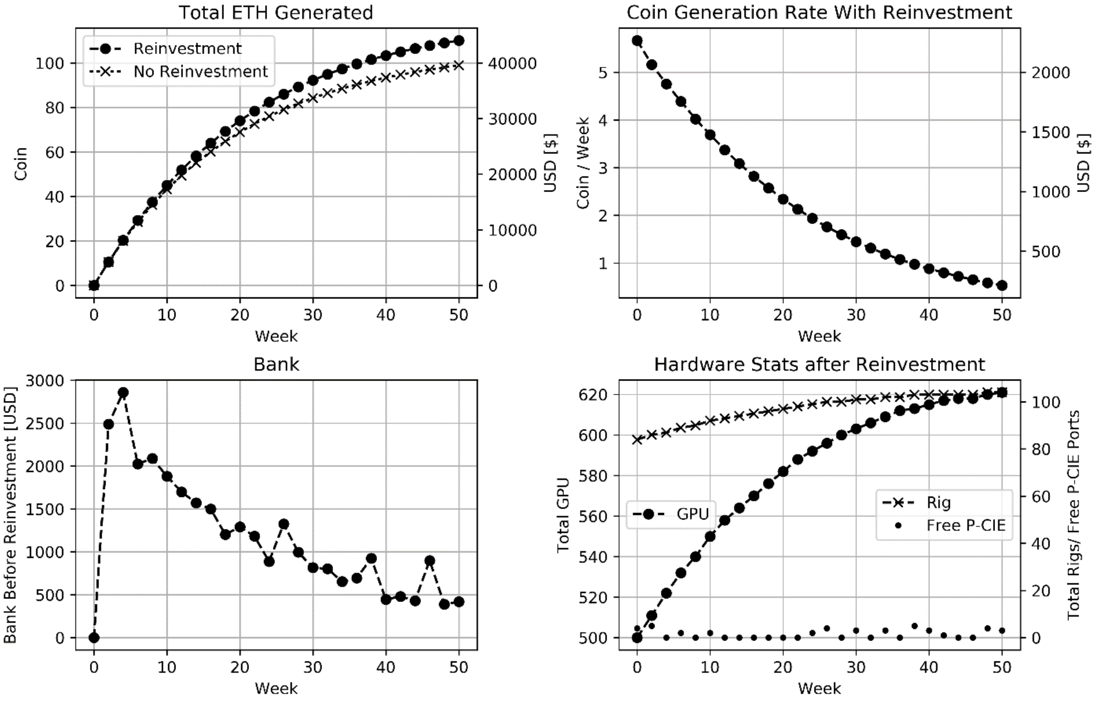


Figure 8. Organic Growth of an Ethereum Mining Operation: Dynamic Price Model (Moderate Gains) & Dynamic Hash Rate (Average) for $2M+ Investment and Power Costs at $0.1

This seems at odds with the practical knowledge that Ethereum mining is traditionally profitable. One of the model's assumptions regards the use of earned coins: by converting them into USD as soon as possible, we forego the secondary benefits of recognizing capital gains on invested earnings. Since our focus in on the mining implications of cryptocurrency alone, we feel comfortable with this simplification.

If we re-run the model again using a buy-and-hold strategy where miners recognize the appreciation in the value of their mined coins, the period beginning in 2015 was remarkably profitable for Ethereum miners (Fig. 9).

Figure 9. Ex-Post Ethereum Mining Profitability Analysis

In this retrospective scenario, Ethereum's break-even price hovers slightly above $200 based on the mining and the appreciation of the value of its coins. Why is our retrospective simulation profitable for miners but our predictive simulation not so?

First, the retrospective simulation incorporates an unprecedented growth in the value of Ethereum. If this value is sustainable, it's likely that mining will continue to be sustainable. However, incorporating a much slower price growth diminishes profitability substantially. Second, the rapid growth in hash rates experienced in the last year increased the traditional costs associated with mining. Modern computing power simply does not mine as much Ethereum as in prior years. Third, the dynamics of hash rate growth and the Ethereum point to a finite life for mining profitability with current market dynamics.

Forward-looking mining strategies were always initially profitable. It was only after an extended period (between 5 and 12 months) that mining strategies became unprofitable. This delay obfuscates the true long-term profitability of this strategy for many miners, making switching costs to other currencies more difficult. The customization of mining rigs means that the substantial hardware could go unutilized for other consumer purposes. Mining could be more profitable if there were a sustained period of stagnation (or even reduction) in the hash rate growth. However, miners have little incentives to *switch off* given the expensive infrastructure that has been invested for mining coins if future price gains are expected. When mining becomes unprofitable, mining rigs should gradually diminish and the hash rate should revert to whatever the market determines is palatable. We expect this to ultimately self-correct, but we lack a full understanding of the frictions that keep miners from engaging in more profitable strategies.

B. Robustness Cases and Revised Scenarios

Since our initial research, we have been closely monitoring and evaluating Ethereum's price and hash rate dynamics. Despite changes in price and demand, we found that our initial models were consistent with Ethereum's price and hash rate. During 2018, prices generally fell after attaining their apogee in the beginning of the year. Meanwhile, the hash rate growth did not diminish by the same margin. During much of 2020 (Figure 10), the hash rate returned to near-peak levels despite prices remaining much more consistent.

Modeling the hash rate has several implications. First, lower hash rates can potentially make mining more profitable as this reduces the need to supply additional hardware (GPUs) and improves the economics of scaling mining rigs. The hash rate changes between October 2018 and October 2020 averaged 1.5%; coincidentally, this was approximately the weekly growth during the most recent period for which there is data (Figure 10, bottom panel).

Figure 10. Historical Price and Network Hash Rate of Ethereum (top) and Weekly Change in Network Hash Rate (%) (bottom) through October 2020

However, following months of reduced hash rate growth, Ethereum reduced the *block reward* from 3 ETH to 2 ETH in February 2019. The economic benefit of lower hash rates was overwhelmed by the more adverse economic outcome of a lower block reward. Modeling these new values in both the fixed and dynamic models, we found that in all cases, profitability was substantially reduced. In moderate price scenarios, mining Ethereum was so unprofitable that it *never generated sufficient coins to purchase a second mining rig*.[17]

If we assume that Ethereum's reduction of block reward never happened, we can observe a different dynamic. Assuming a 1.5% average hash rate growth, we find that coin generation approaches a limit after approximately one year, when the financial resources of the mining operation are exhausted (Figure 11). Prices have to be extraordinarily high and hash rates consistently low to ensure organic mining profitability, an untenable economic situation for most cryptocurrencies.

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[17] Due to space constraints, these models are available from the authors upon request.

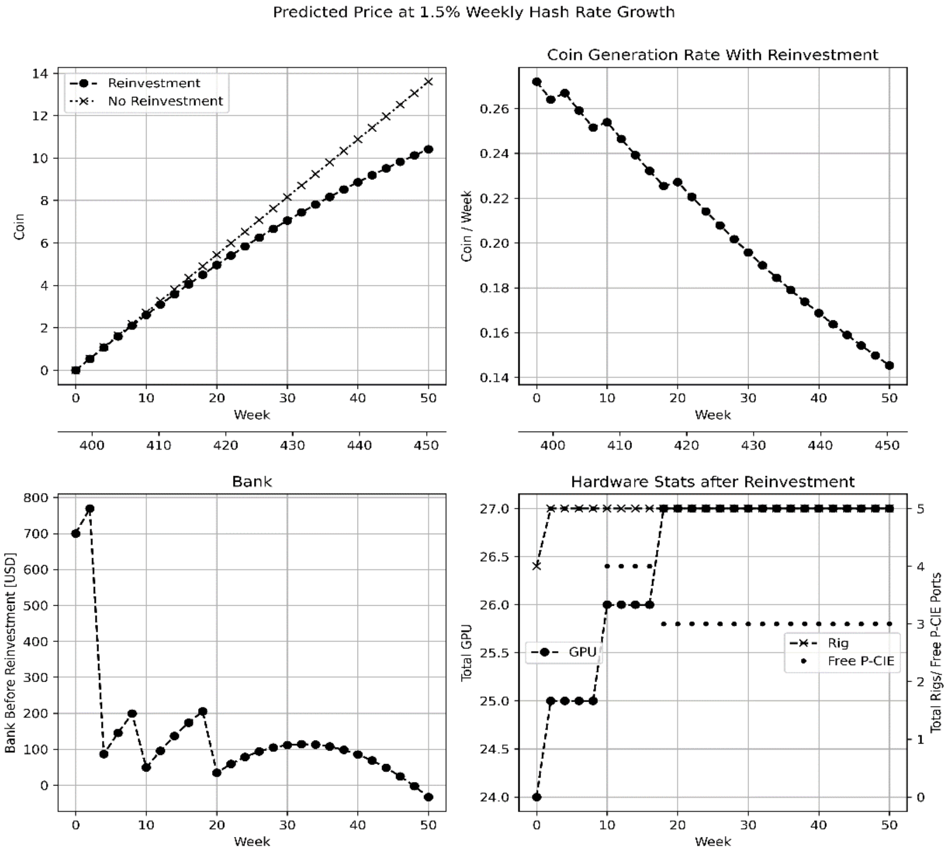

Figure 11. Organic Growth of an Ethereum Mining Operation: Dynamic Price Model (moderate gains), 1.5% Hash Rate (low) and power costs of $0.1/kW.

We further updated our price prediction model (Figure 12) to include data for 2019 and 2020 and extended that forward to 2022. The October 2020 price of $385 used in our robustness models is slightly below the $400 assumption we made two years prior and well within our original forecast estimation.

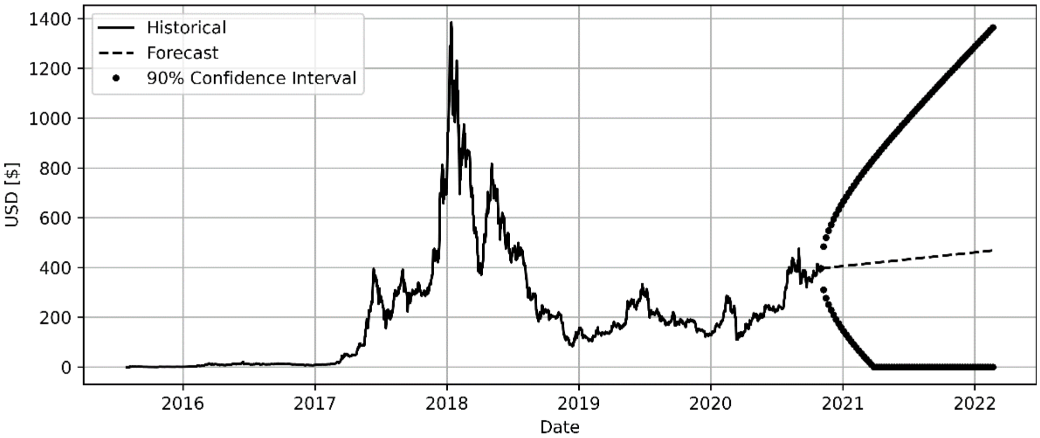

Figure 12: Updated Ethereum Price Prediction, November 2020–February 2022

B.1 Transaction Costs

During 2020, transaction costs became a much more important component of miner income than in prior periods,[18] reaching 40% of income in August 2020. Every computation that miners perform is compensated with *Ethereum Gas*, a measure of effort that includes all data operations from smart contracts to initial coin offerings. Ethereum gas provides incentives for miners to utilize and work with Ethereum and has been the subject of some research (see Grech et al. 2018). While the focus of this paper is the profitability of the mining operation itself, transaction costs merit some discussion as well.

The recent increases in gas prices have been attributed to widespread 'scaling' issues surrounding the Ethereum Virtual Machine.[19] *Decentralized finance*, or DeFi, applications rapidly expanded during 2020, providing cryptocurrency investors a series of financial instruments utilizing cryptocurrencies. However, the rapid increase in on-chain DeFi protocols temporarily drove up the transaction prices for Ethereum; these fees, in turn, substantially dropped during the month of October [20] as demand for DeFi products dropped. As the block reward is reduced, transaction fees become a proportionately greater source of revenue for miners. However, for Ethereum (or any cryptocurrency) to be ultimately successful, transaction fees must be as low as possible to encourage the greatest number of applications. Consequently, we anticipate that the current increase in transactions fees is temporal and that forthcoming technological protocols will ultimately reduce these fees.

V. Conclusion

In this paper, we described in detail the economics behind cryptocurrency mining in Ethereum. We find that despite historical precedence, current hash rate growth coupled with Ether's price growth

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[18] See https://www.theblockcrypto.com/linked/77126/over-40-of-ethereum-mining-revenue-in-august-came-from-fees

[19] See https://cointelegraph.com/news/ethereum-scalability-issues-exposed-as-high-gas-fees-stall-defi-boom

[20] See https://www.coindesk.com/ethereum-fees-plummeted-65-in-october-as-defi-volumes-fell-back-to-earth

currently make it difficult to generate profitable mining operations for more than a year utilizing organic growth.

Using the framework developed in this research, we created an ODE that describes the economics of cryptocurrency mining, adaptable to any mineable currency. This model can be used to investigate specific forms of cryptocurrency investment, such as miner-friendly cryptocurrency or novel forms of compensation for users. Our work is consistent with the increased presence of mining pools over the last few years. Without organically growing a mining operation, users can join consortiums of other users to increase their viability and generate consistent profits. If these strategies fail due to unfavorable economic conditions, the risks associated with concentrated mining operations (Luu et al. 2017) are likely to become more pertinent.

Many limitations for the proposed model exist (such as forecast price and hash rate, limited expense model, etc.) and an ex-post analysis finds that mining for Ethereum has been historically profitable. We posit that organic growth from mining operations can be profitable, but subject to two opposing caveats: first, the weekly growth in the network hash rate must approach 1%; second, the appreciation of cryptocurrency prices must be high enough to compensate for both power consumption and capital investment. Based on these findings, we developed a generalized ODE that can be used to model the profitability of a mining operation in any GPU-based cryptocurrency.

Future research will benefit from a deeper understanding of market frictions and behavioral analysis specific to cryptocurrencies. Further analysis of this type could look at the effects of novel mining compensation programs and updates to this research may appear as changes to mining compensations take place.

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