Submitted to Manufacturing & Service Operations Management

To Mine or to Trade? An Empirical Study of Bitcoin Exchange and Mining Markets

Chen Jin
School of Computing, National University of Singapore
disjinc@nus.edu.sg

Bowen Lou
School of Business, University of Connecticut
bowen.lou@uconn.edu

Jiding Zhang
NYU Shanghai and New York University
jiding@nyu.edu

Problem Definition: The recent upsurge in Bitcoin prices has raised interest in the investment of Bitcoin. However, faced with the investment options of mining and trading, the behavior of investors is not clear and requires a closer scrutiny of both the Bitcoin exchange market and the mining market. Specifically, little is known about the pattern of the interaction of the two markets. As mining significantly determines the reliability and security of the operation of the Bitcoin system, it's important to understand whether the trading market can influence the investment in mining.

Academic/Practical Relevance: Our research bridges the gap between operation management, finance and information technology, and makes contribution to studies in the operations and economics of cryptocurrency systems.

Methodology: Using a variety of datasets at a large scale, our empirical study uncovers the causal impact of the exchange market on the mining market. Specifically, we formulate an empirical framework that encompasses key dimensions of the Bitcoin exchange market, exchange rate and liquidity, and also jointly models the entry and exit of the mining market characterized by supply and demand of Bitcoin mining rigs. The framework also accounts for a holistic set of demand and supply shifters that exogenously alter the investment behavior in the Bitcoin mining market.

Results: We empirically show people tend to associate a higher valuation of Bitcoin with a higher Bitcoin exchange rate, and such exchange rate has significant impacts on both the supply and demand of the mining rigs. Furthermore, we demonstrate that the Bitcoin exchange market serves as a substitute for the Bitcoin mining market for investment. This substitution effect is particularly pronounced to those investors as potential entrants to the Bitcoin mining market.

Managerial Implications: Our study sheds light on the impact of the Bitcoin exchanges on the Bitcoin mining activities which contribute to the operation of the Bitcoin system.

Key words: Blockchain, Bitcoin, Mining rig, Trading

1. Introduction

Cryptocurrency has been rapidly evolving in recent years and is projected to exhibit greater financial investments (Forbes 2020a). As the first cryptocurrency released in 2008, Bitcoin has attracted significant attention among investors. Its financial valuation, the exchange rate against USD grows substantially over time.[1] At the time this article is written (January of 2021), one Bitcoin exceeds $30,000, 100 times greater than it was five years ago. It has also emerged as an important mean of performing financial transactions (Halaburda et al. 2020).

Contrary to fiat money systems with central authorities and other conventional digital currency systems such as national banks, Paypal and Visa, the Bitcoin system is designed as a decentralized system that is reliant on a peer-to-peer network and "Proof-of-Work" (PoW) protocol (Arnosti and Weinberg 2018, Jacob et al. 2019, Nakamoto 2019).[2] The operation of the Bitcoin system leverages a network of participants (known as miners) to verify and secure financial transactions (Montemayor et al. 2018). The core infrastructure supporting the operation of Bitcoin system without a central authority is a communal ledger that consists of a chain of blocks (known as blockchain) that can be accessed, modified, and updated by all the participants in the network (Iansiti and Lakhani 2017). The way to synchronize the ledger of transactions records and prevent the transaction records from being tampered is dependent on the amount of computing power spent by miners dedicated to continually verifying and recording the transactions over time (i.e. known as "mining") (Biais et al. 2019). Miners are required to solve complicated mathematical problems pertaining to cryptographic hash functions that deal with the transaction records contained in the block. The computing procedure requires financial investment and usage of powerful computing machines or mining rigs to conduct the mining activities. Whoever solves the mathematical problem

[1] The Bitcoin price, valuation and exchange rate are used interchangeably in this paper.

[2] The Proof-of-Work protocol has been proposed as a stable consensus mechanism for all the participants involved in the development of the infrastructure since 2008 (Nakamoto 2019). While in recent years, some other protocol, such as Proof-of-Stake (PoS) protocol, has also been designed and evaluated as an alternative for PoW (Saleh 2020), the major decentralized blockchain networks still adopt PoW protocol (Biais et al. 2019).

first has the right to create a new block recording verified transaction records to the communal ledger and also broadcast it through the network. All other miners can thus copy this new block to their ledger, thereby everyone in the network can have the same ledger. Therefore, a growing number of blocks can be dynamically chained, secured and updated by the miners without the need for central coordination (Constantinides et al. 2018). Accordingly, with more miners engaged in recording and verifying the authenticity of the transactions, the reliability and security can be guaranteed for the operations of the Bitcoin system such that its transaction records can be hardly tampered retroactively (Eyal and Sirer 2014, Huberman et al. 2017). A larger number of miners can help sustain the decentralization and egalitarian characteristic of the Bitcoin system as well as promote trust in the transaction verification and bookkeeping functions of the system (Böhme et al. 2015, Jacob et al. 2019).[3]

Although anyone can purchase appropriate mining machines online (in some e-commerce platform such as eBay and Amazon) and take part in the mining competition (Prat and Walter 2018), one notable aspect of the mining process is that it necessitates significantly high amount of computing resources for the miners to win the mining competition. As investors of Bitcoin, the miners need to invest in advanced hardware for computing (i.e. mining rigs) that may result in substantial electricity consumption (Croman et al. 2016, Huberman et al. 2017, Mishra et al. 2017).

To attract and incentivize miners to make the operation of the system reliable and secure over a longer period of time, the miners who can win the mining race are compensated with block rewards

[3] A handful of recent research work raises concerns about the decentralization nature of the Bitcoin's network represented by number of miners (Arnosti and Weinberg 2018, Jacob et al. 2019). Miners can partner together to form more centralized mining pools that allow miners to share their idiosyncratic risk of mining in exchange of a fair allocation of the mining rewards (Prat and Walter 2018). The study by (Cong et al. 2019) finds that the rise of centralized mining pools for risk sharing do not necessarily undermine the decentralization of Bitcoin's network. Individual Bitcoin miners in various mining pools can contribute to decentralization consensus and transaction verifications to make the Bitcoin system sustain. Thereby, Bitcoin investors can purchase mining rigs to gain mining reward and at the same time, contribute to the operation of the Bitcoin system.

associated with the newly created block on which they successfully address the math problem (Huberman et al. 2017). The transaction fee associated with the block is one type of block rewards, but its amount only accounted for approximately 2% of the block rewards (Prat and Walter 2018). The majority of the block rewards is in the form of new Bitcoins (6.25 Bitcoin for mining 1 Bitcoin block at the time of writing). The mining machine provides opportunities for the miners to continue contributing to the operations of the Bitcoin system and simultaneously earn more block rewards if they outperform their peers. Although every four years Bitcoin halving event takes place that the Bitcoin block rewards given to the miners are cut in half, ceteris paribus, if the price of Bitcoin (i.e., exchange rate of Bitcoin against USD) can increase by an order of magnitude, the miners can possess Bitcoins with greater monetary value that can potentially mitigate the cost of investing in computing hardware and electricity, and even gain more payoffs. In this regard, as the Bitcoin price can work as a signal of expectation of Bitcoin value, it may affect the investor's behavior in terms of the entry and exit of the *mining market*, where mining service can be offered for the operation of the Bitcoin system in exchange for block reward (Prat and Walter 2018). The investors can purchase a mining machine to join the mining market or resell the machine to exit the market.

In the meantime, when faced with a high Bitcoin price, investors with Bitcoin can also choose to trade Bitcoin for other currencies alternatively without incurring the continual computing costs when investing in mining. Performing Bitcoin exchanges in a relatively short period of time may render even lower barriers for the investors to earn payoffs through Bitcoin, especially for those investors without Bitcoin but interest in the Bitcoin markets. They can join the Bitcoin *exchange market*, freely purchasing to acquire more Bitcoins or selling the Bitcoin they own for fiat money to perform arbitrage. This can be strengthened by the high liquidity of the exchange market where the investors can make direct exchanges quickly and with minimal cost to reap greater benefits (Ho 1993, Li and Wang 2017, Amihud and Mendelson 1988). Accordingly, the condition of the exchange market can significantly direct investment decision makings. Faced with both Bitcoin mining and exchange markets, the behavior of the investors is thus not clear: for an investor without

Bitcoin, should she mine or purchase Bitcoin through trading? After she obtains Bitcoin, should she continue to mine or sell the Bitcoin through trading? These investment decisions require a closer scrutiny of both the mining and exchange markets for Bitcoin. However, the interaction between the two markets is not well-studied. Little is known about the pattern of the interaction of the two markets. In particular, as mining significantly determines the reliability and security of the operation of the Bitcoin system, it's important to understand whether the trading market can influence the investment in mining.

Therefore, in this study, we exam the following research question: how do the Bitcoin exchange market and mining market interact with one another? Since the investment in the mining market requires continual time and resource spending that may lead to acquirement of more new Bitcoins and associated rewards in a long run, the mining market for Bitcoin could be contingent on the conditions of the exchange market. As we focus on the behavior of players interested in investing in the two markets, we primarily probe into the impact of the exchange market conditions on the investors' behavior in the mining market for Bitcoin. Specifically, we investigate how Bitcoin exchange rate and liquidity, the two pivotal dimensions of the exchange market, can affect the investors' behavior in terms of entry and exit of the mining market.

To address our research question, we undertake large-scale empirical analyses to systematically examine the relationship between the two markets, the market for mining and the market for trading Bitcoins. While each market has been studied individually, it is still elusive how the two markets interacting with each other shape investors' decision makings (Li and Wang 2017, Prat and Walter 2018). As the mining process can constantly guide the state of the communal ledge to enhance reliability and security of the Bitcoin system, it's imperative to study whether the market condition for Bitcoin exchanges can significantly affect the market for mining Bitcoin. To this end, we consolidate a number of large-scale datasets from disparate sources. Specifically, we garner Bitcoin trading records from a premier Bitcoin exchange platform as well as mining rig transaction data from a leading e-commerce platform over more than one-year period. During that time period, Bitcoin price has undergone substantial rise and fall. Thus, we can compile a unique dataset that can comprehensively portray the investors' behavior in both the mining and exchange markets for Bitcoin. To empirically parse out the causal impact of Bitcoin exchange rate and market liquidity on the mining activities over the communal ledge of the Bitcoin system, we develop an empirical framework that can jointly model the supply and demand of computing machines for mining Bitcoins, accounting for a holistic set of demand and supply shifters that exogenously alter the investment behavior in the Bitcoin mining market. The demand of the mining rig can capture the entry decisions of the investors into the mining market, while the supply of the mining rig can be referred as the investors' decisions of exiting the market. We empirically show people tend to associate a higher valuation of Bitcoin with a higher Bitcoin exchange rate, and such exchange rate has significant impacts on both the supply and demand of the mining rigs. Furthermore, we demonstrate that the exchange market serves as a substitute for the mining market for Bitcoin enthusiasts to conduct investments. This substitution effect is particularly pronounced to those investors as potential entrants to the Bitcoin mining market. The findings are robust to a variety of alternative model specifications, additional controls related to the dynamics of the general financial markets, and operationalizations of key variables that capture the activities in the Bitcoin mining and exchange markets. Overall, our study systematically quantifies the impact of trading in the Bitcoin exchange platforms on the Bitcoin mining investment which can contribute to the reliability and security in the operation of the Bitcoin system.

Our study makes a number of contributions to research and practice. First, our study contributes to the burgeoning literature at the intersection of operations management (OM), finance and information technology. In particular, it speaks to recent call of more research studies on the operation of the blockchain supported system and financial markets (Babich and Hilary 2020). Our study can enrich the understanding of dynamics that take place in the two markets, the mining and exchange markets that become integral part of the operation of the Bitcoin system (Huberman et al. 2017). In addition, we extend the recent development in the strand of research studies about the economic value of blockchain as an emerging digital infrastructure of cryptocurrency systems and financial services (Constantinides et al. 2018, Hendershott et al. 2017). While the bulk of the literature has primarily studied the technical aspects of protocol improvements and design of blockchain technologies, which were largely informed by theoretical research studies on the Bitcoin system (Narayanan et al. 2016, Risius and Spohrer 2017, Tschorsch and Scheuermann 2016), there is a scarcity of systematic empirical studies on the economic factors that can shape the operation of the Bitcoin system where the blockchain maintained by mining activities serves as building block and core infrastructure. Our study intends to fill this research gap.

Second, while there has been considerable progress in knowledge development in the strand of research on the Bitcoin exchange and mining markets, the interplay of the two markets is underexplored (Li and Wang 2017, Prat and Walter 2018). One of key contributions of our study vis-à-vis prior studies lies in a comprehensive empirical framework that can study the investment decision and behavior of players in the two markets. To the best of our knowledge, our study is one of the first to undertake a large-scale empirical study to causally identify the economic impacts of the exchange market on the market for mining that can contribute to the enhancement in the operation of the Bitcoin system in a long run.

This paper also renders important managerial implications to Bitcoin investors as well as blockchain practitioners. The documented effect of Bitcoin price can significantly influence the mining market for Bitcoin, and in turn, may also shape the operation of the Bitcoin system maintained by the miners. In particular, the Bitcoin exchange rate can cause substantial changes in the behavior of investors characterized by their entry and exit in the mining market. Furthermore, our study contributes to the ongoing debate about whether the bubble in Bitcoin price and the resulted turbulence in the exchange market are good or not to the development of the Bitcoin system (Wei and Dukes 2020, Acheson and Dantes 2020). As the operation of the Bitcoin system by and large relies on the contribution of miners, without any assumptions of investors behavior and expectations in the exchange and mining market, our data-driven study provides more nuanced results, suggesting that the price surge can incentivize the investment in mining machines that can potentially benefit the operation of the system, whereas the sudden drop in price may still be detrimental to the system.

The rest of the paper proceeds as follows. Section 2 conducts literature review and highlights the position of our study in the literature. Section 3 discusses our hypotheses. Section 4 introduces our datasets collected from disparate sources for the empirical study at a large scale. Section 5 describes our empirical modeling framework and econometric estimation approaches. Section 6 and section 7 discuss the results derived from our proposed framework, and offer concluding remarks.

2. Our Position in the Literature

The development and application of the blockchain technologies have received a great deal of attention, not only from industry practitioners, but also from scholars across a variety of academic disciplines (Babich and Hilary 2020, Constantinides et al. 2018, Halaburda et al. 2020, Risius and Spohrer 2017). Our paper contributes to the strand of literature at the operation management (OM), finance and technology interface. There is a wide variety of blockchain based applications in OM contexts including platform operations (Chod et al. 2019), inventory management (Gan et al. 2019) and supply chain finance (Chod et al. 2020, Cui et al. 2020, Lee et al. 2019, 2020). Our study is mostly linked to the operation of the blockchain supported Bitcoin system, and financial markets that hinge on the technological developments of blockchain (Babich and Hilary 2020, Huberman et al. 2017). Specifically, past research studies in the following two areas lay out the foundations of our study.

2.1. Role of Mining in the Operations of the Bitcoin System

Bitcoin is recognized as both an economic instrument of value transaction and a technology artifact derived from blockchain technology (Li and Wang 2017). Blockchain, organized as a chain of blocks, has grown in prominence for the Bitcoin system (Glaser and Bezzenberger 2015, Morisse 2015, Tschorsch and Scheuermann 2016). It serves as the foundational digital infrastructure, keeping track of transaction records over decentralized networks (Iansiti and Lakhani 2017). Participants in the networks called miners continually spend computing resources to solving cryptographic problems for verifying and recording the transaction records over time to improve the operation of the Bitcoin system (Arnosti and Weinberg 2018, Biais et al. 2019, Huberman et al. 2017). Through a consensus mechanism enabled by the Proof-of-Work protocol, miners with the right to validate new transactions can update the blockchain for the Bitcoin system without the need for central coordination (Constantinides et al. 2018). The Bitcoin system with the underpinning blockchain infrastructure also mainly use block reward to attract the miners to maintain consistent copies of the transaction. Thus, one important way to invest in Bitcoin is through mining, which can contribute to the reliability and security of the Bitcoin system (Eyal and Sirer 2014, Huberman et al. 2017).

2.2. Bitcoin Exchange Market

The Bitcoin exchange market is also an indispensable component for the study of the Bitcoin system. With the rise of online exchange platforms, investors can trade Bitcoin for other currencies in a fast way. There is a growing stream of the literature on Bitcoin exchange market. For example, Cheah and Fry (2015) argue that Bitcoin exhibits speculative bubbles, and provide empirical evidence that the fundamental price of Bitcoin is zero. Glaser and Bezzenberger (2015) examines the intentions of investors in the Bitcoin exchange market and is concerned about the new investors' adoption of Bitcoin limited to trading on exchanges. Li and Wang (2017) models the Bitcoin exchange rate and empirically investigates factors that may affect investment decision makings in the context of the Bitcoin exchange market.

Our study complements the above literature at OM, finance and technology interface in two principal ways. First, while there is a number of empirical studies focused on the exchange and mining markets (Li and Wang 2017, Prat and Walter 2018), we still lack a cohesive empirical framework that can examine investment decision makings in both of the markets and the underlying pattern of their synergy. As one unique feature of the Bitcoin system that investors can obtain more Bitcoins through mining to maintain its reliability and security, our study examines how the conditions of the exchange market can influence the investment decision makings in the mining market that requires continued time and resource spending for the operation of the Bitcoin system. Second, through our proposed framework, we also offer more nuanced ways of investigating each of the two markets. We disentangle demand and supply of the machines designed for Bitcoin mining, while also taking into considerations two important dimensions of the exchange market, Bitcoin exchange rate and liquidity, which may have differing effects on the investors' behavior with respect to the entry and exit of the Bitcoin mining market.

3. Hypotheses Development

The purpose of this paper is to explore the impact of the conditions of the Bitcoin exchange market on investors' behavior in Bitcoin mining market. We first clarify our definition of the market condition and investor behavior.

Our first main variable of interest to characterize the Bitcoin exchange market is Bitcoin exchange rate (i.e., the market price of Bitcoin). From the practical standpoint, market price is a first-order metric to describe the quality of a market.[4] It has also been a long tradition in the finance literature to recognize the signaling effect of market price of an asset, and view it as a way to convey information about the value of an asset (Amihud and Mendelson 1982). In our setting of Bitcoin, if the market is adequately efficient, a higher exchange rate implies higher values of Bitcoin. On the other hand, if information asymmetry and frictions are pervasive and persistent, exchange rates can be misleading in reflecting Bitcoin's true value. A lower exchange rate in this case can imply the undervaluation and hence arbitrage opportunities of Bitcoin.

A second important facet of describing an asset and market condition is liquidity. Liquidity, or marketability, are important attributes of any financial instrument. It reflects the level of difficulty in trading the asset (Amihud and Mendelson 1988). In practice, professional investors spare great effort to tailor portfolios to accommodate their time horizons and liquidity preferences (Amihud

[4] The NYSE authorities view "price stability" and "price continuity" as desirable attributes of market quality (Amihud and Mendelson 1982).

and Mendelson 1986). Liquidity is usually measured through trading volume (Brennan et al. 1998, Angel et al. 2004). Hence, our second variable of interest is the total trading volume of Bitcoin.

As for the investment in the market of mining Bitcoin, we focus on the entry/exit behavior, which is the premise to mining activities that can continually contribute to the Bitcoin system. Practically, we study the demand and supply of mining rigs with the following reasons. To enter the Bitcoin mining competition, the investors have to first purchase a mining rig. Given most rigs are designed for Bitcoin mining and have little use in other activities, the demand of mining rigs effectively reflects the desire for entry of the Bitcoin mining market (Prat and Walter 2018). On the market exit side, the logic is similar: when investors decide to exit the mining competition, the best way to "salvage" the mining rig is to sell it. Moreover, very few manufacturers sell directly on e-commerce platforms. In other words, owners of the listings of mining rigs are mostly investors. Therefore, the exit behavior is captured by the supply of the mining rigs.

Next, we outline our hypotheses. Section 3.1 discusses the impact of the exchange market on the demand side of mining rigs, and Section 3.2 discusses the impact on the supply side.

3.1. Hypotheses on Mining Rig Demand

We discuss both the exchange rate and total trading volumes on the demand side of mining rigs.

3.1.1. Impact of Exchange Rate

Hypothesis 1a: Bitcoin exchange rate has a positive effect on mining rig demand.

Hypothesis 1b: Bitcoin exchange rate has a negative effect on mining rig demand.

The direction of the impact of the Bitcoin exchange rate on mining rig demand can be determined by the belief of investors on the efficiency of the exchange market. If investors believe the market is efficient and hence Bitcoin exchange rate correctly reflect its value, it can be worthwhile to perform investment when the Bitcoin exchange rate is high. In this case, investors are optimistic about the operation of the Bitcoin system bolstered by its underlying blockchain infrastructure, which encourages a long-term investment through mining. Increased mining activities can improve the reliability and security of the blockchain infrastructure (Huberman et al. 2017), which may result in an even higher value of Bitcoin. This leads to our Hypothesis 1a. On the other hand, if the investor believes that a higher exchange rate is caused by overvaluation, the investor might decide to not invest in Bitcoin after all, leading to a lower demand for mining rigs, which is our Hypothesis 1b.

3.1.2. Impact of Total Trading Volume

Hypothesis 2: Bitcoin total trading volume has a negative effect on mining rig demand.

The impact of total trading volume on mining rig demand is closely related to the substitution pattern in investing, i.e., whether investment through mining can crowd out investment through trading in the Bitcoin exchange market and vice versa. There can be multiple causes of such substitution, with the most common reason pertaining to investors' budget constraints. Under substitution, with a higher trading volume and hence higher liquidity, investors are able to obtain Bitcoin with minimal cost in a very short period of time. As a result, a short-term investment through active trading in the Bitcoin exchange market is encouraged and hence lowers the demand for mining rigs. Conversely, when the trading volume is low, it is costly for investors to obtain Bitcoin in the Bitcoin exchange market, and mining as a long-term investment is more attractive with controllable cost and less risk (Prat and Walter 2018).

3.2. Hypotheses on Mining Rig Supply

Similar to our discussions on the demand side of mining rigs, we now analyze the supply side. Note that most analysis on the supply side mirrors our analysis of the demand side, but the exit decisions from the Bitcoin mining market are made by more experienced investors who have better information of Bitcoin mining. Therefore, results might not be exactly opposite to those on the demand side.

3.2.1. Impact of Exchange Rate

Hypothesis 3a: Bitcoin exchange rate has a negative effect on mining rig supply.

Hypothesis 3b: Bitcoin exchange rate has a positive effect on mining rig supply.

The reason why Hypothesis 3a (3b) holds is similar to the logic for Hypothesis 1a (1b). Under a high valuation of Bitcoin and its infrastructure, the desire to exit is less and hence the supply of mining rigs is high. Hypothesis 3(a) is true when the experienced Bitcoin miners as investors associate optimism about the nature of Bitcoin with a higher exchange rate, and Hypothesis 3(b) is true when those investors believe high exchange rates are results of overvaluation.

3.2.2. Impact of Total Trading Volume

Hypothesis 4: Bitcoin total trading volume has a positive effect on mining rig supply.

Hypothesis 4 mirrors Hypothesis 2, with higher desire of mining implies lower intention to exit and reduced supply of mining rigs for those more experienced miners as investors. The justification of Hypothesis 4 is omitted for brevity.

4. Data and Measurement

Our study necessitates datasets that characterize both Bitcoin exchange and mining markets. We combine datasets from four sources for our empirical study: 1) mining rig transaction data from eBay; 2) Bitcoin exchange data from CoinMarketCap[5]; 3) data about electricity consumption regarding Bitcoin mining from Cambridge Centre for Alternative Finance; 4) traditional financial market data from Yahoo Finance.[6]

4.1. Mining Rig

Our dataset of mining rigs is collected from eBay, a leading e-commerce platform based in the United States. The platform operates markets for a large variety of merchandise including mining rigs. For each rig to be sold, a seller posts a listing (with a unique webpage associated), outlining the asked price and detailed information about the rig (oftentimes including the condition, brand, tech specifications, a short description and a few pictures). Potential entrants to the mining market, i.e., buyers who seek purchasing mining rigs, can find all listings in the search page of mining rigs,

[5] `https://coinmarketcap.com/`

[6] `finance.yahoo.com`

and decide whether to purchase a certain rig upon reading the listing. It is worth noting that very few sellers of mining rigs are the manufacturers of these rigs or authorized dealers. Such a unique feature provides us with an excellent opportunity to study the entry and exit behavior of Bitcoin investors, as mining rig purchasing behavior closely ties to entry of mining, and selling behavior ties to exit.

Our strategy of obtaining the sales records of products is based on the following observation. We notice that once a transaction of a product is completed on the platform, the listing is removed from the search page, with the listing's unique webpage still existing but a sign of "Sold" is displayed. Hence, we constantly compare the listings shown in the search page. We check whether the listings are marked as "Sold" when they are removed. We record the price of these sold rigs and the date of sales as well. The price and quantity of the sold rigs are used in our empirical modeling framework.

Our dataset is comprised of over 160 thousand listings from October 16, 2019, to December 31, 2020.[7] We focus on the listings where sellers are based in the United States, which covers around 70% of the entire market.

4.2. Bitcoin Exchange Market

There are many online cryptocurrency trading venues where investors can trade their Bitcoin for other currencies. The Bitcoin exchange rate and total trading volume are collected from CoinMarketCap website that aggregates investors' trading information from many Bitcoin exchange venues on a daily basis. Bitcoin exchange rate of each day is calculated as the average of the "open" price and the "close" price.[8]

In Figure 1, we plot the daily Bitcoin price as Bitcoin exchange rate against USD and total trading volume as number of Bitcoin exchanged during our observation period between October 16, 2019 and December 31, 2020. The Bitcoin price experienced a significant drop around March

[7] We do not have listing data from September 1, 2020 to October 20, 2020 due to a change in the website infrastructure of the platform we study.

[8] In CoinMarketCap's definition, "open" refers to the earliest data in range (UTC time), and "close" refers to the latest data in range (UTC time), see `https://coinmarketcap.com/currencies/bitcoin/historical-data/`.

and April 2020 but the total trading volume experienced a spike, when the COVID-19 pandemic hit the exchange market. After that period, the price steadily increased from July to October 2020, and then skyrocketed in the last two months of 2020.

4.3. Electricity Consumption

Miners invest in mining rigs for computing to solve mathematical problems so that the operation of the bitcoin system can be maintained. This computing process results in substantial electricity consumption (Croman et al. 2016, Huberman et al. 2017, Mishra et al. 2017). The electricity consumption dataset used in our study is retrieved from Cambridge Bitcoin Electricity Consumption Index (`https://cbeci.org/`). It accounts for a plethora of factors such as mining equipment efficiency and electricity cost to estimate the electricity consumption regarding Bitcoin mining. Figure 2 displays the estimated Bitcoin electricity consumption over the timespan that overlaps with our mining rig data.

4.4. Financial Indices

We also include some financial index to account for the general trend of financial markets. Specifically, we obtain financial information about S&P 500 and gold investment from Yahoo Finance. The financial index we use is the S&P 500. It is one of the most commonly followed equity indices, as it covers a wide range of industry sectors including information technology, consumer staples, real estate and financials (Indices 2019). Besides S&P 500, we also consider gold investment in our model due to the similarity between gold and Bitcoin. The supply of Bitcoin and gold is divisible and has a natural limit. They are both considered as speculative investments. Historically, investors used to invest in gold to hedge against stock volatility. Starting from 2019, the stock market displayed enormous volatility and the Bitcoin exchange rate increases 10 times, which advocates the idea of “Bitcoin is the digital gold” (Forbes 2020b).

5. Empirical Framework

In this section, we propose an empirical modeling framework that captures both the demand and supply of mining rigs in order to disentangle the causal effect of Bitcoin exchange market on the mining market. The investors' entry and exit of the mining market can be characterized by supply and demand of Bitcoin mining rigs. To examine both the demand-side and the supply-side effect, we adopt a simultaneous-equations approach that can model both the mining rig demand and supply. The system of equations is then be jointly identified and estimated. In what follows, we formally lay out the model and discuss its key features. Then, we discuss our identification and estimation strategy.

5.1. Model Specification

We use $RigQuantity_t$ to denote the quantity of mining rigs purchased or sold in period t. The model is formally defined as follows:

$$\begin{aligned} RigQuantity_t = {} & \alpha_d + \beta_d RigPrice_t + \delta_d[BitcoinTradingVolume_t, BitcoinPrice_t] \\ & + \gamma_d DemandShifters_t + \omega_d Controls_t + \epsilon_{dt} \qquad \text{(Demand)} \\ RigQuantity_t = {} & \alpha_s + \beta_s RigPrice_t + \delta_s[BitcoinTradingVolume_t, BitcoinPrice_t] \\ & + \gamma_s SupplyShifters_t + \omega_s Controls_t + \epsilon_{st} \qquad \text{(Supply).} \end{aligned}$$

Specifically, we examine a comprehensive set of determinants of demand and supply of mining rigs. First, the price of mining rigs ($RigPrice$) is considered in the model as in most product markets, the price of a product usually constitutes first-order effects on both its demand and supply. The associated coefficients, β_d for demand and β_s for supply, capture the price elasticity on the demand of rigs and its supply, respectively.

Second, we take into account the conditions of the Bitcoin exchange market. The marginal effect of such market conditions on the demand and supply of mining rigs sheds lights on the role of the exchange market in Bitcoin mining, and is the main effect of interest in this paper. The two key metrics of interest in our model are the exchange rate of Bitcoin ($BitcoinPrice$), and the total trading volume of Bitcoin ($BitcoinTradingVolume$).

Third, we add various controls ($Controls$) into our model in order to derive unbiased estimates.

- Electricity consumption: As Bitcoin mining results in consuming electricity, we control for Bitcoin electricity consumption index, which is an estimate of the total electricity consumption of the Bitcoin network.

- Financial indices: Financial indices also should be controlled as they could affect investors' outside options and their budget for Bitcoin investment. We control for two commonly used financial indices, the gold volume, and the S&P 500 volume.

- Day-of-week: We also include a dummy variable that indicates each day of week to control for the weekly seasonality effects. Weekly seasonality might exist because Bitcoin mining is potentially affected by both investors' working schedules and trading activities in other financial markets (e.g., whether the market is open for trading).

5.2. Identification Strategy

5.2.1. Identification of Demand and Supply with Equilibrium Price and Quantity

The typical difficulty of identifying a simultaneous equations system is that we can not observe the entire demand and supply, but rather the equilibrium price and quantity. Therefore, identification is based on such equilibrium. In our case, we take the average price of all mining rigs sold in a day as the equilibrium price, and the total sales of mining rigs as the equilibrium quantity.

In a simultaneous equations system, given only the equilibrium prices and quantity are observed, the demand curve and the supply curve can be rotated without affecting the equilibrium price and quantity. In other words, mere information about the equilibrium (and some factors that may affect both sides) can not uniquely pin down the demand and supply curves, imposing identification issues.

To resolve such issues, various shifters are needed. A demand (supply) shifter $DemandShifters$ ($SupplyShifters$), is an exogenous variable that affects the demand (supply), but does not affect the supply (demand). The intuition behind using such shifters can be summarized as follows: with shifters, there are indeed multiple (exogenous) circumstances, and hence multiple equilibrium points to pin down the curves. For example, a binary supply shifter necessarily implies at least two supply curves to intersect with the demand curve, resulting in two equilibrium price-quantity pairs. A demand curve can thus be determined by connecting these two points. In general, supply shifters identify the demand curve, and vice versa. We take advantage of exogenous policy changes to construct two demand shifters and two supply shifters.

Demand Shifters: The first demand shifter is Chinese government's removal ban of cryptocurrency mining (after November 1, 2019). Since 2017, rumors about the Chinese government considering banning cryptocurrency mining have been swirling among miners in China. In Nov. 2019, the National Development and Reform Commission (NDRC) confirmed that cryptocurrency mining has been removed from a list of activities set for elimination.[9].

Without the ban, Chinese investors are able to mine Bitcoin freely, incurring less hassle cost, and thus the event increases the demand of mining rigs for Chinese investors. On the other hand, it does not affect the exit behavior for Bitcoin miners in the United States (note that our analysis is performed based on sales of mining rigs shipped from the United States). Therefore, such event can serve as a demand shifter.

The second demand shifter is Chinese government's limiting the electricity usage due to a power shortage (after December 14, 2020). In Dec. 2020, China has experienced an unusual electricity supply shortage due to the trade war with Australia on coal import. Factories in some provinces were notified to operate only part-time and companies were ordered not to heat the offices unless temperatures are close to freezing. This electricity supply shortage generates a negative impact on the mining rig demand.[10] Following the same logic of exclusion on geography, this event has no effect on US investors' exit decisions, but a reduction of electricity discourages mining where electricity serves as a major input, and demand is reduced.

Supply Shifters: The first shifter is related to many countries' closing their borders for merchandise shipments due to COVID-19 (from April 3, 2020 to July 22, 2020). In light of COVID-19

[9] https://cointelegraph.com/news/bullish-for-Bitcoin-china-scraps-plans-to-ban-cryptocurrency-mining

[10] https://www.nytimes.com/2020/12/21/world/asia/china-electricity-coal-shortage.html

pandemic, most countries have tightened their border control in April 2020, which has a substantial impact on international delivery. In particular, products shipping from the U.S., have been delayed or denied due to the severe situation in the U.S. By July 2020, some countries updated their border policies and started to allow packages shipping from the U.S. to enter their countries.[11][12] Closings of borders do not affect the demand for Bitcoin mining rigs, but sharply reduces supply: to ship these mining rigs to buyers (if it is ever possible), sellers have to incur higher shipping costs. This, such an event is a supply shifter.

The second shifter is eBay's increasing its zero-insertion fee listings (after August 1, 2020). Due to COVID-19, eBay removed the listing fee from the sellers in April 2020. On Aug. 1, 2020, eBay has extended the free listing fee promotion to all sellers on the platform we study, and the specific number of months that are eligible for this promotion is based on the sellers' store subscription level.[13] The new policy only applies to the sellers on the platform and hence does not affect demand. On the supply side, it slightly encourages the supply of mining rigs, but also encourages business on eBay and hence discourages active trading in the Bitcoin exchange market, as both are labor-intensive. In this regard, investors might decide to stay in the Bitcoin mining market (as mining is capital-intensive rather than labor-intensive), and supply less mining rigs.

In our model, we define shifters as binary variables, which take the value of one if the policy change is effective, and takes the value of zero otherwise.

5.2.2. Remarks on Endogeneity Concerns There are two major endogeneity concerns with our model, reverse causality and omitted variable bias. In what follows, we discuss why our model can be immune from both concerns.

[11] `https://community.ebay.com/t5/Announcements/Update-international-shipments-during-COVID-19/ba-p/31090853`

[12] `https://community.ebay.com/t5/Announcements/Advising-you-about-shipments-during-COVID-19/ba-p/30817957`

[13] https://community.ebay.com/t5/Announcements/We-re-increasing-monthly-zero-insertion-fee-listings-for-most/ba-p/31074844

Reverse Causality: Given the close connection between the Bitcoin exchange market and mining behavior, the entry and exit of the mining market (captured by the demand and supply of mining rigs) can also causally affect equilibrium outcomes in Bitcoin exchange market (captured by the exchange rate and total trading volumes). However, we note that there is typically a time lag between the purchase of mining rigs and being rewarded block rewards through mining. Such time lags mainly include the time taken for solving complicated math problems in Bitcoin mining, as well as the shipping time of mining rigs. Accordingly, the demand of mining rig does not affect our variables of interests with respect to the exchange market and other control variables in the same time period. Similarly, on the supply side, the supply of mining rigs can hardly affect the exchange market on the same day, although it is more likely to affect Bitcoin exchange in the future. Thus, reverse causality does not exist using our current model specification.

Omitted Variable Bias: One might also be concerned that the Bitcoin exchange rate and trading volume are correlated with factors that can also drive the demand and supply of mining rigs, thereby leading to the omitted variable bias. Such factors can be investors' beliefs of the Bitcoin infrastructure and the exchange market. Since such beliefs are usually formed from the risk and return of the Bitcoin exchange market, we add the following additional controls in both the demand equation and the supply equation: the lagged (for one day) monthly percentage return and volatility of the Bitcoin exchange market. They serve as proxies for factors that can jointly drive the trading behavior and entry/exit of mining. The volatility of the Bitcoin exchange market is derived using the absolute return residuals method proposed in Blasco et al. (2012).

5.3. Estimation

We apply the Three-Stage Least Square (3SLS) (Zellner and Theil 1962) method to estimate our proposed model. 3SLS is a standard approach of estimating simultaneous equations systems. Compared to other estimation methods including Indirect Least Squares (ILS) or Limited Information Maximum Likelihood (LIML), 3SLS is more efficient in larger samples (Takeshi 1985).

6. Result

Table 1 shows some descriptive statistics of all the variables used in our modeling framework. The average quantity of mining rigs is approximately 418, and their average price is over $1,800. On the side of Bitcoin exchange market, the average Bitcoin exchange rate against USD is slightly greater than $10,000, and the average trading volume is above 3 million reflecting high market liquidity during our observation period.

6.1. Demand of Mining Rigs

Table 2 and Table 3 reports the results of the demand of mining rigs. The estimation results are consistent. Table 3 uses the lagged monthly return and volatility of the Bitcoin exchange market to address endogeneity concerns while Table 2 not. Our results show that all else being equal, the rig price is negatively correlated with the demand, and the effect is statistically significant across all different model specifications. This is expected and consistent with standard economic theory. For a mining rig with price around $1,900 (close to the mean of mining rig prices from our data), a 5% increase in its price (i.e., $95) leads to a decrease in demand from 9 to 14 units depending on slightly different model specifications. Such price elasticity is relatively low (especially compared to the elasticity on supply), implying that potential investors might not value the price the rigs as much, but rather pay more attention to the future payoffs with mining rigs.

Next, we examine the impact of our variables of interest that characterize the exchange market condition – Bitcoin exchange rate and total trading volume. Other factors held constant, we observe a positive effect of Bitcoin exchange rate on demand, supporting Hypothesis 1a. The result suggests that investors who are relatively new to Bitcoin mining tend to believe in the efficiency of the market, and a higher exchange rate of Bitcoin strengthens their belief for the value of Bitcoin and the blockchain infrastructure. Regarding the magnitude of such effect, by the time this paper is written, the daily increase in Bitcoin exchange rate can reach as high as around $3000. This can translate into an increase in mining rig demand of more than 200 units (up to around 300 units). Furthermore, the effect of Bitcoin trading volume on mining rig demand is negative and significant, supporting Hypothesis 2. The result indicates the substitution between long-term investing through Bitcoin mining, and short-term investing through trading in the exchange market. Our results are also robust to different operationalization of the variables that characterize the liquidity of the exchange market (Brennan et al. 1998, Angel et al. 2004).

In addition, we observe that the total electricity consumption associated with Bitcoin mining has a negative effect on the demand of mining rigs. As a major cost of mining, such effect is also expected. We also find that our demand shifter of the restriction on electricity negatively impact the demand of mining rigs. A restriction on electricity substantially decreases the expected return of mining, and thus, discourages entry of the mining market. The significance of our demand shifter also implies a strong identification of the supply curve.

6.2. Supply of Mining Rigs

We report our results of the supply of mining rigs in Table 4 and Table 5. The estimation results are consistent across the two tables, suggesting that our proposed framework is immune to the omitted variable bias caused by the Bitcoin exchange market. All else being equal, we document a positive effect of mining rig price on mining rig supply as expected. It is worth noting that the magnitude of such elasticity is much higher than the counterpart on the demand side. This is because when current miners decide to exit the market and salvage the mining rig, there is no future value associated with the rig, and hence the price of rigs is more important.

Then we examine the effect of the exchange market on the supply of the mining rigs. We find that ceteris paribus, the effect of Bitcoin exchange rate on mining rig supply is negative, supporting Hypothesis 3a. Also, the magnitude is comparable to its counterpart on the demand side. This implies that for experienced miners who are more informed about mining, they still tend to interpret a higher exchange rate as the real value of Bitcoin rather than overvaluation.

We also find that the effect of Bitcoin trading volume on Bitcoin supply is not statistically significant. Therefore, there is no conclusive evidence about the substitution pattern between mining and trading in the exchange market. Indeed, when the liquidity of the exchange market is high and easier to obtain Bitcoin through trading, a miner as investor might well just keep the mining rig, in case mining becomes worthwhile again in the future. Thus, the effect might not be significant. In addition, we again observe significance of supply shifters with expected directions, suggesting a strong identification of the mining rig demand. Our results are also consistent when different operationalization of the variables about the liquidity of the exchange market are used in the model (Brennan et al. 1998, Angel et al. 2004).

7. Concluding Remarks

In this study, we propose an empirical framework that considers the interaction of Bitcoin mining and exchange markets. Our proposed framework can uncover the causal impact of Bitcoin exchange rate and market liquidity on the entry and exit of the mining market characterized by supply and demand of Bitcoin mining rigs. Our findings show that the fluctuation of Bitcoin exchange rate can lead to changes in both the supply and demand of the mining rigs. We also find that the exchange market can be a substitute for the mining market for Bitcoin investments.

Our findings have significant implications for Bitcoin investors and blockchain practitioners. First, our findings imply that since reliability and security of the Bitcoin system heavily relies on the contribution of miners, the surge in Bitcoin price can incentivize the investment in Bitcoin mining machines, which can potentially benefit the operation of the system. However, some sudden drop in price may still harm the operation of the system.

Second, the substitution effect between investing through mining vs. trading is particularly pronounced to those investors as potential entrants to the Bitcoin mining market. However, we do not find salient such substitution for experienced miners. A more liquid Bitcoin exchange market may discourage mining in general, imposing potential challenges to the maintenance of the Bitcoin system.

Our study can open several avenues for future research. First, as Bitcoin continues to gain economic significance, it would be important to keep track of investor activities in both of the exchange and mining markets (Prat and Walter 2018). It is recognized that Bitcoin is an economic instrument of value transaction, and also a technology artifact derived from the underlying blockchain technology (Li and Wang 2017). As time goes by, in particular in this unprecedented time caused by COVID-19, the interaction of the exchange and mining market may exhibit new noteworthy patterns. Second, on the side of the mining market, other concerns of the operation of the Bitcoin system are centered around the stochastic nature of mining, capacity constraints on block size and excessive computing capacity leading to high level of electricity consumption (Babich and Hilary 2020). Therefore, it would be intriguing to examine the behavior of mining activities at a more micro level after the investors join the mining market or before they exit the market.

References

Acheson, Noelle, Damanick Dantes. 2020. No, bitcoin is not in a bubble.

Amihud, Yakov, Haim Mendelson. 1982. Asset price behavior in a dealership market. *Financial Analysts Journal* **38**(3) 50–59.

Amihud, Yakov, Haim Mendelson. 1986. Liquidity and stock returns. *Financial Analysts Journal* **42**(3) 43–48.

Amihud, Yakov, Haim Mendelson. 1988. Liquidity and asset prices: Financial management implications. *Financial Management* 5–15.

Angel, James J, Jeffrey H Harris, Venkatesh Panchapagesan, Ingrid M Werner, et al. 2004. From pink slips to pink sheets: Liquidity and shareholder wealth consequences of nasdaq delistings. *University of Connecticut, working paper* .

Arnosti, Nick, S Matthew Weinberg. 2018. Bitcoin: A natural oligopoly. *arXiv preprint arXiv:1811.08572* .

Babich, Volodymyr, Gilles Hilary. 2020. Om forum—distributed ledgers and operations: What operations management researchers should know about blockchain technology. *Manufacturing & Service Operations Management* **22**(2) 223–240.

Biais, Bruno, Christophe Bisiere, Matthieu Bouvard, Catherine Casamatta. 2019. The blockchain folk theorem. *The Review of Financial Studies* **32**(5) 1662–1715.

Blasco, Natividad, Pilar Corredor, Sandra Ferreruela. 2012. Does herding affect volatility? implications for the spanish stock market. *Quantitative Finance* **12**(2) 311–327.

Böhme, Rainer, Nicolas Christin, Benjamin Edelman, Tyler Moore. 2015. Bitcoin: Economics, technology, and governance. *Journal of economic Perspectives* **29**(2) 213–38.

Brennan, Michael J, Tarun Chordia, Avanidhar Subrahmanyam. 1998. Alternative factor specifications, security characteristics, and the cross-section of expected stock returns. *Journal of financial Economics* **49**(3) 345–373.

Cheah, Eng-Tuck, John Fry. 2015. Speculative bubbles in bitcoin markets? an empirical investigation into the fundamental value of bitcoin. *Economics letters* **130** 32–36.

Chod, Jiri, Nikolaos Trichakis, Gerry Tsoukalas, Henry Aspegren, Mark Weber. 2020. On the financing benefits of supply chain transparency and blockchain adoption. *Management Science* **66**(10) 4378–4396.

Chod, Jiri, Nikolaos Trichakis, S Alex Yang. 2019. Platform tokenization: Financing, governance, and moral hazard. *Governance, and Moral Hazard (September 25, 2019)* .

Cong, Lin William, Zhiguo He, Jiasun Li. 2019. Decentralized mining in centralized pools. *The Review of Financial Studies* .

Constantinides, Panos, Ola Henfridsson, Geoffrey G Parker. 2018. Introduction—platforms and infrastructures in the digital age.

Croman, Kyle, Christian Decker, Ittay Eyal, Adem Efe Gencer, Ari Juels, Ahmed Kosba, Andrew Miller, Prateek Saxena, Elaine Shi, Emin Gün Sirer, et al. 2016. On scaling decentralized blockchains. *International conference on financial cryptography and data security*. Springer, 106–125.

Cui, Yao, Vishal Gaur, Jingchen Liu. 2020. Blockchain collaboration with competing firms in a shared supply chain: Benefits and challenges. *Available at SSRN* .

Eyal, Ittay, Emin Gün Sirer. 2014. Majority is not enough: Bitcoin mining is vulnerable. *International conference on financial cryptography and data security*. Springer, 436–454.

Forbes. 2020a. Crypto exchanges and bitcoin are poised for massive growth by 2030.

Forbes, Steve. 2020b. Bitcoin could become the digital gold.

Gan, Jingxing Rowena, Gerry Tsoukalas, Serguei Netessine. 2019. Inventory, speculators and initial coin offerings. *The Wharton School Research Paper* .

Glaser, Florian, Luis Bezzenberger. 2015. Beyond cryptocurrencies-a taxonomy of decentralized consensus systems. *23rd European conference on information systems (ECIS), Münster, Germany*.

Halaburda, Hanna, Guillaume Haeringer, Joshua S Gans, Neil Gandal. 2020. The microeconomics of cryptocurrencies. Tech. rep., National Bureau of Economic Research.

Hendershott, Terrence, Michael X Zhang, J Leon Zhao, Eric Zheng. 2017. Call for papers—special issue of information systems research fintech–innovating the financial industry through emerging information technologies. *Information Systems Research* **28**(4) 885–886.

Ho, Wai-Ming. 1993. Liquidity, exchange rates, and business cycles. *Journal of Monetary Economics* **32**(1) 121–145.

Huberman, Gur, Jacob Leshno, Ciamac C Moallemi. 2017. Monopoly without a monopolist: An economic analysis of the bitcoin payment system. *Bank of Finland Research Discussion Paper* (27).

Iansiti, Marco, Karim R Lakhani. 2017. The truth about blockchain. *Harvard Business Review* **1**.

Indices, S&P Dow Jones. 2019. S&p us indices methodology.

Jacob, Varghese, Sailendra Prasanna Mishra, Suresh Radhakrishnan. 2019. Is decentralization sustainable in the bitcoin system? *Available at SSRN 3478373* .

Lee, Hau L, Christopher S Tang, S Alex Yang, Yuxuan Zhang. 2020. Dynamic trade finance in the presence of information frictions and fintech. *Available at SSRN 3632563* .

Lee, Hsiao-Hui, S Alex Yang, Kijin Kim. 2019. The role of fintech in mitigating information friction in supply chain finance. *Asian Development Bank Economics Working Paper Series* (599).

Li, Xin, Chong Alex Wang. 2017. The technology and economic determinants of cryptocurrency exchange rates: The case of bitcoin. *Decision Support Systems* **95** 49–60.

Mishra, Sailendra Prasanna, Varghese Jacob, Suresh Radhakrishnan. 2017. Energy consumption–bitcoin's achilles heel. *Available at SSRN 3076734* .

Montemayor, Leoncio, Thomas Boersma, T van Dorp. 2018. Comprehensive guide to companies involved in blockchain and energy. *Blockchain Business* .

Morisse, Marcel. 2015. Cryptocurrencies and bitcoin: Charting the research landscape .

Nakamoto, Satoshi. 2019. Bitcoin: A peer-to-peer electronic cash system. Tech. rep., Manubot.

Narayanan, Arvind, Joseph Bonneau, Edward Felten, Andrew Miller, Steven Goldfeder. 2016. *Bitcoin and cryptocurrency technologies: a comprehensive introduction*. Princeton University Press.

Prat, Julien, Benjamin Walter. 2018. An equilibrium model of the market for bitcoin mining .

Risius, Marten, Kai Spohrer. 2017. A blockchain research framework. *Business & Information Systems Engineering* **59**(6) 385–409.

Saleh, Fahad. 2020. Blockchain without waste: Proof-of-stake. *Review of Financial Studies, Forthcoming* .

Takeshi, Amemiya. 1985. *Advanced econometrics*. Harvard university press.

Tschorsch, Florian, Björn Scheuermann. 2016. Bitcoin and beyond: A technical survey on decentralized digital currencies. *IEEE Communications Surveys & Tutorials* **18**(3) 2084–2123.

Wei, Yanhao, Anthony Dukes. 2020. Cryptocurrency adoption with speculative price bubbles. *Marketing Science* .

Zellner, Arnold, H Theil. 1962. Three-stage least squares: Simultaneous estimation of simultaneous equations. *Econometrica* **30**(1) 54.

Figure 1 Daily Bitcoin price (exchange rate against USD) and total trading volume (number of Bitcoin exchanged) from coinmarketcap.com

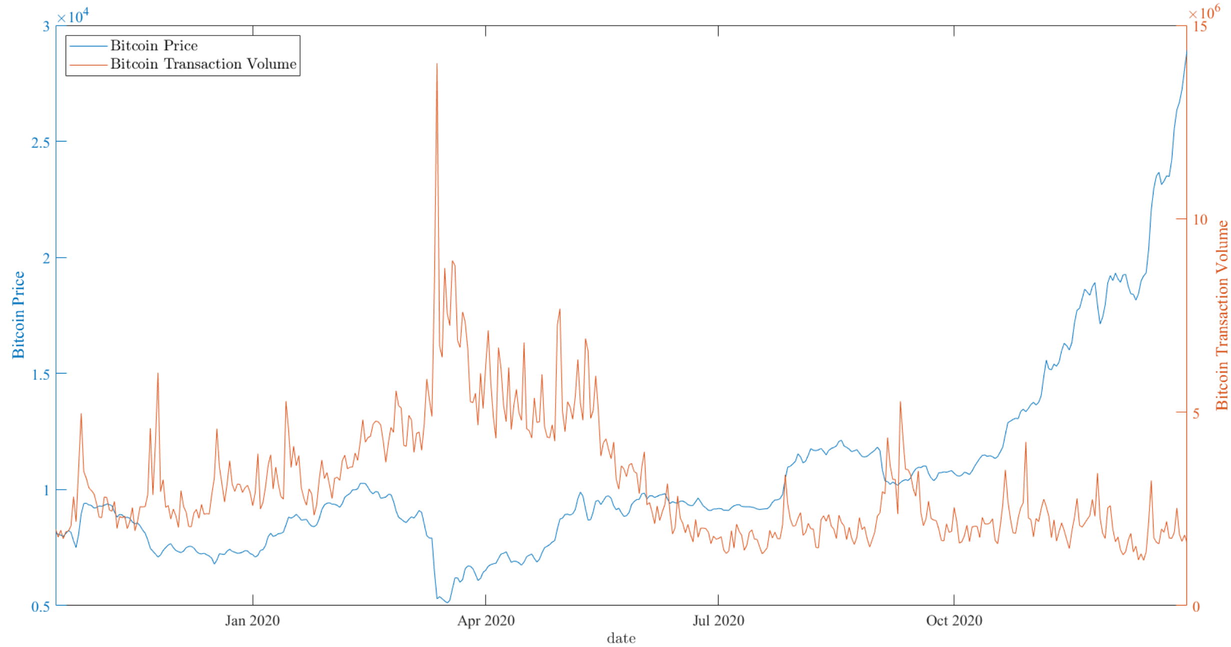

Figure 2 Annualized Bitcoin electricity consumption. The data is annualized assuming constant power at the real-time estimation of the energy consumption over the period of 1 year. A 7-day moving average is applied to the annualized estimate

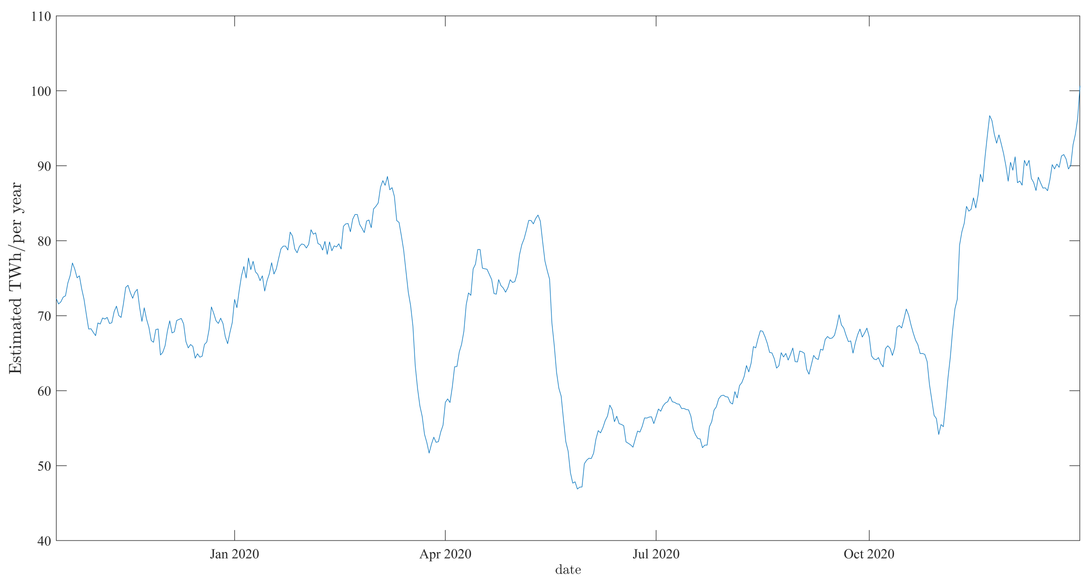

Table 1 Summary Statistics and Correlation Table

VARIABLES	Mean	Std dev.	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Rig Quantity	417.70	438.90	1.00												
2. Rig Price	1,881	2,182	0.11	1.00											
3. Bitcoin Price	10,506	4,301	0.03	0.69	1.00										
4. Bitcoin Trading Volume	3.22×10^6	1.64×10^6	-0.22	-0.54	-0.46	1.00									
5. Electricity Consumption	70.88	6.71	-0.24	-0.15	0.31	0.16	1.00								
6. Volatility (Bitcoin Exchange Market)	0.013	0.015	-0.05	-0.13	-0.05	0.44	0.13	1.00							
7. Monthly Return (Bitcoin Exchange Market)	0.099	0.21	0.12	0.38	0.64	-0.32	0.18	-0.16	1.00						
8. S&P500 Volume	4.73×10^9	1.32×10^9	-0.16	-0.08	-0.20	0.54	-0.18	0.24	-0.27	1.00					
9. Gold Volume	68,372	203,181	0.10	-0.03	-0.10	-0.01	-0.11	-0.02	-0.03	0.03	1.00				
10. Demand Shifter - Electricity	0.046	0.21	-0.11	0.38	0.69	-0.18	0.23	0.03	0.25	-0.13	-0.07	1.00			
11. Demand Shifter - Remove Ban	0.96	0.20	0.02	0.10	0.10	0.07	-0.07	-0.07	0.17	0.18	0.03	0.05	1.00		
12. Supply Shifter - Listing Fee	0.26	0.44	0.13	0.66	0.80	-0.43	0.26	-0.02	0.55	-0.18	-0.06	0.37	0.12	1.00	
13. Supply Shifter - Border Closing	0.28	0.45	-0.13	0.03	-0.25	0.12	-0.57	-0.12	0.02	0.35	0.01	-0.14	0.13	-0.37	1.00

Table 2 Results on the Demand of the Mining Rigs

	(1)	(2)	(3)	(4)	(5)
DV	Rig Quantity	Rig Quantity	Rig Quantity	Rig Quantity	Rig Quantity
Rig Price	-0.102*	-0.130**	-0.0960*	-0.153***	-0.123**
	(0.0550)	(0.0525)	(0.0528)	(0.0553)	(0.0566)
Bitcoin Price	0.0754**	0.0694**	0.0622**	0.0973***	0.0841***
	(0.0321)	(0.0292)	(0.0282)	(0.0317)	(0.0317)
Bitcoin Trading Volume (Share)		-7.57e-05***	-4.57e-05*		
		(2.06e-05)	(2.61e-05)		
Bitcoin Trading Volume (Dollar)				-1.24e-08***	-9.62e-09***
				(2.90e-09)	(3.60e-09)
Electricity Consumption	-30.70***	-28.93***	-27.26***	-30.34***	-28.06***
	(7.690)	(7.029)	(6.798)	(7.213)	(6.989)
S&P500 Volume			-4.04e-08*		-2.71e-08
			(2.32e-08)		(2.31e-08)
Gold Volume			0.000273**		0.000276**
			(0.000133)		(0.000135)
Demand Shifter - Electricity	-659.6***	-598.2***	-606.4***	-626.1***	-613.7***
	(200.9)	(195.5)	(187.9)	(199.2)	(191.2)
Demand Shifter - Remove Ban	-93.29	17.47	17.79	9.024	7.809
	(78.57)	(83.01)	(80.14)	(86.20)	(81.85)
Constant	2,171***	2,268***	2,254***	2,248***	2,210***
	(402.4)	(386.7)	(379.0)	(390.3)	(383.6)
Observations	393	393	393	393	393

(1) Weekly seasonality is controlled; (2) Bitcoin Trading Volume (Dollar) as a a metric of liquidity: Brennan et al. (1998); Bitcoin Trading Volume (Share) as a a metric of liquidity: Angel et al. (2004); (3) *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3 Results on the Demand of the Mining Rigs with Lagged Monthly Return and Volatility

	(1)	(2)	(3)	(4)	(5)
DV	Rig Quantity	Rig Quantity	Rig Quantity	Rig Quantity	Rig Quantity
Rig Price	-0.0961*	-0.131**	-0.0963*	-0.155***	-0.120**
	(0.0556)	(0.0529)	(0.0533)	(0.0559)	(0.0572)
Bitcoin Price	0.0746**	0.0712**	0.0642**	0.101***	0.0855***
	(0.0325)	(0.0292)	(0.0281)	(0.0320)	(0.0319)
Bitcoin Trading Volume (Share)		-7.95e-05***	-4.68e-05*		
		(2.20e-05)	(2.83e-05)		
Bitcoin Trading Volume (Dollar)				-1.21e-08***	-8.94e-09**
				(3.00e-09)	(3.72e-09)
Lagged One Day of Volatitlity	-1,315	2,399	1,973	2,327	2,226
(Bitcoin Exchange Market)	(1,577)	(1,831)	(1,785)	(1,793)	(1,724)
Lagged One Day of Monthly Return	-40.70	-55.12	-91.48	56.52	6.611
(Bitcoin Exchange Market)	(183.1)	(179.9)	(173.5)	(180.1)	(176.5)
Electricity Consumption	-29.86***	-28.62***	-26.95***	-30.34***	-27.89***
	(7.793)	(7.038)	(6.794)	(7.236)	(6.989)
S&P 500 Volume			-4.16e-08*		-3.11e-08
			(2.35e-08)		(2.31e-08)
Gold Volume			0.000280**		0.000284**
			(0.000133)		(0.000135)
Demand Shifter -Electricity	-667.0***	-616.0***	-629.2***	-653.6***	-641.7***
	(204.8)	(197.7)	(190.0)	(202.1)	(193.3)
Demand Shifter - Remove Ban	-78.04	51.25	50.84	31.95	30.27
	(76.22)	(85.89)	(84.60)	(88.45)	(84.80)
Constant	2,106***	2,219***	2,200***	2,204***	2,173***
	(403.6)	(386.5)	(377.7)	(390.4)	(381.7)
Observations	393	393	393	393	393

(1) Weekly seasonality is controlled; (2) Bitcoin Trading Volume (Dollar) as a a metric of liquidity: Brennan et al. (1998); Bitcoin Trading Volume (Share) as a a metric of liquidity: Angel et al. (2004); (3) *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 4 Results on the Supply of the Mining Rigs

DV	(1) Rig Quantity	(2) Rig Quantity	(3) Rig Quantity	(4) Rig Quantity	(5) Rig Quantity
Rig Price	0.258***	0.276**	0.351**	0.244**	0.289**
	(0.0964)	(0.130)	(0.149)	(0.121)	(0.130)
Bitcoin Price	-0.0853***	-0.0881**	-0.105**	-0.0827**	-0.0981**
	(0.0323)	(0.0379)	(0.0421)	(0.0419)	(0.0456)
Bitcoin Trading Volume (Share)		1.87e-05	6.08e-05		
		(3.59e-05)	(4.74e-05)		
Bitcoin Trading Volume (Dollar)				5.63e-10	3.79e-09
				(4.55e-09)	(5.57e-09)
Electricity Consumption	1.035	-1.749	3.749	-4.411	-0.398
	(10.08)	(10.48)	(11.55)	(9.773)	(10.28)
S&P 500 Volume			-5.02e-08*		-3.25e-08
			(2.58e-08)		(2.35e-08)
Gold Volume			0.000263*		0.000255*
			(0.000138)		(0.000134)
Supply Shifter - Listing Fee	-535.0***	-590.7**	-683.1**	-521.8**	-566.2**
	(207.5)	(263.2)	(290.6)	(234.3)	(244.8)
Supply Shifter - Border Closing	-379.4***	-484.3***	-492.7***	-472.5***	-461.4***
	(94.39)	(145.3)	(153.7)	(134.2)	(136.7)
Constant	2892.9	1,066*	827.5	1,286**	1,138**
	(551.1)	(638.6)	(687.9)	(556.1)	(572.0)
Observations	393	393	393	393	393

(1) Weekly seasonality is controlled; (2) Bitcoin Trading Volume (Dollar) as a a metric of liquidity: Brennan et al. (1998); Bitcoin Trading Volume (Share) as a a metric of liquidity: Angel et al. (2004); (3) *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 5 Results on the Supply of the Mining Rigs with Lagged Monthly Return and Volatility

	(1)	(2)	(3)	(4)	(5)
DV	Rig Quantity	Rig Quantity	Rig Quantity	Rig Quantity	Rig Quantity
Rig Price	0.261***	0.282**	0.375**	0.253**	0.311**
	(0.0959)	(0.131)	(0.158)	(0.122)	(0.136)
Bitcoin Price	-0.0843***	-0.0859**	-0.107**	-0.0846**	-0.105**
	(0.0319)	(0.0370)	(0.0432)	(0.0421)	(0.0474)
Bitcoin Trading Volume (Share)		3.00e-05	8.48e-05		
		(4.01e-05)	(5.65e-05)		
Bitcoin Trading Volume (Dollar)				2.41e-09	6.69e-09
				(4.92e-09)	(6.22e-09)
Lagged One Day of Volatitlity	1,367	-35.96	-661.1	389.5	371.7
(Bitcoin Exchange Market)	(1,672)	(1,907)	(2,102)	(1,758)	(1,828)
Lagged One Day of Monthly Return	915.0***	1,018***	1,059***	942.0***	891.5***
(Bitcoin Exchange Market)	(236.5)	(300.9)	(329.6)	(239.1)	(244.3)
Electricity Consumption	2.624	-1.532	4.824	-4.139	0.552
	(10.22)	(10.42)	(12.01)	(9.772)	(10.57)
S&P 500 Volume			-5.92e-08**		-4.17e-08*
			(2.82e-08)		(2.48e-08)
Gold Volume			0.000273*		0.000266*
			(0.000144)		(0.000138)
Supply Shifter - Listing Fee	-529.9**	-593.8**	-711.4**	-525.6**	-582.6**
	(205.8)	(263.2)	(305.3)	(234.1)	(251.5)
Supply Shifter - Border Closing	-362.1***	-494.9***	-515.9***	-484.7***	-476.6***
	(92.30)	(148.3)	(163.4)	(136.4)	(141.7)
Constant	785.4	1,018	739.3	1,250**	1,096*
	(560.7)	(646.5)	(724.1)	(561.1)	(588.4)
Observations	393	393	393	393	393

(1) Weekly seasonality is controlled; (2) Bitcoin Trading Volume (Dollar) as a a metric of liquidity: Brennan et al. (1998); Bitcoin Trading Volume (Share) as a a metric of liquidity: Angel et al. (2004); (3) *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$