Finance Research Letters 52 (2023) 103529

Contents lists available at ScienceDirect

Finance Research Letters

journal homepage: www.elsevier.com/locate/frl

Bounded pool mining and the bounded Bitcoin price

Dun Jia [a,*], Yifan Li [b]

[a] HSBC Business School, Peking University, 729 PHBS Building, Xili College Town, Nanshan District, Shenzhen, 518055, China
[b] School of Finance, Renmin University of China, 59 Zhongguancun Street, Haidian District, Beijing, 100872, China

ARTICLE INFO

JEL classification:
E40
G10
L10

Keywords:
Bitcoin
Market structure
Price variability

ABSTRACT

We present a simple model featuring the supply side of the Bitcoin ecosystem, i.e. the market structure of "mining", to rationalize the relationship between the Bitcoin price volatility and the market concentration in pool mining. An individual miner optimally chooses to operate individually or to delegate the mining capacity in hashrates to a mining pool. The mining pool entertains the trade-off between compromising the network derived from its market power and maintaining sufficient hashrate delegations from dispersed miners. We show that a mining pool finds it optimal to be self-constrained in size while maintaining a positive probability of compromising the network in equilibrium. As a result, the bounded market concentration in pooled mining caps the Bitcoin price fluctuations. We also document important empirical evidence which is consistent with our model predictions.

1. Introduction

Bitcoin's prices are very volatile. Based on the assumptions that the supply trajectory of Bitcoins is exogenously given and is free of uncertainty, the existing literature emphasizes the demand side factors as the main drivers for the riskiness in Bitcoin investment (Gronwald, 2019; Schilling and Uhlig, 2019). Our paper fills the gap by highlighting the non-trivial aspect of the Bitcoin supply side, i.e. the market concentration in pooled mining, and shows both theoretically and empirically that the Bitcoin price volatility can be significantly affected by the market structure of the Bitcoin supply forces.

In addition, looking beyond the price volatility, our paper makes an important contribution to better assessing the stability of the Bitcoin network. That is, while this network hinges on an ecosystem of Blockchains that decentralizes the record-keeping with the proof-of-work (PoW) protocols that provide incentives for dispersed investors to compete for extending blocks of transactions, a.k.a., mining (Nakamoto, 2008), mining has been increasingly concentrated among a few pools of computers, i.e. the mining pools. It is thus concerning for the Bitcoin network to be comprised by the 51% attack on the Bitcoin network, by which a mining pool controls more than half of the total hash power and forks a PoW blockchain to conduct double-spending for private benefits (Budish, 2018; Halaburda et al., 2020; Cong et al., 2020). In particular, we present a simple model in this paper showing that given the incentives of individual miners and the operating mining pools, the Bitcoin network is, however, self-correcting and self-sustaining.

Our model suggests that a large mining pool accommodates the trade-off between compromising the network given its market power and attracting sufficient hashrate delegations from the dispersed miners. A pool thus finds it optimal to be self-constrained in size, even though a positive probability of compromising the network is an equilibrium outcome. Our paper contributes to the

* Corresponding author.
E-mail addresses: dun.jia@phbs.pku.edu.cn (D. Jia), yifan.li@ruc.edu.cn (Y. Li).

https://doi.org/10.1016/j.frl.2022.103529
Received 16 September 2022; Received in revised form 30 October 2022; Accepted 21 November 2022
Available online 28 November 2022

literature by highlighting the mechanism through which the Bitcoin price range is self-bounded per the supply-side market structure of mining.

Related Literature. Our paper is related to two strands of the literature. First, previous works have attributed the Bitcoin price volatility to a few demand factors. Gandal et al. (2018) detect that Bitcoin's prices are very vulnerable to various forms of price manipulations. Walther et al. (2019) find that global financial distress predicts the future Bitcoin price volatility. Schilling and Uhlig (2019) focus on the role of Bitcoin as medium-of-exchange and find the Bitcoin price a martingale. Our paper, however, presents a simple model featuring the supply side of the Bitcoin ecosystem and finds that the Bitcoin PoW protocols of decentralization admit bounded market concentrations in mining, which leads to a bounded range of price fluctuations in equilibrium. Second, our paper builds upon prior literature that examines the market structure of mining but explores its asset pricing implications on the Bitcoin price variability. Budish (2018) examines the conditions including the cost of mining, the population of miners, and mining rewards under which a 51% attack against the network is more likely to happen. Cong et al. (2020) similarly argue for bounded market concentration in hashrates but highlight the role of competition among mining pools.

2. The model

We examine the market structure of the decentralized record-keeping efforts with the PoW protocols, i.e. mining, for miners competing for the right to extend the Blockchain on the Bitcoin network. Specifically, individual miners choose the optimal fraction of their equity hashrates to be delegated to a collection of the mining hash, i.e, a mining pool. However, a mining pool may find it lucrative to compromise the Bitcoin network by initializing the Blockchain forking for its private benefits, if the pool is large enough with sufficient delegations of hashrates from individual miners. In equilibrium, a mining pool strikes the balance between encouraging hashrates delegations and reaping the private benefits by compromising the network. Our model derives the equilibrium bounds of pooled mining concentration, which then caps the bandwidth of the Bitcoin price variability.

2.1. Environment

There are N dispersed individual miners and each is endowed with the same mining productive capacity of size $x > 0$ in the unit of hashrate. With hashrates serving as inputs, an individual miner can conduct mining independently, which yields a return of q units of Bitcoin per hashrate as a block reward if the mining is successful.[1] The probability of successful mining for individual miners is $\lambda^i \in (0, 1)$. With a probability of $1 - \lambda^i$, the mining effort does not yield any return. λ^i thus captures the degree of technical efficiency for doing successful and independent mining, i.e. individuals' productivity. Denoting the market price of a Bitcoin using P, the expected return of independent mining is $P \cdot \lambda^i \cdot q$.

In addition, each miner as indexed by j has the option to delegate a fraction $\eta_j \in [0, 1]$ of its hashrate endowment x to a mining pool, i.e. a collection of hashrates. Denote $R \cdot q$ as the reward in terms of quantities of Bitcoin from the pooled mining, which measures the return per unit of hashrate delegated from individual miners to the pool conditional on a successful block extended by the mining pool. The presence of the reward scale R over q reflects the degree of positive externalities from pooled mining taking on this unit of delegated hashrate as mining input (Cong et al., 2020). More delegations of hashrates across individual miners into the pool, and larger positive externalities from such hashrates complementarities would increase the reward of the pooled mining using this one unit of hashrate. Hence, we model this scale of reward as a function of the total size of delegated hashrates across miners $\sum_{j=1}^{N} \eta_j x$:

$$R = \omega(\sum_{j=1}^{N} \eta_j x) \tag{1}$$

where R increases with the total size of hashrates delegations. Importantly, we further assume the pool reward scale R can be shifted by the degree of Block withholding risk following Rosenfeld (2011) and Toroghi Haghighat and Shajari (2019). The Block withholding risk highlights the fact that the hashrates that are delegated into a pool may be "shirking". While individual miners may potentially withhold or delay submitting the successfully mined blocks to the pool, we assume that only a fraction of $\omega \in (0, 1)$ of individual miners' hashrates is *committed* to block submissions within a pool. Therefore, a fraction of $1 - \omega \in (0, 1)$ of hashrates are withheld which reflects the size of Block withholding risk. Therefore, the total pool reward $R \cdot q$ is negatively affected by the risk of Block withholding.

However, with positive delegations $\eta_j > 0$, a miner only receives a contracted fraction $f \in (0, 1)$ of the pool reward conditional on successful mining. The residual fraction $1 - f$ of the pool reward is retained at the mining pool level. Similarly, the probability of successful pool mining can be denoted by $\lambda^p \in (0, 1)$. With a probability of $1 - \lambda^p$, pooled mining does not yield any pool reward. Therefore, the expected return of pooled mining per unit of delegated hashrate for an individual miner is $f \cdot P \cdot \lambda^p \cdot Rq$.

A necessary condition for the existence of a mining pool follows that $f \cdot P \cdot \lambda^p \cdot Rq > P \cdot \lambda^i \cdot q$. This reflects the fact that the expected return from doing pooled mining per delegated hashrate outsizes that from doing independent mining. It can be written more concisely as

$$R > \frac{1}{f \cdot \lambda} \tag{2}$$

[1] By construction, the Bitcoin block reward given to successful miners is cut in halves every four years.

where $\lambda = \frac{\lambda^p}{\lambda^i}$ denotes the technical efficiency of doing pooled mining relative to that of independent mining. Intrinsically, the condition per Eq. (2) holds to capture the key requirement that the productivity externalities of the pooled mining should be sufficiently large.

Finally, we allow for the fact that a mining pool on the Bitcoin network may compromise the entire operations of the blockchain system by "forking", as long as the pool has sufficiently large market power, e.g. having no less than 51% of the total hashrates of the network.[2] We assume the probability for a mining pool to compromise the network is $\phi \in [0,1]$. Conditional on forking, a mining pool takes away an amount of $\epsilon \cdot q \in (0, R \cdot q]$ from the pool reward per hashrate before distributing the contracted payoff to hashrates delegated from individual miners, i.e. a private gain to the pool. With the probability of $1-\phi$, the blockchain system is intact.

2.2. Individual miners

Depending on how much the endowed hashrates are delegated to a mining pool, i.e. η_j, the value to an individual miner considering the options of doing independent mining and the pooled mining is given below:

$$\begin{aligned} V_j^i(\eta_j) &= (1-\eta_j)\cdot P\cdot\lambda^i\cdot q\cdot x + \eta_j\cdot f\cdot P\cdot\lambda^p\cdot[\phi(R(\eta_j)-\epsilon)+(1-\phi)R(\eta_j)]q\cdot x \\ &= Pqx[\lambda^i + \eta_j(\lambda^p f(R(\eta_j)-\phi\epsilon)-\lambda^i)] \end{aligned} \tag{3}$$

According to Eq. (3), the "excess returns" of delegating one additional unit of hashrate to a mining pool is measured by $\lambda^p f(R(\eta_j)-\phi\epsilon)-\lambda^i$. This term can be considered as some risk premium that increases with the successful rate of the pooled mining λ^p, the pool reward scale $R(\eta_j)$, and the miners' fraction of pool reward f. It decreases with the probability of compromising the network for a mining pool ϕ, the size of the pool's derived private benefit ϵ, and the successful rate of independent mining λ^i. η_j scales this excess return and captures the degree of the risk exposure to pooled mining for a miner j if she delegates her total hashrate x to a mining pool.

Suppose that $\lambda^p f(R(\eta_j)-\phi\epsilon) < \lambda^i\ \forall j$, individual miners would always conduct independent mining for $\eta_j = 0$ and there is no pooled mining in equilibrium. If $\lambda^p f(R(\eta_j)-\phi\epsilon) \geq \lambda^i$ for some j, we can show that the pool mining has non-zero concentration, i.e. $\sum_{j=1}^N \eta_j x > 0$. Specifically, taking P, q, x, ϕ, ϵ, λ^p, and λ^i as given, we have the individual miners' optimization problem over η_j:

$$\max_{\eta_j} \eta_j[\lambda^p f(\omega(\eta_j x + \sum_{z\neq j}^{N}\eta_z x) - \phi\epsilon) - \lambda^i] \tag{4}$$

It follows that the individual miner's objective function is strictly convex in η_j. This is because delegating hashrates to a pool with positive externalities delivers increasing returns to scale in η_j. Hence, with a non-negative risk premium from doing pooled mining, individual miners would want to delegate their hashrates in full to a mining pool, $\eta_j = 1, \quad \forall j$. We summarize the decision rule for individual miners' hash delegations in the following:

$$\eta_j = \begin{cases} 0 & if \quad \lambda^p f(R(\eta_j)-\phi\epsilon) < \lambda^i \\ 1 & if \quad \lambda^p f(R(\eta_j)-\phi\epsilon) \geq \lambda^i \end{cases} \tag{5}$$

2.3. The mining pool

Without the loss of generality, we consider a representative mining pool that operates by attracting individual miners to delegate hashrates. Considering the expected payoffs from compromising and not compromising the network and the participation incentives per Eqs. (5), the value to a mining pool is given by

$$\begin{aligned} V^p &= Pqx\lambda^p \sum_{j=1}^{N}\eta_j[\phi((1-f)R(\eta_j)+f\epsilon)+(1-\phi)(1-f)R(\eta_j)] \\ &s.t. \quad \lambda^p f(R(\eta_j)-\phi\epsilon) \geq \lambda^i \quad \forall j \quad \text{(Incentive Compatibility Constraint)} \end{aligned} \tag{6}$$

Accordingly, the value of a pool increases with the shares of hashrates delegated from individual miners, η_j.

2.4. Symmetric equilibrium

We then study a symmetric equilibrium in which a mining pool exists by having non-trivial concentration in hashrates. That is, $\eta_j = \eta^* > 0, \quad \forall j$ in equilibrium. Therefore, in the symmetric equilibrium, not only $\eta^* = \frac{\eta^* N x}{N x}$ denotes *average* fraction of hashrates delegated from an individual miner to the pool but is a measure of the market concentration in hashrates of the mining pool.

[2] Rosenfeld (2011) finds that a pool operator may allure miners in other competing pools to withhold Block submissions. Therefore, a pool can well initiate forking attacks even if its hashrate concentration is below 51%.

Taking as given the share split of reward $f > 0$, the private gain $\epsilon > 0$, and the delegation share of hashrates from individual miners η^*, the mining pool determines the probability of compromising the Bitcoin network. The pool maximizes the expected gains from unit hashrate delegations of an average individual miner such that

$$\max_{\phi} \eta^*[R(\eta^*) - f(R(\eta^*) - \phi\epsilon)] + \gamma[\lambda^p f(R(\eta^*) - \phi\epsilon) - \lambda^i] \tag{7}$$

where γ denotes the Lagrangian multiplier attached to the Incentive Compatibility (IC) constraint for a miner's decision to delegate positive hashrates.

2.4.1. Market concentration

We first highlight a technical assumption regarding the minimum capacity required for a mining pool to be able to compromise the Bitcoin network. That is, the hashrate concentration of a mining pool has to be large enough, for example, a pool maintaining at least 51% of the total hashrates. Judmayer et al. (2021) further find that the concentration threshold for a mining pool to fork the Blockchain network can be well below 51% as long as it can trigger a relatively larger share of hashrates. Our assumption below thus accommodates a potentially lower minimum requirement of the market concentration other than 51%, $\underline{\eta}$, for a pool to be able to compromise the network with a positive probability $\phi > 0$:

Assumption 1. $\phi > 0$ if and only if $\eta^* \geq \underline{\eta}$ with $\underline{\eta} \in (0, 1)$

Next, we show that the market concentration in equilibrium has an upper bound, $\hat{\eta}$. First, the mining pool maximizes its expected return from compromising the network derived from its market power and from providing higher pool reward driven by the productivity externalities to individual miners to maintain enough hashrate concentration. Individual miners' delegations of hashrates are then exploited to satisfy the incentive compatibility constraint by which their risk premium from joining the pool should cover the expected loss from the network being compromised. Therefore, under the scenario of forking with certainty with $\phi = 1$, the positive externalities as measured by $R(\eta^*)$ should be at the maximum to still attract positive delegations so that $f\lambda^p(R(\hat{\eta}) - \epsilon) = \lambda^i$. This determines the upper bound of market concentration in equilibrium. With lower $\phi < 1$, $R(\eta^*)$ can be lower so that the incentive compatibility constraint still binds. That is,

$$\hat{\eta} = \frac{1}{\omega N x}\left(\frac{1}{f\lambda} + \epsilon\right) \tag{8}$$

According to Eq. (8), the maximum market concentration should be even higher to compensate individual miners with greater pool reward in case of greater withholding risk for lower ω, the smaller number of active individual miners for lower N, smaller mining capacity per miner for lower x, a smaller share of pool reward given to individual miners for lower f, lower relative technical efficiency of the pool for lower λ and greater size of damage of forking for larger ϵ. We then lay out the key proposition that summarizes the model equilibrium as follows

Proposition 1. *(1) The equilibrium* $\phi^* = \frac{R(\eta^*)f\lambda - 1}{\epsilon f \lambda} \in (0, 1]$*, that is, the probability for the mining pool to compromise the blockchain network is positive. (2) The equilibrium market concentration* η^* *is bounded such that* $\eta^* \in [\underline{\eta}, \hat{\eta}]$.

We provide the proof of the proposition in Section B of the Appendix. The intuition of our model results is as follows. A pool cannot be too small in equilibrium for it is productive enough that attracts large delegations of hashrates from dispersed miners. It cannot be too large as well for it is very costly to maintain the pool when a pool has the largest incentives to compromise the network in the extreme while at the same time giving out the maximum pool reward to sustain hashrate delegations and market concentration. While the equilibrium market concentration is bounded, a mining pool maintains a positive probability to compromise the network.

2.4.2. The Bitcoin price and the price bandwidth

We then have the market clearing condition to determine the equilibrium Bitcoin price. First, the total supply of Bitcoin, S is the sum of the quantity of block rewards to newly added blockchains from the successful mining and the stock of outstanding Bitcoins, K. It follows that

$$\begin{aligned} S &= \lambda^i(1 - \eta^*)qNx + \lambda^p\eta^* R(\eta^*)qNx + K \\ &= qNx[\lambda^i + \eta^*(\lambda^p R(\eta^*) - \lambda^i)] + K \end{aligned} \tag{9}$$

Second, we impose the downward-sloping demand schedule for Bitcoin such that $D = P^{-\frac{1}{\xi}}$. $\xi > 0$ denotes the inverse of demand elasticity. Market clearing requires that $D = S$ in equilibrium, which pins down the price of Bitcoin, P such that

$$P(\eta^*) = (qNx[\lambda^i + \eta^*(\lambda^p R(\eta^*) - \lambda^i)] + K)^{-\xi} \tag{10}$$

According to Eq. (10), the Bitcoin price decreases with the hashrate market concentration for $P'(\eta^*) < 0$. Therefore, given the bounds of the market concentration per Proposition 1, we have the following proposition:

Proposition 2. *With bounded market concentration of a mining pool in equilibrium* $\eta^* \in [\underline{\eta}, \hat{\eta}]$*, the Bitcoin price* P *is also bounded within* $[\underline{P}, \bar{P}]$ *where* $\underline{P} = P(\hat{\eta})$ *and* $\bar{P} = P(\underline{\eta})$

In the following, we derive the theoretical bandwidth of the Bitcoin price in equilibrium, M, by taking the log differences of the upper and lower price bounds.

$$M = \log(\bar{P}) - \log(\underline{P}) = -\xi \log \chi > 0$$

where

$$\chi = 1 - \frac{[\hat{\eta} R(\hat{\eta}) - \underline{\eta} R(\underline{\eta})]\lambda - (\hat{\eta} - \underline{\eta})}{1 + \hat{\eta}[\lambda R(\hat{\eta}) - 1] + \frac{K}{\lambda^i q N x}} \in (0, 1) \tag{11}$$

for $\lambda = \frac{\lambda^p}{\lambda^i}$. Note that by assumption, the lower bound of the market concentration of a mining pool, $\underline{\eta}$, is a technical bound. It is thus more interesting to examine the price implications of varying the upper bound. It can be shown that $\frac{\partial M}{\partial \hat{\eta}} > 0$, $\frac{\partial M}{\partial \lambda} > 0$, $\frac{\partial M}{\partial K} < 0$, $\frac{\partial M}{\partial q} > 0$, $\frac{\partial M}{\partial N} > 0$, $\frac{\partial M}{\partial x} > 0$. In the following proposition, we highlight a series of supply-side factors that shift the bandwidth of the Bitcoin price. We provide the proof of the proposition in Section C of the Appendix.

Proposition 3. *The Bitcoin price bandwidth increases with the upper bound of the market concentration of the pooled mining $\hat{\eta}$, the successful rate of doing pooled mining relative to independent mining (i.e. the relative technical efficiency) λ, the blockchain reward q, the number of blockchain participants N, and the average hashrate per miner x, and decreases with the quantity of outstanding Bitcoin K in circulation.*

Intuitively, a mining pool having a larger market concentration has greater productivity and thus supplies more Bitcoins into the market. This pushes down the potential lower bound of the Bitcoin price in the market. Greater blockchain reward and the total hashrates on the network driven by both the margins of the number of miners and the size of the average hashrate per miner would further enlarge the price impacts of the concentrated mining. On the other hand, with the increasing number of Bitcoin circulating in the market, the price impact of the supply side is further reduced.

3. Empirical evidence

With Proposition 3, we test our model predictions against the data and examine the impacts of varying market concentrations of the mining pools on the Bitcoin price bandwidth. Specifically, we estimate the following specification

$$PriceBand_t = \theta + \beta \hat{\eta}_m + \phi_x X_t + \upsilon_t \tag{12}$$

where t corresponds to a day. The dependent variable $PriceBand_t$ denotes the daily Bitcoin price bandwidth constructed from the highest and the lowest Bitcoin price index in US Dollars sourced from the Cointelegraph. The upper bound of the market concentration of a mining pool, $\hat{\eta}_m$ is measured by the monthly hashrate market share of the largest mining pool. In addition, we run the regression using an alternative measure of the market share, i.e. $\bar{\eta}_m$, which is the monthly average hashrate market share across mining pools. Both these market share proxies are downloaded from the btc.com. If the estimate of the coefficient β is positive, it suggests that the rising market concentration enlarges the variability of the Bitcoin price. In the controlled regression setting, we also examine the impacts of other supply-side factors on the price bandwidth per Proposition 3. We consider a range of covariates at the daily frequency including the mining difficulty on the network (sourced from the btc.com), the number of Bitcoins in circulation (sourced from the buybitcoinworldwide.com), the unit reward of a successful block extension (sourced from the btc.com), the number of active Bitcoin addresses (sourced from the glassnode.com) and the average hashrate on Bitcoin network (sourced from the tokenview.com) in the regressor vector X_t for joint identifications. These empirical proxies shed light on the factors of interest corresponding to $\frac{1}{\lambda}, K, q, N$, and x in our model. In particular, except for the average hashrate on the network, other covariates entering the regressions are in natural logarithms. In addition, we are aware of the demand factors that are affecting the Bitcoin price variability, we therefore control for the daily returns on the Bitcoin price index (sourced from the btc.com), r_t, as well as the percentage of transaction fees over block reward (sourced from the buybitcoinworldwide.com), $fees_t$, which effectively serves as the income tax on Bitcoin profits. Concerning the fact that the market concentration is a slow-moving variable of lower frequency, we run additional regressions by checking if the hashrate concentrations are correlated with monthly volatilities of the Bitcoin prices and the Bitcoin supplies.

Table 1 reports the coefficient estimates of Eq. (12). According to Column (1), the results suggest that the increased maximum hashrate market concentration of a mining pool significantly increases the Bitcoin price variability. Estimation results in Column (2) further confirm our model predictions per Proposition 3. First, increasing the pool's concentration indeed predicts a wider Bitcoin price bandwidth regardless of controls. Second, larger mining difficulty, i.e. lower technical efficiency of mining on the network, significantly shrinks the price bandwidth. Given that the network mining efficiency is largely driven by the most productive mining pools, a negative coefficient estimate is indicative of the positive correlations between the price variability and the successful rate of pooled mining that is consistent with our model. Third, the Bitcoin price bandwidth is also negatively correlated with quantities of outstanding Bitcoins in circulation. In addition, both the block reward and the number of active addresses are positively associated with larger price variability. However, the average hashrate on the network is only trivially connected with price width. Moving to Columns (3)(4) and (5), controlling for the returns on the Bitcoin index, the percentage of transaction fees over block reward, and taking an alternative measure of the hashrate concentration of mining pools little affect our baseline estimations shown in Columns (1) and (2). Results in Column (6) suggest that at a monthly frequency, the impacts of market concentration along with

Table 1
The Bitcoin price variability: Hash concentration and the supply-side factors.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	P band	P band	P band	P band	P band	Monthly σ_P	$\log(Monthly\ \sigma_K)$
$\hat{\eta}_m$	0.112***	0.060**	0.061**		0.050*	0.195*	1.257***
	(0.016)	(0.027)	(0.027)		(0.027)	(0.104)	(0.359)
$\bar{\eta}_m$				0.149**			
				(0.061)			
$ln\frac{1}{\lambda_t}$		−0.005***	−0.005***	−0.005***	−0.003**	−0.002	−0.040*
		(0.001)	(0.001)	(0.001)	(0.001)	(0.003)	(0.023)
lnK_t		−0.124***	−0.117***	−0.109**	−0.123***	−0.253**	0.724
		(0.044)	(0.044)	(0.044)	(0.043)	(0.141)	(0.498)
lnq_t		0.005*	0.005	0.004	0.007**	0.007	0.776***
		(0.003)	(0.003)	(0.003)	(0.003)	(0.010)	(0.077)
lnN_t		0.025***	0.025***	0.025***	0.015***	0.053**	−0.011
		(0.003)	(0.003)	(0.003)	(0.001)	(0.028)	(0.138)
x_t		0.001	0.000	0.001	0.000	0.000	0.000
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
r_t			−0.061*	−0.060*	−0.057	−0.929	0.073
			(0.035)	(0.035)	(0.036)	(0.930)	(1.717)
$fees_t$					0.049***	0.037	−0.784
					(0.010)	(0.048)	(0.513)
Constant	0.004	1.869***	1.770**	1.628**	1.918***	3.529*	−3.039
	(0.003)	(0.718)	(0.718)	(0.730)	(0.715)	(1.972)	(7.052)
Observations	3,652	1,660	1,659	1,659	1,659	120	120
R^2	0.045	0.122	0.140	0.141	0.165	0.177	0.904

Notes: Sample: February 2012 to March 2022. This table shows the estimation results according to Eq. (12). The dependent variable for Columns (1) to (4) is the daily price bandwidth constructed from the highest and lowest Bitcoin USD price index within a trading day. The dependent variable for Column (5) takes the monthly standard deviations of the average daily Bitcoin USD price index. The dependent variable for Column (6) takes the monthly standard deviations of daily outstanding Bitcoin in millions. Robust standard errors are in parentheses.

*Significance at the 10% level.

**Significance at the 5% level.

***Significance at the 1% level.

other supply factors on the Bitcoin price variability still hold, whereas the estimated coefficients related to the demand factors are no longer significant. This may well suggest that the supply-side impacts are enduring but those of the demand factors are somewhat short-lived. Results in Column (7) based on monthly regressions further confirm our key model implications per Eq. (9). That is, the maximum hashrate market concentration of a mining pool raises the volatility of Bitcoin supplies. Most importantly, we do see a high R^2 of 90% which reflects that our considered supply-side variables are indeed shifting the Bitcoin supply variability and thus the price bandwidth.

4. Concluding remarks

We present a simple model featuring the supply side of the Bitcoin ecosystem, i.e. the market structure of mining. Our model suggests that a large mining pool entertains the trade-off between compromising the network given its market power and attracting sufficient hashrate delegations from the dispersed miners. A mining pool, therefore, finds it optimal to be self-constrained in size, though it maintains a positive probability of compromising the network in equilibrium. We demonstrate that the bounded market concentration in pooled mining leads to a bounded range of Bitcoin price variability. We document strong empirical evidence that is consistent with our key model predictions. Our results suggest to the individual miners that the potential risk of delegating hashrates to a large mining pool may be well contained because a pool maintains strong incentives to be self-bounded in size simply for ensuring the stability of the network and thus its profitability.

CRediT authorship contribution statement

Dun Jia: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Yifan Li:** Data curation, Formal analysis.

Data availability

Data will be made available on request.

Acknowledgment

Dun Jia is supported by National Natural Science Foundation of China (NSFC) no. 72003191.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.frl.2022.103529.

References

Budish, Eric, 2018. The Economic Limits of Bitcoin and the Blockchain. National Bureau of Economic Research Working Paper 24717.
Cong, Lin William, He, Zhiguo, Li, Jiasun, 2020. Decentralized mining in centralized pools. Rev. Financ. Stud. 34 (3), 1191–1235.
Gandal, Neil, Hamrick, J.T., Moore, Tyler, Oberman, Tali, 2018. Price manipulation in the Bitcoin ecosystem. J. Monetary Econ. 95, 86–96.
Gronwald, Marc, 2019. Is Bitcoin a commodity? On price jumps, demand shocks, and certainty of supply. J. Int. Money Finance 97, 86–92.
Halaburda, Hanna, Haeringer, Guillaume, Gans, Joshua S., Gandal, Neil, 2020. The Microeconomics of Cryptocurrencies. National Bureau of Economic Research, Inc NBER Working Papers 27477.
Judmayer, Aljosha, Stifter, Nicholas, Zamyatin, Alexei, Tsabary, Itay, Eyal, Ittay, Gaži, Peter, Meiklejohn, Sarah, Weippl, Edgar, 2021. SoK: Algorithmic Incentive Manipulation Attacks on Permissionless PoW Cryptocurrencies. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 507–532.
Nakamoto, Satoshi, 2008. Bitcoin: A peer-to-peer electronic cash system.
Rosenfeld, Meni, 2011. Analysis of bitcoin pooled mining reward systems.
Schilling, Linda, Uhlig, Harald, 2019. Some simple bitcoin economics. J. Monetary Econ. 106, 16–26.
Toroghi Haghighat, Alireza, Shajari, Mehdi, 2019. Block withholding game among bitcoin mining pools. Future Gener. Comput. Syst. 97, 482–491.
Walther, Thomas, Klein, Tony, Bouri, Elie, 2019. Exogenous drivers of bitcoin and cryptocurrency volatility – A mixed data sampling approach to forecasting. J. Int. Financ. Mark. Inst. Money 63, 101133.