The Economics of Bitcoin Mining*

ABSTRACT: We analyse bitcoin mining as a case of commodity money production using the framework of the total demand approach known from Austrian economics. We detail the capital and cost structure of bitcoin mining, the importance of the law of costs, and compare how different versions of Bitcoin fare against each other as well as against commodity money.

Introduction

The launch of Bitcoin in 2009 (Nakamoto 2008a) constituted a new departure in monetary reality and theory. Economists have since then been catching up in analysing cryptocurrencies. They have discussed whether Bitcoin is money or can become money (Luther 2016; Nair and Cachanosky 2017; Cachanosky 2019), and what this means for monetary theory (Selgin 2015; L. Davidson and Block 2015). Schilling and Uhlig (2019) study the implications of Bitcoin for monetary policy.

Others have studied Bitcoin at the institutional level, arguing that the blockchain is an important institutional innovation (S. Davidson, De Filippi, and Potts 2018) and Luther and Stein Smith (2020) argue that Bitcoin is better seen as a decentralized payments mechanism rather than simply a kind of money. Marthinsen and Gordon (2021; 2022) analyse whether Bitcoin is an alternative to dollarization, although the Salvadorean introduction of Bitcoin as legal tender has not led to its widespread adoption (Alvarez, Argente, and Van Patten 2022).

Bitcoin has also been analysed in terms of currency competition (cf. Hayek 1990). Hendrickson and Luther (2022) model competition between Bitcoin and fiat money in terms of the Lagos- Wright model (Lagos and Wright 2005) and find that the rate of fiat money creation and the height of bitcoin transaction fees are the key variables in inducing Bitcoin adoption. Jasiński (2023) argues that Bitcoin is disadvantaged in competition against commodity money by its lack of non-monetary use vale. The competition between blockchains has also been analysed (Jiang et al. 2022) with an emphasis on the difference between large and small blocks.

One important aspect of Bitcoin that has so far received little attention is the economics of bitcoin mining. Since the total supply of bitcoin and the rate of production is fixed, there seems to be little to analyse. However, mining is at the core of the Bitcoin protocol (Kroll, Davey, and Felten 2013) and serves, as we shall argue, an important economic function. Indeed, looking specifically at

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mining, Dowd and Hutchinson (2015) argue that Bitcoin is inherently flawed and will come to depend on the major players not abusing their power. A thorough economic analysis is therefore called for.

Previous studies (Kroll, Davey, and Felten 2013; Houy 2016; Huberman, Leshno, and Moallemi 2021) have discussed bitcoin mining in game-theoretic terms, but we propose another approach. Specifically, we will analyse bitcoin mining in Ludwig von Mises's framework of monetary and wider economic theory (Mises 1953; 1998). While bitcoin is not widely used as money, it is a medium of exchange that is valued mainly for its (expected future) purchasing power. Since this is the essential characteristic of money, it follows that we can also analyse bitcoin along the lines of monetary theory (Mises 1998, 395). Another important quasi-monetary use of Bitcoin is as a secondary medium of exchange (Mises 1998, 459), that is, an economic good that substitutes for money, since its market value is stable and it is highly liquid.

Lawrence White (2023) has recently analysed Bitcoin and compared it to gold and fiat money in a framework derived from Mises, but his analysis and conclusions are still notably different from ours. Rothbard (2008) have used the framework to analyse fractional reserve banking and Žukauskas and Hülsmann (2019) have investigated how monetary policy affects financial asset prices as the reservation demand for money declines in an inflationary environment. A crucial point in the Misesian framework is that we don't have to make restrictive assumptions (Long 2006) and can easily go from analysis of Bitcoin to consider the relations between it, fiat money and competition between cryptocurrencies. This enables a straightforward comparison between the different versions of Bitcoin, cryptocurrencies and commodity money. As we shall see, it is in the area of mining that key differences between various versions of Bitcoin become important for their economic function.

While we refer throughout to Bitcoin, our analysis applies to any cryptocurrency that has the same basic attributes, specifically where the production of new coins and the safety of the blockchain is accomplished through proof-of-work. We can understand the process of bitcoin mining as analogous to the production of commodity money. Ciaian et al (2016) study bitcoin by applying Barro's (1979) model of the gold standard, and the idea of Bitcoin as ”digital gold” is widespread among cryptocurrency enthusiasts, but no one to our knowledge has as of yet fully investigated bitcoin mining as a case of commodity money production. Our analysis shows that bitcoin mining is indeed similar to commodity money production but also distinct, as bitcoin mining performs the role that minting and banking do on a gold standard. Transaction fees are closely connected to mining and Bitcoin "governance" plays an important role in transmitting user demand to miners. Bitcoin mining is essential in evaluating the possibility of Bitcoin eventually becoming a widely used medium of exchange.

A Monetary Analysis of Bitcoin

Money is an economic good like others but its value is determined differently. While other goods are desired for their utility in directly (consumer goods) or indirectly (producer goods) serving human needs, money is desired only for its purchasing power (Mises 1990). When people demand money, the specific nominal amount they demand depends on the purchasing power of that nominal amount. Money is also never consumed in the sense of used up. It is simply held in cash balances and sometimes given in exchange, that is, transferred from one to another person's cash balance.

Demand for money is therefore demand to hold money, since all units of money are always held in someone's cash balance (Mises 1998, 399). New production of money is slow, so the stock of money is fixed in the short term and all changes in demand for money leads to changes in the purchasing power of money: an increase in the demand for money leads to a higher purchasing power of money and a fall in the demand for money lowers its purchasing power.

The total demand to hold can be subdivided into reservation demand and exchange demand (Rothbard 2009, 137–42), or into demand by possessors and by nonpossessors. At a given purchasing power, that is, at a given constellation of prices for nonmonetary goods, individuals are willing to exchange specific amounts of the various goods for money. This is the exchange demand for money. Logically, this is mirrored by the exchange supply of money: the amount of money that possessors of money want to exchange for non-monetary goods at a given constellation of prices in a given moment. The exchange suppliers of money value the sums of money that they want to give up less than the quantities of goods they want to acquire, and the exchange demanders of money value the sums of money higher than the quantities of goods they want to sell.

Reservation demand is likely to constitute the greater part of total demand at any given moment in time. This is the demand for specific sums of money exercised by the possessors of money who are unwilling to part with these sums at the present height of prices. When individuals expect the value of money to fall, they are likely to reduce their reservation demand and search for close substitutes, secondary media of exchange (Mises 1998, 459). Financial assets generally is one such substitute (Žukauskas and Hülsmann 2019). Bitcoin is another possible substitute. When a low permanent rate of inflation is expected, where money continually loses a little value such as in the case of most present-day fiat moneys, reservation demand is especially likely to decline in favour of whatever assets are considered the best secondary media of exchange. Note that supply and demand for money are a generalization of all individuals' value scale at any given moment in time. They will change from one moment to the next.

Figure 1 presents the demand for money in diagrammatic form. Total demand intersects with the stock of money and is split into exchange demand and reservation demand. A rise in either component of demand leads to a rise in purchasing power. The reservation demand can rise either by lowering purchases, which shifts the exchange supply of money to the left, or by temporarily offering more goods and services in exchange for money, temporarily shifting the exchange demand for money right before the higher reservation demand is satisfied. In both cases the result is monetary equilibrium at a higher purchasing power of money.

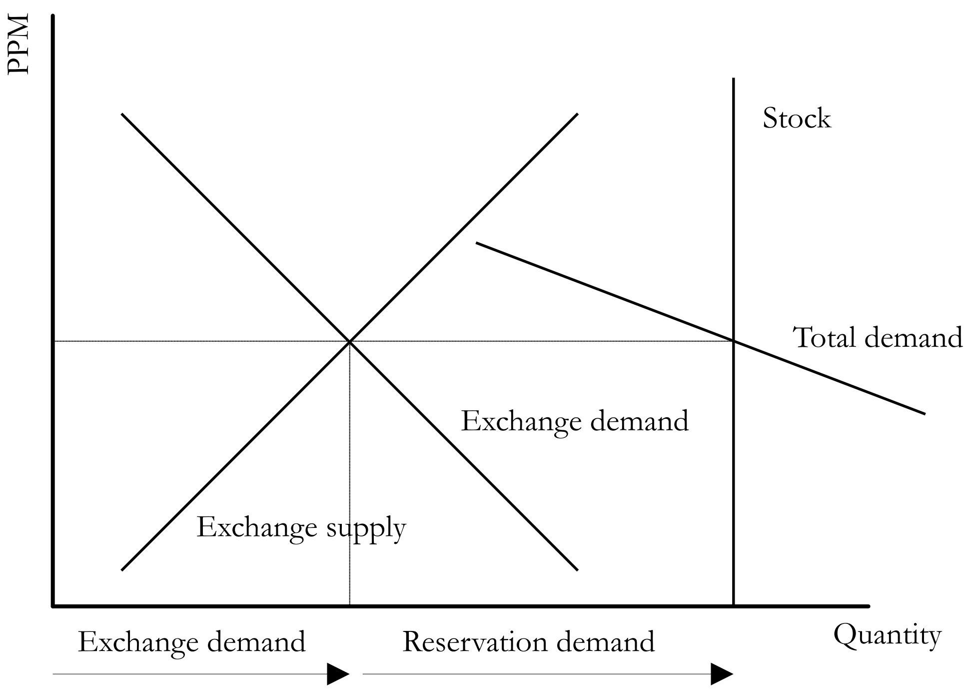

Figure 1: The supply and demand for money

A rise in exchange demand for money has similar effects. The simplest case of such a rise is increased productivity in a growing economy, leading to greater quantities of goods as well as completely new kinds of goods being offered for sale. More goods for sale is the same as a higher exchange demand curve for money. In response, the exchange supply curve may remain in place or even shift to the right, signifying that individuals temporarily lower their cash holdings to take advantage of the opportunity to buy new goods. This is natural, since the point of holding money is the ability to take advantage of unforeseen opportunities (and guard against unforeseen costs) (Hutt 1956). Over time, however, the supply curve will shift to the left. But it cannot a priori be said that it will shift back, ensuring the old proportion between exchange and reservation demand – this is indeterminate. Since the changes in demand for money have induced changing prices across the economy, the height of demand (exchange and reservation) for money of all individuals has changed and is different in the new monetary equilibrium.

A more complete presentation of the relations between exchange and reservation demand is possible if we look at all the separate goods markets. The supply of each separate good constitute part of the exchange demand for money and its variations can thus be traced across all markets (Salerno 2010a; cf. L. Davidson 2012). However, for present purposes, the sketch presented above is sufficient, since we are not concerned with the question of general equilibrium across all markets, but simply pursuing a monetary analysis of Bitcoin.

One good is rarely alone in providing monetary services. Historically, gold and silver circulated as money side by side and even today there various commodities and financial assets that are demanded partly for their liquidity, that is, for the ease with which they can be realized, exchanged against money. Such commodities are secondary media of exchange or quasi-money (Mises 1998, 459–63; Rothbard 2009, 826). They generally are not used as a medium of exchange but as a store of purchasing power. The demand for them is principally a question of how well they preserve purchasing power net of costs relative to the main money (or relative to the other money in the case of multiple moneys). If the main money is expected to depreciate, relative demand for secondary media of exchange is likely to rise. Such demand substitutes for reservation demand for money, since exchanges for goods and services still take place using the main money. In the case of competition between different moneys, exchange demand is also likely to shift from one to the other. These questions of monetary competition can be elucidated in terms of these shifts between exchange and reservation demand for the different moneys and secondary media of exchange, as we will show below.

Bitcoin Characteristics[1]

While Bitcoin is by now more widely known, the following brief summary of its key characteristics should help as a quick reference. It also serves to highlight what the key facts for an economic analysis of Bitcoin are. Throughout, we will simply refer to Bitcoin, but we do not intend to exclude

1 For more detail on Bitcoin, see the white paper (Nakamoto 2008a) as well as more recent explainers (‘FAQ - Bitcoin’, n.d.; ‘FAQs | The Bitcoin Cash Podcast’, n.d.; ‘How the Bitcoin Protocol Actually Works – DDI’ 2013).

any version of the original Bitcoin currently in existence. In fact, the competition between different versions of bitcoin and other cryptocurrencies fits easily into our analysis. We will touch on a key point of contention among advocates of different versions, the blocksize, below.

Bitcoin is a digital, cryptographically secured currency. All transactions are collected in blocks, which are discovered and cryptographically "sealed" every ten minutes by bitcoin "miners". A new block is added to the previous block, so the blocks form a chain into the past, wherein all transactions are recorded. When a holder of bitcoin spends an amount, he broadcast his transaction to the network. The transaction is then included when a block is added to the blockchain. Every new block also includes newly-created bitcoin as a reward to the miner who finds it, but the rate of production is falling – both relative to the stock in existence and in absolute terms – until about the year 2140 the total stock of 21 million bitcoins will have been mined. From then on, no new bitcoins will be produced.

Bitcoin mining is pivotal to the functioning and security of the system. In order to "mine" the next block, a miner spends processing power to find the answer to a mathematical puzzle. As soon as he finds it, he broadcasts it to the network and other miners can check that his is the right answer. Once it is accepted, the transactions included in the block are locked in, including the reward to the miner and any transaction fees. As this reward is valuable, miners invest capital in increasing their chances of finding the next block, increasing the processing power or the "hashrate" devoted to finding new blocks and securing the network. In order to keep the rate of discovery at roughly one block every ten minutes, the difficulty of the work necessary is automatically adjusted. Hence, increasing processing power in the network only has the effect of securing it against attack – any amount of processing power would be adequate to produce the next block in the blockchain, since the difficulty would adjust as necessary.

Each transaction included in a block requires some space, if only very little. However, providing this space is costly, especially once Bitcoin adoption is widespread and transactions number in the millions per block. Miners will not want to include costly transactions, especially once Bitcoin is fully mined. Hence even with a low hashrate, transaction fees to the miners are a necessary feature of the system, but costs per transaction and hence the fee per transaction are likely to remain minuscule. Space on each block may however be limited, if a size limit per block is imposed.[2] Then, transaction fees rise as users bid for scarce space. The transaction fee then serves to allocate scarce block space. We will analyse the consequences of block size and fee structure below, as it is intimately connected to the economics of bitcoin mining.

2 The block size limit is the key difference between Bitcoin Core and Bitcoin Cash

We can apply the monetary basics laid out above to the case of Bitcoin. The value of Bitcoin comes from its possible use as a medium of exchange and its purchasing power (cf. Selgin 2015; Hansen 2019). The more Bitcoin is used in exchange, the more goods and services are offered against it, the higher the exchange demand for bitcoins; the more people use it as a secondary medium of exchange, the higher the reservation demand for bitcoins.

Figure 2 depicts this. The stock of bitcoins is fixed, but moving gradually, at a very slow rate, to the right, until it reaches the final stock of 21 million, indicated by the red arrows. Since Bitcoin is nowhere the most generally accepted medium of exchange, we don't need to present its value in terms of purchasing power but can simply use its value in dollars or euros. Reservation demand for bitcoin, or ”hodling”, is relatively large, since Bitcoin's limited supply and the possibility of exchanging it globally make it a good secondary medium of exchange in a world of fiat money. Exchange demand is also important, but for the time clearly overshadowed by reservation demand. If the rate of production of new bitcoin outstrip increase in demand for bitcoin, the result will be a lower price per bitcoin.

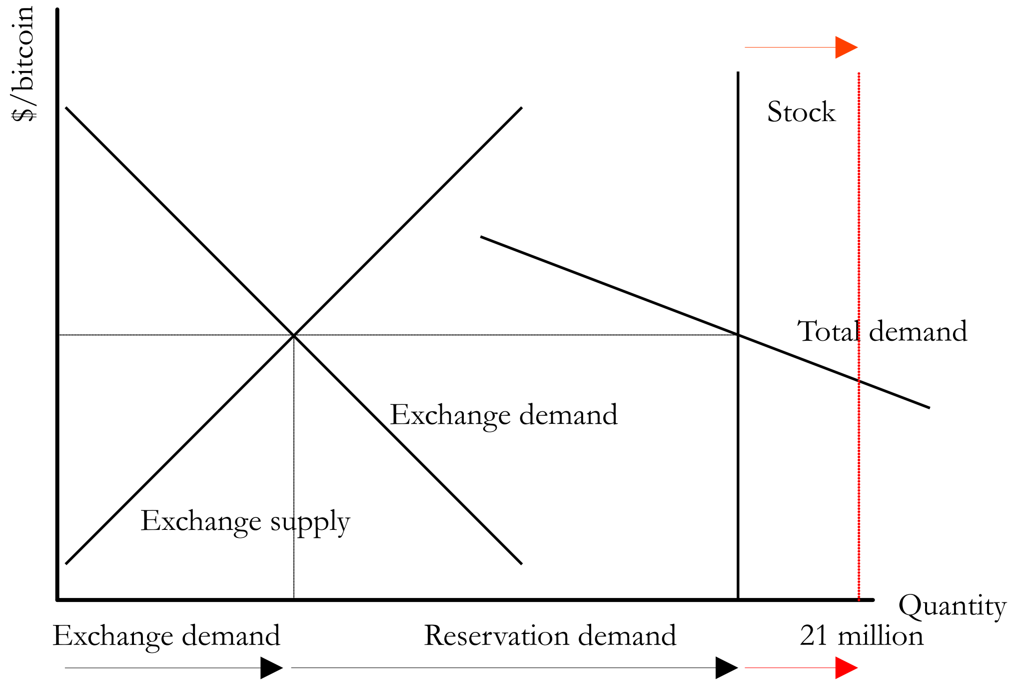

Figure 2: The supply and demand for bitcoins

Since any increase in demand for bitcoins is likely to come from reduced demand for fiat money, the consequences of changes in demand for bitcoin are a little different from the changes in demand for money described above. A rise in exchange demand will raise it relative to reservation demand and increase the value of bitcoin. A rise in reservation demand will raise it as a total proportion of demand and lead to a higher value of bitcoin. The two types of demand are not completely unconnected, since higher exchange demand means that bitcoin is more widely used as a medium of exchange, which in turn makes it more attractive to hold as an alternative to the standard money in an economy. An increase in either kind of demand for bitcoin has the further effect of raising prices in terms of the standard money higher than they otherwise would be, since demand for money falls to the same extent as demand for bitcoin (and all other secondary media of exchange generally) rises.

From this brief overview it is clear that the key quality to consider in analysing Bitcoin is its purchasing power or price, specifically its purchasing power and expected changes in purchasing power relative to fiat money and to other secondary media of exchange. Demand alone drives the price of bitcoin, and demand is based on its subjectively perceived utility as a monetary asset. Once we turn to the supply side, the similarity and difference between Bitcoin and a commodity money like gold become clearer, although as we shall see, the similarities are more important than the differences (contra Houy 2016). On a gold standard, the demand for money influences the nominal supply of gold and the amount of resources devoted to gold production; demand for bitcoin cannot influence the nominal supply of bitcoin, but it determines the amount of resources devoted to bitcoin mining.

Commodity Money Production and Bitcoin Mining

Commodity money production is subject to the same economic laws that regulate the production of other commodities (White 1999, chap. 2; Salerno 2010b). In equilibrium, the stock of monetary gold[3] is stable. It's purchasing power is stable and there is only so much produced per year to equal annual non-monetary use of gold plus the amount used up in monetary employment (due to wear and tear on coins and the like). The supply of new gold may vary, of course: new mines may be opened, or new, more productive extraction processes may be invented, both of which tend to increase the supply of gold, reducing its purchasing power and increasing prices. Gold will then tend to shift out of monetary use into non-monetary uses, as these are now more profitable. Conversely, a fall in the rate of production of gold will increase its purchasing power and gold will shift out of non-monetary into monetary use until the new equilibrium is established.

Changes in demand also lead to variations in the production of gold. An increase in demand raises the purchasing power of gold and this stimulates additional production: more factors of production

3 We will use gold for our exposition in the interest of brevity.

are allocated to gold mining, since this is now more profitable. The additions to the gold stock tend to drive down the purchasing power of gold, until a new equilibrium position is reached, where the stock of monetary gold is higher and the purchasing power of gold may or may not be higher than at the outset.[4] Garrison (1985) points out that the increase in the gold supply is likely to lag behind due to increasing marginal costs, suggesting a gold standard economy would be characterized by increasing purchasing power over time (assuming rising exchange demand over time due to economic growth.) Conversely, a fall in demand for gold tends to lower the purchasing power of gold and raising prices throughout the economy. It therefore becomes more profitable to shift gold to non-monetary uses and diminish the stock of monetary gold until a new equilibrium is reached. These different possibilities are illustrated in figure 3, where the stock of monetary gold shifts in response to changes in demand. We here abstract from the distinction between exchange and reservation demand, since it is the change in total demand that is important. Note that the equilibrium PPM after each change is different because of increasing marginal costs of mining.

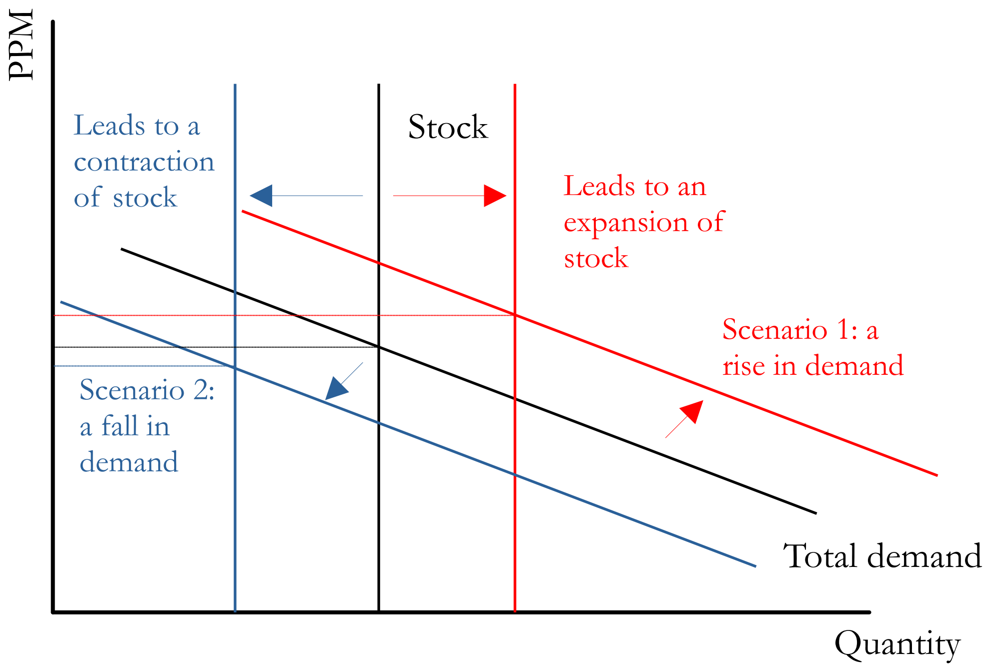

Figure 3: Changes in demand for gold and the stock of gold.

There is also demand for various forms of commodity money. Specifically, while gold is especially suited for the monetary role, there are some costs of weighing and assaying quantities of precious metal. A trusted third party may take on the function of weighing and assaying, issuing standardized coins of a guaranteed weight and fineness. Effectively, mints issue certificates of money integrated with a quantity of physical money (Hülsmann 2008, 35–38). Minting requires labour and capital, so

4 Only if we assume constant costs do we get White's (1999) result, where the purchasing power returns to the same level as before the rise in demand for gold.

only if coinage is valuable to money holders will mints come into existence. Then, coins will circulate at a premium above pure gold. Because mints will expand coin production so long as the coin premium exceeds the costs of coinage, the premium will eventually shrink to equal the marginal cost of coinage. Alternatively, banks may emerge which perform essentially the same function as mints, but rather than certifying coins, they store the gold in vaults and issue claims on gold in the form of checking deposits or bank notes. While this may be less costly in some respects, there are still costs connected to the checking and safekeeping of the precious metal.

Ultimately, the production of money and the various forms in which it may be issued depends exclusively on consumer demand. Only if consumers demand a greater (nominal) supply of money will factors of production be allocated to producing money and only if they demand specific forms of money (coins or bank notes) will issuers of such come into existence. Entrepreneurs will allocate factors of production to money production, minting and banking until the marginal return to one extra factor is less than its marginal return in some other business. That is, commodity money production follows the law of costs like the production of all other economic goods (Hülsmann 2003; Hansen and Newman 2022). While gold mining is a costly business, the resources dedicated to it simply reflect the desires of consumers (in this case, money holders) and cannot therefore be considered wasted, no more than the resources dedicated to any other kind of production can be considered a waste (cf. Israel 2021).

Bitcoin Mining

If we turn to bitcoin "production", it is clear that in some ways bitcoin mining is different from gold mining, but in essential characteristics it is very much alike. Ivey (2023) provides a short overview of the economics of bitcoin mining. Since the amount of bitcoin and the rate of production is set by the protocol, demand for bitcoin has no influence on the nominal supply of bitcoin. The stock simply slowly increases at the rate set by the Bitcoin protocol until the full stock of 21 million is mined (see figure 2). However, in terms of the "supply" of purchasing power or value of bitcoin, this is determined exclusively by demand and is not limited in either direction.

The demand for bitcoin determines the value of bitcoin produced and thereby also the amount of resources devoted to bitcoin mining. Like in the case of gold production for monetary use, bitcoin miners hire factors of production to work on bitcoin mining, raising factor prices and mining costs, until the expected return from employing one additional factor of production is not greater in bitcoin mining than elsewhere. In other words, here too the law of costs holds and there are no special returns to bitcoin mining. Mining revenues change and increase with larger demand, but mining profitability does not (Easley, O’Hara, and Basu 2019, 107).

The expected revenues from mining determine how much entrepreneurs invest in the various inputs. Since bitcoin miners have no control over how many bitcoins are created per control nor over the value of bitcoin, all an individual entrepreneur can do is to maximize his chance of mining the next block. The principal inputs here are mining hardware and electricity to run the hardware. Mining hardware is nowadays completely specific to bitcoin mining, but it is worn out quickly – mostly within six months or so. Electricity on the other hand is very unspecific. When a miner expects higher bitcoin prices and higher block rewards, he is willing to invest more capital to increase his revenues. He therefore bids factors of production away from other uses, that is, he powers up additional miners, in case he has unused capacity, or he invests in new mining hardware. Electricity is directed to bitcoin use and chip manufacturing to bitcoin mine production. Since all entrepreneurs do this, the result is higher prices, especially for mining hardware, since this is the specific factor of production, until the prices of all inputs equal their expected discounted marginal revenue product. More capital is now bound in bitcoin mining, leading not to a higher rate of production, but to a higher hashrate. That is, more computer power is being used to process payments and secure the blockchain. A fall in demand for bitcoin has the opposite effects. Bitcoin miners reduce production, and marginal miners go out of business. Less capital is bound in mining and the hashrate falls, until a new equilibrium is reached where the prices of inputs again equal their expected discounted marginal revenue product.

In the fast-changing world of Bitcoin, such an equilibrium position will be fleeting. Demand for bitcoin has been trending upward and the costs of mining hardware has declined considerably. These costs run down exponentially falling cost curves, as the costs of processing speed, computer memory and bandwidth have been falling rapidly for years (S. Davidson, De Filippi, and Potts 2016, 3).

Mining Costs and Economies of Scale

While bitcoin mining is a relatively capital-intensive business and specialized hardware is required, this in itself does not tend toward concentration or economies of scale. That is, it does not cause a tendency for an ever larger concentration of mining in fewer operations. Economies of scale is about the optimal utilization of non-divisible inputs (Rothbard 2009, 593–600). Computer memory is such a non-divisible input for bitcoin mining. Each miner needs to store a copy of the blockchain (to run a full node in technical terms) and the more popular Bitcoin becomes, the more transactions are made, and the larger each block becomes, increasing the size of the blockchain. Thus storing and updating a copy of the blockchain constitutes a fixed cost and this imposes some minimum size on a mining firm, but it does not by itself constitute a tendency toward greater concentration of mining power. In order for economies of scale to emerge on this account, the blockchain would have to grow faster than memory costs fall. Assuming Kryder's law holds (the cost of memory halves every twelve months),[5] the blockchain has to more than double in size each year for there to be any tendency toward centralization. The key determinant of the size of the blockchain is the number of transactions per block,[6] so this means that the number of transactions would have to more than double every year for scale economies to emerge. Especially in the long run, when Bitcoin is more widely adopted, it is unlikely that the number of transactions is going to continually rise at this rate, but until then it is possible that a short-term increase in the use of bitcoin leads to greater concentration of mining. That is, for any given number of transactions and size of blocks, some minimum capital needs to be invested in storage before a miner can get off the ground and start earning revenue.

A second cause of economies of scale is site costs. Bitcoin miners need to be stored and maintained, and there are more or less efficient ways of doing so. A setup where maintenance and site costs per miner (and hence per bitcoin earned) is lower will tend to outcompete one where these costs are higher. Yet here too, there is an optimal setup – ever-larger mining installations will not provide economies of scale. As a broad empirical point, it seems that site costs are for the moment more important as a cause of economies of scale than memory costs are.

Finally, the emergence of mining pools, where bitcoin miners combine their resources and share block rewards, can be seen as a case of scale economies. Dowd and Hutchinson (2015) argue that bitcoin mining is a natural monopoly, because all miners would be completely sure to earn part of the reward from every block if they all combined in one pool. This prediction has so far not come to pass, and it rests on the assumption that there is one dominant business model in bitcoin mining based on reducing stochastic risks of loss. Yet no business apart from insurance is about stochastic risks but rather about producing for an uncertain future (Foss and Klein 2012). There would also be plenty of opportunities for cartel-busting should a mining monopoly emerge. A monopoly would

5 This is an economic reformulation of Kryder's law, which states that the density of hardware drives doubles every 13 months. Other versions have 18 to 24 months as the doubling time.

6 It is possible to store other information on the blockchain. To the extent that a given blockchain is used for data storage, memory costs will go up.

only earn extra profits by cutting costs since it has no control over bitcoin's value, but cutting costs and reducing its computing power would open an opportunity for other miners to enter or for competing mining pools to emerge. A monopolist could also engage in fraudulent behaviour, but this would likely not be in his own best interest, since corrupt practice is likely to lead to loss of trust in Bitcoin, which would lower demand and hence the value of Bitcoin drastically. The short-run gains a monopolist could make through double-spending are unlikely to outweigh the drastic loss in capital value he would suffer.

Mining pools are a phenomenon of economies of scale, not a natural monopoly. The individual miner is faced with the risk that the block he successfully mined will not be recognised by the network, that it will be "orphaned" in technical terms. This risk increases when blocks are larger (Houy 2016). Better network connectivity reduces this risk and membership in a mining pool achieves this purpose. Such membership also affords the miner with steady income: the mining pool will more frequently mine the next block and the members will therefore have a steadier income, even if their total revenues over the year are the same, whether they mine alone or in a pool. Mining pools help manage bitcoin mining: the individual firms externalize the management (including network) costs to the pool and thus achieve economies of scale without having to merge operations. The fact that there are several large pools in existence shows that there is competition between the pools in providing this service and miners can shift between pools as they wish. Even should one pool become dominant, the miners in the pool would still have no incentive to subvert or attack the blockchain, for instance with a 51-percent-attack. The short-run gains from such behaviour are dwarfed by the losses, since Bitcoin would likely lose credibility, demand would fall precipitously and the value of bitcoin and hence expected revenues to miners would decline drastically. Even if combined in one mining pool, miners would still have every reason to remain honest in order to protect their capital and maximize income.

Energy Costs of Mining

While mining hardware is the specific factor of production for bitcoin mining and determines the size and structure of mining firms, electricity is the crucial input in the mining process. The miner really buys bitcoin against electricity, and he invests his capital in mining hardware to do this at the highest possible bitcoin / kWh price. When bitcoin's value and hence expected revenue increase, entrepreneurs expand their mines and use more electricity, increasing the hashrate, until a new equilibrium is reached where the discounted marginal revenue product from one more unit of input is lower than the price of said input. In the new equilibrium, the hashrate is higher, more capital is bound in bitcoin mines, and electricity consumption is higher.

Electricity consumption is often raised as a concern in the literature (Krause and Tolaymat 2018) and there is no doubt that it is substantial (Stoll, Klaaßen, and Gallersdörfer 2019). The Cambridge Sustainability Index (CBECI 2024) attempts to track the global energy use of the Bitcoin network, but the error margins are wide, although the upward trend it describes is surely correct. Since bitcoin mining is governed by the law of costs, however, there is no particular problem of power consumption here. Electricity is used for bitcoin mining because that is the best use of resources in the judgment of economic actors. That is the import of the law of costs.

Since energy costs vary considerably across the globe, the price of electricity is crucial in determining the geographical distribution of bitcoin mining. Bitcoin can be mined anywhere on the globe so long as the miner has reasonably stable access to the network. Hence, mines are likely to be built in regions with low energy costs or with excess or wasted energy production that cannot find an alternative outlet. The result can be geographical concentration of mining. Thus, China was the key mining region before the Chinese government banned bitcoin mining in June 2021 and since then the United States has emerged as a key region. The actual distribution is not clear however: the CBECI has not updated its map since January 2022 and miners may use VPNs to disguise their IP address and thus their physical location.

In itself, geographical concentration in a few key centres is unproblematic. It might be of concern if one political authority could exert pressure on the majority of miners or even try to shut down the network. This risk appears more hypothetical than real, however – the Chinese ban only led to a momentary drop in the hashrate, it did not have any lasting effects. It even appears that miners still operate in China despite the ban.

More on the Economics of Bitcoin Mining

We have already briefly alluded to the role of transaction fees and the size of new blocks. A limit on the blocksize was introduced in 2010 to prevent spamming and bloat, which might at that early stage have hampered Bitcoin considerably. Bitcoins were still very cheap, so it was possible for an attacker to sabotage the network by sending millions of transactions, which would have led to large blocks, which would have made the blockchain unmanageable at that early stage. Later, however, blocks were “full”, that is, there was not room for all the transactions. Transaction fees arose as the natural response in the protocol as it then was while debates among users and programmers about the blocksize limit and the future direction of the network began.

Such debates are a key part of the governance of the Bitcoin protocol. By proposing and managing updates to the protocol, programmers respond to the various challenges facing the network (Kroll, Davey, and Felten 2013). Bitcoin users (miners and everyone else) download the software from the official repository and check there for updates. In theory, programmers suggesting and uploading updates are simply managing development on behalf of Bitcoin users, since they cannot force a distinct upgrade on everyone but any change has to be accepted by the users and miners in the network, and they do so by upgrading their own software. Thus, governance is simply a means of implementing consumer demand and transmitting it to miners and the rest of the network.[7]

A problem arises if there are incompatible wishes for the development of Bitcoin. Then, a split, a "hard fork" of the blockchain and the emergence of two separate "Bitcoins" occurs. Alternatively, a cryptocurrency completely unconnected to the original Bitcoin protocol may be launched. One example of incompatible governance choices concern the way difficulty adjustment occurs. There is broad consensus that keeping the 10-minute "production time" per block is sensible. In response to added computing power, the difficulty of the proof-of-work has to increase. This is built into the protocol, but there are distinct, mutual incompatible ways of doing it across different versions of Bitcoin such as Bitcoin (BTC) and Bitcoin Cash (BCH).

Transaction Fees

The size of blocks and the role and size of transaction fees is a crucial case of governance. Here, too there are incompatible alternatives. If blocks are limited to a small size, then transaction fees become important to allocate scarce block space and miners' earnings in bitcoin per block increase. However, large fees make bitcoin use costly, reducing demand and bitcoin value. Larger blocks reduce the importance of transaction fees, lowering miners' income in terms of bitcoins per block but increasing bitcoin demand and value (c.f. Jiang et al. 2022).

In the future, as the rate of production of new coins decline, transaction fees become more important in funding bitcoin mining. Satoshi Nakamoto even predicted that transaction fees will become the only source of revenue for miners: "Once a predetermined number of coins have entered circulation, the incentive [to mine] can transition entirely to transaction fees and be

7 There are differences in how governance works across different blockchains, but this high-level summary is adequate for our purposes.

completely inflation free." (Nakamoto 2008a, 4) However, by imposing a ceiling on the number of transaction per block, the role of fees is accelerated. It is doubtful whether we can really call this a welfare loss (contra Kang and Lee 2022), since bitcoin users are still free to shift to another version of Bitcoin (from Bitcoin Core to Bitcoin Cash, for instance) if fees are too high for them, but we can analyse what the consequences of different choices when it comes to block size and fees are.

Let us consider the case of a small-block, high-fee blockchain first. Exchange demand is heavily restricted under these conditions. Assuming that each block is full, the total number of exchanges is set and all that can vary is the amount per transaction. Exchange demand can thus still grow in terms of value, but small exchanges will increasingly be priced out by fees. Other things equal, only high-value transactions will occur on the blockchain.

This restricted exchange demand also constitutes a bottle-neck for reservation demand for bitcoin: it is no longer possible to accumulate bitcoin through direct exchanges of goods and services, since the fees price out this kind of transaction. Rather, an increase of reservation demand will almost exclusively come through financial channels. Individual bitcoin holders will buy bitcoin through middlemen such as exchanges, and only when they have a substantial sum in bitcoin claims will they transfer them to their own private wallets.

In figure 4 we see how, as fees increase, exchange demand falls and eventually only facilitate changes in reservation demand. The figure is somewhat misleading, since the value per transaction is going to increase, thus the exchange demand curve again shifts forwards. However, the figure correctly illustrates the greater importance of reservation demand. To keep the figure simple, we do not depict the changes in total demand and in the value of bitcoin. The red rectangle approximates the volume of "lost" exchanges, some of which is transformed into transaction fees. If reservation demand rises, exchange demand may again shift to the right, as holders exchange their claims on exchanges against bitcoins. The use of second-layer solutions may also shift exchange demand right, as holders pay into and take bitcoin out of various second-layer solutions or middlemen.

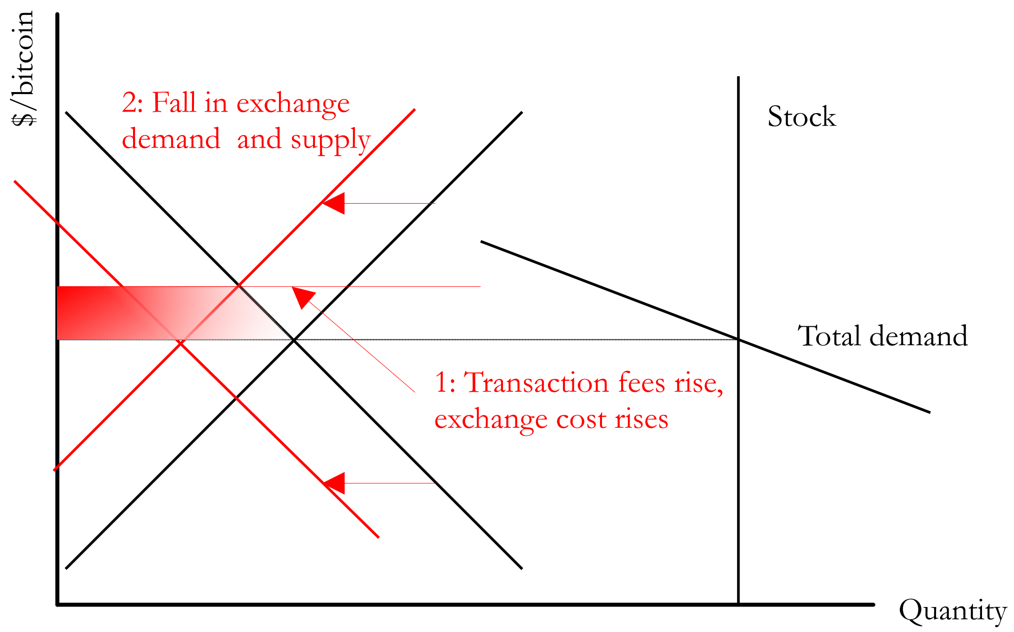

Figure 4: Bitcoin demand with small blocks.

The consequences of small blocks and high fees for bitcoin mining point in two directions. On the one hand, insofar as high fees discourage exchange demand, demand goes down, the price of bitcoin goes down and revenues for miners are lower than otherwise. On the other hand, transaction fees constitute an extra source of income to miners. Since extra miner income means an increase in capital devoted to mining and an increase in the hashrate, the safety of the blockchain increases. If this increase in safety is desired by bitcoin holders, demand for bitcoin will go up (Jiang et al. 2022). But this would only be reservation demand and bitcoin is effectively constrained to be a financial or speculative asset. The use of bitcoin as a medium of exchange becomes impossible because users have to go through middlemen (or second-layer solutions) to exchange it. In terms of monetary functions, it can still be demanded and used as a secondary medium of exchange, but its lower liquidity also hampers it in this function.

On a big-block, small-fee blockchain, there are no restrictions on exchange demand, assuming that the block size will always expand ahead of a rise in demand. High and low-value transactions will occur on the blockchain and there is no need for third parties to facilitate exchanges outside of specific business cases. Both accumulation (an increase in reservation demand) and business use (an increase in exchange demand) can take place without crowding out each other, since there is room for all transactions on each block.

Bitcoin miners will face a different cost and revenue structure when blocks are large. Transaction fees will emerge as we describe below, but the fee per transaction will likely remain minuscule and fees will not be necessary to pay miners for space on blocks. Since blocks will grow larger, miners face increased memory costs with the consequences described above. There is a direct causal link between memory cost and each individual transaction, so transaction fees will emerge to cover this particular cost, a point that Nakamoto himself made (Nakamoto 2009). Such a fee will be very low, however, since it will only cover the memory cost of that one transaction. A second source of fees may come from the need for instant or so-called “0-conf” transactions. Since a block is only mined every 10 minutes, a waiting time is imposed on commerce before the transfer of bitcoins is secured in the blockchain. Especially in retail commerce this waiting time can be prohibitive. Yet governance – either through the protocol or through mining pools – can overcome this problem. Mining pools can set up policies for monitoring the pool of waiting transactions, the “mempool”, and clear waiting transactions ahead of time – that is, check that the transaction is legitimate and that a fraudulent double-spend is not attempted. The same is possible through updates to the protocol, but it will in any case be a costly procedure, and miners and mining pools will want to be paid for providing this service. Hence, transaction fees will arise also in the case of big blocks in order to cover the memory and management costs of transactions.

These transaction fees will not directly stimulate mining producing a larger hashrate. A large-block version of bitcoin may therefore lag behind the small-block version in this regard, but ultimately, income to miners can only come from increased demand. Extra mining income comes from the larger value of bitcoin, whether directly from transaction fees or new coins. Demand must increase for miners’ revenue to increase. Fees are small when blocks are large, so exchange demand is not priced out, but may expand freely, as shown in figure 5. Indeed, an increase in exchange demand may cause a rise in reservation demand, since there are now greater possibilities for the direct use of bitcoin and since a rising value of bitcoin is desirable for holders who want to keep it for the long term. Exchange demand thus supports reservation demand, and the two may rise in tandem. Rising demand raises the value of bitcoin, leading to more capital being invested in bitcoin mining, which raises the hashrate.

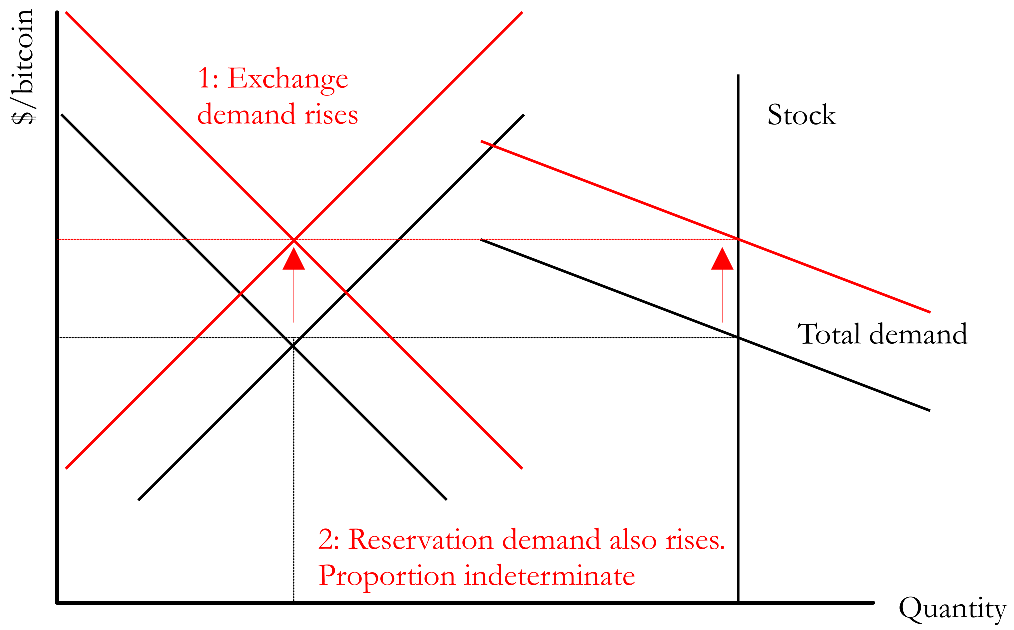

Figure 5: Bitcoin demand with large blocks.

The distinction between big blocks and small blocks is not only academic but led to the first major fork of Bitcoin in 2017. It is to this day the essential difference between Bitcoin Core (or simply Bitcoin) and Bitcoin Cash. It might therefore be argued that the above depiction is erroneous, for since the fork into BTC and BCH, Bitcoin has risen substantially in value against Bitcoin Cash. However, our argument here concerns only the narrow question of big versus small blocks, and demand for bitcoin is not only a question of blocksize. The added security from the high fees on BTC may be valued by holders, and the widespread perception that BTC is the "real" Bitcoin may also add to the prestige of BTC and hence the demand for BTC (cf. Bier 2021 for an overview of the split between BTC and BCH). Bitcoin may also increasingly be held as a speculative asset rather than as a medium of exchange, and then high transaction fees are, as we saw, not a relevant problem.

Mining Without Inflation

Once the total supply of bitcoin has been produced, miners' revenue will only come from transaction fees. Memory and management cost per transaction, as explained above, imposes a minimum, albeit also minuscule, fee per transaction. Yet a fee that only covers memory costs would produce virtually no hashrate and would leave the Bitcoin network vulnerable to fraudulent attacks. The point of bitcoin mining – and what really distinguishes it from gold mining (Houy 2016) – is that it is necessary to ensure the safety of the network. If gold mining ended, this would not compromise the use of gold as money. It would only mean that increases in the demand for gold would not cause a larger stock to be produced but would only increase the purchasing power of gold. If bitcoin mining ended, great uncertainty concerning transactions would emerge, as new blocks could be cheaply falsified.

Transaction fees are therefore a necessary component of the fully mined Bitcoin system. The need for a replacement for inflation was seen already by Bitcoin's creator (Nakamoto 2008b). Again, however, the economic analysis is straightforward. The security of the bitcoin network is a question of maintaining a given hashrate, and the hashrate is a function of how much capital entrepreneurs invest in bitcoin mining. Through governance, the desire of Bitcoin users for a given hashrate can be communicated to miners. In addition to the transaction fee necessary to pay for memory and management services, an extra fee will be included. Only transactions that include some minimum transaction fee will be accepted by the network. Alternatively, mining pools could take on the governance role, announcing what the minimum fee for inclusion in a block would be. A market would then form consisting of mining pools offering their services against fees and transactors accepting these services. Since larger miners would require more income to stay in business it would not be possible to invest in mining power and accept all fees. Bitcoin users, on the other hand, would determine what fee they would accept and hence what amount of capital should be devoted to bitcoin mining. Whether through changes to the protocol or mining pool fee policy, consumer demand would ultimately determine the fee structure and hence the hashrate in the network.

A mining system funded entirely out of transaction fees is in some respects an improvement over the present situation where coin creation funds mining. When coins are created, mining costs are born by all holders of bitcoin the value of their bitcoin holdings falls beyond what it otherwise would have been. This is not a welfare loss, since by holding bitcoin, market actors show that they prefer this asset allocation even when taking account for the known addition to the bitcoin supply. This is completely analogous to the case of commodity money: here too, the resources devoted to mining and the addition to the stock are an outcome of consumer demand (Hansen and Newman 2022). However, bitcoin mining is directly connected to securing transactions on the blockchain, that is, it is narrowly connected to exchange demand. When coins are created, holders subsidize exchanges: both exchange demand and reservation demand bear the costs more narrowly associated with exchange demand. Once mining is funded entirely out of transaction fees, the costs are narrowly born by the individuals wishing to transact on the blockchain. This situation is similar to the one depicted in figure 4 above, but it is unlikely that the fee per transaction will become substantial and thus greatly hamper exchange demand. Substantial transaction fees are a consequence of scarce block space, the situation analysed above. The consequence of large blocks, as already explained, is that capital is invested in memory and the transaction fee covers the costs of memory, any management costs, and the desired safety of the blockchain (hashrate). Through governance of the protocol and mining pool policies, bitcoin users can achieve the desired degree of safety, as they, through the choice of fee structure, determine how much capital is bound in bitcoin mining.

Bitcoin mining here appears again very similar to the economics of a gold standard, but it is no longer the analogy to gold mining that springs to mind. Rather, the role of bitcoin miners is similar to the role of mints, banks and other intermediaries in a commodity money (or fiat money) system. This conclusion is not that surprising, since early speculation on what eventually became Bitcoin foresaw that mining would perform minting services (Szabo 2008). Mints and banks, as we saw, help guarantee the integrity of coins and payments and are paid for this service. Money certificates arise, because this is the most efficient way of ensuring the quality of the metal and of transferring it. In the Bitcoin system, if all transactions take place on the blockchain, then third parties like banks are unnecessary for the system to work. The function of securing individual payments is taken over by bitcoin miners, who “certify” that the funds are not being double-spend and secure transactions in the blockchain. To the extent that there is demand for these services, they will be paid for out of transaction fees. In the current Bitcoin (BTC) setup transaction fees are primarily payments for scarce block space that also generate a higher hashrate, but the blocksize limit is not necessary to generate adequate fees to support a desired hashrate.

Competition Between Blockchains

We have already noted that there are incompatible governance choices and that when a consensus cannot be reached, the result is a hard fork and the emergence of two versions of Bitcoin. Alternatively, rival blockchains are developed and launched from scratch. The size and importance of every cryptocurrencies is always determined by the total demand for each. Mining too follows demand. In the case of rival blockchains, where the mining hardware is incompatible, the adjustment process is slower, as miners reinvest in the rising blockchain and do not replace their worn out mines in the falling blockchain.

In the case of Bitcoin forks the hardware is common to all, since they all use the SHA-256 algorithm for the proof-of-work. This means that miners can at very low cost switch from mining one version of Bitcoin to another. Profit-driven miners therefore change what they mine based on expected profitability. They key determinant of profitability is the price of bitcoin, secondarily the amount of transaction fees in new blocks. The first is determined by total demand and the second exclusively by exchange demand and the volume of transactions in a given period. Thus, whenever demand for one version of Bitcoin, or for a cryptocurrency that also uses SHA-256, goes up relative to other versions or cryptocurrencies, miners will shift more power to mining it, and when it goes down, relatively less mining power will be spent on it. Here as everywhere when it comes to bitcoin mining, the law of costs rule. The amount of capital bound and hence the hashrate in a given Bitcoin network therefore follows demand very closely, but it can also shift quickly, if demand shifts.

In a sense, insofar as mining hardware is common to different versions, the total amount of hardware secures all blockchains. Demand determines where it is invested at the moment, but it can change very quickly.

While the adoption of one commodity as money is seen as superior since it simplifies economic calculation, the existence of more cryptocurrencies is not therefore problematic. It is simple to convert holdings of different assets into a single unit of account for purposes of calculation, and holding different cryptocurrencies and moneys can be seen as a hedge against the failure of any single one of them, or simply against losses specific to one version of Bitcoin, whether from falling demand or from corruption of the protocol. If corrupt miners come to dominate one version, users can shift to another. As over time capital follows demand, other entrepreneurs may invest in the rival blockchain, meaning that the corrupt miners are weeded out. Unreliable or dysfunctional governance structures will also lead to an exodus from one blockchain to its closest rivals.

Conclusion

A number of conclusion emerge from our analysis of bitcoin mining. First, there is no specific problem of centralization of mining, either from the side of individual miners or from the side of mining pools. The necessity of paying for memory storage necessitates a certain minimum size of mining firms, and the pooling of management costs leads to the emergence of mining pools, but neither is a process of ever-greater centralization resulting in a mining monopoly. Some given size is necessary for the economic running of bitcoin mines, that is all.

Second, mining bitcoin, whether in the present situation of coin creation or in the final state where miners' revenue comes exclusively from fees, is simply a response to consumer demand. The capital devoted to bitcoin mining follows the law of costs, like the case of commodity money production. Competition between blockchains and between Bitcoin and other forms of money determine how much capital is devoted to mining a specific cryptocurrency. The hashrate and safety of a given blockchain is also determined by the desires of consumers.

Third, there are important similarities and differences between bitcoin mining and commodity money production. The key similarity is, as stressed throughout, that the capital bound in bitcoin mining as in gold mining is determined by the law of costs. The key difference is how bitcoin mining substitutes for the services of minting and banking. On the one hand, this means that transactions no longer require these third parties, but on the other hand, it means that some kind of governance through mining pools or the Bitcoin protocol is necessary in order to transmit consumer wishes to miners. This element of centralization may be considered a weak point in comparison with commodity money (Hansen 2023), where authentication services are performed decentralized.

Finally, our analysis shows that big blocks are superior when it comes to performing the monetary function. If Bitcoin is to serve a monetary function, then there cannot be a hard limit on the number of transaction, and while it is crucial to invest capital in bitcoin mining to secure the blockchain, a blocksize limit is not necessary for this purpose. Bitcoin in its current version operates with a blocksize limit and is growing in demand. This suggests that there are other factors at play in determining demand and that it is not principally seen as a monetary medium. Rather, it is a speculative asset that hedges against fiat money inflation. Small blocks and the reputation of being the real Bitcoin may boost demand for this role. If demand for bitcoin comes to emphasize the monetary role, then a change to the blocksize limit will become necessary or another version of Bitcoin without a small blocksize will rise in demand.

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