2015

Cryptocurrency Value Formation: An Empirical Analysis Leading to a Cost of Production Model for Valuing Bitcoin

Adam Hayes
The New School for Social Research, New York, hayea411@newschool.edu

CRYPTOCURRENCY VALUE FORMATION: AN EMPIRICAL ANALYSIS LEADING TO A COST OF PRODUCTION MODEL FOR VALUING BITCOIN

Hayes, Adam, The New School for Social Research, New York NY, hayea411@newschool.edu

Abstract. *This paper aims to identify the likely source(s) of value that cryptocurrencies exhibit in the marketplace using cross sectional empirical data examining 66 of the most used such 'coins'. A regression model was estimated that points to three main drivers of cryptocurrency value: the difficulty in 'mining 'for coins; the rate of unit production; and the cryptographic algorithm employed. These amount to relative differences in the cost of production of one coin over another at the margin, holding all else equal. Bitcoin-denominated relative prices were used, avoiding much of the price volatility associated with the dollar exchange rate. The resulting regression model can be used to better understand the drivers of relative value observed in the emergent area of cryptocurrencies. Using the above analysis, a cost of production model is proposed for valuing bitcoin, where the primary input is electricity. This theoretical model produces useful results for both an individual producer, by setting breakeven points to start and stop production, and for the bitcoin exchange rate on a macro level. Bitcoin production seems to resemble a competitive commodity market; in theory miners will produce until their marginal costs equal their marginal product.*

Keywords: Bitcoin, cryptocurrencies, altcoins, asset pricing.

1 Empirical Analysis to Define Which Factors are Determinants in Cryptocurrency Value Formation

1.1 Introduction

Due to Bitcoin's growing popular appeal and merchant acceptance, it has become increasingly important to try to understand the factors that influence its value formation. However, price fluctuations of bitcoin versus national currencies such as the U.S. dollar, euro or Chinese yuan, have been extremely volatile. This extreme price volatility produces a lot of noise which makes meaningful analysis difficult. In fact, there is increasing evidence that the rise in price for one bitcoin to over $1,000 around December 2013 was largely caused by coordinated price manipulation at the Mt. Gox exchange involving fraudulent trading algorithms which pilfered customer accounts.[1] The subsequent failure of the Mt. Gox exchange and the associated customer accounts was likely a direct result of this market manipulation. Fortunately, there is an active and fairly liquid market for various altcoin–bitcoin trading pairs. By looking at bitcoin-denominated relative prices and removing the external dollar, euro, yuan, etc. exchange rates, much of the noise and price volatility can be removed, making for a much better analysis of the data. Comparing how the variations in several shared attributes of cryptocurrencies affects their relative prices with bitcoin, factors that influence value formation can be identified.

This paper describes a cross-sectional data analysis of 66 cryptocurrencies in such a manner using objective factors shared by each one of them. The findings indicate that relative value formation occurs in production at the margin, much like other commodities.

[1] See: *The Willy Report*: https://willyreport.wordpress.com/

1.2 A brief overview of Bitcoin

The technical specifications of the Bitcoin and altcoin protocols are beyond the scope of this paper, however some key points must be understood before going any further, under the assumption that many readers have little to no prior knowledge of this topic.

Taking bitcoin as the generic example, one can then extend those concepts to the greater universe of altcoins. This overview is purposefully brief and meant only to clarify some points that will be referred to in this paper.

Bitcoin is an open source software-based online payment system that emerged in 2008-2009. Payments are recorded in a shared public ledger using its own unit of account, which is also called bitcoin, symbolically BTC. [2]

Transactions occur peer-to-peer without a central repository or single administrator – it is a decentralized virtual currency which also can be completely anonymous. New bitcoins are created as a reward for transaction processing work in which users offer their computing power to verify and record payments into the public ledger. Also known as "mining", individuals or companies engage in this activity in exchange for the chance to earn newly created blocks of bitcoins.

Mining is carried out by specialized hardware which has a certain amount of computational power, measured in *hashes* per second.[3] The aggregate bitcoin network has a cumulative computational power additive of all the mining effort employed around the world. For every one GigaHash/second (GH/s) any individual miner puts online, for example, that amount will be added to the overall network power.[4] Mining is quite competitive, in the sense that somebody mining with more computational power or with greater efficiency has a better chance of finding a block than somebody with less. Computational effort in cryptocurrency production is often referred to as alternatively *hashpower*, *hashing power*, *mining effort*, or *hashrate*.

Besides mining, bitcoins can be obtained in exchange for currencies such as dollars, euros, etc., for other altcoins, or in exchange for products, and for services. Users can send and receive bitcoins electronically using 'wallet' software on a personal computer, mobile device, or a web application.

1.3 A short survey of relevant literature

There is a new and emerging academic literature regarding cryptocurrencies, with most emphasis surrounding Bitcoin. Much of the economic study undertaken has attempted to address the "moneyness" of bitcoin or whether it is more analogous to a fiat versus commodity money, like a 'digital gold' (Gertchev, 2013) (Harwick, 2014) (Bergstra, 2014).

Yermack (2013) looks at bitcoin's moneyness and points out weaknesses in bitcoin as a currency. Yermack claims that bitcoin (and all cryptocurrencies by association) have no intrinsic value. I consider the potential that while its characteristics are intangible and the labor employed to mine for them is computational rather than human or mechanical, a bitcoin does indeed have an intrinsic value, albeit virtual, which cannot be directly compared to tangible intrinsic value possessed by gold, for example. I don't disagree with the premise that bitcoin and its cousins are not money in the strict sense and that many issues stand in the way of it moving

[2] Bitcoin with a capital "B" refers to the protocol, network and system; while bitcoin with a small "b" refers to individual units of the cryptocurrency.

[3] Hashes are somewhat analogous to the processing power of a CPU microchip, which is measured in hertz in defining how many individual computations can be achieved per second.

[4] A GigaHash/second (GH/s) is one billion hashes per second.

toward mass acceptance and appeal. Yermack makes a very valid point that the price volatility of Bitcoin as expressed in dollars is quite high and that its dollar price may vary significantly among the various exchanges. He mentions that this can cause problems when trying to analyze price data.

For this paper, I have used only bitcoin as the denomination for the various cryptocurrency prices, without the need for dollars. Of course, one can then transpose all prices to dollars using a current dollar-bitcoin exchange rate if they chose. Hence, bitcoin is always worth 1 BTC, and all other cryptocurrencies expressed in decimal form as x.xxxxxxxx BTC. It is worth noting that for many of these cryptocurrencies there only exists pairwise trading on exchanges between itself and BTC (or another cryptocurrency); there are far less altcoin/USD trading pairs than altcoin/BTC pairs. Attempts thus far at valuation, or sources of value, have focused almost entirely on bitcoin without consideration to the scope of alternative cryptocurrencies or altcoins.

Hanley (2013) argues that the value of bitcoin floats against other currencies as a pure market valuation with no fundamental value to support it. Woo, et al. (2013) proposes that bitcoin may have some fair value due to its money-like properties as a medium of exchange and a store of value, but without any other underlying basis.

Jenssen (2014) identifies the “proof-of-work” feature of the mining protocol, implying there may be some sort of computer-labor power source of value. Jenssen also argues that the observed market price of bitcoin in dollars is due to demand given a limited supply. The fact that there will only be 21 million bitcoins as a bounded limit on eventual supply could very well be a red herring; since each bitcoin is divisible to eight decimal places and that number of decimal places can be theoretically increased. There is nothing to prevent the functional unit from being a nano-bitcoin, for example. Although dealing with leading zeros might be cumbersome, it is not prohibitive. With traditional money, there is no effective way to have the functional unit as a fraction of a cent. This paper shows that what is more important as a source of value seems to be the rate of unit formation.

Van Alstyne (2014) considers a source of bitcoin value to be the technological value in solving the so-called double spend problem. While this breakthrough has certainly allowed for the viability of bitcoin, it does not in and of itself make for value. For why then would other cryptocurrencies, which have the same or similar protocols underlying them, have disparate relative values?

Bouoiyour & Selmi (2014) attempt to describe bitcoin value by regressing its market price against a number of independent variables including those such as the market price of gold, occurrences of the word 'bitcoin' in Google searches, the velocity of bitcoin measured by transaction data, and so on. Largely, the variables when regressed were not statistically significant at the 5% or better level of significance. Lags on the price of Bitcoin itself were found to carry some weight, but that can be an artefact of the time-series analysis. Seemingly, only the regression on lagged Google search results were significant at the 1% level. While this finding is interesting, it shows that many variables which may be hypothesized to confer value actually do not. In fact, in an 18-variable multiple regression the R^2 value they obtained was only 0.4586, indicating that some other variables must account for over half of bitcoin’s dollar value. Because cryptocurrencies are nascent and still highly speculative and volatile, using time series analysis can be misleading and uninformative over the short life time of its existence.

Polasik et al. (2014) concludes that bitcoin price formation is the result primarily of its popularity and the transactional needs of its users. They, too, utilized Google search results and found this variable to be highly significant, while the number of transactions (a proxy for velocity) was found not to be. I argue that use of Google search results is not a good metric and that the found correlation might be spurious. In the period when these studies took place, the dollar price of bitcoin was rising rapidly. This rapid price increase caused increasing media attention and word-of-mouth introducing it to more and more people who subsequently searched the internet to gain more information. The people actively mining for or transacting in bitcoin, I surmise, would not need to repeatedly input the word 'bitcoin' as a Google search term, rather people looking at it for the first time, or to investigate it to a greater degree would utilize such a search.

Zhang et al (2014) looks at alternative cryptocurrencies (altcoins) in conjunction with bitcoin, however they only consider three such altcoins (litecoin, dogecoin and reddcoin). Their work is largely descriptive, but lays the groundwork for future research on cryptocurrencies in general and in the framework of micro- and macroeconomics.

Gandal and Halaburda (2014) analyze the competition among a small number of cryptocurrencies in the marketplace and competition between four online exchanges. They found that arbitrage opportunities, for the most part, do not exist. The small sample size makes their findings a bit incomplete; they also relate cryptocurrency prices to the dollar instead of using bitcoin as the base for comparison. Due to a number of frictions in transactions between cryptocurrencies and national fiat money, markets tend to be more efficient and less volatile when looking at cryptocurrencies relative to a bitcoin base.[5] This transactional friction and the noise it creates may also be why it was found that gross trading opportunities were much greater across exchanges than within exchanges – where conversions to and from fiat currencies are required.

Garcia, et al. (2014) asserts that the cost of production through mining does matter in coming up with a fundamental value for bitcoins insofar as it represents a lower bound. This paper will elaborate on that general idea and formalize it to identify a cost of production model for bitcoin. Doing so can identify theoretical break-even levels in market price, electricity cost, mining energy efficiency, and mining difficulty for individual miners – and may be extended to impute averages for the aggregate network.

While it may be tempting to objectify these results to impute a true intrinsic value for bitcoin, I would caution against making such a leap. Even if the models developed in this paper can theoretically determine an intrinsic value, extreme volatility and frequent market price fluctuations in the few years since bitcoin has been around could make identifying such an intrinsic value meaningless in application. There is also the matter of subjective components of value formation which are more difficult to quantify.

1.4 Assumptions and hypotheses

I will use Bitcoin as the generic example to explain the more general case of cryptocurrencies. There are a few fundamental variables that have been hard-wired into the Bitcoin protocol at its inception. As most altcoins share a common Bitcoin lineage, the majority of cryptocurrencies have the same set of built-in variables. The numerical values of these variables can be thought of as arbitrary to some extent when they were created. These variables include:

1- The total number of "coins' ever to be created. For bitcoin, this value will be 21,000,000 and no more. I will refer to this variable as *Total Money Supply.*

2- Each block found by mining will contain a specified number of units. A block of bitcoins initially contained 50 BTC, currently it stands at 25 BTC per block, and that amount will continue to be halved over time, approximately every four years. I will call this variable representing the number of coins in a block the *Block Reward.*

[5] Transaction costs & fees, regulatory issues, time waiting for bitcoin confirmations, and time waiting to clear fiat money deposits/withdrawals are just some of these frictions

3- A block of coins will be found by mining over the same interval, on average, regardless of the magnitude of mining effort. Bitcoin blocks will be found, on average, once every 10 minutes. I will refer to this variable as *Block Time*.

4- The network will check to ensure that the specified Block Time as been achieved on average over some number of blocks previously mined. In the case of bitcoin, after 2,016 blocks have been found, the system will check and see if the actual average time in creating blocks was greater or less than 10 minutes. If it was less than 10 minutes, the system will increase the marginal difficulty in finding new blocks so that the 10 minute average will be restored. This I will call the *Difficulty Retarget.*

5 – The underlying *Algorithm* is the cryptologic hash function used as the basis for the protocol. Bitcoin uses what is known as SHA-256d.[6] Many altcoins use that method, while others use a function called scrypt. The inner workings of the algorithms used are beyond the scope of this paper.

6 – The *Difficulty* variable is exogenous and describes how hard (in computational power) it is to find a new block given a fixed level of hashpower. Because of the Difficulty Retarget mechanism, the difficulty will adjust up or down as aggregate mining effort is employed or removed from the network.

7 – The market *Price* is the observable price on exchanges where altcoin/BTC trading pairs are listed.

By endowing a cryptocurrency with a steady and known rate of unit formation, it cannot be influenced by any central authority. It is important to note that by employing more computational power (e.g. mining hardware) to the network, it may temporarily increase the likelihood that the individual miner with the most power will be most productive; however, the network will check the Difficulty Retarget and adjust the Difficulty accordingly to restore the Block Time. Therefore, if hypothetically somebody were to put online the most powerful new technology, say many Peta-Hashes/second (1,000,000s GH/s) of computational power, once the network detects that the average time between block creation was too low it would adjust the difficulty up accordingly, rendering that new technology merely adequate, and also rendering every other miner's technology inferior or even obsolete.

In devising new and alternative cryptocurrencies, the creator of a fresh 'coin' need only look at the open source computer code, copy it, and change one or more of the above variables to suit their liking. Thus, there are is a diverse universe of altcoins: some that have only a 1 Difficulty Retarget instead of 2,016; some which set the Total Money Supply to either a small handful, or any number including an infinite amount; some set the Block Reward to a fraction of a coin per block while others issue many thousands of coins per block; virtually any combination conceivable.

Because there are active markets on the internet, exchange ratios and prices for each of these altcoins is known and are tradeable in real-time and across a number of platforms. The open source nature of the underlying code also makes finding the values for the above variables easy to obtain.

The fact that there are altcoins with all sorts of configurations makes it a rich data set with which to inquire into what factors may be determinants of value on to them.

[6] SHA-256d and scrypt remain the most commonly used mining algorithms. New algorithms such as X11 exist too but for this study only SHA and scrypt coin data are used for simplicity.

a priori, my hypotheses are:

H1. The amount of mining (computational) power devoted to finding a 'coin' is positively correlated to altcoin value. The more aggregate computational power employed in mining for a cryptocurrency, the higher the value. I make this assertion for a number of reasons. First, the more mining power there is, the more acceptance for that 'coin' can be inferred – since mining also serves to verify transactions, the amount of mining power in use is a proxy for overall use and acceptance of that altcoin.

A cryptocurrency with no acceptance or usage will have neither value nor computational power directed at it. Second, a rational miner, motivated by profit, would only seek to employ mining resources to a profitable pursuit. Therefore, if the marginal cost of mining exceeded the marginal price of mining, that miner would redeploy his resources elsewhere, removing the computational power from the network of that altcoin and into another. Third, the computational power is a proxy for the mining difficulty since the more network power employed, the greater the difficulty will become in order to maintain the pre-programmed Block Time. Therefore, difficulty can be used as an indirect proxy of aggregate mining power.

There is the possibility that the causal relationship between price and computational power is reversed, or bidirectional. It is certainly plausible that computational power will be deployed to where it is already profitable to do so (e.g. prices are already high). To check this, a Granger causality test was run on price and aggregate hashpower. The results strongly indicate that causality runs one-way from mining effort to price and not the other way.

H2. The rate of 'coins' found per minute is negatively correlated to altcoin value. Extending the law of diminishing marginal utility, the more readily something is available, and the more rapid that pace of availability, the lower the value; in other words, the faster the rate of unit formation, the lower the price. If an altcoin is configured such that it produces an abundance of units per block, and/or blocks are found in rapid succession, it will negatively impact the value of those units. On the other hand, scarcity per block would tend to lead to greater perceived value. This hypothesis takes into account the variables of Block Reward and Block Time.

H3. The percentage of coins mined thus far compared to that which is left to be mined before the Total Money Supply is reached is positively correlated to altcoin value. Since there is an exogenous future limit to the money supply, the closer the percentage of units that have been mined compared to what is still left to be found will increase its scarcity and confer value.
This can be computed by dividing the number of coins found So far to date by Total Money Supply. This can be used to measure relative scarcity.

H4. Altcoins based on the scrypt algorithm will be more valuable than SHA-256d, all else equal. The scrypt system was put into use with cryptocurrencies in an effort to improve upon the SHA-256d protocol which preceded it and which bitcoin is based on. Specifically, scrypt was employed as a solution to prevent specialized hardware from brute-force efforts to outmine others for bitcoins. As a result, scrypt altcoins require more computing effort per unit, on average, than the equivalent coin using SHA-256d. The relative hardness of the algorithm confers relative value.

H5. The longevity of the cryptocurrency is positively related to altcoin value. In other words, the longer a cryptocurrency has been around and used, the more value it will have. This is because in a competitive environment, such as that in altcoins, the 'losers' will simply cease to exist. Therefore, the longer a cryptocurrency has persisted, the more valuable it should be. All cryptocurrencies have a 'genesis' date which is easy to ascertain.

1.5 Empirical results of regression analysis

A least-squares (OLS) multiple regression was estimated using cross-sectional data from 66 of the most widely used and actively traded altcoins with the following specification:

$$\ln(PRICE) = \beta1 + \beta2\ln(GH/s) + \beta3\ln(COINS\_PER\_MIN) + \beta4(\%COINS\_MINED) + \beta5(ALGO) + \beta6\ (DAYS\_SINCE) + e$$

where:
ln(PRICE) is the natural logarithm of the bitcoin-denominated market price on September 18, 2014.
ln(GH/s) is the natural logarithm of the computational power in GigaHashes per second.
ln(COINS_PER_MIN) is the natural logarithm of the number of coins found per minute, on average which is computed by dividing Block Reward and Time Between Blocks.
%COINS_MINED is the percentage of coins that have been mined thus far compared to the total that can ever be found.
ALGO is a dummy variable for which algorithm is employed, taking on the value of '0' if SHA-256 and '1' if scrypt.
DAYS_SINCE is the number of calendar days from inception of the cryptocurrency through September 18, 2014.

The resulting regression output produced *Model A*:

$$\ln(PRICE) = -9.68^{***} + 0.67\cdot\ln(GH/s)^{**} - 0.98\cdot\ln(COINS\_PER\_MIN)^{***} - 0.57\cdot COINS\_MINED + 7.43\cdot ALGO^{***} + 0.00067\cdot DAYS\_SINCE$$

$R^2 = 0.844$, Adjusted $R^2 = 0.830$, DW-statistic = 2.24,F-statistic = 63.71
t-statistics are indicated according to each explanatory variable.*** indicates $p < 0.001$, ** indicates $p < 0.005$

The R^2 is quite high, suggesting that approximately 84.4% of the variation in relative cryptocurrency prices are determined by the variables in the model.

Hypothesis *H1* is supported in that the coefficient is positive as expected *a priori* (prices increase as computational power increases), and the t-statistic indicates that it is highly statistically significant that computational power influences price.

Hypothesis *H2* is supported in that the coefficient is negative as expected *a priori* (prices decrease as the rate of coin production per minute increases), and the t-statistic indicates that it is highly statistically significant that coins produced per minute influences price.

Hypothesis *H3* is *not* supported in that the sign of the coefficient is unexpected, and also the t-statistic indicates that percentage of coins mined is not statistically significant. One possible reason for this result is that while the total number of coins is determined at the inception of a cryptocurrency, the 'coins' themselves are divisible down to 8 decimal places by default, and that number of decimal places can be increased, potentially without limit. Therefore, it may be the case that an absolute Total Money Supply may not actually be a limiting factor since once that ceiling is reached, the units can simply be divided and subdivided. For example, 1 BTC is actually 1.00000000 BTC, and there is nothing preventing 0.00000001 BTC from having useful value (except perhaps that it is cumbersome).

Hypothesis *H4* is supported in that the coefficient is positive as expected *a priori* that scrypt altcoins are more valuable than SHA-256, on average, and the t-statistic indicates that it is highly statistically significant that scrypt as opposed to SHA-256 influences price.

Hypothesis *H5* is *not* supported by the regression output, although the sign of the coefficient is positive which was expected *a priori*, the number of days since inception is not statistically significant. One possible reason for this result is that the vast majority of altcoins are less than two years old, which hasn't given the market enough time for competition to weed out the losers and reward the winners.

Removing the independent variables that were not statistically significant in *Model A,* a new regression was estimated to produce *Model B*, which had the following output:

$$\ln(\text{PRICE})=-9.53^{***} + 0.69\cdot\ln(\text{GH/s})^{***} - 0.98\cdot\ln(\text{COINS\_PER\_MIN})^{***} + 7.46\cdot(\text{ALGO})^{***}$$

$R^2 = 0.843$, Adjusted R2 = 0.835, DW-statistic = 2.12,F-statistic= 111.04
t-statistics according to each explanatory variable and full regression outputs available in the appendix.
*** indicates $p < 0.001$.

Model B represents a more parsimonious output with a very similar R^2 compared to *Model A*, while improving the F-statistic and slightly improving the t-statistics for each explanatory variable. The model was checked for consistency with the assumptions of a linear regression, and exhibits normality of residuals, does not exhibit heteroscedasticity, collinearity, or other common regression errors.

Model B infers that holding all else constant:

- given a 1% increase in aggregate GH/s output, the price will rise by approximately 0.69%.
- given a 1% increase in coins produced per minute, the price will fall by approximately 0.98%.
- given that the altcoin uses the scrypt protocol, the price will be higher by approximately 7.46% compared to it's SHA-256 counterpart., all else equal.

I would argue that in either of these regression models the intercept term has no valid economic interpretation.

1.6 Discussion of results

These econometric models can be useful in a number of ways. It specifies the factors that influence relative prices across a wide variety of cryptocurrencies that exist, inclusive of Bitcoin, and without the noise generated by price volatility with exchange rates against national currencies. Using these findings, pricing existing or newly created cryptocurrencies can be undertaken with some greater degree of confidence.

It shows that more than 84% of relative value formation can be explained by the three variables: computational power (which is a proxy for mining difficulty), rate of coin production, and the relative hardness of the mining algorithm employed. This suggests that relative rates of production for given level of mining effort are paramount. For a given level of hashpower, increasing the difficulty will yield less units, and thus the relative cost of production. Similarly, reducing the block reward or employing a more rigorous mining algorithm will yield fewer units. In other words, this suggests that differences in the relative cost of production on the margin drive value formation for cryptocurrencies.

Using Model B, it is possible, in theory, to create an altcoin of high value simply by increasing its cost of production: choosing scrypt (or another even more difficult protocol) and reducing the coins produced per minute to some minuscule amount – this can be accomplished by increasing the Block Time and simultaneously reducing the Block Reward. Once that is achieved, the hard part is getting the computational power (and thus the mining difficulty) of the network up – and that is largely out of the control of the altcoin creator.

One important implication is that the total money supply, or ultimate number of units to ever be created is not a driving factor in value creation, rather it is the rate of unit creation that matters.

Of course, there are other subjective factors in determining the market price not included in the model, but which are yet to be identified. At any given point in time, any individual cryptocurrency may trade above or below its modelled value, the same as any other asset.

There is likely to be a speculative premium, as well as the tendency to hoard mined coins which will play an additional role in value formation, but which is more difficulty to quantify and measure

2 The Decision to Mine for Altcoins and Miners' Arbitrage in Cryptocurrency Production

2.1 The decision to mine for altcoins

There exists efficient mobility of capital in switching mining effort from that of one coin to another; all one has to do is change the settings for the software or hardware to point the miner's hashing power towards mining another coin. Once those coins are mined and accumulated, they may be exchanged for bitcoin on any number of online exchanges.

Today, bitcoin is the stable equilibrium digital currency, and, for the most part, anybody wishing to transact in the real economy with a digital currency needs to use bitcoin. If obtaining bitcoins is the ultimate goal, a rational cryptocurrency miner would only direct mining effort at an altcoin if it provided for greater profitability than mining bitcoin directly over some period of time. What tends to happen is that any opportunities for excess profits are short-lived as competition drives all profit rates down to at least that of mining for bitcoin itself.

This apparent efficiency in removing opportunities to earn excess profits in mining seems to be the result of two forces: 1) competition of capital, as it is mobilized to mine for the more profitable coin it raises the aggregate network hashing power in that coin, causing the difficulty to subsequently increase. As the difficulty increases, profitability falls per unit of mining effort; and 2) the market exchange rate will change as mining participants actively produce and then sell relatively 'overpriced' coins.

Thus, both the bitcoin-denominated exchange price and the current difficulty of mining for the cryptocurrency in question relative to bitcoin's difficulty determines if there is an arbitrage opportunity, and acting on either variable will serve to eliminate that opportunity.

The baseline for profitability, then, or the regulating level of daily production, is the own-rate of return for bitcoin mining, measured in expected bitcoins per day per unit of mining power. For simplicity, I will peg that level of hashing power at a standard 1000 GigaHashes/sec (GH/s) of mining power, or 1 TeraHash/sec (TH/s). In practice, the actual hashing power of a miner is likely to deviate more or less from 1,000 GH/s, however this level tends to be a good standard of measure under current circumstances. The rate of bitcoin creation at the time of writing this paper is approximately 0.00831 BTC/day for every 1 TH/s of mining effort employed.[7] The expected number of bitcoins expected to be produced per day can be calculated as follows:

$$\mathrm{BTC/day}^* = [(\beta \cdot \rho)/(\delta \cdot 2^{32})/\mathrm{sec}_{hr}] \cdot \mathrm{hr}_{day} \qquad (1)$$

where: BTC/day* is the expected level of daily bitcoin production when mining bitcoin directly,
β is the block reward, ρ is the hashing power employed by a miner, and δ is the difficulty.[8,9]
The constant sec_{hr} is the number of seconds in an hour, or 3600.
The constant hr_{day} is the number of hours in a day, or 24.
The constant 2^{32} relates to the normalized probability of a single hash per second solving a block, and is an attribute of the SHA-256 algorithm.

[7] Given a current difficulty value for bitcoin of 60,813,224,039 and a block reward of 25 BTC.

[8] Block reward is expressed in units of BTC/block

[9] Difficulty is expressed in units of GH/block

The constants which normalize the dimensional space for daily time and for the mining algorithm can be summarized by the variable θ, which would equal $\theta = 24\ hr_{day} \cdot 232\ /\ 3600sec_{hr} = 28{,}633{,}115.30667$. Equation (1) can thus be rewritten:

$$BTC/day^* = \theta\ (\beta \cdot \rho)/(\delta) \qquad (2)$$

The only variables therefore are β, ρ and δ, and the hashing power, ρ, will be pegged to a fixed rate of 1,000 GH/s of hashing power.

An arbitrage opportunity exists when mining for any other cryptocurrency with the same amount of hashing power would produce a greater expected level of BTC/day than BTC/day*. To generalize equation (1) to account for any other altcoin, we simply introduce the current exchange rate of the altcoin/BTC pair, ε. [10] Specifically, the market bid of the exchange rate is the price that matters since an arbitrageur would only be concerned with selling the altcoin to buy BTC.

Equation (3) indicates how many bitcoins would be obtained on average indirectly by mining for an altcoin instead:

$$BTC/day_{altcoin} = \theta\ (\beta_{altcoin} \cdot \rho)/(\delta_{altcoin}) \cdot \varepsilon \qquad (3)$$

Under the no-arbitrage assumption that BTC/day* will be given as the own-rate of return for BTC, equation (3) can be re-arranged to solve for a theoretical equilibrium market price (of the bid) of the altcoin, holding the altcoin's difficulty constant:[11]

$$\varepsilon^* = [BTC/day^*]\ /\ [\theta\ (\beta_{altcoin} \cdot \rho)/(\delta_{altcoin})] \qquad (4)$$

If the altcoin's difficulty remains the same, there is a market opportunity for an arbitrageur to sell the relatively overpriced cryptocurrency until it reaches ε* when exchanged for bitcoin on the market.

If, instead, the market price is held constant at ε*, the difficulty can be thought of as relatively 'undervalued' and directing mining effort to that coin will produce excess profitability by subsequently exchanging those mined coins for bitcoin at price ε*. Employing more mining power will necessarily increase the difficulty of that coin over time, so the arbitrage opportunity only exists until the difficulty is normalized and equilibrium is restored.

$$\delta^* = (\varepsilon \cdot \beta_{altcoin} \cdot \rho \cdot sec_{hr} \cdot hr_{day})\ /\ (BTC/day^* \cdot 2^{32}) \qquad (5)$$

Because equations (4) and (5) can be worked on by many different agents at the same time, arbitrage opportunities tend to be short-lived.

An example is useful here. A hypothetical individual miner has enough hashing power to earn 1 BTC/day*, on average. Alternatively, her same mining effort now could produce an expected 33,000 XYZ Coin per day, where XYZ Coin is a hypothetical altcoin that is traded against BTC on one or more exchanges. If the market bid is 0.00003996 BTC, she can exchange her XYZ and get in return: 33,000 x 0.00003996 = 1.32 $BTC/day_{altcoin}$, making XYZ Coin mining right now 32% more profitable than mining bitcoin directly. As she and other miners continue to mine and subsequently sell their XYZ Coin, the market price in XYZ/BTC will fall as bids are cleared. The addition of new mining power in the XYZ network will also

[10] All exchange rates are expressed in terms of Altcoin/BTC, or 1 Altcoin = X BTC

[11] BTC/day* also assumes Bitcoin's difficulty is constant during this period, not just that of the altcoin.

tend to make its difficulty rise, making it a more costly and less attractive alternative. It is worth noting that since there will tend to be orders of magnitude more mining effort directed at mining bitcoin than any altcoin at a given moment, while the new hashing power added to XYZ Coin may be a significant amount to XYZ Coin, the effort being removed from aggregate bitcoin mining is likely to be inconsequential and have no effect on bitcoin difficulty.

3 A Cost of Production Model for Bitcoin

3.1 Bitcoin production

As I have shown, the decision to mine for bitcoin comes down to profitability. A rational agent would not undertake production of bitcoins if they incurred a real ongoing loss in doing so. Bitcoin mining employs computational effort which requires the consumption of electricity to function, which must be paid for. This computational effort is directed at mining bitcoin, in competition with many other miners who presumably are also motivated by profit, on average. The more powerful the mining effort (the higher the hash-rate), the more likely it is to successfully mine bitcoins during a given interval (typically measured per day) for a given level of mining difficulty.

Therefore, success in finding bitcoins depends not only on the hashing power, but also on the difficulty level of the algorithm at the time that mining is undertaken. The difficulty specifies how hard it is to find a bitcoin during some interval, the higher the difficulty the more computational effort will be required to mine bitcoins at the same rate as with a lower difficulty setting. The bitcoin network automatically adjusts the difficulty variable so that one block of bitcoins is found, on average, every ten minutes. As more aggregate computational effort is added to mining bitcoins, the time between blocks will tend to decrease below ten minutes, the result being that the network will adjust the difficulty upwards to maintain the set ten minute interval accommodating the excess mining effort. Likewise, if mining effort is removed from the network, the length between blocks would grow longer than ten minutes and the network will adjust the difficulty downwards to restore the ten minute interval.

Each unit of mining effort has a fixed sunk cost involved in the purchase, transportation and installation of the mining hardware. It also has a variable, or ongoing cost which is the direct expense of electricity consumption. Each unit of hashing power consumes a specific amount of electricity based on its efficiency, which has a real-world cost for the miner. Because miners cannot generally pay for their electricity cost in bitcoin, they must refer to the currency price of a bitcoin to measure profitability given a real monetary cost of electricity.

It seems to be the case that the marginal cost of bitcoin production matters in value formation. Instead of approaching bitcoin as a digital money or currency, it is perhaps more appropriate to consider it a virtual commodity with a competitive market amongst producers.

The important variables in forming the decision to mine are: [1] the cost of electricity, measured in cents per kilowatt-hour; [2] the energy consumption per unit of mining effort, measured in watts per GH/s (or Joules per GH), a function of the cost of electricity and energy efficiency; [3] the monetary price of bitcoin in the market; and [4] the difficulty of the bitcoin algorithm.[12]

An individual would undertake mining if the marginal cost per day (electricity consumption) were less than or equal to the marginal product (the number of bitcoins found per day on average multiplied by the dollar price of bitcoin). If bitcoin production is a competitive com-

[12] The block reward also matters, but this value changes only after much longer intervals, approximately once every 4 years.

modity market, albeit a virtual one, then we would theoretically expect marginal cost to equal marginal product – which would also equal selling price.

The main cost in bitcoin mining is the energy consumption which is needed to facilitate the computational labour employed in mining.[13] The actual market price is determined by the supply and demand for bitcoin at any given moment, while the cost of production might set a lower bound in value around which miners will decide to produce or not. While this lower bound could represent an intrinsic value, the actual observed price may deviate from that expected value for long periods of time, or may never converge to it.

Of course, there are likely to be many subjective motivations for bitcoin mining beyond the objective components elaborated in this paper. Individual decision makers may operate regardless of cost if they believe that there is enough speculative potential to the upside. Bitcoin mining may draw in those who find the features of anonymity and lack of governmental oversight attractive. Some miners may decide to hoard some or all of their lot and not regularly engage in offering mined bitcoins in the open market, a sort of bitcoin 'fetishism'. Some miners may be subject to an opportunity cost whereby it would be more profitable to expend the same electrical capacity for some other pursuit. Subjective rationales for mining may induce some individuals to make the decision to produce at a marginal loss for prolonged periods of time. The speculative and money-like properties of bitcoin, as a means of exchange and a potential store of value, add a subjective portion to any objective attempt at forming an intrinsic value. New and innovative uses of the bitcoin network for non-bitcoin specific applications are also likely to add value for mining.

3.2 The decision to mine for bitcoin and its cost of production

The objective decision to mine for bitcoins can be modelled. The necessary inputs are the dollar price of electricity, the energy consumption per unit of mining power, the dollar price of bitcoins, and the expected production of bitcoins per day which is based in part on the mining difficulty.[14]

Recall the model for determining the expected number of cryptocurrency coins to be mined per day on average given the difficulty and block reward (number of coins issued per successful mining attempt) per unit of hashing power, equation (1):

$$\text{BTC/day*} = [(\beta \cdot \rho)/(\delta \cdot 2^{32})/\text{sec}_{\text{hr}}] \cdot \text{hr}_{\text{day}}$$

The cost of mining per day, E_{day} can be expressed as:

$$E_{\text{day}} = (\$\text{price per kWh} \cdot 24\ \text{hr}_{\text{day}} \cdot \text{W per GH/s})(\rho\ /\ 1{,}000) \tag{6}$$

Where E_{day} is the dollar cost per day for a producer, ρ is the hashpower employed by a producer, the $price per kWh is the price per kilowatt-hour, and W per GH/s is the energy consumption efficiency of the producer's hardware.

The marginal product of mining should theoretically equal its marginal cost in a competitive market, which should also equal its selling price. Because of this theoretical equivalence, and since cost per day is expressed in $/day and production in BTC/day, the $/BTC price level is simply the ratio of (cost/day) / (BTC/day). This objective price of production level, p*,

[13] Other much smaller costs include internet service, hardware maintenance, computer cables etc.

[14] For illustrative purposes only, the US dollar will be the currency used to price bitcoin. In reality, there are bitcoin miners worldwide, notably in Russia, Europe, and China who will buy electricity in their own regional currency and at their local rate.

serves as a logical lower bound for the market price, below which a miner would operate at a marginal loss and presumably remove them self from the network. p* is expressed in dollars per bitcoin, given the difficulty and cost of production:

$$p^* = E_{day} / (BTC/day^*) \tag{7}$$

Note that p* is a function of mining difficulty and the block reward in the denominator. Given an observed market price (p) and a known difficulty, one can solve for the break-even electricity cost per kilowatt-hour:

$$\$price\ per\ kWh^* = [p(BTC/day^*)/24hr_{day}] / W\ per\ GH/s \tag{8}$$

Given a known cost of production and observed market price, one can solve for a break-even level of mining difficulty:

$$\delta^* = (\beta \cdot \rho \cdot sec_{hr} \cdot hr_{day}) / [(E_{day}/p) \cdot 2^{32}] \tag{9}$$

And, to solve for a break-even hardware energy efficiency, we can again rearrange terms given a market price, cost of electricity per kilowatt-hour, and difficulty:

$$W\ per\ GH/s^* = (p \cdot BTC/day^*)/(price\ per\ kWh \cdot 24hr_{day}) \tag{10}$$

3.3 Discussion

These equations are useful in application as well an in theory. It informs miners objectively as to which price they should undertake or else give up mining. It also informs miners when to stop or start mining given changes in difficulty and electricity costs. Furthermore, looking at market prices for a given difficulty and known average electricity cost, the average energy efficiency of mining for the entire network can be imputed.

It is useful to consider a hypothetical example:

Assume that the average electricity cost for the world is approximately 13.5 cents per kilowatt-hour and the average energy efficiency of ASIC mining hardware currently deployed is 0.62 J/GH. The average cost per day for a 1 TH/s mining rig would be approximately: $(0.135 \cdot 24 \cdot 0.62) \cdot (1{,}000 / 1{,}000) = \$2.01/day$.

The number of bitcoins that same 1 TH/s of mining power can find in a day with a current difficulty of 60,813,224,039 is approximately 0.00831 BTC/day.

Because these two values (marginal cost and marginal product) are expected to be theoretically equivalent, to express them in dimensional space of \$/BTC we simply take the ratio: (2.01 \$/day) / (0.00831 BTC/day) = \$241.877/BTC.

This is surprisingly close to the current market value of around \$240-245 per BTC.

If the market price were to drop below that value, miners would be operating at a marginal loss and halt production. Continuing the analysis of this example, if the difficulty were to increase to greater than 61,404,400,615 holding all else constant, miners would cease operations. Also in this example, and holding all else constant, miners would cease operations if their energy costs rose to more than 13.6 cents per kilowatt-hour. Likewise, a miner would cease operations if their mining hardware consumed energy at an efficiency worse than 0.626 Watts per GH/s.

These figures are hypothetical for the purposes of elaborating the applicative usage of the equations introduced above, but have been chosen to be fairly close to current real-world practical, observed averages. It is worth noting the very small margins that exist for a variable to change and make mining for bitcoin no longer worthwhile for the average producer: for example electricity costs only need rise 0.01 cents or the difficulty by 1%.

As real-world mining hardware efficiency increases, which is a likely result of competition, the break-even price for bitcoin producers will tend to decrease. Low cost producers will compete in the marketplace by offering their product at lower and lower prices. Mining hardware energy efficiency has already increased greatly since the days of CPU or GPU mining. A research study found that the average mining efficiency over the period 2010-2013 was a staggering 500 Watts per GH/s (Garcia, et al., 2013). Today, the best ASIC mining rigs available for purchase have somewhere around 0.15 Watts per GH/s energy efficiency. The average energy efficiency right now across the mining network, which is the value which regulates the marginal cost, seems to be around 0.60-0.65 Watts per GH/s. This speaks to the rapid pace of technological advancement produced over the past few years and months in mining energy efficiency. The Bitcoin mining network is vast in size and scope and it is likely that some miners are at work with hardware that is older and less efficient than the best available.

Figure 1, below, illustrates how rapidly the energy efficiency of mining hardware for Bitcoin has improved over time. The rate of technological progress in this case has actually exceeded that predicted by Moore's Law.[15]

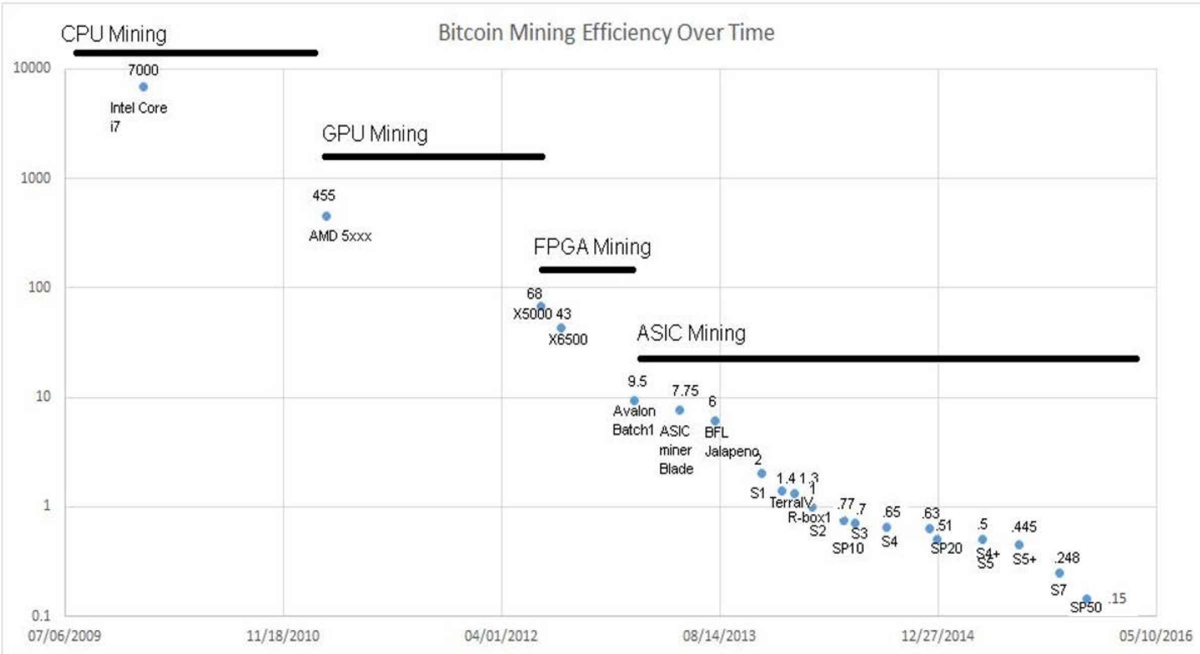

Figure 1: *Bitcoin mining energy efficiency over time (log scale)*

Bitcoin mining, unlike traditional commodity production, has the unique feature of a regular difficulty adjustment in order to maintain a steady rate of unit production over time – specifically, a block of bitcoins will be mined on average once every ten minutes, regardless of aggregate mining power. Unlike most produced commodities where the supply can change to accommodate fluctuations in demand, the supply of bitcoin is hardwired at its steady rate with the difficulty setting adjusting up and down to maintain that linear rate of production through time. In other words, the elasticity of supply is manifest in changes in the mining difficulty.

As energy efficiency increases. the difficulty adjustment acts as a stabilizing mechanism, increasing the cost of production; as more aggregate mining power is brought on line, the mining difficulty increases. For example, if a mining rig can find 1 BTC/day on average with to-

[15] "Moore's law" is the observation that, over the history of computing hardware, the number of transistors in a dense integrated circuit, and therefore its processing power, has doubled approximately every two years.

day's difficulty, the same rig can expect to produce less per day when the difficulty increases 10% or 20% etc. If miners are not able to supply enough new coins to meet an influx of new demand, the market price can see increases while the cost of production remains largely the same. This would induce miners to increase their mining efforts which would then cause the difficulty to increase, raising the cost of production until presumably a new breakeven level is reached. This mechanism tends to counteract the downward tendency caused by increasing energy efficiency.

Figure 2, below, illustrates the relative change in mining efficiency compared to changes in mining difficulty over time. The left y-axis represents the inverse of the mining difficulty on a logarithmic scale, and is denoted by the dark blue line on the chart. The right y-axis is the mining efficiency, measured in joules per GH, and is denoted by the orange line. The x-axis is time from bitcoin's origin in 2009 to the present.

Initially, when bitcoin mining was only accomplished via a computer's central processor, or CPU, there were not many individuals involved with bitcoin mining, and the difficulty was very low. At the same time, mining was very inefficient. A computer's processor is designed to do many tasks such as run software and applications. It was discovered that a computer's graphics processor (GPU) was much better at solving the cryptographic algorithm used to mine for cryptocurrencies, and the difficulty grew rapidly as more mining power suddenly came on line. In Figure 2, the purple shaded areas indicate periods where the network size (difficulty) was increasing at a faster pace than technological change in mining efficiency. Green-shaded areas indicate periods where technological change has outpaced the growth\ of the network.

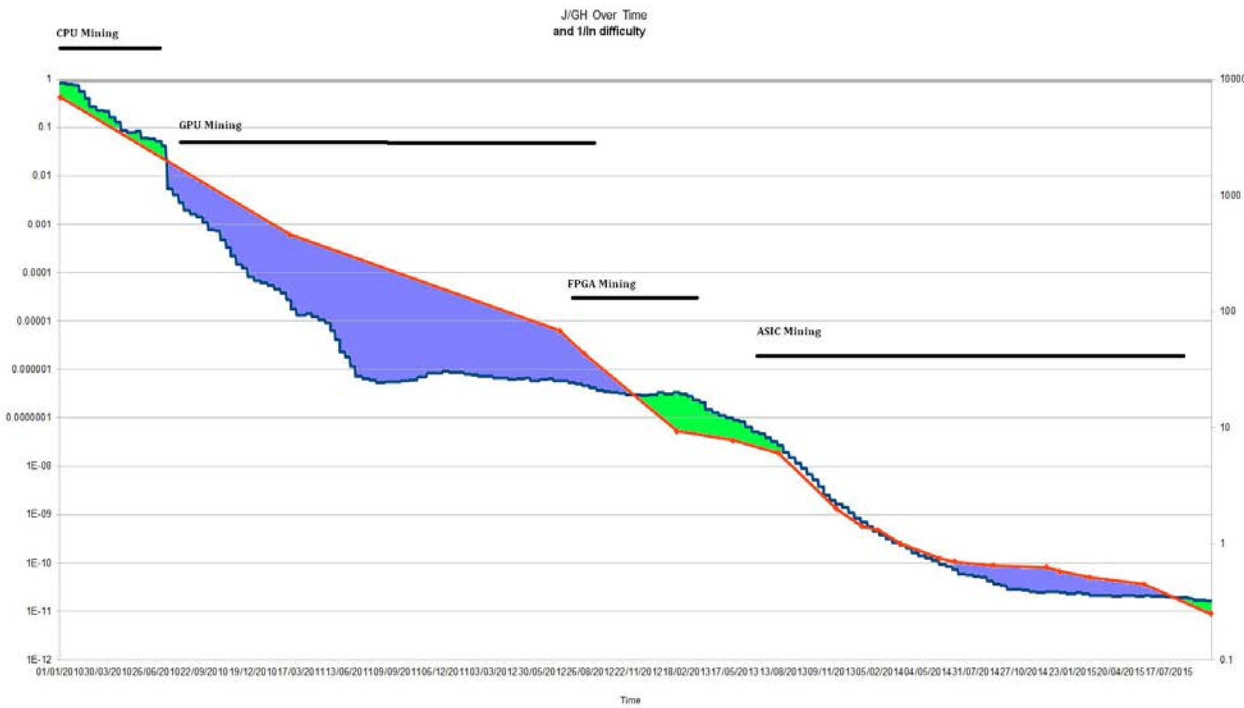

Figure 2. *Bitcoin mining difficulty vs. mining energy efficiency over time (log scales)*

GPU mining, while more efficient that CPU mining, was still not ideal. Video cards are designed for computer graphics and optimized for application such as gaming or design. As a result, mining with a GPU is not optimized for cryptocurrency mining. Furthermore, the manufacturers of graphics cards (and of CPUs for that matter) do not concern themselves with increasing the efficiency of their products to mine for cryptocurrencies. These manufacturers typically produce newer, better GPU hardware only when they can improve their primary functionality. Therefore, there is no induced technological change to make these devices more efficient at mining even when the network size and mining difficulty is growing rapidly.

This all, however, changed with the introduction of application-specific integrated circuits, or ASICs, designed with the sole purpose to solve the encryption underlying cryptocurrencies. As a result, we begin to see marginal cost and marginal product begin to converge in mid- to late-2013 as they made their way to producers worldwide. Since then, there has been evidence of induced technological change, evidenced by the continued convergence of network size and mining efficiency since.

It is important to note that in the pre-ASIC period of bitcoin mining, the cost of production model outlined above would not hold. The capacity utilization of a CPU or GPU to mine for bitcoin is simply not efficient enough. One would not expect marginal cost to converge to marginal product when the hardware being used is not subject to competition. An apt comparison is that with ASICs it is like mining for gold with a pick and shovel – specifically made for such an activity – and when mining with CPUs/GPUs is like mining for gold with a shoe. While a shoe is not meant to mine for gold, one could conceivably collect some dirt in the shoe and find gold by happenstance. Just as the picks and shovels used for gold mining were induced to adapt and change, becoming steam shovels and later industrial mining operations, so too has bitcoin mining in the ASIC age seen such technological progress and consolidation due to competition.

One insight that could have sizable consequences for the cost of production of bitcoin relates to the block reward amount and how changes in this variable will impact BTC/day production. When bitcoin was launched, each block mined was composed of 50 bitcoins. That amount is set to halve every four years, and in 2012 the block reward became 25.[16] The block reward will again halve to 12.5 bitcoins per block, expected mid-September, 2016, and will again in the year 2020, and so on. If we refer back to the illustrative example above and substitute a 12.5 BTC block reward for the current 25, the expected BTC*/day' becomes half of 0.00831, or 0.004155 per 1 TH/s. Using the hypothetical example above and given this new BTC*/day', the break-even price for a bitcoin would increase suddenly to $483.75, holding all else constant.[17] If the market price of bitcoin does not increase in turn, it will suggest that the breakeven efficiency has also increased at a more or less equivalent rate. This could have the effect of eliminating all but the most efficient producers all at once.

Conclusion

Beginning with a cross-sectional analysis to define the causes of relative value formation amongst cryptocurrencies, it was found that relative differences in costs of production on the margin are the main determinants. By looking at bitcoin-denominated relative prices, which are available on a number of online cryptocurrency exchanges, the high degree of price volatility found in the dollar-bitcoin exchange rate was eliminated. Cross-sectional analysis also was able to remove a number of other issues found in time-series analysis including any chance of non-stationary data or a small time horizon for the data set.

Next, using this result as a springboard, a series of equations were formalized to calculate how many units of a cryptocurrency a producer with a fixed amount of hashing power could expect to find, on average. Because Bitcoin is the stable equilibrium digital currency, even if some other altcoins are better or have various interesting features that Bitcoin lacks, it will be very difficult to dislodge. Therefore, the ultimate goal of any cryptocurrency producer operating in the real economy will to obtain bitcoins.

[16] Lags in difficulty adjustment over time may result in the actual halving date occurring somewhat prior to or after 4 years.

[17] The change in block reward will have no impact on difficulty. Rather, less BTC/day will be found given the same difficulty.

Given an efficient mobility of capital, a cryptocurrency producer will only mine for an altcoin if there is a greater profitability in that than using their equipment to mine for bitcoin directly. When these cases occur, markets tend to efficiently correct arbitrage opportunities ensuring that no altcoin is more profitable to produce than mining for bitcoin directly.

Finally, a cost of production model is put forward to establish break-even values for a bitcoin producer. Extrapolating that model to account of the average or regulating values for the aggregate Bitcoin mining network, the cost of production model can closely approximate the market price for Bitcoins versus dollars.

The implications are that cost of production drives value and anything that serves to reduce the cost of bitcoin production will tend to have a negative influence on its price. Increased mining hardware energy efficiency, lower worldwide electricity prices, or lower mining difficulty will all reduce the marginal cost of production. As mining efficiency increases due to technological progress, it lowers the cost of production and puts a negative pressure on the price. At the same time, the additional hashing power added to the global mining network will tend to increase the mining difficulty, and positively influence the price. The question will be which factor will outpace the other: technological progress (energy efficiency) or the size of the mining network (difficulty). A further implication is that when the Bitcoin block reward halves, it will effectively increase the cost of production overnight.

References

Bergstra, Jan Aldert. *Bitcoin: not a currency-like informational commodity*. Informatics Institute, University of Amsterdam, (2014).

Bouoiyour, Jamal, and Refk Selmi. *What Bitcoin Looks Like*? . No. 58091. University Library of Munich, Germany, (2014).

Garcia, David, et al. *The digital traces of bubbles: feedback cycles between socio-economic signals in the Bitcoin economy*. Journal of The Royal Society Interface 11.99 (2014): 20140623.

Gertchev, Nikolay. *The Moneyness of Bitcoin*. www.mises.org (2013).

Halaburda, Hanna, and Neil Gandal. *Competition in the Cryptocurrency Market*. Available at SSRN 2506463 (2014).

Hanley, Brian P. *The false premises and promises of Bitcoin*. arXiv preprint arXiv:1312.2048 (2013).

Harwick, Cameron. *Crypto-Currency and the Problem of Intermediation*. Available at SSRN 2523771 (2014).

Nakamoto, Satoshi. *Bitcoin: A peer-to-peer electronic cash system*. Whitepaper. Consulted 8.2015 (2008): 28.

Polasik, Michal, et al. *Price Fluctuations and the Use of Bitcoin: An Empirical Inquiry*. Available at SSRN 2516754 (2014).

Van Alstyne, Marshall. *Why Bitcoin has value*. Communications of the ACM 57.5 (2014): 30-32.

Woo, David, et al. *Bitcoin: a first assessment*. FX and Rates (2013).

Yermack, David. *Is Bitcoin a Real Currency?*. No. w19747. National Bureau of Economic Research, 2013.

Zhang, Yiteng, and Guangyan Song. *Economics of Competing Crypto Currencies: Monetary Policy, Miner Reward and Historical Evolution*. (2014).

* Additional data sets collected from: coinmarketcap.com, coinwarz.com, cryptsy.com, bitcoinwisdom.com, and blockchain.info

Appendix

Dependent Variable: LOG(_PRICE)
Method: Least Squares
Date: 09/18/14 Time: 22:18
Sample: 1 83
Included observations: 66

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-9.526966	0.779882	-12.21591	0.0000
LOG(GH_S_HASHPOWER)	0.685330	0.064390	10.64349	0.0000
LOG(COINS_PM)	-0.983477	0.061908	-15.88620	0.0000
TYPE="Scrypt"	7.461170	0.875470	8.522473	0.0000

R-squared	0.843083	Mean dependent var	-5.493893
Adjusted R-squared	0.835491	S.D. dependent var	3.888541
S.E. of regression	1.577183	Akaike info criterion	3.807849
Sum squared resid	154.2253	Schwarz criterion	3.940555
Log likelihood	-121.6590	Hannan-Quinn criter.	3.860287
F-statistic	111.0381	Durbin-Watson stat	2.119851
Prob(F-statistic)	0.000000		

Pairwise Granger Causality Tests
Date: 12/11/14 Time: 10:11
Sample: 1 66
Lags: 2

Null Hypothesis:	Obs	F-Statistic	Prob.
GH_S_HASHPOWER does not Granger Cause _PRICE	64	65.5462	1.E-15
_PRICE does not Granger Cause GH_S_HASHPOWER		0.01678	0.9834