Bitcoin energy index: A transparent and dynamic model

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ABSTRACT

Blockchain, the technology used by the cryptocurrency bitcoin, has proven to be very useful in other applications than just cryptocurrencies. It allows for options such as electronic voting and recording of history of transactions/trades, which cannot be tampered with once it has been added to the chain. Even though most properties of blockchain seem very promising like transparency, decentralization and anonymity, it is also very resource demanding. Because of the decentralization and so-called consensus protocols, the technology consumes a lot of energy. Some applications already consume more energy than entire countries. However, how much energy these applications consume is unclear and hard to measure. In this paper, a dynamic model will be presented which can be used to predict the energy consumption of bitcoin's network in the future.

Keywords

E-waste, blockchain, cryptocurrency, energy consumption, consensus protocol, predict, dynamic model, bitcoin

1. INTRODUCTION

Blockchain is a technology that allows peer-to-peer transactions to be made without the need for intermediaries [1]. Bitcoin [2] was created back in 2008 by an unknown individual or group of people that go by the name *Satoshi Nakamoto*.

A block (or link) in the blockchain is a summary of transaction records, which is hard to alter once put in a block. The transactions that form a block are created by clients using the blockchain network and verified by other clients within the network.

Additionally, blockchain comes with multiple promising properties, such as immutability, (limited) anonymity and transparency. These properties can be used in applications other than cryptocurrencies, such as electronic voting [3], which was considered impossible until now due to lack of trust in machines, and tracking of inventory in pharmaceutical supply chains [4].

However blockchain also comes with some downsides. It is computationally heavy and requires a lot of storage. Bitcoin alone already requires 350 GB of storage for the entire blockchain as of right now and this is only one of many cryptocurrencies. Especially in the application of cryptocurrency, blockchain is used in a very computationally heavy process. Multiple so called consensus protocols exist which are used to verify blocks in the chain, such as proof-of-work (PoW) and proof-of-stake (PoS) [5]. Both with their advantages and disadvantages.

One of the problems with blockchain is energy consumption. It consumes so much energy that, at the time of writing, bitcoin's energy consumption alone is equivalent to about 90% of the energy consumption of the entirety of the Netherlands [6], and this is only the consumption of one cryptocurrency.

Additionally, some consensus protocols, such as proof-of-work, are designed in such a way that makes it computationally heavy to approve any transaction. This makes the blockchain more tamper proof but the amount of energy it consumes is enormous. The consensus protocol proof-of-stake on the other hand is a much less resource demanding protocol, with similar immutability. However in a proof-of-stake protocol, the richer will get richer as the higher your stakes, the more you are able to mine. This is, according to most people, an undesired side effect [5].

As of right now, there is a lack of *dynamic models* that approximate the energy consumption of blockchain applications. Although there exist some indices that estimate bitcoin's current energy consumption such as Digiconomist's bitcoin energy index [6] and Cambridge's Bitcoin Energy Consumption Index (CBECI) [7], it is sometimes unclear what exactly the assumptions are and how some of the parameters are exactly determined.

For this reason, the goal of this paper is to provide a dynamic model, specifically for bitcoin, that is clear and transparent. One of the best ways to make concepts more transparent is through visualization and detailed explanation. Additionally a publicly available model will allow others to run the calculations/simulations on the model with different input parameters. Making it possible for others to, for example, figure out how much a specific parameter impacts bitcoin's energy consumption. Even though many attempts have been made to estimate bitcoin's energy consumption, most tend to only provide a few mathematical equations to be calculated which makes it hard to find the relations in such complex systems.

The article is structured in the following way. First a section is dedicated to related work. Afterwards a small portion is dedicated to introduce some of the terminology of blockchain. Thereafter the methodology used is explained and then the model is presented. Finally, the simulation results are shown and discussed.

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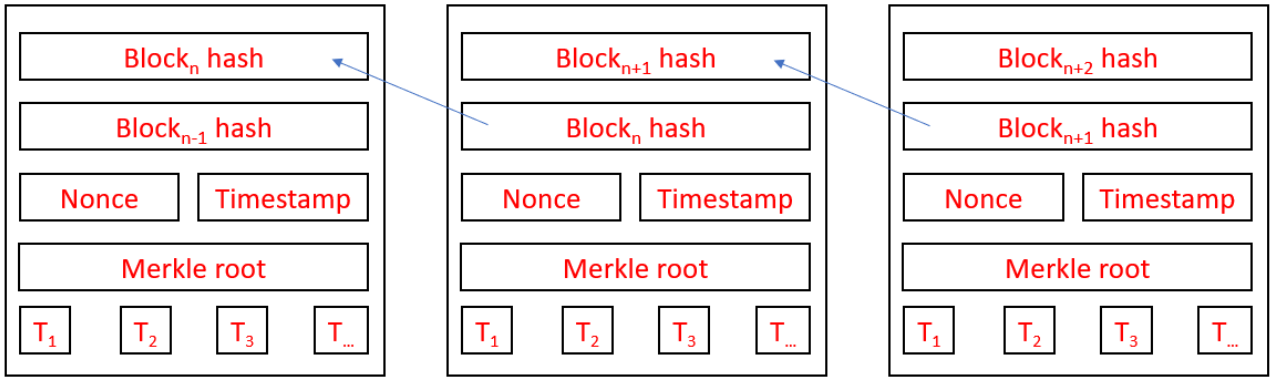

Figure 1. The contents of a block in the blockchain and the relation between the previous blocks where T_i is the approved transaction i of the block

2. RELATED WORK

Monrat et al. [3] provide a comparative study which shows the possibilities of blockchain as well as its benefits and trade-offs. Additionally, it explains the transactions process as well as the overall structure and architecture of blockchain technology.

Li et al. [8] set up an experiment to measure the energy consumption during the mining process of blockchain applications. They found that the hashing algorithm used to mine had the greatest impact on mining efficiency (hashes per Joule). Additionally, they found that the hashrate (the number of hashes per second) had a linear relationship with energy consumption.

Truby [9] presents the possible laws and policies that could be enforced by regulatory organizations to reduce the carbonization of blockchain technology. Truby shows multiple policies and laws that could lead to decarbonization of blockchain and shows the positive and negative sides of all the proposed policies, including whether it is possible to apply the policy in the current set of laws and policies of governments.

Schinckus [10] provides an overview of the sustainability of blockchain technology and concludes that better alternatives exist to proof-of-work, such as proof-of-stake, that provide similar security but with much less *waste* of resources.

Nair et al.[11] provide an overview of options that are under development as to how to make the blockchain technology more sustainable. Similarly Li et al. [12] provide both a novel protocol to reduce energy consumption based on a reward and punishment system as well as an algorithm for storage optimization based on RS-erasure code. However the scenarios used for simulations provided were not realistic.

3. TECHNOLOGY

Before presenting the model, an understanding of the block chain and some of the terminology is required, which will be briefly discussed in the following subsections.

3.1 Blockchain

Blockchain was created by Stuart Haber and W. Scott Stornetta as a means to prevent tampering with timestamps and was first applied to Bitcoin, after some crucial modifications, by Satoshi Nakamoto [13]. Essentially the blockchain is a linked list of blocks. In case of bitcoin, a block contains several header values such as block hash, previous block hash, nonce, timestamp and the Merkle root. Following the header information is the list of transactions [2, 3, 14]. Figure 1 shows the contents of a block and its relation to the previous block. The nonce is an arbitrary number that is found by a node in the network to conform to the protocol. The Merkle root is a hash that incorporates all the transactions made in that block. Because a new block depends on the hash of the previous block, it makes it that all blocks in the chain depend on all other blocks that came before it, making it impossible to modify parts of the chain without completely replacing the chain.

3.2 Hashing algorithm

A hashing algorithm is a one-way function that given data of any size, produces a fixed size output, called hash. A hashing algorithm is considered good when it is fast and when it minimizes the odds of duplication between two unique inputs.

3.3 Consensus protocol

To verify newly created blocks in the blockchain, applications make use of consensus protocols which determines the verification process. Because every node in the network uses the same consensus protocol, it is not possible to add a 'malformed' block to the chain. The following two subsections provide a brief explanation of the two most popular consensus protocols.

3.3.1 Proof-of-Work

Protocol in which participating nodes try to solve a cryptographic puzzle which requires a lot of computational power. This puzzle is nothing more than trying out random values for the nonce in a block which will be fed into the hashing algorithm. The difficulty of finding the correct output scales with the total computational power of the nodes in the network. An advantage of PoW over other cryptocurrencies that it is very secure, it is very hard to alter a block once added to the chain. A disadvantage is that it costs a lot of electricity, sometimes more than entire countries, trying to find an acceptable output. This is the protocol used by bitcoin.

3.3.2 Proof-of-Stake

Protocol in which each round a node will be selected to create a new block rather than using computational power to solve a puzzle. Instead of trying out a random number for the nonce, the stake (or wealth) by the node is used for the hashing process [5]. An advantage of PoS over PoW is that it takes over one thousand times less electricity

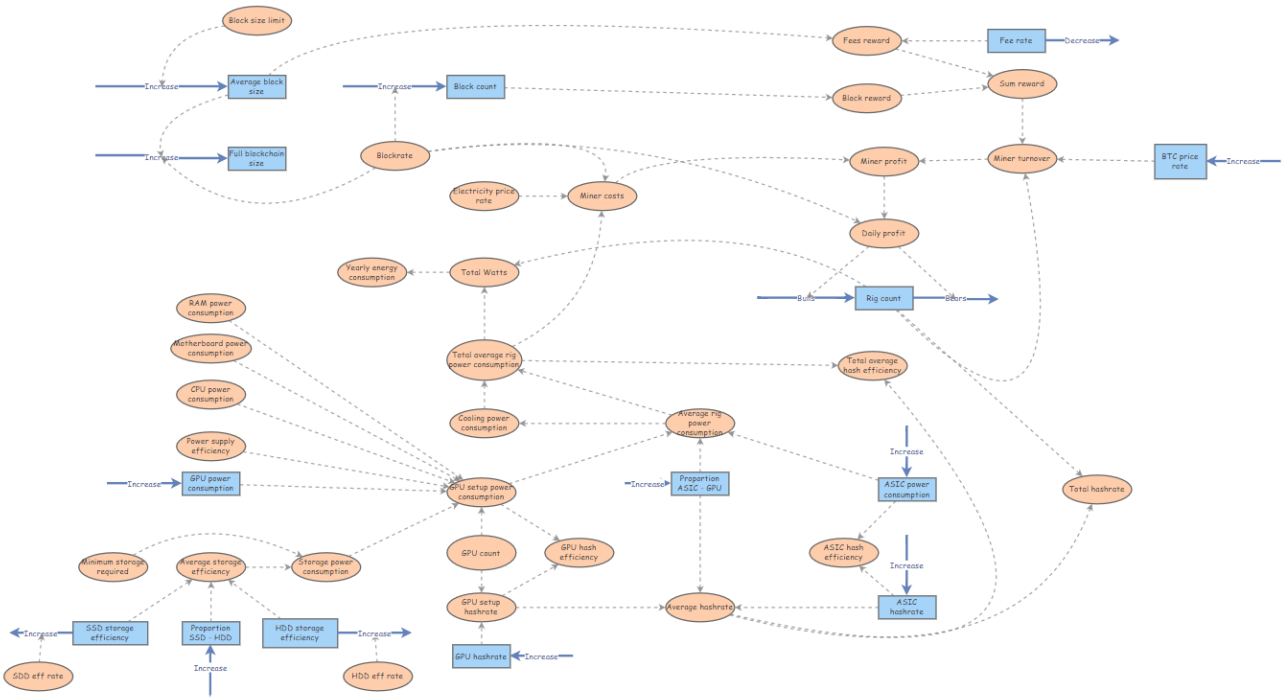

Figure 2. The bitcoin model

to verify a new block, purely based on the fact that the GPU consumes the most energy in a proof-of-work scheme, which is not a required component for PoS. However a disadvantage is that the richer get richer, because the more stake you have the more opportunities you get to create blocks and receive the rewards [3].

4. METHODOLOGY

The goal is to make a clear and transparent model that simulates bitcoin's energy consumption. The energy consumption depends on many dynamics such as supply and demand, profitability and technological developments. Another aspect aside from modeling are the input parameters. To establish the proper values for the parameters, the parameters from other articles are used if and only if these parameters are properly addressed. Many sources have slight differences in the parameter values used and it may be necessary to merge the parameters together to achieve a more accurate simulation.

Throughout this paper, we will make use of the web application Insight Maker [15]. In this application, stocks are presented as blue rectangles which can increase or decrease in stock over time. The flow of the stock is presented as a bold arrow. Flows can be between stocks but can also come from or be moved to the void, not modifying the other stocks in the process. Variables are presented as orange ovals and are dynamically updated to produce an output based on other inputs from stocks and variables, or they can be used as constants. Links are presented as dashed arrows and allows stocks and variables to access the current value held by the linked object.

5. MODEL

Figure 2 shows the dynamic model of bitcoin which is publicly available on insight maker through the following link [16]. The following subsections are dedicated to the explanation of the different parts in the model as well as their parameter values.

	Load	10%	20%	50%	100%
80 Plus		-	82	85	82
Bronze		-	85	88	85
Silver		-	87	90	87
Gold		-	90	92	89
Platinum		-	92	94	90
Titanium		90	94	96	91

Table 1. 80 Plus label efficiency ratings at specific loads [17]

Component	**Power rating (W)**	**Hashrate (Gh/s)**
GPU	185	2.1
Motherboard	30	-
CPU	55	-
RAM	3	-
HDD	3	-
SSD	2	-

Table 2. GPU rig parameters

5.1 Mining rig parameters

Mining rigs are split into two types of rigs, namely a GPU rig and an application-specific integrated circuit (ASIC) rig. GPU rigs have become almost obsolete because of the ASICs being many times more efficient, however there are still GPU rigs being used to mine bitcoin even in 2021 but only when the miners have access to near free electricity. Although mining Ethereum could be more profitable at the moment, some miners still stick to bitcoin mining because they believe that bitcoin will reach a price rate over 100 thousand euro. For this reason the model contains a stock 'proportion ASIC - GPU' that will start at 0.9 and increases yearly by 0.01, due to the ASICs becoming even more efficient than GPUs overtime. The mining rig parameters are located at the bottom of the model.

5.1.1 GPU rig

A GPU rig contains the minimal components you need

to run a regular desktop. This includes RAM, motherboard, CPU, power supply (efficiency), storage units and GPU count. The GPU count corresponds to the number of GPUs a motherboard can support simultaneously, which is 6. For mining with a GPU rig, the RAM and CPU need not be of the best quality, therefore a power consumption of 3 and 55 Watt have been chosen respectively. The motherboard does not draw that much power but still takes 30 Watts.

The GPU consumes the most power in the mining rig with over 90% of the total power draw. For the GPU we are going to use the statistics of Nvidia's RTX 2070 and RTX 3070. These GPUs have a power draw of 185 Watt and 220 Watt [18, 19] respectively, and a hashrate of 2.1 GH/s and 2.8 GH/s [20, 21] respectively. Note that the algorithm used by bitcoin is double SHA-256 [22] whereas the benched hashrates provided are only single SHA-256. Taking the 2-year CAGR from these values results in a yearly increase of power consumption and hashrate by 9.0% and 15.5% respectively. The values of the 2070 will be used initially in the model. The reason for not using the 3070 is that there is currently a global chip shortage caused by the pandemic, causing the manufacturers not being able to uphold supply to the demand [23, 24].

The power supply should have the gold label 80 plus, otherwise you should not even consider mining with any GPU rig on any cryptocurrency, see table 1. This sets the power supply efficiency rating at 0.89, assuming 100% load.

For storage units, a few more variables are introduced, namely SSD and HDD storage efficiency as well as the proportion of SSD to HDD. The efficiency of SSD and HDD are set at 2 and 3 Watt per terabyte respectively. These efficiencies increase yearly with 2.3% for SSD drives and 5.3% for HDD drives. The proportion of SSD to HDD starts at 0.5 and increases by 12.4% each year [25]. The minimum storage required is set at one TB, even though you can get away with less, if you opt-out of mining you at least still have a well sized storage drive that can be used for other purposes.

Because the rig contains six GPUs, the total power consumption is at 1350 Watt (power supply efficiency included) with a hashrate of 12.6 gigahashes per second, meaning a hash efficiency of 9.3 megahashes per Joule. Table 2 displays the power ratings and hashrate described.

5.1.2 ASIC rig

An ASIC works out of the box and does not require additional components other than some wires, the hashrate and the power rating is defined by the distributor and no study exists to verify the ASICs ratings. For this model, we only take a look at Antminer's S series, see table 3 for the ratings of the miners. The model will incorporate the merged ratings from the S17 and S19 with a ratio of 3:2 as a consequence of the global chip shortage. The merged ratings will set the power consumption at 2731 Watt and the hashrate at 69800 GH/s. Consequently resulting in an efficiency of 25.6 GH/J, making the ASIC almost 3000 times more efficient than the GPU rig. One can also compute a 7-year CAGR, considering S1 and S19 Pro, for the power consumption as well as the hashrate which are 36.9% and 150.0% respectively. However, I expect the technological improvements for the ASICs to decrease from now on. So instead I will use the 4-year CAGR, considering S9 and S19 Pro, resulting in a yearly increase of power consumption and hashrate by 24.0% and 67.4% respectively.

5.2 Blockchain parameters

The blockchain parameters include block rate, block count, block size limit as a constraint and the average block size and can be found at the top left side in the model. The block rate is, as defined by bitcoin's protocol, six blocks per hour. Though not part of the model, the protocol fixed this rate by scaling block difficulty with total hashrate. The block count increases with six per hour, as defined by the block rate. The block size in a Segwit transaction is set at 4 million weight units [27], theoretically this means that a block can have a size of 4 MB, however in practice this is not possible. The practical block size is close to 2 MB so that will be the value used for the limiter. The average block size starts at 1.286 MB [28] with a yearly increase of 5%. There is also a stock for the entire blockchain size, with initial size of 317.38 GB [29] and an inflow that depends on blockrate and the average block size.

5.3 Financial parameters

The parameters for this section includes all those that deal with costs and revenue. These include electricity price rate, bitcoin price rate, fee rate, fee reward and block reward and are mostly located at the top right in the model. From these parameters, one can compute the sum reward, miner turnover, miner costs and miner profit. Miner profit will be a stimulus for rig count.

The electricity price rate has been set at five cent per kWh, which is a lot cheaper than you can get in most western residential areas [31]. The reason for this is that miners know that the key to profitability is low electricity costs, resulting in professional miners setting up special contracts with electricity distributors as well as non-professional miners, for example, not having to pay for additional electricity usage as part of the rental agreement. This price rate is 19% higher than the one used by cbeci, which was set at five USD cents per kWh.

BTC price rate has been set at 23943 euro, as that was the price at the start of 2021. Table 4 shows the price rates of the last seven years. If one would take the 7-year CAGR from the price rates provided, the price rate would increase yearly with approximately 68.8%. However this would result in bitcoin's price rate to exceed 18 million Euro by 2031 and this is unrealistic. Since the circulating supply of bitcoin is 20.51 million by 2031, this would result in a market cap of 369 trillion Euro whereas the current top 100 companies' market caps [32] combined would not even have half of that. Considering this, a CAGR of 16.4% is a lot more reasonable as this would result in a price rate of approximately 110 thousand Euro by 2031 with a market cap of 2.26 trillion Euro. Compared to some other bitcoin price predictions, this prediction is quite minimal [33] and is closest to the predictions by Kay Van-Petersen (€84000 by 2027) and Mike Novogratz (€300000 by 2029).

Block reward has been defined such that it corresponds to bitcoin's block reward halving. Finally fee rate is defined as Satoshi per byte which in the model is initially at 63 Satoshi per byte decreasing yearly by 3.2% with minimum at 1 Satoshi per byte, this yearly decrease has been chosen as a response to the increasing BTC price rate as well as bitcoin's block reward halving. Fee reward can be calculated from the fee rate and the average block size.

5.4 Cooling

Dedicated bitcoin farms have thousands of mining rigs spread over their properties, however these rigs need to be properly cooled to prevent overheating. For this reason the cooling power consumption is the result of taking

Antminer Series	Release	Power consumption (W)	Hashrate (GH/s)	Efficiency (GH/J)
S1	2013	360	180	0.50
S3	2014	366	441	1.20
S5	2014	590	1155	1.96
S7	2015	1293	4730	3.66
S9	2016	1375	14000	10.18
S15	2018	1596	28000	17.54
S17	2019	2385	53000	22.22
S19	2020	3250	95000	29.23
S19 Pro	2020	3250	110000	33.85

Table 3. Antminers' performance ratings [26]

Year	Bitcoin price rate (Euro)
2014	614.26
2015	260.22
2016	355.61
2017	796.45
2018	8284.78
2019	3054.88
2020	5918.10
2021	23942.97

Table 4. Bitcoin's yearly price rates [30]

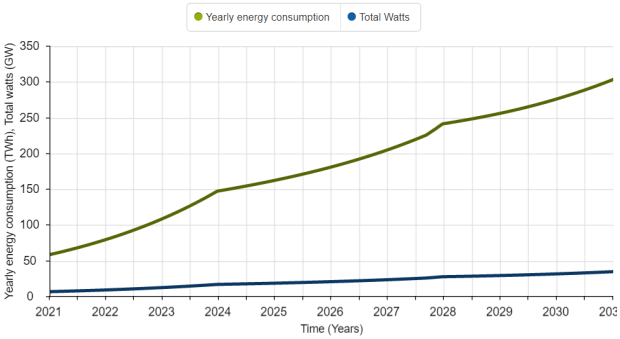

Figure 3. Yearly energy consumption and the total watts consumed according to the *baseline* model

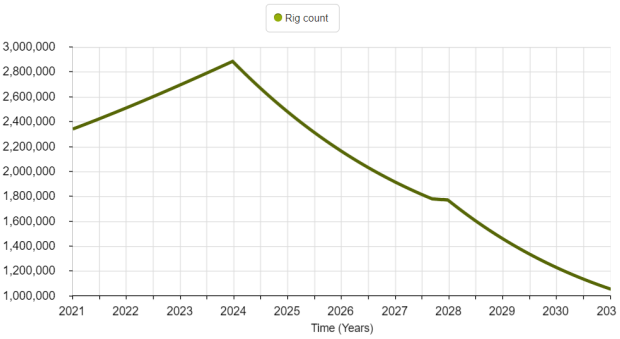

Figure 4. The number of active rigs according to the *baseline* model

a percentage of the average rig's power consumption and has been set at 10%, equivalent to cbeci's best guess PUE [7].

5.5 Rig count

The rig count is initialized with 2.34 million. This value has been chosen by manually calculating the number of rigs required in the model to reach a hashrate of 147.7 EH/s, which was the hashrate on the first of January 2021 [34]. The inflow depends on the daily profit of the miners, it has been defined such that when there is n euro profit per day, the number of rigs increase by $n\%$ per year. However when the daily profit reaches less than 6 euro, the rig count will stop increasing as it then would take over a year of mining to cover the costs of an S17 Antminer which was about 2250 euro before the global chip shortage. The outflow also depends on daily profit, but only acts when there is less than 6 euro profit per day. When this happens, the rig count decreases with 10% plus an additional $d\%$ per year where d is the difference between the daily profit and the target daily profit, which is 6. So if the daily profit drops to -8, the yearly decrease will be 24%.

5.6 Total energy consumption calculation

The total energy consumption can simply be calculated by multiplying the number of active rigs with the average power consumption of the mining rigs and a time period of 1 year. The result is stored in the variable 'Yearly energy consumption'.

There are also other variables in the model that have not been explained yet, such as 'Total hashrate' and 'Total average hash efficiency' but that is because these do not have an impact on the result of the model. The only purpose of these variables are to display statistics.

6. SIMULATIONS

Now that we have the baseline model, we can run some simulations. With this baseline we can also test out other scenarios and compare the results with each other. Sensitivity analysis is not possible yet in the current state of the model, since it does not use Insight Maker's randomness features. The following subsections provide the simulation settings and the results of the baseline (estimate), a lower bound and an upper bound.

6.1 Simulation settings

The settings are straight forward and are the same for every scenario. The simulation will start at the year 2021 and will simulate the next 10 years. Units of time have been set to 'Year' and the analysis algorithm used is Euler with a simulation time step of 0.01.

6.2 Baseline

The baseline simulation is a simulation using just the default values provided in section 5. With these parameters, the total electrical power consumed by the network is 6.67 GW, slowly increasing to 34.67 GW at the start of 2031. This means a yearly energy consumption of 81 TWh in 2021 and 289 TWh in 2030, calculated by taking the average of the data from that year, see figure 3. In 2024 and 2028 you can also see a small hiccup in the trend,

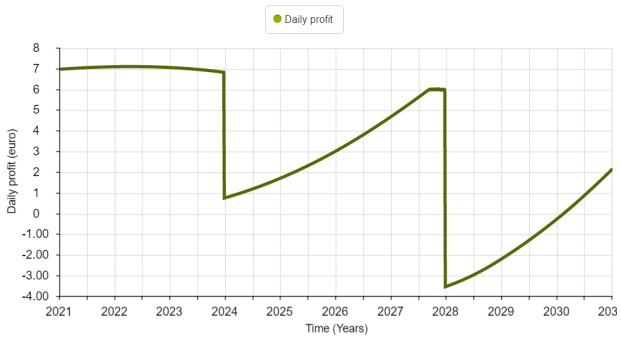

Figure 5. The daily profit per rig according to the *baseline* model

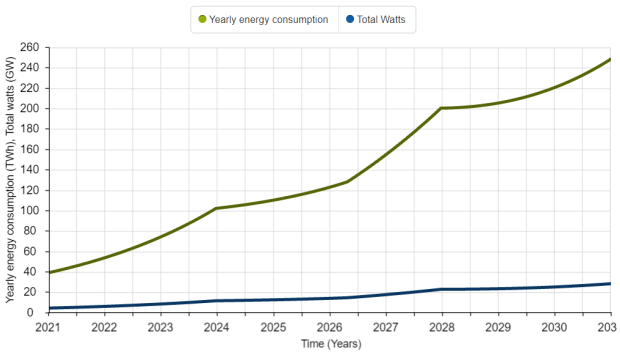

Figure 6. Yearly energy consumption and the total watts consumed according to the *lower bound* model

this is due to bitcoin's block reward halving. Comparing the results to digiconomist's index [6] estimate at the first of January of 2021 which was at 78 TWh, the estimated energy consumption is quite similar. CBECI's annualised energy consumption on the other hand was set at 102 TWh [7], however this 25% difference is the consequence of the annualization they apply. Thus they also take into account some rigs that are only profitable due to the sharp price surge of bitcoin, which was already at 30 thousand euro in February 2021, even though these rigs are a lot less efficient. Although not tested, I suspect a similar yearly energy consumption around the 80 TWh mark if this price surge had not occurred. With these results and comparisons, it can be said that the model proposed is valid and that the simulation results are a valid estimation of the network's future energy consumption.

Figure 4 shows the number of currently active rigs. Before the first bitcoin halving, the number of rigs steadily increases to a little over 2.8 million. However the moment the halving hits, the daily profit immediately drops to almost zero and the number of rigs sharply decreases. When finally halfway through 2027 the profit stabilizes, another halving hits in 2028 causing another sharp decline in active rigs with approximately 1.1 million left in 2031. See figure 5 for the daily profits.

6.3 Lower bound

Similarly to cbeci's lower bound calculation, the model will now only use the most efficient hardware available, no parameter in the model will be modified unless stated otherwise. Additionally to assuming the use of the most efficient hardware, cbeci also assumes a PUE of 1.01. However it is deemed unlikely that such a PUE is achieved by any professional mining operation and thus we will use a PUE of 1.06 instead. Meaning only a slight improvement in cooling by 4%.

To adhere to the new assumptions, the following parameters will be updated in the model. The proportion of ASIC to GPU will be set to 1. The ASIC power consumption and hashrate will be set to 3250 Watt and 110 TH/s. Also the initial rig count will be updated accordingly to 1.3 million rigs. The cooling consumption is set to be 0.06 of the average rig power consumption. If we assume an estimate cost of 5 thousand euro for an S19 pro (estimated by scaling the price of S17 according to efficiency), we should also update the inflow and outflow of rig count accordingly to break even in one year. This break even in one year is met at a daily profit of 13 euro. However the original equations from the baseline model will not work properly with this, so the inflow is updated such that for each n euro per day, the number of rigs increase by $(n-7)\%$ yearly, and it only increases rig count if n is greater than 13. The outflow only modifies rig count when n is smaller than 13 and the difference d is now calculated from 13 as well.

Using these settings we find that the yearly energy consumption in 2021 is at 38.5 TWh, increasing towards 235 TWh in 2030. Compared to the baseline, it is about half as energy demanding in 2021 and about 20% less energy demanding in 2030. Cbeci's estimation for the lower bound was at 37.5 TWh yearly on the first of January 2021, which is very similar to my own findings. Figure 6 shows the lower bounded energy consumption of the network.

6.4 Upper bound

Estimating the upper bound is hard for such a dynamic model as the initial values dictate the magnitude of the growth. So to establish the upper bound, we disregard the GPU side and only consider the least efficient but still profitable ASIC miner. Keep in mind that the initial rig count should be set accordingly such that it matches the hashrate in 2021. Again, assume that we use the exact same values as defined for the baseline unless stated otherwise.

For the upper bound we will set the proportion ASIC to GPU to 1 again. However we reduce the efficiency of the ASIC by reducing the initial power consumption and hashrate to the ones of the S9 Antminer, those are 1375 Watt and 14 TH/s respectively. Additionally we set the PUE to 1.15, meaning that the cooling consumption adds 15% power required to run a rig. To match the 2021 measured network hashrate, we are required to have 15.55 million rigs. Because the rigs ought only to be a slightly bit profitable, the costs of an S9 does not dictate whether the rig count increases or decreases, even if it takes a 100 years to pay back. This means that the inflow now acts when the daily profit is greater than zero and increases rig count by $n\%$ yearly for each euro of daily profit. The outflow acts when the daily profit is less than zero and makes sure that the rig count decreases by $(10 + 2 * n)\%$ for each n euro daily loss.

With these settings, the yearly energy consumption in 2021 is 166 TWh with a daily profit of 35 cents per rig, averaged over 1 year. See figure 7, 8 and 9. Closing in to 2024, the daily profit drops to less than a cent and when the block reward halving occurs, the daily profit goes below zero at -1.70. The total energy consumption is then at 290 TWh. Even though from 2024 onward, the rig count decreases yearly by about a million, the miners cannot recover in terms of profitability with the settings used for the outflow of the rig count because of the inefficient initial rig used for the model. The simulation ends with

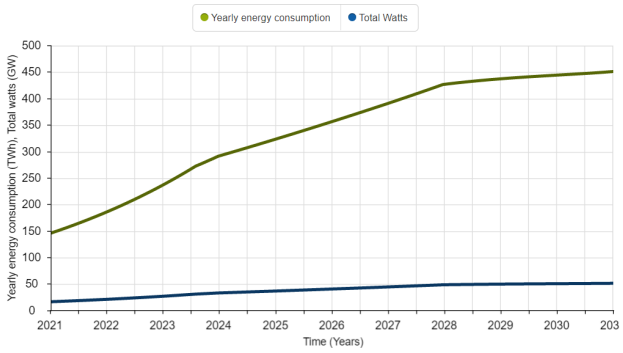

Figure 7. Yearly energy consumption and the total watts consumed according to the *upper bound* model

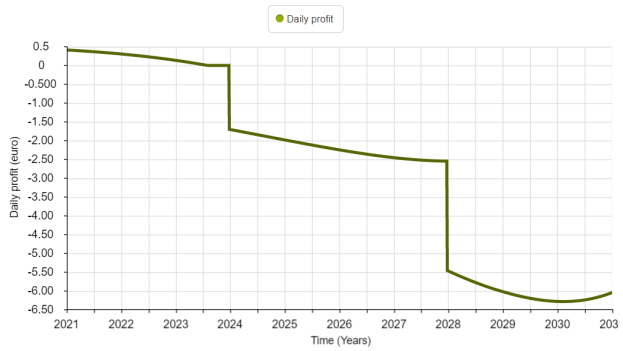

Figure 8. The daily profit per rig according to the *upper bound* model

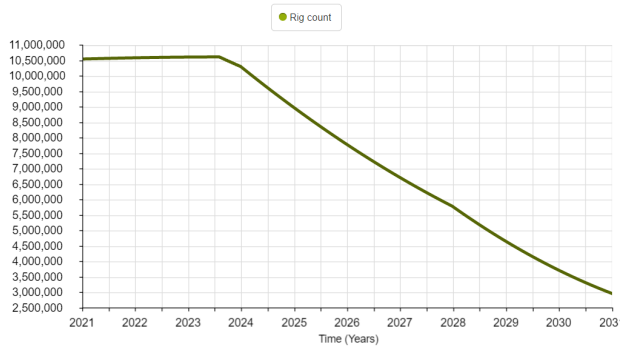

Figure 9. The number of active rigs according to the *upper bound* model

a rig count in 2031 of almost 3 million, an averaged daily profit of −6.16 in 2030 and an averaged yearly energy consumption of 448 TWh in 2030.

7. DISCUSSION

In the following sections we will discuss the limitations and future work.

7.1 Limitations

All models suffer from limitations [35], especially those that are simulated to estimate values from the future. And so also this model exhibits limitations:

- The model ignores some other expenditures, such as maintenance and rental costs, these costs may be significant for professional mining farms.
- The model assumes that every miner uses the same rig, and that each rig's efficiency increases (or decreases) by a constant amount yearly. The only distinction made is whether a miner uses a GPU or an ASIC rig. This also means that the model disregards the time and money it takes for miners to replace old rigs for better ones.
- Strongly dependent on financial parameters. The model assumes, in all scenarios, that bitcoin's price rate increases to over 100 thousand euro within ten years, and that the electricity costs remains constant. Also, the model uses a price target for the daily profit for when new miners join in or opt-out, this price target is constant as well.
- The model only takes into account the energy consumption of miners, ignoring entities such as mining pools that store data and distribute the workload over the miners.

7.2 Future work

Although the model is a good base, there is always room for improvement. Also because the model is publicly available, it is important that the model has been made in such a way that it can be easily modified. The model can scale in its current state, but there are a few aspects that could be added in to make it more scalable and more accurate:

- Add mining pools to the model. As said in the limitations section, mining pools distribute the workload to the miners over the internet and may consume energy similar to that of datacenters.
- Add propagation delays to the model. Propagation delay caused by the distance between nodes in the network may cause temporal forks and orphaning may occur, essentially deeming a portion of the network's work done useless.
- Detailed section for transaction behaviour. An increase in price rate of bitcoin may attract more users and increases the number of transactions requested per second, consequently modifying the fee rate and thus the total block reward.
- The addition of the block difficulty, which updates every 2016 blocks (according to protocol). This addition would indirectly modify blockrate through rig count by total hashrate.

- A scalability improvement by adding constants that represent the rates instead of being hidden inside the flows of stocks. This would also reduce the odds of human error, such as forgetting to update the outflow accordingly when updating the inflow.

8. CONCLUSION

This paper has presented a transparent dynamic model which can be used for simulations to predict the energy consumption of bitcoin's network in the future. Using the model, we have been able to find a lower bound, an estimate and an upper bound for the energy consumption. The expected energy consumption in 2021 ranges from 38.5 TWh to 166 TWh where the well educated guess is set at 81 TWh. In 2030 the energy consumption is expected to be bound between 235 TWh and 448 TWh and is estimated at 289 TWh. The models are publicly made available on Insight Maker [36, 16, 37] for others to experiment.

9. REFERENCES

[1] T. Aste, P. Tasca, and T. Di Matteo, "Blockchain technologies: The foreseeable impact on society and industry," *Computer*, vol. 50, no. 9, pp. 18–28, 2017.

[2] S. Nakamoto, "Bitcoin: A peer-to-peer electronic cash system." [online] https://bitcoin.org/bitcoin.pdf.

[3] A. A. Monrat, O. Schelen, and K. Andersson, "A survey of blockchain from the perspectives of applications, challenges, and opportunities," *IEEE Access*, vol. 7, pp. 117134–117151, 2019.

[4] G. K. Badhotiya, V. P. Sharma, S. Prakash, V. Kalluri, and R. Singh, "Investigation and assessment of blockchain technology adoption in the pharmaceutical supply chain," *Materials Today: Proceedings*, 2021.

[5] S. Zhang and J.-H. Lee, "Analysis of the main consensus protocols of blockchain," *ICT Express*, vol. 6, no. 2, pp. 93–97, 2020.

[6] Digiconomist, "Bitcoin energy consumption index," Apr 2021. accessed 25th April 2021.

[7] "Cambridge bitcoin energy consumption index." [online] https://cbeci.org.

[8] J. Li, N. Li, J. Peng, H. Cui, and Z. Wu, "Energy consumption of cryptocurrency mining: A study of electricity consumption in mining cryptocurrencies," *Energy*, vol. 168, pp. 160–168, Feb. 2019.

[9] J. Truby, "Decarbonizing bitcoin: Law and policy choices for reducing the energy consumption of blockchain technologies and digital currencies," *Energy Research & Social Science*, vol. 44, pp. 399–410, Oct. 2018.

[10] C. Schinckus, "The good, the bad and the ugly: An overview of the sustainability of blockchain technology," *Energy Research & Social Science*, vol. 69, p. 101614, 2020.

[11] R. Nair, S. Gupta, M. Soni, P. Kumar Shukla, and G. Dhiman, "An approach to minimize the energy consumption during blockchain transaction," *Materials Today: Proceedings*, 2020.

[12] C. Li, J. Zhang, X. Yang, and L. Youlong, "Lightweight blockchain consensus mechanism and storage optimization for resource-constrained iot devices," *Information Processing & Management*, vol. 58, no. 4, p. 102602, 2021.

[13] A. Narayanan, *Bitcoin and cryptocurrency technologies : a comprehensive introduction*. Princeton, New Jersey: Princeton University Press, 2016.

[14] F. Tschorsch and B. Scheuermann, "Bitcoin and beyond: A technical survey on decentralized digital currencies," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 2084–2123, 2016.

[15] "Insight maker homepage." [online] https://insightmaker.com.

[16] M. de Roos, "btc model v3 baseline," June 2021. [online] link unavailable: will be published after review.

[17] Clearesult, "What is 80 plus certified?." accessed 15th June 2021.

[18] Nvidia, "Introducing nvidia geforce rtx 2070 graphics card."

[19] Nvidia, "Nvidia geforce rtx 3070 family."

[20] guanting112, "Nvidia geforce rtx 2070 hashcat benchmarks." Published on gist.github.

[21] zyronix, "Nvidia 3070 benchmarks." Published on hashcat.net.

[22] coinmarketcap, "What is sha-256?."

[23] M. Sweney, "Global shortage in computer chips 'reaches crisis point'," March 2021.

[24] D. Leprince-Ringuet, "The global chip shortage is a much bigger problem than everyone realised. and it will go on for longer, too," May 2021.

[25] M. Koot and F. Wijnhoven, "Usage impact on data center electricity needs: A system dynamic forecasting model," *Applied Energy*, vol. 291, p. 116798, June 2021.

[26] "Antminer distribution europe b.v.," June 2020. accessed 15th June 2021.

[27] J. Frankenfield, "Segwit (segregated witness)," June 2021.

[28] ycharts, "Bitcoin average block size." accessed 16th June 2021.

[29] Statista, "Size of the bitcoin blockchain from january 2009 to may 20, 2021." accessed 16th June 2021.

[30] CoinDesk, "Bitcoin price index - coindesk 20," June 2021. accessed 15th June 2021.

[31] Globalpetrolprices, "Electricity prices around the world." accessed 15th June 2021.

[32] A. Murphy, E. Haverstock, A. Gara, C. Helman, and N. Vardi, "How the world's biggest public companies endured the pandemic," May 2021.

[33] Bitcoinprice, "Bitcoin price predictions - future bitcoin value 2022, 2030," Apr 2021.

[34] CoinWarz, "Bitcoin hashrate chart."

[35] J. D. Sterman, "All models are wrong: reflections on becoming a systems scientist," *System Dynamics Review*, vol. 18, no. 4, pp. 501–531, 2002.

[36] M. de Roos, "btc model v3 lower bound," June 2021. [online] link unavailable: will be published after review.

[37] M. de Roos, "btc model v3 upper bound," June 2021. [online] link unavailable: will be published after review.