Tampere University of Applied Sciences

Bitcoin environmental impacts

Narrative literature review

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ABSTRACT

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Following the recent interest in cryptocurrency markets and talks about its sustainability, this thesis aimed to review the current state of Bitcoin mining and how it is affecting the environment. Cryptocurrency mining consumes huge amounts of energy each year, comparable to amounts spent by entire countries, with Bitcoin having the largest energy demand. Most of this energy is currently being wasted as many blockchains use a validation method that has every miner compete for a reward, but only one person receives it. Everyone else working to get the reward ends up wasting the energy they dedicated to it.

Many of the existing studies focus mostly on Bitcoin’s carbon footprint and this thesis attempted to compile all the different ways environment is impacted by Bitcoin mining and what the reasons for that are. Secondary objective was to examine how mining is likely to develop and solutions that could be implemented to reduce the effects on the environment in the future. Cryptocurrency is a new subject and most of the up-to-date information is found online. This is why this thesis used online sources when physical books were not available and it was necessary to evaluate the reliability of each new piece of information. Information was gathered from primary data sources where possible to try and preserve the accuracy of the information. There is need to further study the ways to make Bitcoin mining more efficient and how to make better use of the heat energy that currently mostly goes to waste.

Cryptocurrency, Bitcoin, blockchain, environmental impacts, energy consumption.

TABLE OF CONTENT

GLOSSARY

Altcoin	Bitcoin was the first cryptocurrency and all subsequent cryptocurrencies are called “altcoins” or “alternative coins”
ASIC	Application-specific integrated circuit, a machine made specifically for cryptocurrency mining
Bioenergy	Renewable energy generated from living organisms.
Bit	A basic unit of information in computing
Bitcoin	Protocol and payment network using a blockchain.
bitcoin	Digital currency using peer-to-peer technology for instant payments (BTC)
Block	Files containing transaction information that are added into a blockchain
Block reward	Cryptocurrency awarded to a miner who solved cryptographic problem required to create a new block on a given blockchain
Blockchain	Decentralized networks containing information on cryptocurrency transactions
Centralized network	A single figure is responsible for the entire network
Cloud mining	Third party provided cryptocurrency mining service
Code	Programming instructions for a program.
Coin	Single unit of cryptocurrency
Geothermal energy	Renewable energy produced by the Earth’s core
Greenhouse gas	Gas contributing to warming of the climate by absorbing infrared radiation
Carbon footprint	Total amount of greenhouse gasses produced by an action
CPU	Central processing unit executes programs in a computer

Cryptocurrency	Digital currency using cryptography to validate transactions
Cryptography	The practice of encrypting information
Decentralized network	No one holds power over others in the network, relies on consensus method of validation
Decentralized currency	A currency that does not rely on third party to be able to function
Decrypting	Transforming encrypted data back into understandable form
Digital currency	A currency existing only in a digital form
Emission	Particle pollution causing adverse effects on humans and the environment
Encryption	A way to make data into code that hides its meaning.
E-waste	electronic devices that are no longer wanted and need to be disposed of
Fossil fuel	Originate from prehistoric dead animal and plant material found in Earth’s crust. (Coal, natural gas, oil)
Full node	Contain a blockchain’s entire history
Genesis block	The first block of a cryptocurrency ever mined forming the first block in a blockchain
GPU	Graphical Processing Unit, creates 3d images on computers
Grid	Network for electricity distribution
Hacking	Using a computer to gain unauthorized access to other computers
Hash	Output result of hashing program, a unique, fixed-length string used to encrypt data
Hash rate	Amount of computing power used to operate in a network

Hydroelectric power	Renewable energy generated from altering the natural flow of water bodies
IP address	Device identification on the internet or local network.
Merkle Tree	Hash based data structure used for verification of data
Miner	Contributing to a blockchain by validating transactions and getting rewarded for it
Miner node	Full or lightweight nodes competing to add blocks into blockchains
Mining	The process of adding new blocks to a blockchain by verifying transactions creating new cryptocurrency
Mining algorithm	A set of rules miners use to create new blocks
Mining rig	Equipment used for mining cryptocurrencies
Network	All nodes taking part in a blockchain
Node	Base unit of a blockchain that stores data
Non-fungible token	Used as a digital proof of ownership (NFT)
Nonce	Resulting number of solving a cryptographic problem, used once for secure communication
Processing power	Computer’s ability to manipulate data
Proof-of-Stake	Blockchain validation method using stakes to bid on access to blocks. (POS)
Proof-of-Work	Blockchain validation method using complex mathematical problems that miners compete to solve. (POW)
SVP node	Lightweight or simple payment verification nodes only store a part of a blockchain
Terahash per second	1 trillion hashes a second. Indicates the power of a mining machine
Virtual private network	creates encrypted connection to the internet hiding IP address (VPN)
Wind energy	Using wind turbines to generate renewable energy

1 INTRODUCTION

Different kinds of a currencies have been used by humans for thousands of years as a transaction tool to represent value of different things and services. Money started as purely a physical thing in but with technology developing, money can now be used without ever even seeing but as a number on a screen. First writing on cryptocurrency was back in 1983 when American cryptographer David Chaum thought of a currency that would not need banks to control its movement. In 1995 he built a proto cryptocurrency called Digicash that required software to withdraw money from a bank by using encrypted keys. (Nigeria G 2021)

The precursor of Bitcoin called Bit Gold was created in 1998 by Nick Szabo. It was similar to the blockchain today in a sense that it required a computer to solve a cryptographic puzzle and then the solver would receive a reward. The early system however, had the problem of not being able to stop copy pasting data without a central network to control it. Only a decade later someone using a pseudonym Satoshi Nakamoto published a paper called “Bitcoin – A Peer to Peer Electronic Cash System.” The publishing of the paper eventually led to all the different cryptocurrencies and the blockchain that is known today. The first block of Bitcoin, now called the Genesis Block, was mined by Nakamoto in January of 2009. (Nigeria G 2021)

There has been a lot of discussion about cryptocurrencies in recent years. Cryptocurrency is a relatively recent concept and has only started to get attention due to how popular it has become as an investment and a replacement for traditional currencies. The popularity of mining cryptocurrency has only increased since then as the value of cryptocurrencies has continued to rise. Bitcoin is one of the first cryptocurrencies that was created, and it has become the biggest, most popular, and highest energy consuming digital currency on the market. With the global goal of making the planet more sustainable and environmentally friendly, it is surprising that there has been so little focus on environmental impacts of cryptocurrency mining. With cryptocurrencies becoming such a popular investment asset to many, it now takes more resources to mine cryptocurrency than it does to mine gold. Most studies today are only focusing on Bitcoin as it is the most known currency consuming the most energy, however there are over

four thousand different digital currencies on the market which pose a risk to the environment if the situation does not change. The electricity consumption of Bitcoin has increased from 4,8 TWh to 73,12 TWh over the last two years. Globally, Bitcoin mining consumes more energy each year than some smaller countries. Every Bitcoin transaction consumes an amount of energy used by 350,000 bank card transactions. Bitcoin is responsible of two thirds of the energy consumed by the entire cryptocurrency market. Ethereum, the second largest digital currency, consumed around the same amount of energy as Cyprus already in 2017. (Wang Y, Lucey B, Vigne A S & Yarovaya L 2022)

Every 10 minutes a new block of Bitcoin becomes available for mining, which adds 6,25 new bitcoins into circulation. The total cryptocurrency market has reached a cap of over a trillion euros (Coinmarketcap). Mining cryptocurrency can create big profits in a short amount of time. This makes more people and companies interested in investing into mining them. The mining process consumes a lot of electricity depending on the equipment used and the size of the mining facility. It also produces a huge amount of thermal energy, which usually goes to waste and requires cooling systems to keep the systems from overheating. (Bedford T & Bedford M 2017)

Only recently has there been more discussion about trying to reduce environmental impacts of cryptocurrency mining. Tesla’s Chief executive officer, Elon Musk recently made headlines stating that Bitcoin would not be accepted as a payment method due to its impacts on the environment. Some countries and US states have started to try and regulate mining, but in many places, it is still completely unregulated. (Wang Y, Lucey B, Vigne A S & Yarovaya L 2022).

This thesis subject selection was motivated by trying to find out the current impact cryptocurrency mining has on the environment. This thesis was made to review the current literature and research on the subject.

This thesis will mainly focus on the environmental effects today and what solutions there could be to try and remedy the situation in the future. The main goal should be to bring attention to the issue and stop it from getting any worse. The interest in cryptocurrencies continues to increase and mining operations

keep getting larger and more energy consuming despite the technological advancements.

1.1 Research objective

The objective of the thesis was to find out the global environmental impacts of Bitcoin mining by reviewing literature and studies done on the subject. This was done through a narrative literature review. Due to there being no global regulations or anyone representing cryptocurrencies, there is lack of existing studies on the field. There is lack of information to general public that would cover the issue as a whole. Opinions on the subject are mixed and sources provide differing information that might not be subjective. Even with the impacts to the environment, some consider cryptocurrency mining to be worth it due to the economic value it generates.

It is hard to evaluate the entire situation as there are many things to be considered and with mining being accessible to anyone, it is almost impossible to track all mining activities around the world. Cryptocurrency mining is sometimes done by an individual using a single machine and then there are also entire facilities and companies dedicated to it. These facilities have thousands of miners mining Bitcoin around the clock. The objective is to find out the different ways mining operations are harming the environment and what can be done to reduce the effects in the future. This includes the emissions from transactions as well as the mining process and having to keep up with current technology, which leads to replacing mining equipment. Mining is harming the environment in many ways and most of the current studies are only focusing on its carbon footprint, but there is much more to it than that. This thesis aims to collect information from reliable sources to try and get a more complete and objective understanding of the current situation.

Research Questions:

1. How is Bitcoin mined and what are its environmental effects today?
2. What energy sources are used for mining today and what happens to the heat energy produced?
3. Can Bitcoin mining be more environmentally friendly?

2 METHOD

This thesis was written as a narrative literature review covering recently published research on consumption of cryptocurrency mining as well as the broader environmental impacts focusing on Bitcoin in particular. Exploration of more environmentally friendly methods in the future is also a goal of this research.

The method chosen for this thesis was a narrative literature review due to the extensive quantity of information on the subject. Conducting other methods of gathering information such as interviews would be challenging as miners tend to be secretive about their operations to keep a competitive edge over others. Cryptocurrencies are a recent invention and only in the past few years have people started raising concerns regarding the rapid growth of mining operations and their impact on the environment. This means that there are no long-term studies and fewer experts in the area.

Literature chosen for the thesis was selected based on what was available and the reliability of sources. Most current studies are focusing on carbon dioxide emissions and other impacts are less studied. Because Bitcoin and cryptocurrencies in general are highly volatile and the situation is constantly changing there was a need to find as recent information as possible. The search was narrowed down to Bitcoin and how it works as well as blockchain technology and the hardware needed to mine cryptocurrency. The information gathering was focused on energy consumption and how much of it is renewable as well as environmental impacts that are currently considered.

2.1 Data collection process

Data was mainly collected online. Cryptocurrencies as a new subject have relatively few recent physical books written about them. The data in most books gets outdated quickly as new currencies are created and their value can multiply or crash in a matter of days. The growth of and interest in cryptocurrencies increases rapidly, leading to multiple online sources being available. Most of the recent publications on the subject are found on the internet rather than as

physical books. Many diverse sources were used to try and find the up to date information in each area. Research done on the subject mostly focuses on a carbon dioxide emission and this thesis will try to compile all of the different opinions and topics into one cohesive paper. Many of the sources have similar contents but give different figures or differing conclusions, making it necessary to evaluate the credibility of each new piece of information. Primary data sources were used, where possible, to try and preserve the reliability of information.

3 LITERATURE REVIEW

3.1 What is Bitcoin?

Bitcoin is a cryptocurrency, meaning that it is decentralized and not backed by a central bank or other financial institutions. It is used to buy and sell things as well as being an investment to many. Created back in 2009, Bitcoin is the first largely used cryptocurrency and the most known. Its network consists of a peer-to-peer network (the bitcoin protocol), public transactions (blockchain), consensus of rules, and a Proof-of-Work algorithm. As Bitcoin was the original cryptocurreny, other currencies are sometimes called altcoins or alternative coins. Different cryptocurrencies have been growing in popularity and value over the past few years and there are now thousands of different currencies available and new ones created every month. (Antonopoulos A M 2017)

Cryptocurrencies are held in a digital wallet and bought and sold through online exchange. These wallets can be found online on an exchange site or stored offline for example in a USB drive. Unlike physical currencies like the euro or the US dollar, cryptocurrencies are only backed and maintained by their users and the value of the currency is based on demand and the number of transactions made using the currency. (Antonopoulos A M 2017)

Cryptocurrencies have some benefits over physical currencies. They have lower transaction fees, the amount depending on the amount of money that is being transferred. The person who owns the cryptocurrency is in full control of their assets - no bank or government can restrict or control access to funds. Transactions are more confidential, and fraud is much less of an issue because of how blockchains operate. Additionally, the value of bitcoin cannot be artificially inflated by printing more money. (Summers A 2022)

3.2 Decentralized network

All digital networks need regulations and rules to function. A decentralized network is a form of governance that can be used to run a network. The difference

between a centralized network and decentralized network is that one has an authority in control of the entire system and the other is a shared authority with all the participants of the network having access to all the data. There is also something called distributed network, which is spread over several other networks and managed jointly or separately by each network. Examples of this are the telephone networks and world wide web and peer-to -peer networks. (Luther W J & Stein Smith S 2020) These differences between networks are shown below in Figure 1 (Cepero R 2020).

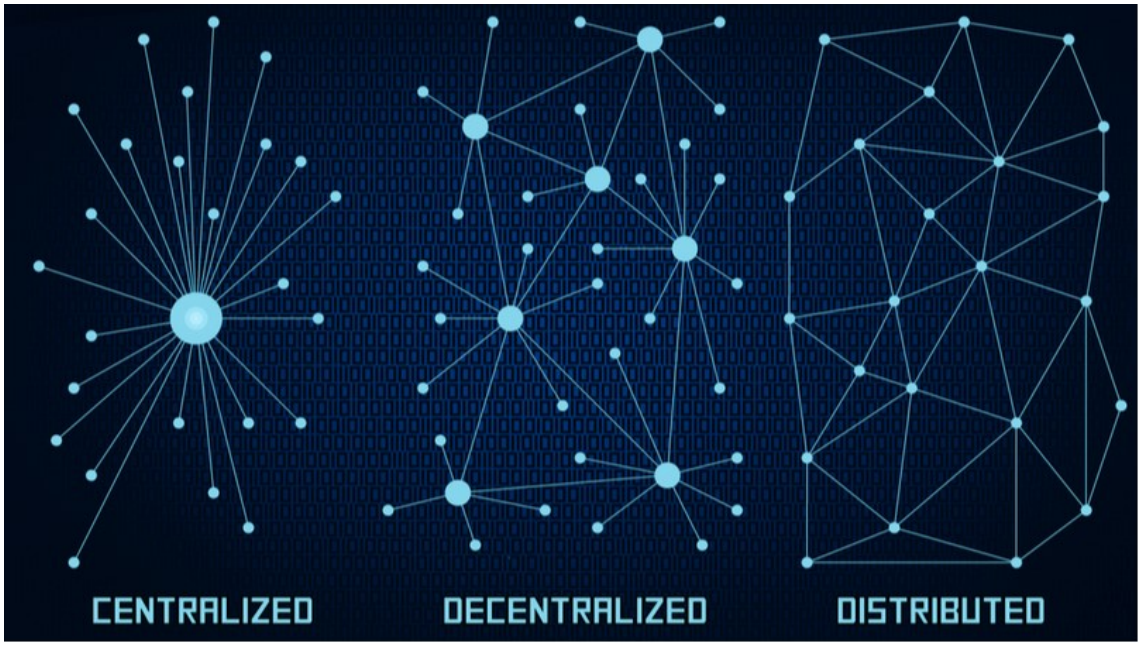


Figure 1. Centralized, decentralized and distributed network. (Cepero R 2020)

In a centralized system the user has to trust the authority holding all the data as only they are able to control it. Most of the networks are centralized, for example government sites, online banks, and Google. As you use the network the user gives information and asks for access to information in the centralized network trusting the network to handle the data. (Luther W J & Stein Smith S 2020)

In a decentralized network everyone that is part of it has access to data and all changes have to be approved by the majority of the network. In this type of data exchange no one has to trust anyone else as the need to get approved by the network makes entering false data very difficult. It is also a lot less vulnerable to hacking, system failures, power outages or corruption. The trade-off of a decentralized network is that it is slower. As the network grows it becomes more

secure, but each transaction takes longer because the number of nodes that need to confirm the data is larger. Nodes can have different roles within the network, but all data is transparent to everyone. (Luther W J & Stein Smith S 2020)

All data in decentralized network is real time data, meaning that it is different from a typical data that is stored somewhere in a centralized network. When data gets stored, there is a chance of data being lost or corrupted. Having access to real-time shared data is more reliable since the data will never be transformed to another form that would create the openings for the data to get changed or tampered with somehow. (Luther W J & Stein Smith S 2020)

Centralized networks can also work as cryptocurrency exchange platforms. There are online websites like Coinbase where anyone can buy cryptocurrency with another currency and trust the website to handle the transactions and hold onto the money until it is taken out. These websites make money by acting as the middleman and taking a small transaction fee when an exchange happens.

3.3 Blockchain

According to Summers (2022), blockchain is the main reason cryptocurrencies work even while being fully digital currencies. They were first designed to use for cryptocurrencies assets management. There is no downtime in a blockchain, meaning that because they don’t require people for operating, they provide a continuous service. Compared to more conventional ways of storing data, blockchains are powerful but energy demanding. The simplest way to describe a blockchain is to say that it stores data as blocks and links them together. Each block is linked to the previous one, comparable to pages in a book. Blockchain distributes copies of the database across the world making them available to anyone. This makes creating fake cryptocurrency or cheating the system very difficult as every transaction is traceable by anyone with an internet connection. There is no need to trust anyone as the information can be checked and verified by anyone wishing to do so. Blockchain database is decentralized on multiple computers spread across a network, these computers are called nodes. For new data to be added into the blockchain, multiple nodes must confirm the new data

and only once multiple sources have confirmed the legitimacy of the transaction will it be approved, this action is called Proof-of-Work (PoW) and it is one of the ways a blockchain can reach a consensus. (Summers A 2022) Below Figure 2 shows how the blockchain operates. (Raj R 2022)

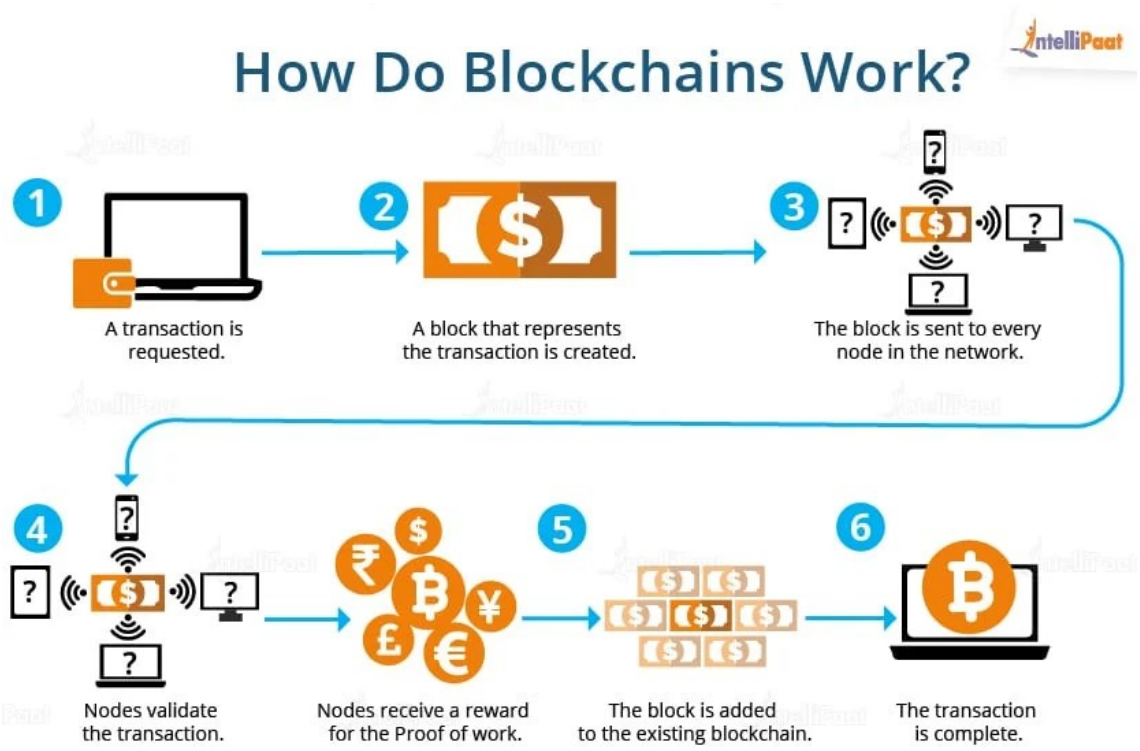


Figure 2. Blockchain operation. (Raj R 2022)

The Blockchain starts with a transaction request, which creates a new block. The block is then sent to every node to be mined (PoW) or nodes can bid on it with stakes (PoS) depending on the type of the blockchain. Node that validates the transaction gets a reward and the block is then added into the blockchain completing the transaction. The structure of the blockchain looks simple but the process behind it is quite complex. Blocks are connected to each other with their hash codes. Hashing is a mathematical process that takes input of any size data, performs required operations on it and then returns the data at a fixed size. The return data is a fixed size sequence of letters regardless of the amount of input data, which makes each transaction output comparable and fixed. The chain needs to approve every transaction by majority agreeing on cryptography and digital signatures insuring the validity of the transaction. (Summers A 2022) Below Figure 3 shows of structure of blockchains (Raj R 2022).

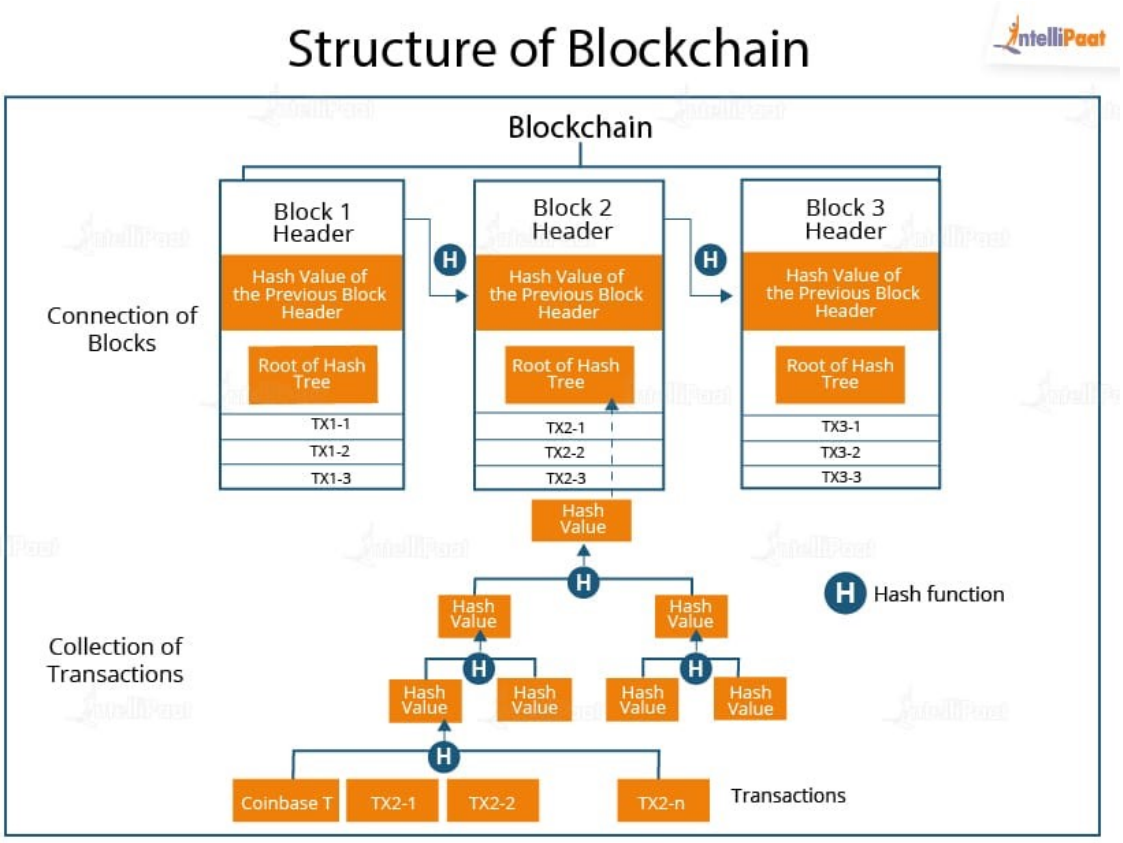
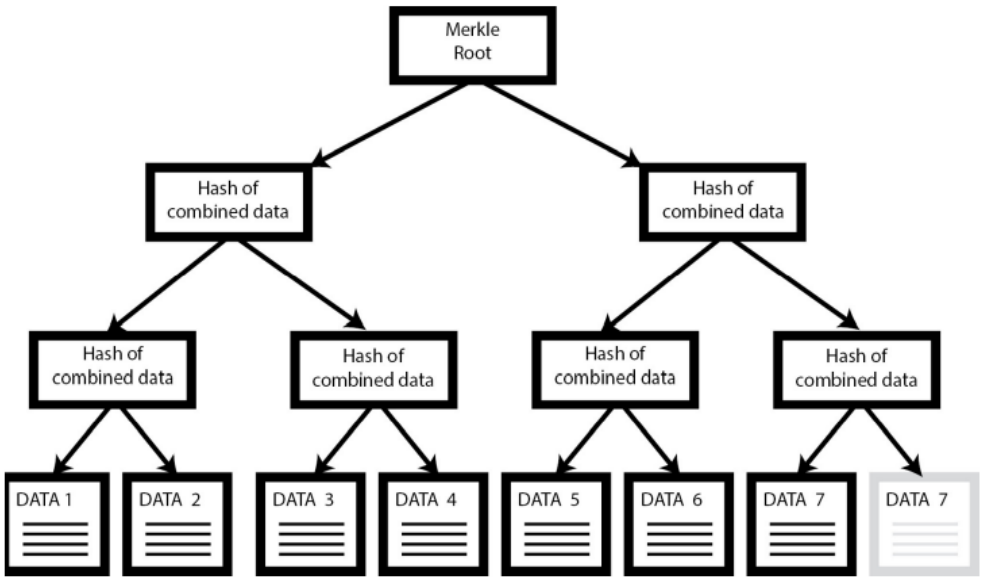


Figure 3. Structure of blockchain. (Raj R 2022)

The blockchain uses hashing to differentiate between blocks. The hashing process gives each block in the chain a unique identity like a fingerprint. Blocks are identified by this hash which removes the need for identification and verifications. Different hashing algorithms produce hashes of different lengths. The output hash is measured in the number of bits that the final value takes to store. For example, the Bitcoin blockchain uses SHA-256 hash function that produces a hash of 256 bits so 32 bytes. So, what Bitcoin hash algorithm does is that is takes a message made by placing an order and creates a 32-byte hash code out of it. If the message is tampered with, the code changes. This makes reconstructing the original message impossible without the hash code, making hacking almost impossible. (Summers A 2022)

Each block, apart from the genesis block, contains the hash code of the previous block. This means that changing data of a block changes the hash code making it no longer match what is in the next block, invalidating it. It is impossible to change data in a blockchain without invalidating every block after it, this is what makes data in a blockchain so reliable. Blocks contain a piece of hashed data

stored as a Merkle Root of a Merkle Tree. Merkle Three is a structure of hashed data. Below is a Picture 1 showing the structure of a Merkle tree. (Summers A 2022)



Picture 1. Structure of a Merkle Tree. (Summers A 2022)

This picture shows how each hash is divided into to hash pieces of data that together make up the hash code of the previous node. If any part of the data is changed, it changes the root. In blockchains the Merkle Root verifies data stored in a bock. If any block changes, it invalidates the data and gets rejected. (Summers A 2022)

Even though all nodes in Bitcoin blockchain are equal there are different nodes in the network that have their own roles. All nodes validate transactions and blocks and maintain connections to other nodes. Full nodes act as servers in the network maintaining consensus of transactions verifications. They also store a complete up-to-date copy of the blockchain. Simple payment verification (SPV) nodes or lightweight nodes rely on full nodes for information and do not store the full blockchain in them. Miner nodes compete to create new blocks. Miner nodes can be either full or lightweight nodes. The main network consists of 7000 to 10000 nodes running various versions of Bitcoin reference client. The extended network includes nodes running peer-to-peer protocol and specialized nodes. There are also pool servers and protocol gateways connecting nodes. (Antonopoulos A M 2017)

Transactions are secured using a method called cryptography meaning the study of encrypting and decrypting data. This means that nodes need to solve complex mathematical problems to process transactions making a cipher that only the sender and the recipient understands in a form of a hash code. This is how new cryptocurrency gets mined. Nodes that confirm transactions in the blockchain get rewarded with a small amount of the cryptocurrency native to it. For example, Bitcoin blockchain awards bitcoin to its miner nodes. All cryptocurrencies awarded by blockchains are new, meaning that they are added to the previously existing amount of the cryptocurrency. However, this does not mean that there are infinite amounts of any cryptocurrency. The cap of a cryptocurrency is encoded within its source code and enforced by the nodes in a blockchain. This means that all the cryptocurrency available is already in the blockchain and once it all has been mined there will be no more of the currency to get. (Antonopoulos A M 2017)

Both public and private blockchains exist. Anyone can participate in a public blockchain. Private blockchain are controlled by organizations and only they can give access to it. Blockchain is more secure as a decentralized network and it is highly efficient with no need for intermediaries and some potentially very good applications in the future. One of the negative sides of a blockchain is high energy cost. Having all nodes work on confirming transactions takes a lot more energy than a single database. This creates burden on the environment as well as higher transaction costs. (Antonopoulos A M 2017)

3.4 Cryptocurrency mining process

Calling the process of getting new cryptocurrency “mining” is slightly misleading. Mining in a blockchain means securing the network, new currency is only created as an incentive to validate transactions. Cryptocurrencies are most often mined using high powered computers that are specifically made for the purpose. The objective of a miner is to create as many hashes as possible in the shortest possible time and using as little energy as possible to do it. Mining can be done from anywhere in the world by anyone, using any computer able to compete

solving problems in a blockchain. Mining operations prioritise fast internet connections and low energy cost, regardless of the source. Computers mining in a blockchain are called nodes. Nodes change information between themselves over the network. In a blockchain using Proof-of-Work, like Bitcoin, mining nodes compete to solve the new block to get rewarded a small amount of bitcoin as a reward. Proof-of-Work blockchains work by having miners invest energy into finding the resulting number that is the solution to the problem, known as a nonce. Every new block has a timestamp, version number, the previous block hash, the hash of all the previous transactions, the target hash, and the nonce. Basically, the miners compete to solve the hash to get the nonce of the new block. The new nonce is accepted if it is equal to or lesser than the target hash of the block. The nonce is then added to the data in the block and passed through a hash function. The value of a nonce is always a value between 0 and 4 294 967 296, making it almost impossible to guess. The only way to find the right answer is to keep guessing until the mining machine gets it right, it is completely up to luck. When one node gets the right answer, it shares it with the rest of the network, so the others stop working on the block. (Aljabr A Sharma A Kumar K 2019)

Only the node that got the right answer gets the reward, but an unlimited number of nodes can compete for any given block. The total hash power of the network shows the amount of work done by miners for a block. As the number of nodes increase, getting the rewards gets more unlikely resulting in tighter competition and increased energy consumption. Hash power of the network affects the amount of time required to mine a block. The difficulty of a block is changed based on the average time of new blocks generating. New block is generated every ten minutes, so if mining a block takes longer than ten minutes the difficulty is decreased and then increased again if it was done too fast. (Summers A 2022)

As a result of the increased competition, the technology keeps improving and getting more specialized to mine certain blockchains. The people wanting to compete seriously must dedicate more energy and larger number of machines to get a return in their investments, resulting in more and more energy being wasted for each block, as the number of nodes competing for the reward increases. Bitcoin is limited to 21 million coins and once they have all been mined, there will

be no more coins to mine. 17,3 million bitcoins have been mined so far. (Aljabr A Sharma A Kumar K 2019)

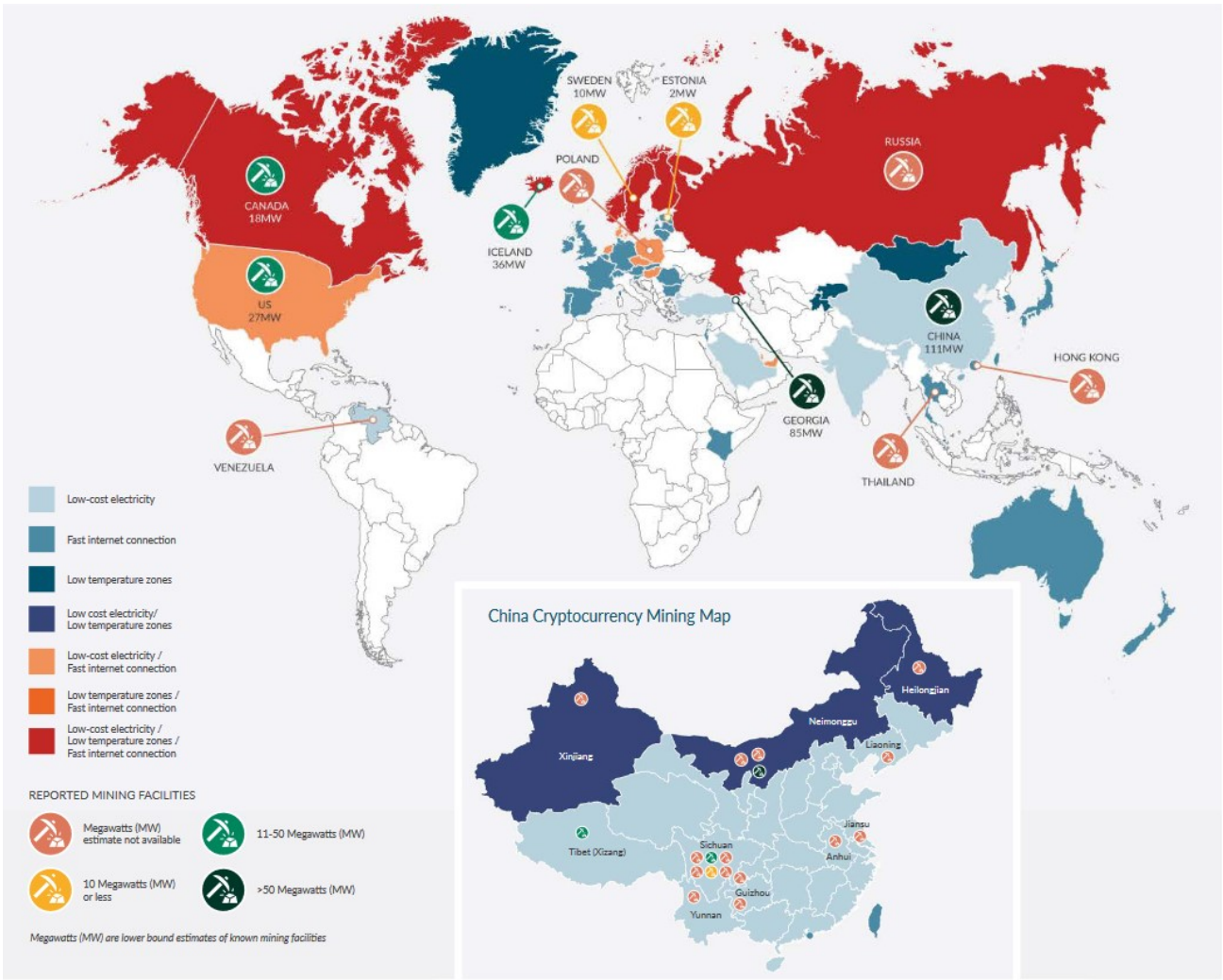
3.5 Large scale mining operations

Since Bitcoin mining offers substantial rewards, it has become a business model to many. Information about large scale miners is scares because they want to protect any advantages they may have achieved. Big mining facilities have to consider the same things as everyone else, but due to their scale they are looking to be even more efficient. Because miners get paid in bitcoin no matter where they are, they have to consider the local exchange rate as they calculate costs and profitability. Mining equipment gets outdated much faster that regular computers, most efficient operators replace their miners after just a few months. Some large operators are cutting down costs by manufacturing the equipment themselves. (Szmigielski A 2016)

Electricity is the largest running cost of mining operations and a big part of it is due to cooling. Mining facilities prefer locations with low energy costs and colder climates for this reason Iceland, Scandinavia and North America being very popular. Many of the bigger facilities are also located in Asia with majority of them being in China. Good network connection is also crucial as well as access to latest mining hardware. There are many mining facilities around the world that mine cryptocurrency for themselves and also sell mining services. These are meant for anyone who wants to start mining cryptocurrency, but don’t have enough knowledge or the hardware needed to start mining. A company called Genesis mining has set up operations in Iceland and Sweden where they use geothermal energy to generate electricity for mining. (Szmigielski A 2016)

A Cambridge University study in 2018 was able to map mining facilities around the world. They made a map that shows an estimate of the locations of mining facilities consuming a total of 288 megawatts (MW) mining mainly Bitcoin. However, this map does not cover nearly all of the mining operations. Many of

the facilities are hidden but at the time the map was made in 2017, it can be estimated that it was able to cover half of them. The map shows what other studies have also estimated, that most of the bigger mining operations take place in China and in colder climate areas of the world. The trend of mining facilities location should have stayed similar since then as colder climates are preferred. Picture 2 below shows the mining locations map made for the study. (Hileman G & Rauchs M 2017)



Picture 2. Cryptocurrency mining locations. (Hileman G & Rauchs M 2017)

36% of the large mining facilities interviewed for the Cambridge study believe that PoW energy consumption could be compensated by using renewable energy sources. But interestingly none of the interviewed large operator were open to swapping to another method of validating transactions. This would mean that none of them consider the large energy consumption to really be an issue as long as they try to compensate and reduce their energy consumption. In fact, the large

scale miners consider the biggest risk to be competition from other miners when they were given a list of operational risks and asked to rank them. (Hileman G & Rauchs M 2017)

China used to be the biggest crypto miner in the world with 65% to 75% of the total hash rate of the Bitcoin network. The country's mining capacity dropped to zero in late summer of 2021 when mining cryptocurrency was banned. A lot of miners from China have moved to neighbouring countries like Kazakhstan and the US. Mining has since started again in however, with several underground operations. Now in 2022 China once again makes up 22% of the Bitcoin market with only the USA having a bigger share. It can also be hard to see where miners are located with tools like VPN making it possible to hide their internet traffic by hiding their IP address. (Browne R 2022)

There are plans to build the world's biggest cryptocurrency mining facility to Corsicana Texas. The mining complex itself would be around 37000 square meters in size filling a square kilometre in mining computers. The company planning this called Riot Blockchain already has the biggest Bitcoin mine in the country in Rockdale Texas. They are building in Texas because of a power line moving electricity from West Texas to the east side and the close proximity to water. Texas is still welcoming Bitcoin miners even when other states and countries around the world are starting to become vary of the increasing energy needs of the business. Texas even recognized it as commercial business in their bill in summer 2021 as only the second state to do so. (Mernit J L 2022)

3.6 Mining hardware

Everyone mining cryptocurrency use some kind of computer hardware to improve computing power of the miner to process blocks in a blockchain faster. Mining hardware is also often called a mining rig. While most people that are serious about mining use custom-built rigs, general build machines like any regular computers can also be used as miners. Crypto mining rigs can utilize CPU (Central processing unit), GPU (Graphics processing units), ASIC (application-specific integrated circuit), FPGA (field-programmable gate array) and cloud mining. These methods provide different hash rates and mining rewards and

come in various sizes and costs using different amounts of energy. (Bedford T & Bedford M 2017)

CPU mining was used in the early days of cryptocurrency mining mainly to mine Bitcoin. This was possible because there were only a few miners at the time, so the overall hash rate needed to be successful was lower. The scale of mining has since increased making CPUs fall behind with their lower energy efficiency and hash rates. Some blockchains use CPU friendly methods for mining to keep them competitive for everyone. However, many of the major blockchains don't, which makes CPU miners not able to keep up. (Bedford T & Bedford M 2017)

The first software for GPU mining was released in 2010 allowing more effacing energy usage and higher hash rate. Many miners construct rigs with as many as 12 GPUs linked together, which multiplies their hash rate, and some even have multiple of these setups as home-based mining operations. However, a new kind of hardware was developed fast called ASIC, taking over the market from GPU rigs. (Bedford T & Bedford M 2017)

ASIC, or application-specific integrated circuit, was only designed for cryptocurrency mining. The first one was sold back in 2012 and it was about 200 times more powerful than the GPU computers at the time. In 2021 ASIC miners mining power is 90-100 terahashes a second which far exceeds any GPU machines (Cambridge University 2022). The only thing stopping ASIC computers from taking over the entire market is their high cost. This makes using them risky as miners need warehouses full of hundreds or thousands of ASIC machines to be competitive. In addition to that, most ASIC miners are specialized to certain coins or solving specific algorithms. (Bedford T & Bedford M 2017)

Field-programmable gate array (FPGA) miners are faster and more efficient than GPUs for most algorithms and they are not as specialized as ASIC being able to mine most coins. This makes some serious miners consider FPGA miners to be the best option with their flexibility and high hash rate. "Gate array" in the name refers to the fact that they can be customized and programmed for specific needs even by the miners on the fly. The downside is that they are less user friendly

and downloadable mining algorithms charge a developer fee which can be up to 8% of profits got using the algorithm. (Bedford T & Bedford M 2017)

Cloud mining works the same way as any other purchasable cloud storage. Cloud service provides can sell mining services allowing anyone to mine without purchasing the systems themselves. The contracts vary with different hash rates and durations. The downside of this is that these services are often sold out and there is a need to find a reputable seller to avoid getting scammed. (Bedford T & Bedford M 2017)

3.7 Electricity consumption

Just running Bitcoin requires more energy than some countries energy consumption put together. Bitcoin energy consumption increased nearly 62-fold between 2015 and 2021. According to an ongoing study by University of Cambridge the energy consumption of Bitcoin is 80,92 TWh annually. (Cambridge University 2022)

The electricity consumption estimation is based on a model developed by Marc Bevand in 2017 that uses a profitability threshold of different mining equipment as a start point. The exact amount can’t be known by the consumption of energy is estimated by making a realistic estimate of the energy consumption of equipment the mining process. The Cambridge university research team calculated the minimum energy consumption that would be possible as the lowest amount and then the maximum amount that the equipment could consume while still being profitable. Then a more realistic estimate was made by knowing what machines the biggest companies Bitmain, MicroBT and Canaan which hold around 85% of the market share, were using. The rest were assumed to use a mix of machines that are comparable to the big companies. All mining facilities were assumed to have PUE of 1.1 based on conversation which miners and mining experts. PUE means power usage effectiveness of a machine. (Cambridge University 2022)

Below is figure four made in excel using data from U.S. Energy Information Administration, Country Data from 2019. The Figure 4 compares electricity consumption of countries and shows where Bitcoin would be if it was a country.

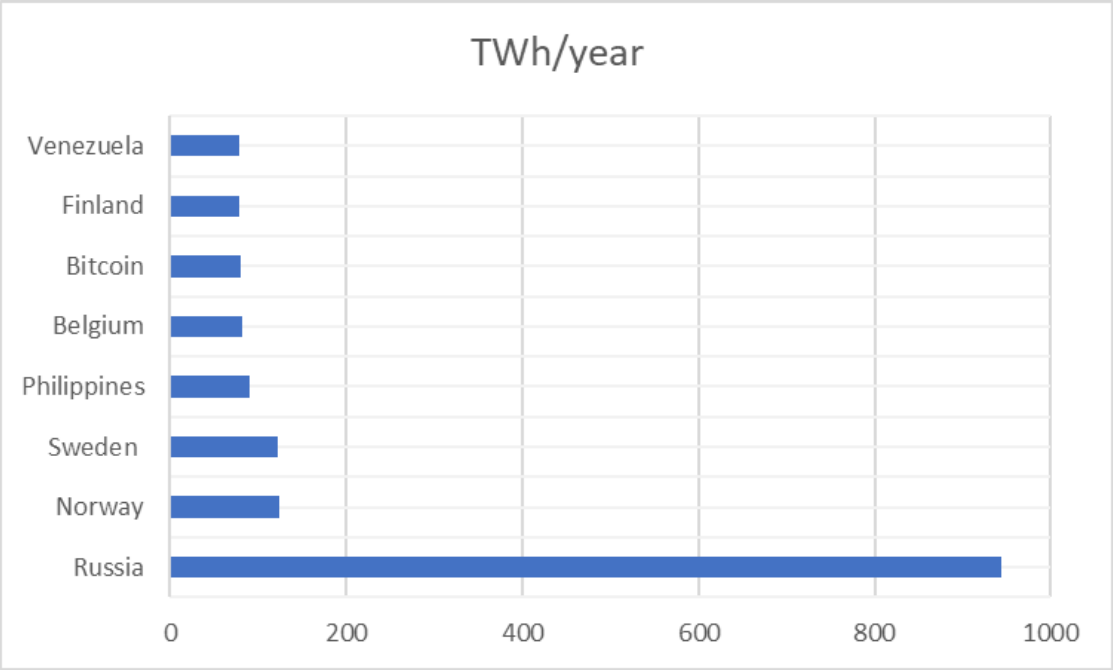


Figure 4. Energy consumption in TWh annually (U.S. Energy Information Administration)

The energy consumption comes from having to run a massive peer-to-peer network for blockchain to work. High powered computers solve increasingly difficult math problems and to keep them from overheating a cooling system is needed. If cryptocurrency prices go up that increases the incentive to add more machines which leads to increasing energy consumption over time. If a lot of people try to use Bitcoin at the same time, it also gets more expensive as the network can only process five transaction every second. This leads to increased need for miners and higher profits. Many countries have unstable power grids that might not be able to support the increase in consumption by mining. (Rooks T 2021) Below Figure 5 shows monthly energy consumption of Bitcoin in TWh since it was released to be mined (Cambridge University 2022).

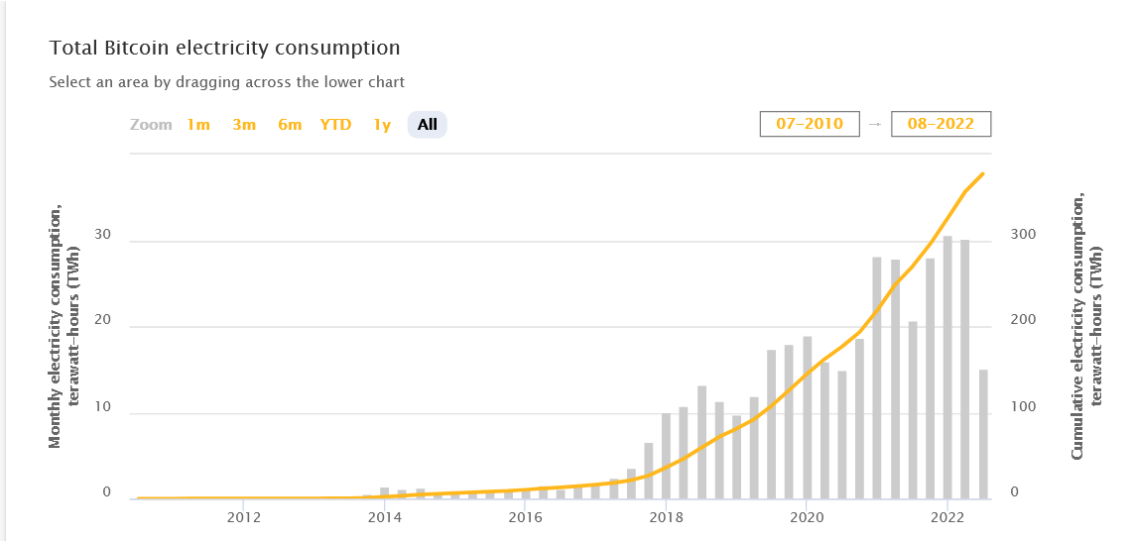


Figure 5. Bitcoin monthly energy consumption over time in TWh. (Cambridge University 2022)

Total Bitcoin electricity consumption has increased massively since 2018 with slight drops between then and now but the trend shows that the consumption is only increasing.

3.8 Renewable energy

Some see the increased energy demand from mining as an opportunity to expand on the existing renewable energy sources. The increased demand is creating market for new energy sources making investments in environmentally friendly solutions more likely. The increase of energy demand from crypto mining is equivalent of adding 2400 wind turbines into the grid every year. If the increased energy demand would be fulfilled by renewable energy, then that would create new long-term renewable energy production. Currently, 57% of the energy used for crypto mining comes from renewable sources. At the moment the cheapest available energy sources in countries wanting to cut their carbon footprint are from green energy so it is hoped that miners wanting to maximize profits would switch over as well. With cryptocurrency mining being able to happen anywhere in the world they are likely to start new operation in places with lowest operation costs. (Kemp B, Samaties P, Sanaulla F & Vaughan C 2022)

Sometimes even if a large mining company uses renewable sources of energy, it turns out to be a problem. There is an example of a Bitcoin company that set up

operations in a smaller city in Montana USA using their supply of hydropower. The problem was that they needed more energy than they could supply, using almost as much energy as third of the population in the entire county. The company went bankrupt when Bitcoin plummeted in 2020 and the county took the chance to require all future mining operations to supply their own new renewable energy sources. (Mernit J L 2022) This clearly shows that currently even if miners are using clean energy, they might be forcing others needing that energy to turn back to using fossil fuel for their energy needs. There is no clear way to measure the impacts this has on the environment.

Nordic countries have been popular for their use of renewable energy for cryptocurrency mining. 8% all Bitcoin have been mined in Iceland. Geothermal and hydroelectric power generate nearly 100% of the energy used in Iceland. The energy is cheap sustainable and reliable attracting a lot of energy intensive production including blockchains. With the increase in cryptocurrency popularity in recent years, Iceland is reaching its limits and today Iceland's global share is only 1-2% of Bitcoin mining. Companies are now looking to go to Norway and Sweden. Currently the operations in Nordic countries are only around 1% of the total hash rate, which means power per second when mining. (Walter D 2021)

Norway has the cleanest cryptocurrency miners in the world thanks to its renewable energy sources. 100% of Norway's electricity is generated from renewable sources with 88% coming from hydropower and the rest being wind and geothermal energy. Hydropower is a popular renewable energy source as it is the most reliable, not relying on weather. Another option would be for the mining facilities to have their own renewable energy sources they could temporarily use to relieve stress from the local grid in high demand times. They could have their own small renewable energy plant, wind turbines or perhaps solar panels depending on the location and the size of the mining operation. (Newar B 2022)

One potential concern is that the industry might not be big enough to create renewable energy grids to replace the old non-renewable energy solutions we are still using today. Developing countries would also be great locations for new renewable energy sources instead of having to replace the old existing systems.

Since they are still growing and need new energy sources no matter what, there is a chance now to make them renewable from the start instead of using fossil fuels and later changing it like most industrialized countries have and are still in the process of doing. Until more renewable sources are created, Bitcoin and other cryptocurrencies will continue to use fossil fuels to power its blockchain activity.

3.9 Environmental impacts of cryptocurrency mining

Many of the past studies have focused only on the carbon footprint of Bitcoin, however there are many other environmental issues to consider. For example, the amount of space mining facilities occupy or the amount of water used to cool down mining equipment as well as the electronic waste resulting from upgrading technology. Higher processing power means that a computer has higher probability to solve a problem in a blockchain, which means that power-intensive equipment is used. With rewards from mining getting lower, the computers used as miners have to get more powerful and energy efficient to stay profitable.

All environmental effects of cryptocurrencies include air, water, noise, and electronic pollution. The total cost of cryptocurrency mining is almost impossible to determine because of the nature of how it is done. Anyone can set up small mining operations without anyone knowing about it. With VPN it is possible to hide the location of nodes and hackers can even make computers other than their own to mine coins without the owner knowing about it. German official investigated a case in February 2021, where an individual mined over $85 million worth of bitcoin at $50,000/BTC exchange rate using computers owned by other people, who had no idea it was even happening (Chamanara S, Ghaffarizadeh A & Madani K 2021).

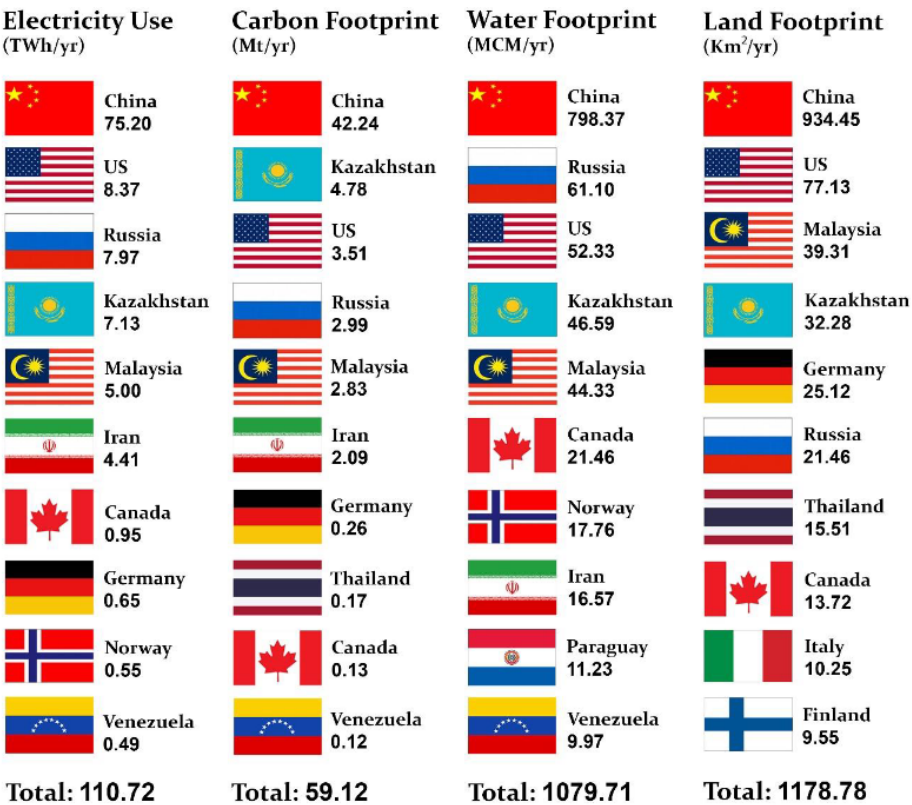
To truly get the full picture of what is going on with cryptocurrency mining, national and global policies would be needed to make mining more transparent.

3.9.1 Environmental cost of Bitcoin

While it is difficult to fairly compare Bitcoin to anything else, it is still useful to put the values into perspective to get a scale of the problem. Bitcoin is responsible

for most emissions since it is the most popular cryptocurrency. Goodkind et al estimated in 2018 that each 1 USD of bitcoin created 0,49 USD worth of health and climate damage in the US and 0,37 USD in China. The implications for climate change are dire because Bitcoin is estimated to create 0,66 million tons of CO2 (carbon dioxide) emission a year. Li et al showed in 2018 that is 4,7% of Bitcoin mining takes place in China, the consumption of energy is at least 30,34 GWh. This would generate 19,12 to 19,42 thousand tons of CO2 emissions. Electricity in China is cheap and mostly relies on coal. China's mining locations are remote and also rich in hydro- and wind power and it is likely used to power mining if it is the cheapest energy option. (Badea L & Mungiu-Pupazan M C 2021)

To offset the carbon emissions by Bitcoin mining about 2,8 billion trees would have to be planted taking up an area close to the size of UK. The water used is comparable to the amount used by three hundred million people in rural Sub-Saharan Africa. The land area used for Bitcoin mining is estimated to be around 1200 square kilometres. Below in Picture 3 shows the world's top ten Bitcoin miners in terms of electricity consumption as well as carbon, water, and land footprint as of May 2021. (Chamanara S, Ghaffarizadeh A & Madani K 2021)



Picture 3. The world's top ten BTC miners in terms of electricity consumption, carbon, water and land footprint as of May 2021. (Chamanara S, Ghaffarizadeh A & Madani K 2021)

Showing the environmental impacts in this way shows the different resources used depending on the type of energy used to mine Bitcoin. China mainly uses coal as a power source. Kazakhstan has a high carbon footprint because of fossil fuels being responsible of over 84% of electricity production. Electricity in Kazakhstan is cheap, and they have passed legislations encouraging miners to set up operations there. Countries generating renewable energy from hydropower are higher on water footprint. Thailand, Italy and Finland are relatively high on land use footprint because of using land-intensive energy sources like bioenergy. (Chamanara S, Ghaffarizadeh A & Madani K 2021)

3.9.2 Bitcoin created air emissions

The massive amounts of energy consumed by Bitcoin mining mean that is also has a large carbon dioxide footprint. Below in Figure 6 an estimate of the carbon emissions of Bitcoin in megatons. The figure compares amounts estimated by different sources. (De Vries A & Stoll C 2021)

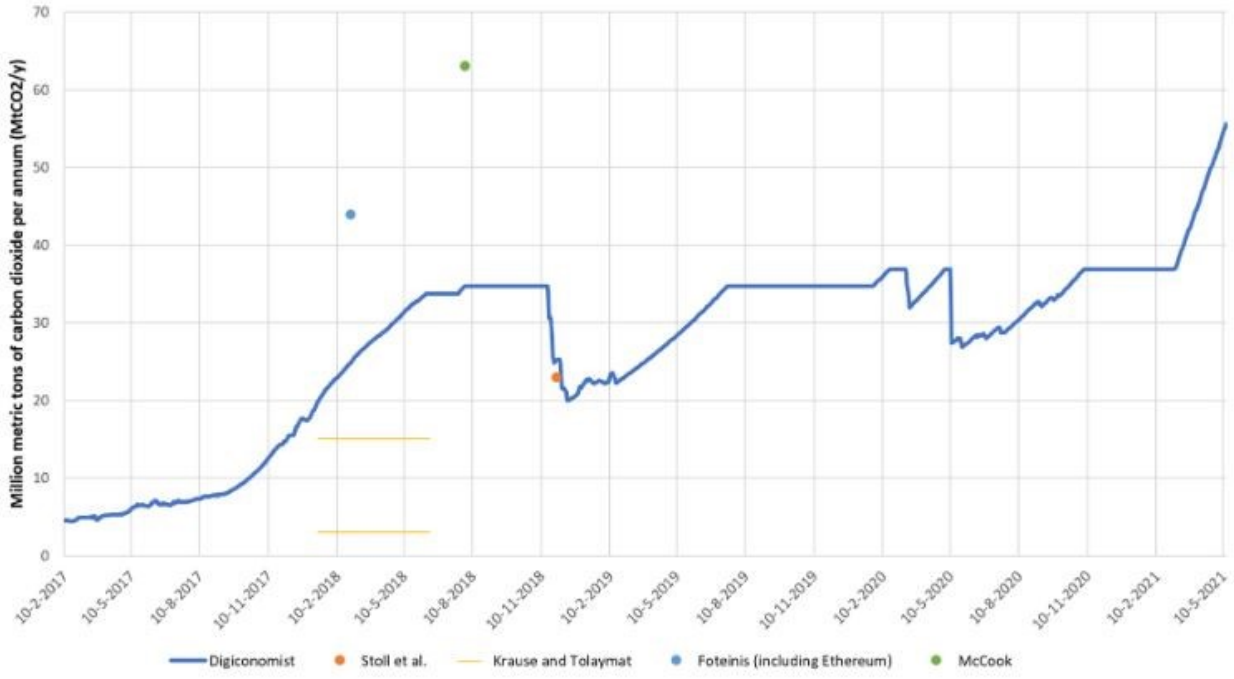


Figure 6. Bitcoin carbon emission over time (De Vries A & Stoll C 2021)

Digieconomist uses carbon intensity of 475g per kilowatt-hour (gCO2/kWh) to calculate the carbon footprint of Bitcoin. Stoll et al found the emissions to be 22,0 to 22,9 million tons of carbon dioxide in 2019. McCook estimated 63 Megatons of CO2 in 2018. Foteinis estimated the combined footprint of Bitcoin and Ethereum to be 43.9 Megatons of CO2 in 2018. Krause and Tolaymat estimated the emission to only be between five to 15 megatons of CO2 in 2018. These estimations usually use conditions of a certain day and assume that the same conditions persist for the whole year. This is not very accurate, but it gives a comparison to other emission sources and national emission levels. (De Vries A & Stoll C 2021)

Bitcoin mining can have adverse effects on local communities. In New York, Bitcoin mining caused the reopening of Greenidge coal power plant. In June 2022 they were denied an application renewal to continue operation and the plant was closed again. This was due to Greenidge violated the state emission reduction law and caused lowered air quality. Communities in the area are already burdened by pollution and additional impacts from mining using coal created cumulative burdens. (White House Office of Science and Technology Policy (OSTP) 2022)

It is actually possible to calculate the amount of deaths caused by Bitcoin. Bressler has estimated that the average lifetime emissions of CO2 from 3,5 Americans (4434 tons of CO2) will kill one person who wouldn’t have died otherwise between 2020 and 2100. Based on this it is possible to calculate death rates from blockchain transactions by finding estimated emissions of a blockchain and dividing it by the number of transactions to find the emissions from one transaction. The estimations will differ depending on the blockchain because each one consumes energy at a different rate. Bitcoin with an estimated annual carbon footprint of 83,44 megatons of CO2, would be responsible for an estimated 18 thousand deaths in the future per year as of October 2021. Bitcoin network is currently not willing to change away from its Proof-of-Work validation method despite how energy consuming the process is. (Truby J, Brown R D, Dahdal A & Ibrahim I 2022)

3.9.3 Water as a cooling system

Mining facilities can also use water to cool their systems. Server racks exceeding 20kW, it is more economical to move away from air cooling systems. Liquid heat transfer capacity is much higher than air making liquid cooling systems more efficient. There is new technology being developed that tries to use metal plates installed throughout the servers to cool the system. A more promising solution that was developed for crypto industry is liquid immersion cooling. Two phase immersion cooling has the capacity to decrease server energy consumption by 5% to 15%. (Quirk D & Stabinski M 2021)

Bitcoin mining facilities draw water from local water sources to use in cooling systems for their mining equipment resulting in thermal water pollution. Standard data centres require about 24000 litres of water per year for a single 10kW rack of servers. This can be reduced by water immersion or closed liquid cooling systems, but it still uses up substantial amounts of water. In traditional cooling systems, water is taken from a local source and warmed water is released back into the environment. This can include chemicals used to clean the cooling systems, which also harm wildlife and impact water quality. Heated water has lower oxygen solubility, which puts stress on aquatic life. Higher water temperature also promotes algae blooms, leading to toxic conditions. (White House Office of Science and Technology Policy (OSTP) 2022)

If air cooling is used instead, nose pollution becomes a problem. Cooling is done by utilizing high velocity fans and while there is no scientific study on the subject, the fan noise is continuous and loud. Noise pollution can lead to stress, cardiovascular problems, and sleep loss in addition to other issues. (White House Office of Science and Technology Policy (OSTP) 2022)

The problem is widespread and on top of the energy used by specialized computers for the cryptocurrency mining, they also need to be kept cool which adds additional energy consumption. Currently the people mining don’t really need to think about the environmental effects past their need for cheap energy to

make more profits. The goal for the future is to make the ones doing the damage pay for the costs as well so that it is part of the consideration when planning the mining process. (Whitt R 2019)

3.9.4 Non-fungible tokens or NFTs

NFT (non-fungible token) is a new type of digital ownership offering security and ownership verification advantages. NFTs are created by mining blockchains supporting NFT transactions creating a unique cryptographic token that can be then attached to digital files of photos, music, videos, or other kinds of digital art as a proof of ownership. Ethereum is currently the most popular blockchain for creating NFTs. The one making the NFT must own whatever art piece they want to make into one. They have been around since December 2020 and got very popular since then selling for various prices and some are even sold for millions of USD. An estimation of buying and NFT artwork shows that it creates the same amount of carbon emissions as one US household in a month. This new craze in cryptocurrency market has many of the artists worried about their environmental impacts and are looking for more sustainable ways to create them. The troubling thing about NFTs is how fast the number of sales is increasing. Sales rose from around $1 billion to $10 billion between Q1 and Q3 of 2021. (Truby J, Brown R D, Dahdal A & Ibrahim I 2022)

3.9.5 E-Waste

E-waste is consumer and business electronic equipment that is no longer wanted. These electronics contain precious metals like gold, aluminum, silver, copper and palladium so there are countless companies and individuals around the world recycling and breaking apart these items to get to the desired materials. However, these electronics also contain toxic materials like arsenic, mercury and lead making them hazardous waste. E-waste problem keeps getting worse as technology is advancing very quickly and new models and innovations are coming out yearly. (Anish K 2020)

This means that not only is the mining process a problem for the environment, but it also creates a lot of waste making an already massive e-waste problem

worse. As technology improves and machines get more powerful there is a constant need to keep up with the competition and replace old models of computers. Newer computers that miners use cannot be used for anything else as they are specifically made for that single purpose, and they get replaced whenever they stop being profitable. (Anish K 2020)

It is possible to calculate how much e-waste Bitcoin is creating by using data provided by Cambridge Center for Alternative Finance. It can be assumed that a device will get replaced once it is no longer profitable. To see when this happens a profitability threshold should be calculated. This will be based on estimated computational power of the entire network in terahashes per second (TH/s), total amount of coins mined a day including fees and energy cost of mining. This gives break-even threshold in Joule per Terahash (J/TH). This way the device will be profitable when its energy efficiency is lower than the break-even energy efficiency of the Bitcoin network. (De Vries A & Stoll C 2021)

To calculate this a price for electricity is needed that was estimated. Additionally, a generic performance adjustment factor of 1,05 as introduced by De Vries in 2020. A power usage effectiveness (PUE) factor of 1,1 was also applied in accordance of Cambridge University's estimate.
The break-even efficiency of the network is then:

$$B = \left(\frac{BTC * M}{p * PUE * PA * 24h}\right) \div (H * 1000)$$

Where:
BTC = network rewards and fees per day in bitcoin
M = market price in euros per bitcoin
p = cost of electricity per kWh in euros
PUE = power usage effectiveness factor
PA = performance adjustment factor
H = estimated network hash rate

Applying the value of B will show the profitability of a crypto mining machine on a specific date. It is possible to find out when each machine became obsolete

because it would cost more to run than the profit it would create. To do that the efficiency of a machine would have to be compared to the history of the Bitcoin network to see when they stop being profitable. That would then give an idea of when the machines were replaced with newer models. The number of machines can be estimated by the hash rate of the network and what the hash rate of a single device is. Then by knowing the weight of a device it would be possible to come up with the amount of e-waste generated. (De Vries A & Stoll C 2021)

Using this method in their study, De Vries and Stoll found out that the average age of a mining machine is between 1,12 and 2,15 years. In addition to this, the growing number of devices used for mining after 2020 has lowered the average lifetime of devices. The computational power of Bitcoin network was roughly 180M TH/S on May 14. 2021. The lowest TH/s possible is 120g, which means the network contained at least 21,45 kilotons of mining devices. Because the network contains a mix of all kinds of equipment, the network has grown from 1 metric kiloton in July 2014 to 39,75 metric kilotons in May 2021. Based on the weight of the machines it would amount to around 2,9 million devices mining Bitcoin. As the lifetime average of a device is calculated to be 1,29 years the e-waste generated by Bitcoin would be 30,7 kilotons per year as of May 2021. According to a new report by the White House, e-waste generated from Bitcoin mining is 35000 tons per year as of June 2022 (White House Office of Science and Technology Policy (OSTP) 2022).

Below figure 7 is showing the amount of e-waste generated by Bitcoin in kilotons over the years as well as the average 7-day hashrate and active mining equipment. (De Vries A & Stoll C 2021)

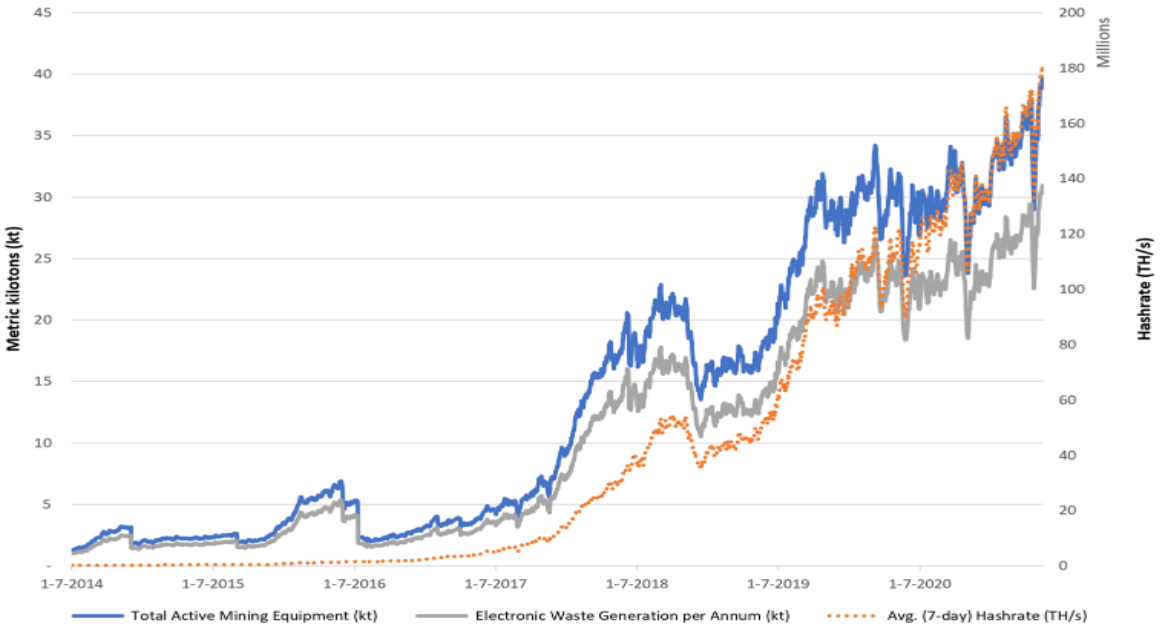


Figure 7. Bitcoin electronic waste, hashrate and active mining equipment. (De Vries A & Stoll C 2021)

E-waste is a huge environmental problem that people might not be very aware about yet as the worst of it is out of site in developing countries. There is a lot of talk about different kinds of waste and recycling, but a lot of the used electronics end up in developing countries where they are broken apart and anything valuable is extracted and the rest is burned. The developing countries do not have the right tools to break apart these machines safely. The sites in Ghana Africa where electronics are being dismantled, a study made by UK found that the soil there had over 100 times the amount of mercury, arsenic, lead, cadmium, and chromium that the other nearby areas. Despite there being laws in place that prohibit the export of broken electronics to these countries it still happens. The countries that are mostly affected are China, India, countries in Africa and some other areas like Taiwan. (e-Life 2018)

3.10 Different cryptocurrencies environmental impacts compared

The energy used to mine cryptocurrency is enormous but there are differences between them, which tell that there are things that can be done to decrease the emissions created. The main reason for the high energy use is each transaction where cryptocurrency is used and the mining for new coins. (Knutson T 2022)

Sometimes it can be hard to compare cryptocurrencies to each other simply because the scale is so different between them. Bitcoin uses huge amounts of energy compared to a smaller coin because of the number of transactions happening each day. If the smaller coin grew as big it might be just as bad environmentally.

House Energy and Commerce Committee Chairman Frank Pallone (D-NJ) said that “The energy required to validate just one Ethereum transaction could power a U.S. home for more than a week, the energy required for a Bitcoin transaction could power a home for more than 70 days”. (Knutson T 2022)

There are also big differences between CO2 emissions of cryptocurrency transactions. The combined emissions of Ethereum and Bitcoin create the same amount of CO2 than 15,5 million cars. However, Ethereum transaction adds 40 kg of CO2 when Bitcoin adds 453 kg of CO2. The difference is that Ethereum uses a different kind of blockchain called Proof-of-Stake (PoS), which uses as much as 99,99% less energy than the Proof-of-Work (PoW) blockchain used by Bitcoin. (Knutson T 2022). PoS works differently in a way that instead of having everyone compete solving puzzles with computing power, it gives the puzzle to one system randomly to solve. Each one wanting to have a chance of getting picked will stake 32 Ethereum for one chance with multiple stakes increasing their chances to get picked. The one validating the transaction will get their stake back with the rewards. This saves huge amounts of energy as only one system is working on a puzzle at a time but there are concerns of the people with most ETH have more power over the system making it less decentralized and equal. (Truby J, Brown R D, Dahdal A & Ibrahim I 2022)

There are also differences between different PoW blockchains. Some of them are made to resist the more powerful ASIC machines making solving the algorithms take mor energy than would be expected for their market share. There are some coins that are trying to be more environmentally friendly in other ways as well. SolarCoin markets itself as being verifiably produced by solar power. Stellar network uses a few trustworthy nodes for its consensus protocol. This helps keep the energy use lower since the whole network is not working on the problem.

IOTA uses Fast Probabilistic Consensus in which nearby nodes to quickly come into agreement whether transaction is legitimate. This uses even less energy than some established financial networks like VISA uses. Holochain is unique in a way that it does not require mining for HoloTokens to be awarded. They are given in exchange for hosting hApps on computers and each user provides computing and storage to the network. There are over 10000 different cryptocurrencies, and many have found their own solutions to the energy problem. There are also many small coins using Proof-of-Stake but as they only hold a small market share their impact on the total crypto created emissions is not very big. As long as Bitcoin keeps using its current method for mining the total energy consumption of the market will stay enormous and keep growing larger. (Matthews L 2022)

Below Figure 8 shows an estimate of yearly energy consumption of some of the cryptocurrencies compared to an average US household. (Crypto Carbon Ratings Institute (CCRI))

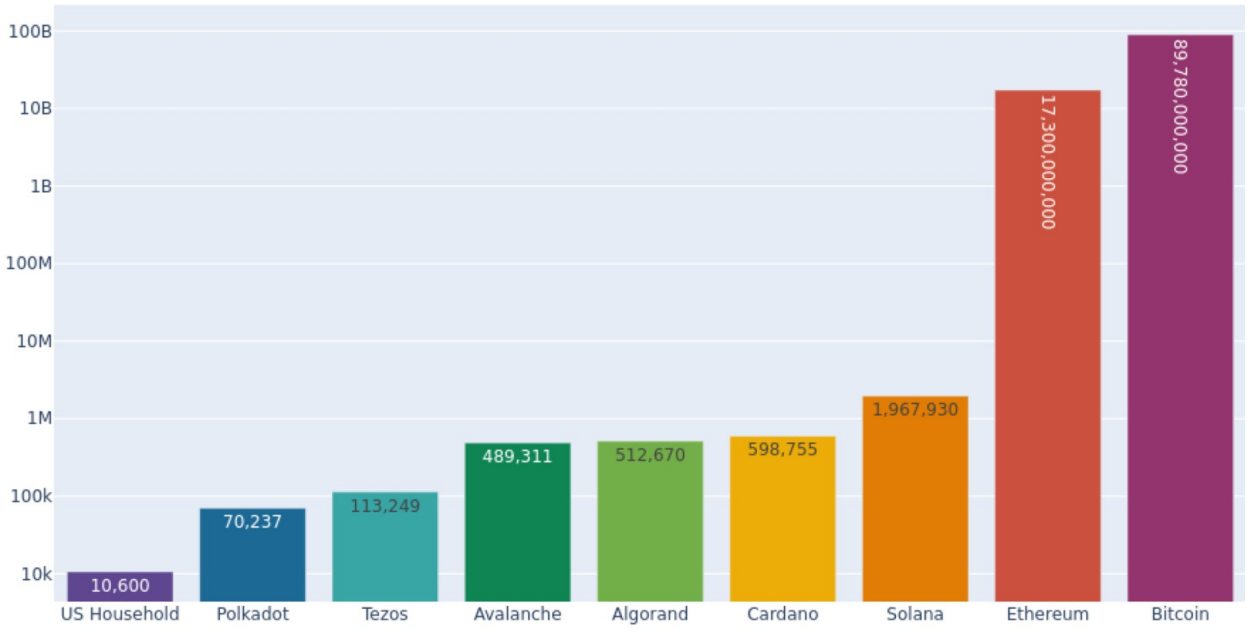


Figure 8. Yearly energy consumption of currencies compared to US household. (Crypto Carbon Ratings Institute (CCRI))

From this figure we can see that Bitcoin is the most consuming cryptocurrency, but lately Ethereum has been catching up due to the trend of creating NFTs by mining Ethereum.

Figure 9 below, shows how much energy in Wh each transaction takes. It compares some of the biggest cryptocurrencies and Visa transactions.

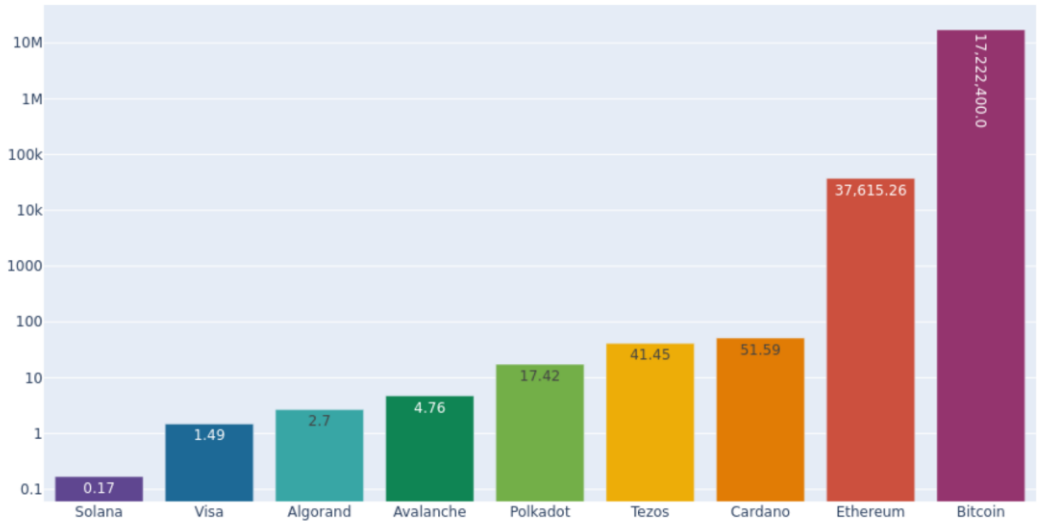


Figure 9. Electricity consumption per transaction in Wh (Crypto Carbon Ratings Institute (CCRI))

In this figure Bitcoin is ahead by a larger margin, because of only utilizing PoW validation method. Ethereum is still high as well because NFT transactions consume more energy. Most smaller coins are using a validation method that does not consume as much energy as PoW. This comparison gives a good picture of how energy expensive transactions are without taking the size of the network into account. More popular blockchains are always going to be more energy consuming however, due to needing equipment that is powerful enough to stay competitive. Less popular currencies have smaller networks and less competition.

3.11 Utilizing waste heat energy

The process of mining Bitcoin generates a lot of heat energy. Most of it is not being utilized in any way, instead it is just released into the atmosphere or back into water bodies. The primary challenge is finding effective ways to capture the heat and transfer it to be utilized. Being able to re-use waste heat could

compensate some of the energy consumed by mining and the generated carbon emissions. (Kuhn D 2021)

There could be potential safety issues with using ASIC machines as heaters since they were not designed for that and did not pass any heater related safety tests. Instead, some bitcoin miners like Heatbit were designed as heaters. Heatbit sells for 1150 USD and can heat up to 16 square meters while mining bitcoin using 1300W. (Donovan K & Stewart M 2022)

Almost all waste heat could be captured and utilized. In air cooled servers, the heat can be recovered from the return air flow between 25 °C and 35 °C. In liquid cooled systems, waste heat could be captured from 50°C to 60°C. Liquid cooling systems allow the heat to be received closer to CPUs (central processing unit) where temperature from operating is higher. A typical CPU has an upper limit of processing temperature of 85°C. Waste heat can be captured at a higher temperature compared to air cooling systems because of liquid's better heat transfer properties. Waste heat could also be collected from chilled cooling water at around 10-20°C. (Wahlroos M, Pärssinen M, Rinne S, Syri S & Manner J 2018)

Waste heat can be utilized in multiple different ways and not all of them require investing into connections to direct heating network. Some utilization for mining facility's own use include heating the premises, hot water and melting snow. Space heating is the easiest use for waste heat, but the need for it is highly seasonal. Waste heat can also be utilized in outside uses like selling it to heating network, using it for drying processes at 60°C. electricity production is also possible, but the conversion rate is very low making it less realistic as an option. (Wahlroos M, Pärssinen M, Rinne S, Syri S & Manner J 2018) Globally electric space heating uses over 600 TWh a year, which is three to four times more than Bitcoin mining. If some of the heating could be done by the existing mining instead that would lower the total electricity consumed. (Donovan K & Stewart M 2022)

While heating with energy produced by cryptocurrency mining has been happening around the world on a small scale for a while now but it is still a new thing. In Canada a crypto miner called MintGreen is working with Lonsdale Energy Corp. to use the waste generated from mining to heat the city of North

Vancouver, British Columbia. It will be the first city in the world to be heated by Bitcoin. Doing this will prevent 20000 tons of greenhouse gasses per megawatt from being released into the atmosphere. They will start providing heat in winter 2022 and recover 96% of the electricity they use as heating for industry and communities supplying around 100 buildings. They use a water-based cooling system that captures the heat into water that can then be used for heating. (Ashraf A 2021)

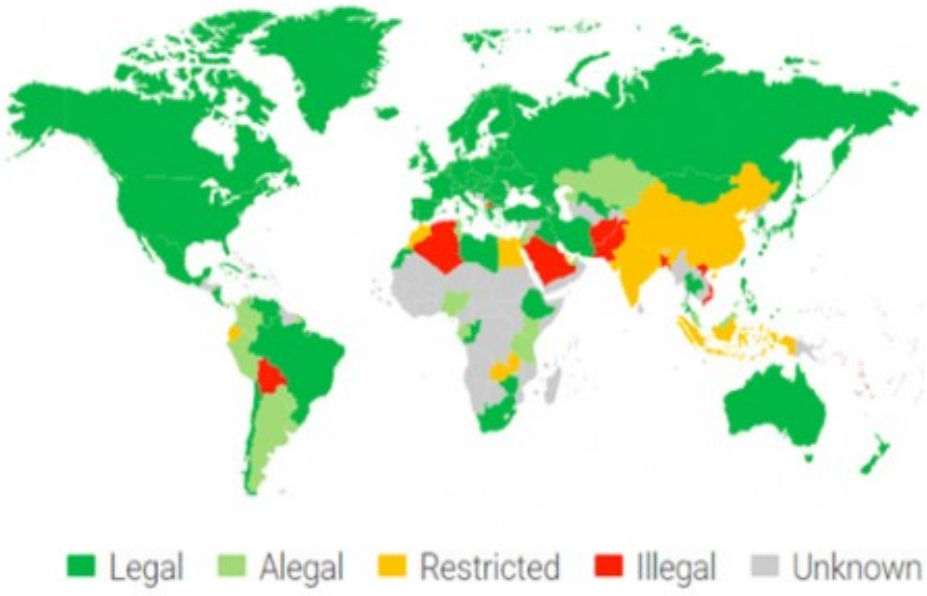
There are some issues with utilizing waste heat as well. This includes the low quality of the waste heat as well as low demand for it. Needing additional heat production in addition to utilizing waste heat. High investment costs and infrastructure being inconvenient. Revenue outcome being unreliable. If the waste heat was distributed by linking into the direct heating network, the source would have to be close as connection fees increase with distance. The best revenue options from selling heating would be in areas that only have access to expensive heating options. Wase heat utilization is not really an existing business model at the moment. In cases of renting the mining facility space, the points of utilization for waste heat might be included in the rent, making collecting waste heat less appealing. Collecting waste heat also increases operating costs because of the equipment used for collection needing energy and maintenance. (Wahlroos M, Pärssinen M, Rinne S, Syri S & Manner J 2018)

Selling waste heat into the direct heating network would be the most efficient option but the networks are not obligated to implement waste heat into their networks. Investment into waste heat recovery must be profitable and cover initial set up costs in a reasonable time to become something cryptocurrency miners would be willing to implement. If waste heat is to be utilized better in the future, there needs to be further development of the business model.

3.12 Cryptocurrency legislation

Legality of Bitcoin has always been a challenge and tax revenues from mining are incentivizing nations to keep regulations at a minimum. There are several propositions for legislation to restrict Bitcoin mining but there are issues with categorizing the new laws under money and financial assets. Some countries

have made their own decisions regarding the legality of Bitcoin. Legislation on Bitcoin are meant to both regulate it and at the same time make it more legitimate as a currency. Below Picture 4 shows the legality of Bitcoin around the world. (Badea L & Mungiu-Pupazan M C 2021)



Picture 4. Legality of Bitcoin. (Badea L & Mungiu-Pupazan M C 2021)

Germany for example does not recognize bitcoin as a valid currency, but it does allow it as an accounting unit. Germany taxes Bitcoin revenue by 25% if revenue was obtained within one year of getting the bitcoin. In Bulgaria the tax rate for bitcoin is 10%. Czech has a law where identification is required to exchange virtual currency. They also proposed to add VAT (value added tax) to virtual currencies. In Denmark only companies' Bitcoin transactions are taxed. Slovenia decided that Bitcoin is taxed depending on circumstances as either trade or mining profit. Romania has a specific law for sale of virtual currencies, and they get taxed if they exceed a certain annual revenue limit. (Badea L & Mungiu-Pupazan M C 2021)

In the United States, bitcoin is allowed to be used as payment in e-commerce, many restaurants, hotels, and stores in many of the states. Some US states have more restrictions on the use of Bitcoin, such as New York, New Hampshire, Connecticut, Hawaii, Georgia, North Carolina, Washington, and New Mexico, while in Texas, Kansas, Tennessee, South Carolina, and Montana the

environment is conductive to heavy use of Bitcoin. In 2015, New York introduced a licence that would be required to enter the cryptocurrency business. Japan made cryptocurrency a valid payment method in 2017, which led to increased interest in Bitcoin in the country. (Badea L & Mungiu-Pupazan M C 2021)

China banned financial institutions from trading using bitcoin, but individuals were still allowed to use it. Bitcoin is considered illegal in: Russia, Vietnam, Bolivia, Ecuador, Colombia, Saudi Arabia, and Northern Africa. (Badea L & Mungiu-Pupazan M C 2021) Canada and Australia have recently put laws in place to try and counter money laundering using cryptocurrency. Many countries view the technology as potential and are trying to attract companies to develop it further. Many countries are also currently developing their own digital currencies. (Riley J 2021)

At its peak 90% of cryptocurrency transactions and 75% of all crypto mining was done in China. This was due to low power costs, local miner equipment production and cheap labour. After the financial institution ban in 2013, the issue was considered again in 2017 when China banned coin offerings and cryptocurrency exchanges. This led to a temporary drop in the price of bitcoin but despite the ban, transactions remained active. China is working on creating the world's first digital currency that would be backed up and controlled by a central bank and have made cryptocurrency inheritable by law in 2021. (Riley J 2021)

China's ban of cryptocurrency mining in 2021 led to many leaving the country to continue mining elsewhere, which has actually made the situation worse. A lot of bigger crypto miners in China used hydro power during the wet season because it was the cheapest option. Now that they have moved to the US and Kazakhstan, they have started to use natural gas and coal for energy instead making it even less environmentally friendly. China made the decision after an energy crisis in 2021 justifying it by saying that virtual currency related business is illegal and endangers people's assets. (Fan S, Gyllensvärd E, Farkas E & Schutzner J 2022)

In New York a bill has passed in April 2022 to try limit cryptocurrency mining done burning fossil fuels. It is first of its kind in the United States and if it becomes law, it will limit fossil fuelled plants mining Proof-of-Work blockchains by having a 2-

year moratorium on air permit renewal and new permits. This would not affect pending applications from companies like the one Greenidge has made. Some are worried that because there is nothing tying crypto miner to New York thy will just move elsewhere instead of looking for alternative energy sources. (Hill M 2022)

Plattsburgh municipality in New York has a monthly limit on the amount of energy the city can use. The Bitcoin miners in the city made then exceed that limit and made utility bill rise by 30 to 40% for everyone heating their homes with electricity. City then imposed a new regulation that would have crypto miners recycle a part of their heat energy waste. The new regulation made mining companies relocate to another area with less regulation. (Mernit J L 2022)

Also, in late 2021 Iceland's national power company Landsvirkjun started to deny power to new miners. Iran has also banned crypto mining due to it overtaxing their energy grid first for four months in May 2021 and then again in December the same year. (Mernit J L 2022)

Some citizens of Texas are worried about the increasing energy prices and the cost of upgrading the local energy grid to meet the constantly increasing demands from mining companies. The price for electricity has already gone up by 70% from what it was a year before. In winter 2021 the grid was overloaded during a snowstorm that caused more than 4 million homes and companies to be without electricity. Hundreds of people died from being exposed to the cold or medical equipment failing during the blackout. Electric Reliability Council of Texas gives credits to miners that shut down their processes when grid is being overworked but they are not yet limiting their energy use in any other way. There are no current plans to make legislation for the mining industry that keeps growing in Texas. (Mernit J L 2022)

3.13 Future of cryptocurrency mining

Because cryptocurrency miners have already invested into hardware and infrastructure it could be difficult to change it into something more sustainable.

There are only a few regulations in place for mining cryptocurrencies but there are projects trying to reduce the carbon footprint. Sources of energy for Bitcoin mining have been mainly fossil fuels with renewable energy slowly getting a bigger share. Below figure 10 shows of energy sources used for Bitcoin mining in 2021. (Chamanara S, Ghaffarizadeh A & Madani K 2021)

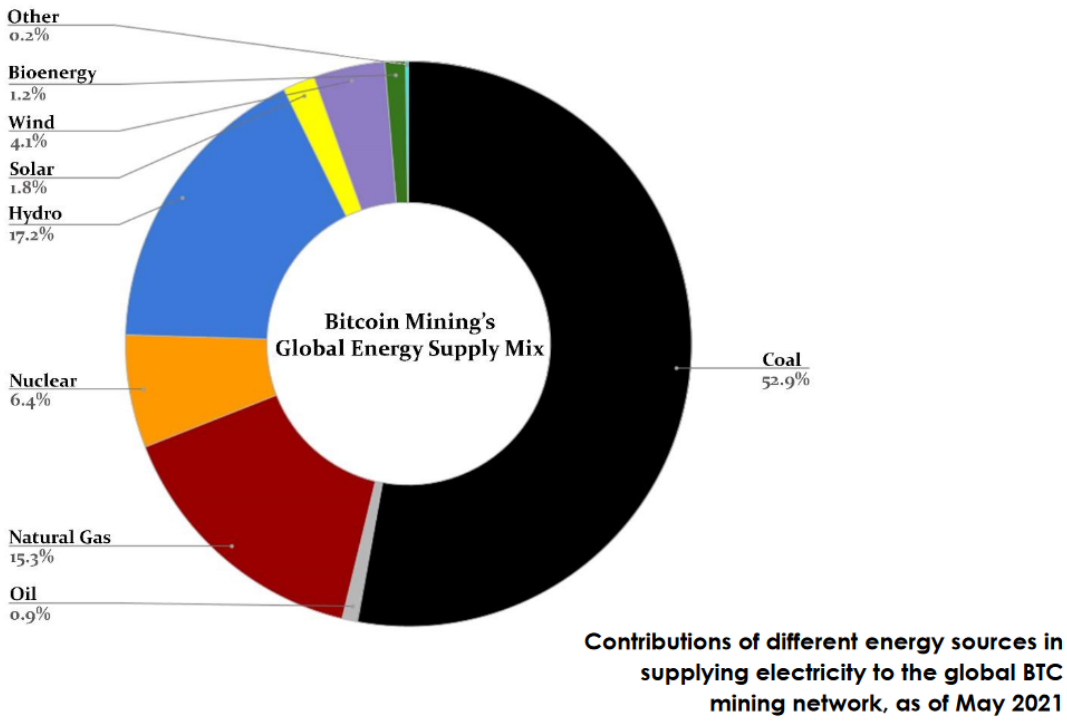


Figure 10. Energy sources of Bitcoin mining. (Chamanara S, Ghaffarizadeh A & Madani K 2021)

Over 50% of energy used to mine Bitcoin has been from coal, mostly because it is still widely used in China, where many of the big mining facilities are. One idea to increase renewable energy used for Bitcoin mining is a proposal called Bitcoin clean energy initiative. This proposal wants to combine renewable energy production and storage with mining projects. They are claiming that this way, it would be possible to increase profitability of solar and wind energy as miners would use excess energy that would not be used otherwise. However, critics are calling this wishful thinking because it is not clear how it would be beneficial to the miners, and if they would follow the new proposal to only use excess energy. (Köhler S 2021)

There have been propositions of regulating mining equipment to have at least a certain level of energy efficiency. There are potential issues with this idea because regulating mining machines would be more likely to increase the hashrate. More powerful and efficient machines are capable to compute more terahashes per second, leading to everyone having to replace their equipment to stay competitive. Then on top of the generated technology waste, there would a shortage of machines, as microchip shortage limits the production of computers. (Köhler S 2021)

Some energy companies have developed ways to use methane created by oil and gas drilling to power crypto mining. This would be good for the environment as currently the gas is being vented or flared releasing gasses into the atmosphere. Currently 4% of global methane production is being wasted to flaring and venting. It is not utilized currently because of the high costs of setting up a network of pipelines or energy transmission. Mining facilities could be more efficient in converting methane to CO2. There could be other similar opportunities to use energy that is currently going to waste as side produce of other industries. (White House Office of Science and Technology Policy (OSTP) 2022) However, there is an argument to be made that being able to use side products of a harmful industry is incentivising keeping it around instead of moving away from oil and gas mining to something more environmentally friendly.

Another way to use energy as efficiently as possible might be having mining facilities located right next to the energy source thanks to their geographical flexibility. This way they could utilize sources that would otherwise suffer from transmission problems. It can also be beneficial to build mining facilities near areas where renewable energy sources produce more energy than they are using, like some areas that produce solar power, making energy production more profitable in these areas. (Kemp B, Samaties P, Sanaulla F & Vaughan C 2022)

With renewable energy suffering from fluctuating demand crypto miners would be an optimal customer. They are not limited to certain times of operation and their energy needs are flexible, mining requires short spurts of high energy, making shot term overproduction and occasional lower availability of energy ideal. Often energy production companies offer a discount to customers willing to lower their

energy usage at certain times. This demand response saves money for both the customer and the producer making it an ideal situation for cryptocurrency mining in both economic and environmental fronts. Some energy companies are even using their own excess energy to mine Bitcoin themselves. Companies providing mining services make direct deals with energy providers to use their excess energy for mining. (Kemp B, Samaties P, Sanaulla F & Vaughan C 2022)

Cryptocurrency mining also has potential to help local areas with stabilizing their energy grids. Mining facilities can take up the excess energy and lower their energy usage as needed making the whole grid run more smoothly.

There are also potential issues of increased energy demand from cryptocurrency mining in the future. If a local energy grid cannot handle the extra demand, there is a possibility of power outages happening. Countries like China, Iran and Turkey have already regulated or banned crypto mining. Miners are also highly mobile, and it is a volatile market that can change at any time. There is a risk of miners leaving before the costs of building a new energy facility have been covered, making building new infrastructure to provide for them extremely risky. The risks can be mitigated with long-term purchase obligations and prepayments, but miners are reluctant to commit to something that will commit them into anything long term in a volatile market. (Kemp B, Samaties P, Sanaulla F & Vaughan C 2022)

While it will be hard to put regulations in place for a decentralized network like the Bitcoin blockchain, it can be done in many ways. The question now just is which ones will be implemented in the future.

4 DISCUSSION

In this thesis, the mining process of Bitcoin was examined. The needed equipment and space required were also studied. The amount of energy consumed was estimated and further estimation were made on how large portion of it was renewable. General environmental impacts of cryptocurrencies were estimated first. Bitcoin was focused on as it is the largest cryptocurrency and for that reason it contributes most to environmental issues. Bitcoin was compared to other cryptocurrencies to get a comparison of how different operating methods affect environmental effects. Some of the energy consumption could be compensated by utilizing waste heat generated by mining as massive amounts of energy is used for heating. Cryptocurrencies have been under a lot of scrutiny recently and there is need for more regulation. Propositions and ideas for the have been brought that would make cryptocurrency mining more environmentally friendly.

To make sure the information presented in this thesis is reliable, the reliability of sources used were considered. Gathering information can prove difficult due to the nature of blockchains as decentralized networks. Current studies have been able to closely estimate the true scale of environmental effects. Much heavier regulations are needed to get a fully transparent picture of cryptocurrency mining.

Bitcoin is currently being mined using a very energy inefficient method of validating transactions in a blockchain called Proof-of-Work (PoW). Methods like Proof-of-Stake (PoS) consumes 99,99% less energy than PoW and it could be used for the Bitcoin blockchain instead of the current method. In a PoW blockchain like Bitcoin network, every miner node is competing against each other to solve a hash code first to get a nonce and win the reward for validating a transaction. Only one node will get the bitcoin reward for doing the work and every other node, that used energy to try and get the nonce first, ended up wasting the energy. This repeats every 10 minutes when a new block is generated in the Bitcoin blockchain. PoS method allows only one node to work on a block, eliminating the waste of energy resulting from work being done for no reward.

Bitcoin mining facilities can consist of thousands of miners which creates problems beyond just the energy consumption. They need space, create noise, and take water to use in cooling systems for mining equipment. Application-specific integrated circuit (ASIC) miners have shorter life spans when compared to regular technology. Crypto mining is a constant arms race and new machines, and algorithms are being developed constantly. ASIC machines are very specialized and cannot be used for anything else than what they were programmed for. They are inflexible and need to be replaced if a new model is developed that outperforms the older models. Because PoW is up to luck, the computers need to be able to produce as many hashes in as little time as possible while using as little energy as possible. Even slight improvements in the algorithm create huge competitional advantages in facilities with thousands of machines working to solve the same problem.

The most important thing for cryptocurrency sustainability is to move away from PoW as a validation model. Even when renewable energy is used, it could often be used for other purposes. It is hard to compare the necessity of Bitcoin to other business models, but some optimization of utilizing assets should be done. In some areas there has been a need to open old fossil fuel power plants to keep up with energy demand. In some places the energy consumption of Bitcoin has caused electricity grids to be overloaded resulting in blackouts with sometimes catastrophic consequences. It can be argued that Bitcoin mining has increased the demand for new renewable energy sources, resulting in new renewable energy networks being created that otherwise might not have been. However, the demand for energy keeps growing from other sources as well and crypto mining cannot be given credit for transition into using renewable energy sources. Over half of the current Bitcoin mining is done using non-renewable energy sources. Most of the energy currently being used would not be needed at all if the validation method of Bitcoin was changed to something else.

Bitcoin also creates relatively huge amounts of carbon dioxide (CO_2) emissions from each transaction. Each transaction creates 453 kg of CO_2, which is comparable to heating an average US household for 70 days. Bitcoin has an estimated annual carbon footprint of 83,44 megatons of CO_2. It has been predicted that Bitcoin could be pushing the climate change over the 2 degrees

Celsius limit if nothing is changed. The way Bitcoin is currently wasting most of the energy it consumes is not in line with the global climate goals and something should be done on a global scale. Because of the nature of the blockchain network, localized restrictions will not be effective as miners will just move to a location that does not have legislations in place.

The new craze of non-fungible tokens (NFTs) have increased cryptocurrency related emission even further. So far it is mostly due to Ethereum mining as it is the most popular blockchain supporting NFT transactions. NFTs have great potential as digital proofs of ownership that are like fingerprints and cannot be copied or stolen. Currently NFTs are mostly used as proof of ownership of digital art and other media. There is great potential to use NFT technology for other identification purposes in the future, but something needs to be done about the emissions each transaction generates. NFT popularity has exploded in the past year, and something should be done before the damage emissions cause get out of hand. It is likely that blockchain technology is going to be inspiring many other new technologies in the future and regulations are going to struggle to keep up with the speed of development.

Electronic waste is another huge issue that is not only caused by cryptocurrency mining, but the added unwanted technology from it is only aggravating the problem. Technology is known for getting outdated very fast as new systems are being developed very rapidly. People are conditioned by technology industry to keep upgrading their devices, even when there was no real need to do so yet or the improvements are very minor. The problem is that ASIC miners that are most commonly used to mine cryptocurrency by all who want to stay competitive, have even shorter life spans than most other devices. Some miners are replaced after only a few months of use, but the average is a few years. ASIC miners can only be used to mine specific blockchains they were developed for and because they were made specifically for cryptocurrency mining, they cannot be used for other purposes either. There are other more flexible options like field-programmable gate array (FPGA), but they charge a fee for using their algorithms and are less efficient and not as powerful as ASIC. ASIC machines should have a better recycling program and their producers could design the miners in a way that parts

of them could be repurposed. E-waste creates all kinds of issues due to containing toxic materials and heavy metals making recycling a difficult process.

Bitcoin farms like any other datacenters have to use some kind of cooling systems to stop their equipment from overheating. These miners run around the clock and need constant cooling. Most effective way is to use liquid cooling systems as liquid has a higher heat capacity than air. The issue is that the water needs to come from nearby natural water sources, and it is released back warmer than it would naturally be. The released waters can also contain chemicals and lead to decrease in water quality.

The heat energy from cooling systems could be collected and utilized instead. However, there is currently no business model for utilizing waste heat. Most people doing so are only using it for personal needs with some recent development trying to use waste heat to heat up homes in parts of a city. For cryptocurrency miners to invest in equipment needed to extract waste heat, they would need a return for the investment. Connecting into local heating networks is expensive and those networks don’t have to receive or utilize the waste heat they receive from mining facilities. One option to incentivize waste heat collection could be covering some of the costs of the equipment or making a deal with the local heat distributor to have them pay for the equipment and receive waste heat to cover the costs. The problem with this is that Bitcoin miners are not happy to be tied down to a certain location for extended periods of time. Cryptocurrency markets are highly volatile and profit margins change all the time. Also, miners are trying to avoid restrictive legislations by moving to other locations and they cannot do that if they have contracts binding them into providing heat energy. This is also the problem with building renewable energy networks specifically for cryptocurrency mining.

The most likely and realistic scenario would be that a mining facility could be taking up excess energy from the grid and use renewable energy to power their mining. The miners however would not like long and unanticipated downtimes in mining as they would lose money without being able to plan around it. It is likely that they would also be connected to the local power grid and use that for energy

when renewable energy source has fluctuations. Hydro power would be ideal with its reliability, but it is not always possible.

The only way to stop miners from relocating to avoid laws is to have some global agreements in place, but that is not very realistic to happen. Some nations are trying to attract mining operators with minimal legislations in order to gain tax revenue and in hopes to develop the technology further. Getting even nationwide legislations in place takes time and usually they only happen after cryptocurrency mining has gotten to the point where it causes severe problems in the county. Most nations where mining is illegal have suffered an energy crisis leading up to the laws being put in place.

Some things to limit crypto mining could be increasing electricity price when its used for mining, taxes, carbon offsets, banning non renewable energy sources to be used for mining operations and banning currencies using environmentally unfriendly methods, other ways to compensate environmental impacts and taking up water or land space.

Future studies on this subject will need to research more about the total cost of cryptocurrency mining on the environment. The existing studies focus too much on carbon footprint and not enough on the other issues created by the mining processes. Life-cycle assessments of cryptocurrencies should be studied more. There is a need to develop waste heat utilization further and make it into a profitable business model. With Bitcoin eventually getting mined out, there is a need to look into cryptocurrencies as a whole and prepare for future developments of the blockchain technology.

So, to answer the question of whether Bitcoin can become more environmentally friendly, the answer is maybe, but it is not very likely in the short term. Miners have invested too much into the current network and are not willing to transition into using other methods. Instead of focusing too much on just Bitcoin, the question now should be what can be done to make cryptocurrency in general more environmentally friendly.

This thesis should be considered to be successful in what it was meant to accomplish. The aim was to bring more attention to an issue that is overlooked by many as it is not very visible. Many opinions about Bitcoin are biased or focus on only some aspects of it and this thesis set out to collect a more complete set of information on the situation today. Bitcoin is being mined all over the world in non-disclosed locations with minimal regulations in place that would limit its environmental impacts. The goal for the future is to have awareness and knowledge of the situation and what could be done to remedy and compensate the harm that has already happened and will keep happening. It is unrealistic to find a perfect solution, but some kind of balance could be achieved. Cryptocurrency was ground-breaking for technology development and new applications for systems designed for it are going to keep being discovered in the future. Hopefully there can be a way for it to happen in a sustainable way.

4.1 Research limitations

The information online is limited to more general information on most sources. It is harder to find anything too detailed related to energy consumption of mining facilities as they do not release specific information. Cryptocurrencies are still very recent, and the situation keeps shifting and evolving very rapidly. Values of different currencies fluctuate, and technology goes old fast and new inventions are made. Most of the information even online is already outdated and anything that would be printed on paper or available in physical books would be very old and not relevant anymore apart from some general information.

Many sources of information repeat the same things but have different results on the same research, because the results depend on speculation in many areas. This makes securing the most accurate data harder. Many of the areas trying to find out the environmental impacts have to use estimates to get to conclusions as there is no mandate for anyone to tell what they are using to mine, what they are mining and even where they are. These things can be estimated to pretty precise estimations, but they are still estimations as long as no transparency is necessary, and it is in miners' interest to hide what they are doing. Larger mining operations are harder to hide so there is more information on them, but because

they can move to areas where legislation and regulations are minimal, it can be hard to find the full extent of their operations.

Results of the research are limited in trying to see where the technology will go in the future. This makes any predictions for the future to be just assumptions based on the current situation. The future cryptocurrency environmental impacts might be greater or lesser than the estimations of what they are today. Results of studying the subject get varying results depending on multiple variables and no matter how accurately they are estimated, they are still estimations. Results of the research are limited by the information that is reliable and available to be studied.

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