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Mapping the Impact of Proof-of-Work on Cryptocurrency Regulation

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Table of Contents

Dedications

This paper is dedicated to my Uncle Dennis Brian Franks, my academic inspiration, and loving father and husband, thank you for filling the world with your presence and knowledge, it will never be forgotten

To Mary-Ann, Annette, Michael, and Jacob, I could not have started or finished this journey without your unwavering support, I am forever grateful

List of Figures

Figure 1. Bitcoin’s Annual Energy Consumption Compared to Energy Consumption by Country Ranking

- Digiconomist, 2022. Bitcoin Energy Consumption index. *Digiconomist*. Available at: https://digiconomist.net/bitcoin-energy-consumption [Accessed June 11, 2022].

Figure 2. Figure 2. Historic Bitcoin energy consumption estimates and price development

- de Vries, A., 2021. Bitcoin boom: What rising prices mean for the network’s energy consumption. *Joule*, 5(3), pp.509–513.

Figure 3. Bitcoin’s Energy Consumption Increase from 2018 – 2022

- Digiconomist, 2022. Bitcoin Energy Consumption index. *Digiconomist*. Available at: https://digiconomist.net/bitcoin-energy-consumption [Accessed June 11, 2022].

Figure 4. Industry Implementation of Renewables into Hashing Energy Mix

- Blandin, A. et al., 2020. 3rd global cryptoasset benchmarking study. *SSRN Electronic Journal*, pp.1–71.

Figure 5. Energy Profile Mix of PoW Mining by Region

- Blandin, A. et al., 2020. 3rd global cryptoasset benchmarking study. *SSRN Electronic Journal*, pp.1–71.

Figure 6. Comparison of Mining Devices and their Energy Consumption

- Vranken, H., 2017. Sustainability of Bitcoin and blockchains. *Current Opinion in Environmental Sustainability*, 28, pp.1–9.

Figure 7 Carbon Intensity of Region by Countries with mining operations

- CoinShares. 2022. *The Bitcoin Mining Network*. [online] Available at: <https://coinshares.com/research/bitcoin-mining-network-2022> [Accessed 11 June 2022].

Figure 8. Carbon Intensity of North American Regions with mining operations

- CoinShares. 2022. *The Bitcoin Mining Network*. [online] Available at: <https://coinshares.com/research/bitcoin-mining-network-2022> [Accessed 11 June 2022].

Chapter 1: Introduction to the Evolution of Cryptocurrency Mining

Today Cryptocurrency has amassed over 1.2 trillion USD in market cap (CoinMarketCap, 2022), making it one of the fastest growing industries to date (Coinslate Database, 2022). Nakamoto's white paper in 2008, that created a decentralized digital currency through a distributed database, has sparked a revolution of payments without need or use of financial intermediaries. As of today, over 295 million people worldwide (roughly 3.9% of the world's population) hold and have used varying amounts of cryptocurrency (Crypto.com Annual Report, 2021). Widespread adoption of cryptocurrency amongst private users has spawned a massive, interconnected network of users, miners, and has evolved its market to use of third-party intermediaries. Together miners, exchange platforms, and users participate in collaborative efforts to ensure the decentralized nature of the currency remains in tack. Miners must validate the user's transaction data, exchange platforms deal with pricing and Initial Coin Offerings (ICOs), and users make use of the network by sending payments to other users. Marinating this structure requires a massive number of resources. Today's cryptocurrencies are significantly dependent on the energy demands of the network to facilitate the processes (de Vries, 2018). Energy demands are interconnected to individual blockchains and coins, which vary heavily between computational methods known as consensus algorithms. One of such is the proof of work (PoW) algorithm has found itself front and center in academia and media spotlight. The PoW consensus algorithm and its protocol is the underpinning operation to the world's two largest cryptocurrencies, Bitcoin (BTC) and Ethereum (ETH) (ETH operates two parallel blockchains, one on PoW and another on Proof of Stake). PoW's protocol has been at odds with its inherent lack of efficient resource use (Stoll, Klassen, & Gallersdorfer, 2019). In fact, PoW is designed to be energy inefficient or "power hungry" for the purpose of preventing fraudulent activities by bad actors (Howson & de Vries, 2022). Despite the academic consensus that the PoW consensus algorithm is energy inefficient, there is no governance consensus on how mitigate what has been describe as *cryptodamages* (Goodkind, Jones, & Berrens, 2020).

As states begin to experiment with their own digital currencies, regulators are still asking the question how they should classify the asset. Cryptocurrency's decentralized nature has netted an extremely volatile asset that has sounded the alarm bells for regulators where others have been unbothered. Due to this nature, external threats to sovereignty and control of monetary and fiscal policy have been associated with cryptocurrency's adoption. This mass adoption of cryptocurrency around the world has prompted a variety of state lead actions from central banks. Central banks such as the People's Bank of China (PBOC) have spawned and rolled out their own digital currency the Digital Yuan. China hopes to integrate the blockchain technology into infrastructure to make vital upgrades to transportation and energy efficiency (Pessarlay, 2022). Rollouts of state-owned digital currencies are defined in technical terms as a Central Bank Digital Currency (CBDC). As of today, 10 central banks have either implemented or are developing their own CBDC, totals 87 countries (CBDC Tracker, 2022). Cryptocurrency's decentralized architecture has caused regulators difficulty in their efforts to control the digital currency because it does not fit into traditional security regulations (Xie, 2019). The rise of the cryptocurrency has caused degrees of concerns over threats to monetary control and has escalated socio-environmental risks through activities of mining.

Cryptocurrencies that operate under the PoW consensus algorithm require miners to validate transactions into "blocks" and in turn will receive transaction fees and a predetermined number of coins set by market prices and remaining number of coins to be mined (Hossin & Hosain, 2018). Some cryptocurrencies like Bitcoin have finite supply of coins (21 million) and others such as Ethereum do not. PoW does not dictate blockchain formation but does dictate production of coins and therefore how blocks will be added to the blockchain. PoW mining specifically can be linked to energy-intensive demands that could hinder a given state's ability to meet Sustainable Development Goals pertaining to carbon neutrality (Mora et al., 2018). PoW protocols have resulted in mining operations for popular coins such as Bitcoin, which have been emphasized as a sizeable contributor to the negative environmental externalities. Bitcoin energy consumption alone is rivaling top energy consuming countries yearly demands (Bitcoin Sustainability Index, 2022). This can be seen in the figure below.

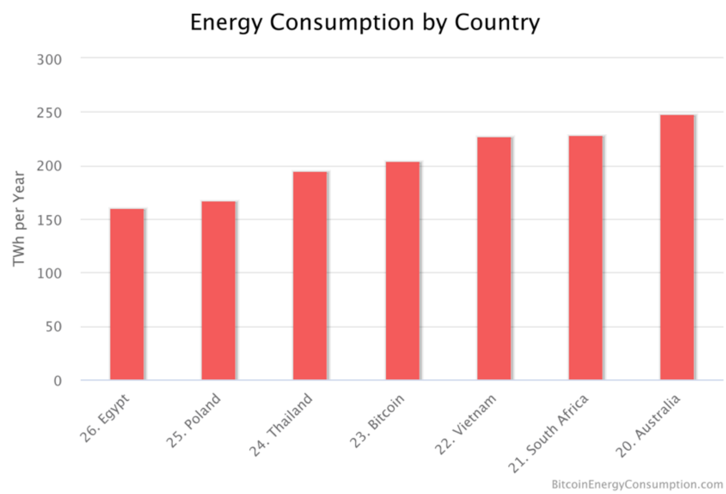

Figure 1. Bitcoin's Annual Energy Consumption Compared to Energy Consumption by Country Ranking

According to Digiconomist, Bitcoin alone uses more than 200 TWh (Terawatt hours) annually, which makes Bitcoin the 23rd largest consumer of energy when compared to countries. This is of course distributed amongst all states where PoW cryptocurrency mining operates but is found to be problematic by developing and developed states alike. This is in part due to the energy profile of mining operations. PoW mining now has evolved to incorporate renewable energy resources (hydropower, solar, and wind) into their operations but only as an energy mix. The use of fossil fuel sources remains extremely prevalent in the industry where Bitcoin alone is estimated to account for 114.06 Mt Co2e per year (Bitcoin Sustainability Index, 2022). Air pollution from electricity, heat, and transportation already account up to 73.2% of world CO2e emissions per year (Ritchie & Roser, 2020), and PoW activities are now contributing to the mounting Green House Gas issue. If PoW operations are to continue, the industry which is dominated by PoW coins will continue to increase their carbon footprint which will show a long last impact from negative socio-economic externalities.

It is important for regulators and researchers to understand the reasoning why mining and therefore trading can negative impact the state. To properly assess the impact of cryptocurrency is to examine its implications on the environment, societal strains, and consumers in the financial market. Currently, Sweden has joined the opinion of Finansinspektionen (Swedish Financial Supervisory Authority) that has published a letter claiming that energy intensive cryptocurrency mining (PoW) is not only detrimental to achieving carbon neutrality, but its actively hindering the green transition for public expenditure projects and produces enough emissions to cause serious future health concerns (Finansinspektionen, 2021). This paper aims to foster an understanding the fractured landscape of security regulations which hopes to illustrate that outright bans by individual states do not mitigate or solve the issue but instead displace the issue on the rest of the world. The issue requires a call to action for the international bodies to foster an understanding and agreement across the globe of how to mitigate *cryptodamages*. The aim is not to identify blockchain technology as a problematic but shed light the PoW protocols have deferential socio-economic repercussion's that are only beginning to unfold. The free-market mechanisms will not purge the industry of these costs. Ultimately this paper asks the question that regulators are beginning to look towards, which is if banning proof of work activities will quell the negative socio-environmental externalities that have been attributed to mining and trading. By outlining the risks associated with mining activities and problems with mining facility structures, future research can use practical analysis of environmental indicators associated with energy profile to assess the capacity of a country's energy infrastructure to build a greener PoW cryptocurrency without barring its activities.

This paper will draw upon current regulations surrounding PoW mining to identify what states believe to be pertinent issues. The aim is to answer the question of why states choose to act or not to act against cryptocurrency operations and if said regulation of PoW mining has had a helpful impact to curbing emission, societal, and political concerns. Chapter 2 of this paper will outline Proof of Work as the catalyst of risk. Following that will be Chapters 3 will draw upon environmental data associated with mining facilities structure, operations, and geographical ties to define the true impact PoW mining has on a given environment. Chapter 4 contains a analysis of the Great Mining Migration that resulted from the 2021 Chinese Ban of mining and trading. Drawing upon events that transpired in Kazakhstan and United States mining expansion post September 2021, future assessments can use indicators of energy mixes and infrastructure evaluations to judge the capacity of mining industry expansion. This will in turn answer the underling research question. The paper will then conclude with policy recommendations for the national and international level.

1.1 Current Literature

Beginning with the research question of "what the true impact of unregulated proof of work cryptocurrency mining will be," research has led to a myriad of complex and differing opinions and arguments. Recognizing early in the research process, that the accompanying peer-review articles, sentiment analysis surveys, and annual reports surrounding the topic of the impact of proof of work cryptocurrency outlined risk factors but lacked proper analysis of the future impact of mining operations. As the distinction between traditional Fiat currencies and proof-of-work cryptocurrencies has widen over time, research and analysis have spanned across multiple dimensions surrounding proof-of-work blockchain validation process and production. What has failed to appear from a multi-faceted approach has been a consensus on the methodology to evaluate the totality of risks associated with cryptocurrency mining.

Current debates pertaining mechanisms of blockchain validation begin with the energy consumption concern of the PoW consensus algorithm and its protocol. The now well-established "Cambridge Bitcoin Electricity Consumption Index" published by the *Cambridge Centre of Alternative Finance*, has outlined that the entire Bitcoin blockchain validation process consumes 0.53% of global electricity production and 0.18% of global energy production. Coupled with its publishing of the comprehensive "3rd Global Cryptocurrency Benchmarking Study," *Cambridge Centre of Alternative Finance* (CCAF) reports on objective quantitative data which is updated and revised on a regular basis.

Another prominent database used for this paper been generated out of the need for further data into mining operations. Alex de Vries, a PHD candidate and researcher at VU Amsterdam, founder *Digiconomist* which has developed the "Bitcoin Sustainability Index" and the "Ethereum Sustainability Index." Each index measures mining operations of the given cryptocurrency's impact on environmental, geographical, energy, and emission risks. A range of power and electricity and consumption data does exist, and Dichotomist's estimates are near the top of that range. This paper uses estimates from both *Cambridge Centre of Alternative Finance* and *Digiconomist* because the databases are updated frequently and have robust, but slightly different, indicators that go beyond traditional measurement techniques for emission data. Both operate on publicly assessed data but frame their data much differently. Digiconomist takes a sustainability perspective and therefore judges social costs into its measurements, whereas the CCAF frames their data as benchmarks and progress indicators for the industry and remains objective in its analysis. Remaining quantitative data sourced for this analysis derives from mainstream databases such as CoinMarketCap and Cryptoslate. Mainstream databases focus on market externalities of usage trends and baseline information of sector dominance and market share of respective coins.

Much of the research used in the following exploratory analysis of the governance impact of regulation on cryptocurrency lacks a critical dimension of analysis. Resources used in this evaluation will cover environmental costs, political costs, financial costs, and social costs. Despite the massive overlap between each field of research, a holistic approach for cost benefit analysis of cryptocurrency mining has yet to be fully recognized. Regulators across the world must reach objective consensus to properly address risks and concerns of domestic cryptocurrency mining.

To outline the problematic ties of cryptocurrency mining, literature sourced will start with academic papers analyzing the Proof of Work Consensus Algorithm and why certain features take priority over others. Proof-of-work (PoW) consensus algorithm now governs 341 cryptocurrency coins (Adejumo, O.A. et al., 2022), which now makes up 66.23% of all crypto sector coins. Nakamoto's white paper in 2008 launched a PoW revolution as it outlined a way forward for a peer-to-peer decentralized network to validate and preform financial transactions (Nakamoto, 2008). This was not the first instance of PoW as a theory of change. In fact, PoW was first brought into the academic sphere with David Chaum's publishing of "Blind Signatures for Untraceable Payments (Chaum, 1983)." The theory associated with the algorithm's aims of preventing double payment and a decentralized monitoring system would be adapted into Nakamoto's white paper and fully actualized with the mining operations of Bitcoin starting in 2009. In 2022 however, the sentiments of PoW in the academic world as a revolution are few and far between. PoW has an array of variables that make its subsequent blockchains unsustainable. In their 2019 study titled "Blockchain Technology in the Energy Sector," Andoni et al. lay out a systematic review of the PoW consensus algorithm that mining operates under but goes further by outlining how the energy sector can benefit from blockchain technology in terms of efficiency, but the algorithm is energy intensive and requires massive amounts of computational power when applied to cryptocurrency mining. Comparative studies by Schinckus in 2021 and Sutherland in 2019 take retrospective approaches to analyze PoW efficiency after sustainable market growth. Sutherland concluded that the structure of PoW is the determining factor of power consumption and hence its structure will be nearly impossible to fully decarbonize a PoW blockchain. Schinckus then linked this idea to mining's exponential power consumption demands and illustrated that PoW within a finite number of mineable coins will require more operational power with the supply of coins and other mining rewards halfling each year. According to Nakamoto's white paper, PoW must answer the questions of what level of security must a blockchain ensure and what is the probability that the security level is achieved by a given project. Zochowski determines that the power consumption inefficiencies present in PoW hinder the security of PoW blockchains and open the blockchain to potential external and malicious threats (Zochowski, 2019). Academics have achieved an overwhelming consensus that PoW is inherently inefficient, and this fact has led to negative externalities when the consensus algorithms is blown to scale of a global industry with increasing power consumption trends coupled a consensus algorithm that outputs increasingly complex puzzles to solve.

Power usage is not the final dimension to PoW mining's negative externalities. Amid its extremely high electricity dependency for mining operations, Nadarajah and Chu's study demonstrates that volatility of price places a key role in determining power consumption. In fact, because of its high volatility which is over a whole standard deviation of investment returns compared to common commodities of oil, gold, and copper, cryptocurrency's commodity spike in pricing puts extra strain on power grids. This strain also puts and emphasis on a further problem of emissions associated with mining operations. Asumadu-Sarkodie, Ahmed, and Leirvik continued this analysis by identifying trade volume is also a determining factor in energy and power consumption which has negative effects on a given cryptocurrency's carbon footprint (Ahmed, Leirvik, & Sarkodie, 2022). The authors found that dynamic shocks in trade volume have potential 50% increases on energy consumption that drastically alter a cryptocurrency's carbon footprint. In terms of price volatility and trade volume, miners cannot possess the ability to predict dynamic market changes and this in turn levies uncertainty in how much power will be needed on a monthly, daily, or even hourly basis. This leads to worsened energy profile mixes and further dependency on fossil fuels to subsidize remaining demands of power consumption. Emissions are a natural outcome of the industry but are mainly tied to fossil fuel usage. Li et al. in 2019 called for further research into the problematic dependency of power consumption. Concluding that power consumption and efficiency are predominantly affected by which algorithm the mining operation is utilizing. Along with an exponentially growing demand of electricity, more miners are entering the field and opening operations or expanding mining pools. The study also dissected different models of mining operations and outlined the various forms of mining hardware which are based on one of the following options. Central Processing Units (CPUs), Graphics Processing Units (GPUs), Application Specific Integrated Circuits (ASICs), and Field Programmable Gate-Array (FPGA). Vranken had analyzed the four competing methods of mining in 2017 and predicted that only ASICs would be the only profitable mining method in the longer term. Individual miners would be unable to achieve a cost effective hashrate and large-scale mining facilities and mining pools would be viable options. Implementation of the PoW consensus algorithm to this scale has created environmental fallouts of Green House Gas emissions because of mining's us of fossil fuels in the global energy profile mix of mining. This comes to fruition despite boasting a higher mix of renewables than any other industry. The annual electricity consumption levels of Bitcoin (204.50 TWh) and Ethereum (93.97 TWh), have created an estimated 114.06 Mt (Digiconomist Bitcoin Sustainability Index, 2022) and 52.42 Mt of CO2 (Digiconomist Ethereum Sustainability Index, 2022) respectively. The emerging industry with increased private participation and widespread adoption on a consumer level has seen a sustainable increase in emissions since its inception in 2009. In an unregulated and decentralized structure, mining facilities have the burden of mitigating the concerns associated with mining. Data from the industry's energy mix profile shows and increasing effort to integrate renewables into mining operations. When examining data at regional or even domestic levels, the energy mixes vary and access to renewables is geographically dependent. At the University of Washington, Samford and Domingo identified that location of mining activities and access to renewables does not have a higher correlation than does mining activities to access of cheap electricity (Samford & Domingo, 2019). The authors also identified that mining farms or facilities make use of renewables as well as cheap electricity. In China, the researchers found, that mining facilities were densely located within the provinces of Sichuan, Yunnan, Xinjiang, or Inner Mongolia which are all surplus produces of renewable energy. Heavy rain season within these provinces made hydropower the leader in energy used for mining displacing coal as the top consumed resource.

As problems and concerns of mining continued to mount, Alex De Vries published a paper with Christian Stoll titled Bitcoin's growing e-waste problem. The authors calculated that Bitcoin's annual e-waste generation adds up to 30.7 metric kilotons annually and 272g of e-waste per transaction processed. Here price volatility and trade volume also affect the total lifespan of ASIC units and other mining hardware. Coupled with the strain on supply chains during the global COVID-19 pandemic, mining hardware was in high demand and continued to manufacture new strains on the semiconductor industry which is required for the world's green transition into renewable energy and sustainability. The authors also calculated with a sharp rise in total hardware in the network along average lifespans drastically decreasing because of number of computations made per device and constant uptime, cryptocurrency mining's e-waste problem will only grow exponentially just as power demands would grow exponentially because cryptocurrency lacks a price cap. Haas McCook echoes the sentiments of supply chain disruption in his paper "The Cost & Sustainability of Bitcoin," by finding his own calculation that the total cost of mining one bitcoin is 6,450 USD. McCook evaluated the entire value chain of mining production and was able to aggregate economic and environmental costs to compare cryptocurrency mining to traditional mineral mining, specifically gold. McCook proposes that with positive of increased network participation trends, Bitcoin's energy consumption alone will surpass the entirety of the gold mining industry.

Cryptocurrency is generally known to have relatively low externalities outside of the market, but new research and studies are committed to predicting and outlining social costs associated with the mining industry. The leader in this field has been Alex de Vries as he has published a series of papers dedicated to correlating power usage and emissions data into social risks for regulators to act on. In his paper "Preying on the Poor," de Vries highlights that communities that are experience deprivation of resources are most at risk when mining operations enter or expand in their communities. Massive amount of energy and resources needed to sustain a profitable mining operation will divert resources away from the most marginalized peoples. Goodkind, Berrens and Jones, use a similar approach to outline costs but focused on defining monetary values to crypto mining fallouts (Truby, 2018). Coining the term *crytpodamages*, the authors use predictive analysis to illustrate that *cryptodamages* will follow a similar path to Bitcoin damages. Smaller currencies such as Ethereum, Litecoin, and Monero will eventually exceed the $1 value they create.

Ending with an analysis of the great migration of cryptocurrency mining, literature pulled is limited considering this event occurred in 2021. However, results are already being felt across continents. Examining the comparative case study by Rain Xie, titled "Why China Had to "Ban" Cryptocurrency but the U.S. Did Not," frames the outcomes of the events through a regulator's lens. The United States, classifying cryptocurrency as property versus

China classifying cryptocurrency as "coin substitution" changed the landscape of hashrate dominance in China and exported it across Russia, Kazakhstan, and ultimately made the United States the global leader in hashrate (Xie, 2022). "Bitcoin: Currency or Fool's Gold?" authored by Seth Litwack also shed light on how regulatory bodies across the world have fractured approaches. Regulators do not wish to hinder blockchain technology, but struggle because cryptocurrency does not fit neatly into general security regulation (Litwack, 2022). Culminating in use of data from national energy administrations in Kazakhstan and The United States, assessment of a countries capacity to welcome a massive intake of energy-intensive industries should be a key indicator in identifying the externalities of the Great Mining Migration.

1.2 Internationally Fractured Legal Approach

Cryptocurrencies operate fundamentally on a peer-to-peer basis. This core attribute enables private individuals to exchange digitally mined cryptocurrencies with real currency value without validating the transaction through a central monetary authority. Without proper legal classification, states lose the ability to tax cryptocurrencies and therefore lose their controls on monetary policy. As a result, states across the global sphere implemented restrictions across a spectrum of decisions. In many instances, regulation and state intervention in crypto markets is done on a case-by-case basis. The governance structure of economies and political regimes have largely dictated a state's position on cryptocurrency as a fully actualized or "real" (in terms of ability to control, tax, or regulate) asset (Janson & Karoubi, 2021). Even with proper controls, the uncertainty of the cryptocurrency markets has led to extreme volatility rates, higher than any currently traded commodity despite its similarities to gold or crude oil (Ji et al., 2019).

In his comprehensive book *Digital Currency: An International Legal and Regulatory Compliance Guide* that was published in 2016, Matsuura outlined then that regulation would be difficult because states will create their own interpretation and classifications of cryptocurrency and blockchain technology. Matsuura points to a measured and holistic approach that lumps digital payments into their own category rather than commoditize individual cryptocurrencies. Without a strong government backing like traditional fiat currencies, the decentralized architecture of cryptocurrencies exposes the asset to a myriad of legal compliance issues and leaves consumers vulnerable to the highly volatile nature of private money systems (pg. 15 Matsuura, 2016). Being a private money system, regulators face the challenge quelling unsustainable practices associated with cryptocurrency (mining, capital flight, terrorism, illicit trade) without impacting the market that lacks consumer protections. As of writing, only El Salvador and The Central African Republic have adopted digital currencies as legal tender (Browne, 2022). The Decentralized architecture of digital currency challenges regulators to classify digital currencies but most oppose accepting the form of payment as legal tender (Kolhatkar, 2021). Now countries have moved to either ban private or foreign owned cryptocurrencies such as China and Iran (Tassev, 2021) and have displaced the unregulated industry on neighboring countries like Kazakhstan. It is now apparent that individual state action is far too disjointed to mitigate the damages associated with cryptocurrency and legal regulation must take the form of international agreements that align themselves with the Sustainable Development Goals and green transformations in the digital age.

1.3 Research Methodology

The overall aim of this paper is to establish environmental and social risks of PoW mining. By outlining the true risks this paper will identify what risks regulators should deem actionable and what is negligible in the world of cryptocurrency. Examining cryptocurrency data without separating the various consensus algorithms leads to a conflation of ideas and complication of measurements and assessments. Cryptocurrency mining is the core of protocol to how cryptocurrencies increase adoption efforts. Mining as a concept is no niche to PoW, and data for the entire cryptocurrency industry is far to spread and distinctions of risks and impact must be made because of the various validation methods and consensus algorithms such as Proof of Work, Proof of Stake, Proof of Burn, and others. A wide variety of risks pertain to cryptocurrency mining and consensus algorithms exhibit overlapping issues but with different levels of impact. For this purpose, the analysis found in this paper will pertain to private Proof of Work cryptocurrencies such as Bitcoin, Ethereum, Litecoin, Monero and others. With a 66% sector dominance of all cryptocurrencies, PoW and its mining find themselves as pillars of the industry.

Pulling from academic journals, the PoW consensus algorithm maintains an inefficient protocol that is said to put security and privacy above an efficient process. Journals, and research papers outline that the consensus algorithm is not inherently flawed but the process itself requires incredible computational power to not only solve cryptographic puzzles but to stay competitive and therefore profitable in the industry. Analysis of the consensus algorithm Sutherland, Andoni et al., and Schinckus will be coupled with ASIC lifespan experiments conducted by de Vries and Stoll to show the harmful relationship that PoW has on its own operations.

Research from environmental scientists and financial experts will also be used to calculate actual costs of PoW mining. Goodkind, Jones, and Berrens adopted and create new indicators to judge how the fallouts from emissions directly correlation to human health. This will also be further coupled with research from de Vries that focus on social repercussions for marginalized communities. Analysis of energy diversion from state and local power grids will take away from new public expenditure projects that will improve public well-being. Data will then be pulled from mining facilities and research papers that detail the growing trends of mining participation that will lead to expansion of operations and therefore exacerbate the negative externalities associated with PoW mining.

Finally, this paper will illustrate the outcomes of regulating the negative externalities through practical examples of the fallout of the Great Mining Migration. China has completely banned trading and mining of foreign and privately owned cryptocurrency which has resulted in strain on the network and has been causing social externalities within other mining regions. The analysis will dive into which risks China independently acted upon and what their underlying motivations might have been. Following that will be a regulatory outcomes brief that explains if the ban has quelled issues of sustainability within the nation. Regulation should mitigate damages and states have the responsibility to quell unsustainable businesses and practices, but in practice regulation has maintain control on monetary policy but instead cryptocurrency regulation in China has only pushed the negative externalities of mining onto neighboring countries. Examining the fallouts through the regulatory lenses of Kazakhstan and the United States we can uncover the spillover effect of the ban.

Chapter 2: Proof of Work Consensus Algorithm as a Catalyst of Change

PoW protocols and its cryptocurrencies are dependent on its extensive network of users, miners, and financial mediums such as exchanges. PoW attempts to maintain and support this peer-to-peer transaction network, without compromising its decentralized core attribute. Having a highly competitive network of miners racing to solve cryptographic puzzles and with the number of mining computers has grown exponentially since the year of inception in 2009, the network houses several million computers in the PoW arm's race (Howson& de Vries, 2022). The consensus algorithm requires a high volume of miners to naturally increase security measures of the network (Nakamoto, 2008). PoW has roots in humble origins of Chaum's initial white paper on consensus algorithms (Chaum, 1983) but has been modified and adapted to fit Nakamoto's vision post the global financial crisis. When blown up to its current scale of several million mining computers, the PoW consensus algorithm displays critical faults despite its innovative technology. This section will examine the overview of PoW operations as the catalyst to worldwide adoption of cryptocurrencies. PoW has spawned an entire industry of miners that operate on multimillion dollar budgets and require significant resources. Well known to be energy-intensive, PoW's guessing game through the secure hash algorithm 256 (SHA-256) demands high computational power to validate blocks before the sequence changes again. This is PoW mining and miners that participate in the validation process will be rewarded for their participation and strengthening of the network.

This chapter will dissect the algorithm for the purpose of laying the groundwork to describe the inefficacies of the consensus algorithm. Literature points to its inherent inefficient process for the sake of security protections on double spending and preventing fraud. This section ultimately aims to identity how the holes in PoW protocols leave room for reforms. Further exploratory paths ask if PoW is accomplishing the protections it set out to ensure without use of a third party or financial intermediary. Its problematic dependency on cheap energy resources, positions the protocol's subsequent operations in jeopardy of being unsustainable and exploitative.

2.1 Overview of the Proof of Work Protocol

Cryptocurrencies and cryptographic algorithms were first conceptualized in 1983 by David Chaum, with the proof of work algorithm being published in 1992 (Dwork and Noar, 1992), and then actualized by Nakamoto in 2008, the proof of work consensus algorithm has become the dominant choice for publicly accessed blockchain technologies and operations of cryptocurrency mining. This algorithm is dominating the cryptocurrency sector at above 66% percent of all blockchain validations (Adejumo, O.A. et al., 2022). The mining process for coins that follow proof of work, is the underpinning function that verifies the new "blocks" (1 MB of transaction data) to the existing chain, hence the blockchain.

To verify transactions and sensitive data, blockchains operate under fault tolerance, or more widely known as consensus mechanisms (Investopedia, 2021). Describe above is the consensus mechanism of Proof of Work (PoW). Consensus mechanisms underpin blockchain technologies because of the lack of a financial authority or intermediary that would verify data values and foster agreements of change for record keeping. Without such intermediaries, consensus mechanisms monitor users or nodes in the network by verifying blocks were not fraudulently amended or duplicated or targeted by external threats to the network (Alsabah and Capponi, 2020). For PoW, the operation goes as follows; (1) Potential and unfirmed transactions are uploaded to the cryptocurrency's network. Here is where miners will take multiple uploaded transactions and compile unverified transactions into a "block." (2) Miners will then attempt to solve the cryptographic puzzle by guessing the 256-digit long hashing sequence. This in turn verifies the data (transactions) stored within the "block." (3) Verified blocks will then be sorted onto the blockchain, which attaches each new block to the original or "genesis" block. This also means once the block has been verified, it can no longer be amended as the verification has been submitted to the digital ledger for all users to access and examine. (4) The peer-to-peer system then rewards miners with new coins or tokens (according to which PoW cryptocurrencies the miner is hashing) for the service provided under validation.

Blockchain technology is intuitively made up of “blocks” or validated transactions to the cryptocurrency sector, but the PoW protocol is how blocks are validated. Blocks contain transaction data which is known in technical terms as block size (Nakamoto, 2008). The block size is determined by a given blockchain (bitcoin’s size limit is 1 megabyte of transaction data) and must be linked a previous block onto the chain that can be traced back to the very first validation or genesis block. Currently, in the Bitcoin network, a block is added to the blockchain every 10 minutes (Sutherland, 2019) and therefore is limited to validating 7 transactions per second and 220 million financial transactions annually (Howson & de Vries, 2022). This creates a sizeable difference in transactional power when compared to the global financial system that processes 700 billion financial transactions annually (McKinsey Global Payments Report, 2021). Despite this issue of scalability, cryptocurrency carves out its niche in its ability to be decentralized through its consensus mechanisms. PoW is the only permission-less blockchain with security measures of transparency and traceability that operate completely without human oversight (Schinckus, 2021). Transparency relates to the level of access to data on the digital ledger. Traceability refers to the ability of individuals and actors to recall unaltered data and retraced the history of the transaction. These two pillar attributes are defining how PoW maintains its pure decentralized nature. To accomplish this, PoW cryptocurrencies need individual participants to provide computing power. Computing power is necessary to solve cryptographic puzzles to correctly guess the N.O.N.C.E. Once a participant or miner has identified the phrase, they are rewarded with a Cryptocurrency coin. PoW uses its number only used once or N.O.N.C.E., to generate a 256-digit long code under the SHA-256 hash function (Vranken, 2017). The hashing algorithm goes a step further for the Bitcoin protocol as double hashing is used within the subgroups of SHA-0, SHA-1, SHA-2, and SHA-3 (de Vries, 2018) to prevent from “double spending” or where one block can be represented twice on the blockchain. To ascertain the hash sequence miners have tuned their computers and facilities to run on dedicated cryptocurrency hardware. Cryptocurrency mining runs on either Central Processing Unit (CPU), Graphics Processing Unit, (GPU), and now most facilities run on a series of Application Specific Integrated Circuits (ASIC).

ASIC units are computers that have been stripped of extraneous hardware that does not contribute to mining operations (Küfeoğlu and Özkuran, 2019). Specifically, to bitcoin, PoW has netted the cryptocurrency an average hash rate of about ten minutes per new block because of efficiency improvements of specialized equipment but the PoW race to solve the hashing implores miners to maintain facilities that house thousands of units to increase the probability of guessing the SHA-256 first or before it changes.

The inherent inefficiency of this validation process comes within simple trial and error. To correctly “solve” the cryptographic puzzles, miners are programing their facilities with specific programming to guess the SH-256 hash sequence. In the infancy of mining under PoW, dedicated mining laptops were seen as a competitive tool (Howson & de Vries, 2022). The total amount of miners projected to increase 11.5% in 2021 to 2029 (Databridge Market Research, 2021) despite the increasing complexity to solve cryptographic puzzles for dominant PoW coins like Bitcoin. This is exacerbating the inefficiencies of the PoW protocol through increased energy demands for new and expanding mining facilities which will net the mining industry a larger carbon footprint.

2.1.1 Market Variables of Proof of Work

To be competitive within the mining industry and under the PoW protocol, mining facilities must be position to profitability on cheap electricity. This has given large miners higher the computational power of the facility, the more profitable an operation becomes because it can generate hash sequences faster. Conversely, as the industry and mining facilities become larger, PoW weighs combating external threats of fraud above efficient processes.

PoW consensus algorithm is used to validate any transaction and therefore block for the Bitcoin (and many other coins) system. To validate these processes through cryptocurrency mining, miners must solve complex cryptographic puzzles or tasks that seek a value known as N.O.N.C.E. or a number only used once. Outlined in the previous section, the Bitcoin mining process operates under PoW with the hashing sequence corresponding to SHA-256.

This is of course done in a decentralized manner, where the network is reliant upon individual actors to maintain the security of the network. PoW cryptocurrencies are the benefactors of increased participation through new miners entering the network or size of facility. The increased number of users and miners that are integrated into the network will curb fraud because more individuals are active on validating and verifying the digital ledger of a given blockchain, however it will increase the energy consumption which hurts the resulting industries. The more decentralized a PoW protocol is, the more secure the blockchain will be (Schinckus, 2021) which makes this feature an incentive for more actors to participate. Directly linking this to cryptocurrency mining, more miners on the network means global impact on energy consumption will exponentially increase over time because of the endless amount of PoW currency coins to be mined. PoW demands can never fully be estimated because of this fact, but individual coins with finite supplies (Bitcoin, Binance, Cardano, etc.) breed competition to mine as many coins to secure as much value as possible before mining ends and value of the coin will ultimately dictate how many further resources will be committed to meeting PoW demands.

PoW does not set price of coins, but rather price dictates PoW efficiency and therefore hashrate (Budish, 2018). Data from Figure 1 shows there is a strong correlation in price increase and complexity of cryptographic puzzles which leads to high electricity loads when price is higher (de Vries, 2021). PoW's incentive for increased participation benefits the security of the network but indirectly levies strains on the physical operations. Hashrate will increase because more miners will participate in a system that is returning high yields, but mining operations will expand by purchasing new equipment. This is because price will incentivize miners to participate and up hashrate. Duality of PoW of price to consumption, has bred a work around for miners who must maintain cost effective solutions to mining expansion called mining pools. Pools use collaboration efforts to create between borderless mining locations that pool computational power to a share of mining rewards (Sharma, 2021). Mining pools have become and industry norm where 99% of the hashrate today is dictated by mining pools (Heulot et al,. 2022). The PoW consensus algorithm will also increase the difficulty in solving cryptographic puzzles when more miners and facilities are operational regardless of supply of unmined PoW coin. This means that the computational power required to solve cryptographic puzzles increases not only with increased competition but also when price fluctuates.

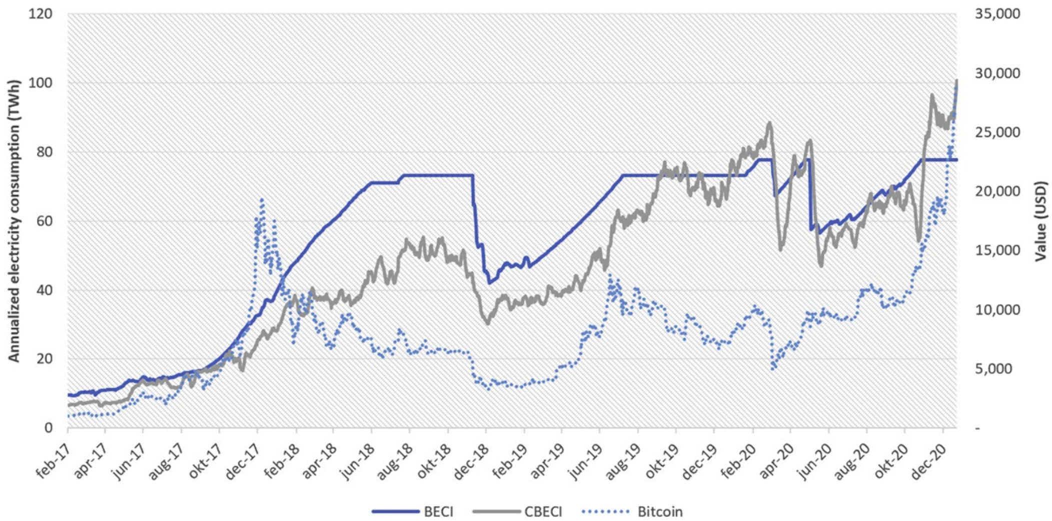

Figure 2. Historic Bitcoin energy consumption estimates and price development (de Vries, 2021)

Increased participation in PoW cryptocurrency mining is a double-edged sword. Although the more actors operating within a network improves transparency and traceability, actions are dictated by price which is volatility. Need for increased participation during periods of high volatility and price increases, can be mitigated by mining pools operations. Mining pools can be described using the 3rd Cryptoasset Benchmarking Study's (Blandin et al., 2020) definition which states that mining pools, "Combines computational resources from multiple miners to increase the likelihood and frequency of finding a new block, and then distributes mining rewards among participating miners based on the proportion of contributed computational resources (Blandin et al., 2020)." Mining pools operating under PoW networks which means there are still incentivized to seek the cheapest electricity available. PoW's demands require facility uptimes (amount of time a computational process is online and functioning) to match mining uptimes Bitcoin at 98.987% to be a profitable and efficient operation. Furthermore, a computational process with high uptimes will inevitably degrade the hardware to the point of obsoletism. ASIC unit, although specialized to solve cryptographic puzzles, deteriorate much faster because of the high computational demands of PoW (Stoll & de Vries, 2022). This will further be explained in chapter 3 that outlines how the growing power demands correlates to a growing issue of e-waste and manufactures a strain on the semiconductor supply chain. This fact is then amplified through price volatility and trade volume, which effects the number of participants and therefore impacts the carbon footprint of the PoW mining industry.

It is important to mention that variables list is the section pertain to permission-less public blockchains such as Bitcoin, Litecoin, Ethereum, etc., and are not indicative for privately owned blockchains. Privately owned blockchains can inflicted special rules for transparency and validation that create new compliance measures not found in mainstream permission-less public blockchains (Schinckus, 2021). This paper will focus on permission-less public blockchains as their ecological footprint and industry impact will have much greater effect.

2.2 Why the Focus is on Proof of Work

To properly assess the impact of mining, regulators must employ high levels of scrutiny to PoW mining as it represents 66.66% of all cryptocurrency mining (Adejumo, O.A. et al., 2022). Within the two-thirds sector dominance of PoW, 341 coins operate under its protocol (CoinMarketCap, 2022). With a heavy market share, operations that utilize PoW must be seen as greater contributor to the negative socio-environmental externalities associated with mining and trading of cryptocurrencies.

Opposed to other consensus algorithm protocols such as proof of stake (PoS) and proof of burn (PoB), the carbon footprint of PoW mining is sustainably larger than competing consensus mechanism (TQ Tezos, 2021). PoS has achieved lower barriers to entry by requiring less computational power to guessing hash sequences. PoS has a reverted to the days of mining at its inception, where laptops have become competitive devices for validation (Li et al., 2019). In fact, the other consensus algorithms operate under different structures than mining. PoS uses validators and staking processes instead of miners. This means that validators must contribute, usually financially, to the blockchain by locking their PoS token in a smart contract to be deemed a validator (Staking Facilities, 2022). Validators still operation on extensive networks of computers but require less energy and preforms validation faster than PoS. Unfortunately, rewards are still unbalanced as validators with higher stake are delegated block creation tasks than validators with less stake. This is the same imbalance of higher computational power to efficiency seen in PoW but energy requirements for mining create unique externalities of Green House Gas emissions (Bligen, 2014). This in turn means that as the industry grows, more participation will net a greater cost to mitigating socio-environmental damages specific to the PoW protocol. Its dependency on resources will be exacerbated because the PoW protocol will generate increasingly complex cryptographic puzzles to solve, which in turn levies further strain on mining operations. To combat this, the industry has turned to renewable energy but faces the duality of the cheap energy and the impact on the industry's carbon footprint.

PoW makes sacrifices in efficiency to incentivize higher participation in the network, which nets a higher level of security. An increased number of active miners equates to more validations and therefore lessens the likelihood of fraudulent actions (Schinckus, 2021). However, the mechanism is inherently inefficient and requires more energy to fuel the computational processes associated with solving cryptographic puzzles for mining. Alternatives do exist but, PoW mining was at the epicenter of the cryptocurrency mining revolution in 2009 by being the initial consensus algorithm to the world's largest cryptocurrency, Bitcoin. This tied the early adoption of cryptocurrency to production process of mining. Over time the industry gained mainstream appeal and expanded, however, so have its problematic links to socio-environmental damages. The following chapter will build off this academic consensus of inefficiency by outlining the negative externalities and data associated with PoW mining.

Chapter 3: Negative Externalities of PoW Mining

For regulators to gain a holistic perspective on the impact of cryptocurrency regulation outcome, they must understand the true environment risk that mining operations pose. The process of cryptocurrency mining has caused concern and confusion amongst mainstream media and regulators alike. The precarious relationship of energy and consumption demands of PoW mining is at the root of these concerns. Publications unfortunately information from mainstream sources exhibit an extremely limit scope and a wide variance of opinions from proponents and critics. This has led to a misunderstanding of the true risks stemming from PoW. Firstly, making a distinction between all cryptocurrencies and PoW is key in understanding where the problem lies. As stated in chapter two, PoW is the original consensus algorithm that operates under a protocol of mining and miners. PoW is inseparable from the benefits and fallouts of the current state of cryptocurrency mining. Secondly, PoW mining has gained recent scrutiny in places such as recent as June 3rd in New York State over its production of GHG (Sigalos, 2021). Data outlined in the rest of this chapter point towards the energy profile of mining facilities as the culprit. Additionally, this chapter will discuss a dimension concerning the geographical ties of mining operations to exploitation regulatory bodies energy infrastructure. The extreme dependency on fossil fuels to power massive mining projects threatens the sustainability of the project and hinders a state's ability to achieve targets outlined by carbon neutrality agreements such as the Paris Agreement (Villiers, Dissanayake, & Kuruppu, 2021). Finally, PoW inefficient process costs mining operations in the form of necessary hardware upgrades. To maintain a competitive edge in hashrate, individual mining units are upgraded on average every 1.5 years (Stoll & de Vries, 2022). This in turn has created a mounting e-waste problem with little room for reform because of the specialization of the equipment. Environmental risks posed by the industry ask the question if industry wide trends towards renewables will halt externalities.

With notable exceptions of China, New York State and Iran, regulation of cryptocurrency trading and mining has been focused on security regulation of the asset rather than the mining methods that create negative socio-economic externalities (Xie, 2019). Risks associated have increasing costs to mitigate (Berrens, Goodkind, & Jones, 2020). Predictive analysis models show the industry's energy demands will increase exponentially over time (Williamson, 2018) as the PoW algorithm will be harder to solve and major cryptocurrencies such as Bitcoin, Ethereum, and Litecoin will be nearing their end of mineable supply. Meanwhile emissions and e-waste will continue to mount and be heavily exhaserbated by price volatility and number of operations. The variables associated in PoW show that without regulatory control or incentive to operate on other consensus mechanisms, the crypto mining industry will levy further strain onto issues that are known to cause long term harm to health and natural environment.

3.1 Demands of PoW Mining

What is apparent about the problematic dependencies of cryptocurrency mining across the world has been its energy need for computer processes. According to the Digiconomist, the estimate energy threshold eded to sustain the Bitcoin blockchain alone has reached 204.5 TWh annually. Displayed in figure 2, the trend for consumption also shows an exponential growth in energy demands. This comes despite the Chinese 2013, 2017, and 2021 restrictions and bans. This fact alone raises the question on the relationship to states banning PoW mining and its impact on worldwide industry demands. Diving further into this topic, primary energy consumptions (electricity, heat, and transportation needs) statistics show that even after banning trading and mining of cryptocurrency, China remains the largest consumer globally (bp Statistical Review of World Energy, 2021). Bitcoin alone cements itself as the 23nd largest consumer of primary energy (Digiconomist Bitcoin Sustainability Index, 2022). PoW makes mining operations energy inefficient process where (1) the consensus algorithm prioritizes decentralized security measures over computational efficiency, (2) the more miners operating in network means the hash sequence is more difficult to solve and therefore requires more computational power (more energy), and (3) the geographical location of where PoW mining takes place has extreme importance on the efficiency of the mining operation. The novelty of this analysis will shed light on how the exponential growth trends of the industry call for regulatory intervention.

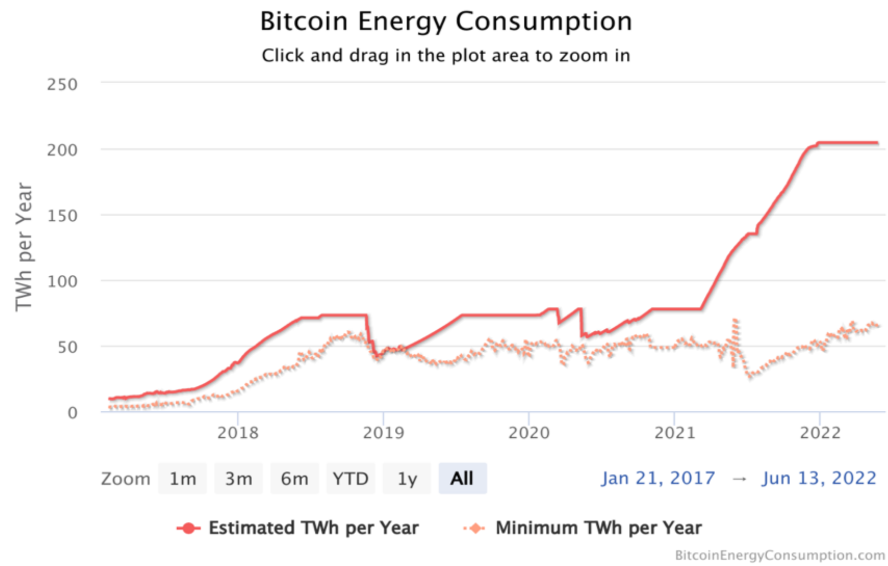

Figure 3. Bitcoin's Energy Consumption Increase from 2018 – 2022 (Bitcoin Sustainability Index, 2022)

Changes in energy demands of PoW mining are directly link to global hashrate and moreover the computational challenges associated with a given cryptocurrency's hash sequence (de Vries, 2018). Global hashrate is also directly linked to the number of computing devices on a given blockchain (Corbet, Lucy, & Yarovaya, 2021). Furthermore, hashrate will increase and decrease based on the number of active miners, inversely energy demands do not show drastic decreases unless mining from a pool or nation halts. Whether a mining operation exits the network, is forced physically relocate, or are barred from participating due to regulation, primary energy consumption will increase because the network leaves a larger market share to be gained and/or mined. This manufactures a unique strain on the energy demands. Competing miners will expand their operations and upgrade equipment to achieve a higher hashrate (Sang et al., 2022). This very scenario is unfolding, as the multiple bans from the People's Bank of China (PBoC) have caused a massive whole in the cryptocurrency mining network. Predictive models done by Sang et. al, show that upgrades done by the state and private actors after the Chinese bans on trading have affected the power grid and energy mix of the industry which have drastically altered the industry's carbon footprint.

Researchers although recognize these problematic ties, have differed when creating estimates and attempting to accurately measure the fallouts from massive energy demands. Reportedly, Bitcoin alone has a single transaction cost of 1238.54 kgCO2 which has been likened to over 200,000 hours of video streaming on YouTube (Digiconomist Bitcoin Sustainability Index, 2022). This number means very little without the context of how mining operations are powered. Understanding the energy profile of the industry is key for regulators to assess the problematic issues within mining. That is not say there are no alternatives for the mining industry but in fact miners do face an uphill battle towards sustainability because of how efficiency and structure dictate profitability and work against a greener currency.

3.1.1 Power Consumption

In the post-pandemic era, cryptocurrency has been met with negative press by regulators and the media alike. November of 2021 the Swedish Financial Authority Finansinspektionen spearheaded a new wave of skeptics as the organization released a series of articles and conferences explaining its call to action for regulators to move to ban PoW cryptocurrency operations. The organization outlined that the high energy demands which have resulted in varying large estimates of CO2e production are a threat to climate change. Moreover, a study by Mora et al. in 2018 called the industry into question and outlined the Bitcoin mining alone risks pushing climate change above the 2ºC threshold outlined in the Paris Agreement. This was disputed at time of publishing (Dittmar & Praktiknjo, 2019), but has raised a discission on efficiency This trend in energy consumption does not appear to be slowing down over time despite the finite number of coins to be mined. Goodkind, Jones, and Berrens wrote that, "in January of 2016, each BTC mined required 1005 kWh of electricity; but by June 2018, each coin mined required 60,461 kWh. In 2016 there were ∼1 million BTC mined, which consumed 2.5 billion kWh of electricity; in 2018 the total number of coins mined dropped to 700,000, but electricity consumption increased to 47.9 billion kWh (Goodkind, Jones, & Berrens)." Now the

Bitcoin Consumption Index marks total CO2e production at 114.06 Mt annually with conservative estimates putting Bitcoin mining around 90 Mt CO2e.

Long gone are the days of cryptocurrency mining that solely required a stable broadband connection, a laptop, and wall outlet electricity. Today, profitability of mining is highly dependent on specialized computer hardware to compete in the PoW arms race. Mining facilities or farms require cheap and a massive amount of electricity to remain profitable. This razor thin margin of profitability is then further called into question when comparing the traditional mineral mining industry and cryptocurrency mining. In their 2018 analysis, Krause and Tolaymat analyzed the consumption patterns and emissions output of four largest PoW cryptocurrencies (Bitcoin, Ethereum, Litecoin, and Monero) and compared data to environmental impact data from the gold, copper, platinum, and rare earth metals mining industry (Krause & Tolaymat, 2018). Moreover, research conducted found that not only do the 4 largest coins account for over 57% of the market capitalization of PoW cryptocurrencies but consume more energy than the traditional mining industry (with the exception to aluminum that uses a high amount of energy to produce a single unit). The two less demanding PoW cryptocurrencies being Ethereum and Litecoin consume more energy at 7 MJs to produce a single digital asset worth one US dollar than the equivalent consumption of copper, gold, and platinum at 4, 5, and 7 MJ respectively. Bitcoin and Monero must consume 17 and 14 MJ respectively which puts the coins well over the encompassing rare earth metals demand of 9 MJ but drastically under aluminums at 122 MJ. Trends pointing towards the direction of increased mining operations, the energy dependent industry is plagued poorly optimized energy profile mix that amplify its environmental risks.

3.1.2 Energy Mix

Regulators, researchers, industry giants are not blind to this matter for energy dependency. However, the environmental concern for the industry is much more nuanced than mining networks require large amounts of electricity to maintain daily operations. When analyzing renewable energy use from a global perspective, the cryptocurrency mining industry demands appear negligible as industry has a much better energy mix than comparable commodities (Coinshares, 2022). On the contrary, Bitcoin alone accounts for 0.5% of global energy consumption and accounts for 73% of cryptocurrency mining energy consumption (Cambridge Bitcoin Consumption Index, 2022). Scrutiny of the industry's risks at the global scale does not reflect an accurate representation of impact at the micro-level of mining within regions. This industry cannot be judged as a whole because of the variable of the geographic location mining facilities are located and buying power. Reported in January of 2022, the top five highest hash rate countries for Bitcoin mining are currently the United States (37.84%), China (21.11%), Kazakhstan (13.22%), Canada (6.48%), and Russia (4.66%) (Statista, 2022). On par, the industry when operating in these countries has been able to improve their energy mix over time, and not boasts one of the world's highest uses of renewables in operations. Figure 4 illustrates this through data collected from the 3rd Global Cryptocurrency Benchmarking Study.

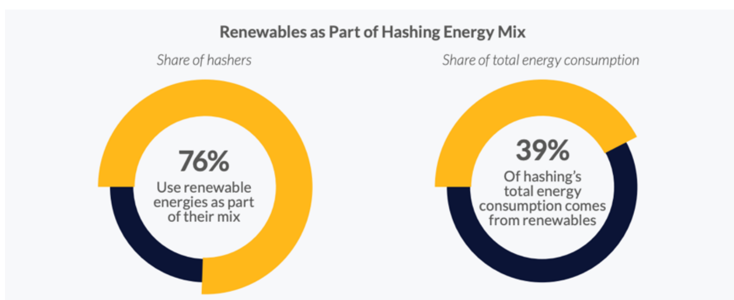

Figure 4. Industry Implementation of Renewables into Hashing Energy Mix

Although emissions and consumption estimate for the cryptocurrency mining industry are difficult to measure due to the lack of accurately reported information from certain countries like Russia and China, the estimate energy profile mix attributed to the Bitcoin (the largest energy consumer and most popular coin in the sector) network is higher than any other industry or even country (Holmes, 2021). Generous of estimates report that global PoW mining operations are running at 56% of renewables to fossil fuel energy mix.

This high rate of renewables in the Bitcoin energy mix is highly attributable to the dominance of hydroelectricity in the sector. Figure 5, which is taken from the benchmarking study, shows that hydroelectricity is not only the leading choice of renewable energy for mining operations (Blandin et al., 2020), but is the power preference across the industry.

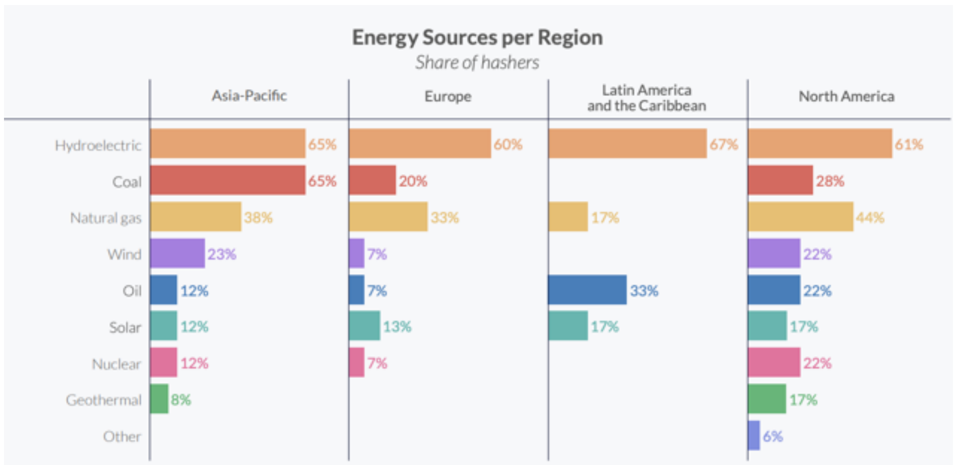

Figure 5. Energy Profile Mix of PoW Mining by Region

Although trends of renewables integrating themselves into the energy mix for the entire industry is growing in a positive direction, mining is done on a much more macro-level. Wang et al. notes that hydroelectricity in China is directly responsible for biodiversity loss across multiple regions (Wang et al., 2016). Hydroelectricity is cleaner than coal but when dissecting the facilities structure, the authors found that power grid improvements made by the state in turn fueled harmful resource extraction that was not mitigated. Another example being, Kazakhstan after the Great Mining Migration (Chinese 2021 ban of trading and mining of privately owned cryptocurrencies) now boasts the world's third highest hashrate (13.22%) behind United States (37.84%) and China (21.11%) respectively (Cambridge Bitcoin Energy Consumption Index, 2022). This is especially problematic because Kazakhstan only has a renewable energy mix around 1% of total resources (Caiou, 2021) (IEA, 2022). Along with this Black Rock Petroleum and Optimum Mining Host limited Liability (OMH) have proposed and announced an agreement on the 15th of July 2021. The

Blackrock would accommodate and relocate over 1 million units of PoW mining equipment sourced by OMH from the mass exodus of mining operations in China (Black Rock Petroleum, 2021). This itself is especially problematic when analyzing the firm's energy mix for the massive project in Alberta, Canada. The project will span across three sites different in the region all of which are natural gas producing sites. The casts doubt on the overall trajectory of the industry's energy mix.

Ultimately mining is a business and to maintain profitability, running a cost-effective mining operation requires specialized equipment, cool temperatures, and most importantly cheap electricity. The concept of economics of scale can simply be defined as when economies reach a level of efficiency that a company then can take cost advantages through (Kenton, 2022). The concept applies to cryptocurrency mining through its levels of power consumption when correlated with the size of the mining operation (Digiconomist, 2014). Established in Chapter 2, PoW demands will grow exponentially because cryptocurrencies lack a price ceiling. Moreover, PoW requires a massive amount of energy to solve the cryptographic puzzles and the puzzles themselves will require more energy over time because of the increasing complexity as supply of unmined coins halves each year. If miners remove themselves from the mining pool once their operation is operating at a loss, then it is important to factor in electricity costs (economic variable) into how overall energy mix (environmental variable) to determine the true impact of a mining operation. In practical terms, small scale miners will be eventually phased out of the network as more large-scale facilities become operable (de Vries, 2018). Miners will always seek the cheap electricity for fractions of the price of what local citizens pay in utility usage (Benetton et al., 2021). In addition, the competitiveness of the mining market drives prices even lower because miners are taking advantage of economies of scale (de Vries, 2021), which ironically pushes back against the decentralized architecture of PoW. Within this conundrum, PoW rewards efficiency over any other metric and "block rewards" for mining equate to a miners total share of the network hashrate. As we know that miners with the highest efficiency will have higher shares of the network hashrate, eventually small-scale operations will in turn end up running at a loss and close its doors. This issue has a centralizing effect on the network, meaning that the future industry energy profile will be dictated by large scale mining operations that seek cheap power over clean power to maximize profitability (de Vries, 2018).

If cheap electricity is derived from countries with energy mixes that have low amounts of renewables, the negative externalities of mining will worse. From the perspective of the business owner (miner), their facility should seek a cost-effective approach that will always position themselves in a country or region, or city that supplies cheap energy, regardless of the energy mix. Specifically researching mining locations, Stoll, Klaassen, and Gallersdorfer identify that large scale miners are inclined to continuing operations under PoW because of the capital invested to create large scale facilities. The consensus algorithm benefits large scale mining operations greatly because the highest computational power will end up with the highest hash rate (Bitflyer, 2022). This is not to say miners are unaware of the industry's desperate need to transition to renewables. The sentiments are drastically changing, and the Bitcoin Mining Council (BMC) reported a 9% increase in PoW miners who incorporated renewables into their energy mix, within Q3 and Q4 of 2021 (BMC Annual Report, 2021). The transition for the mining industry has transformed itself into a global leader in renewable energy mixes but leaves the question on feasibility of decarbonization within a PoW blockchain. Within the push of the organization many miners still operate under cost-benefit guidelines are continuing to use fossil fuels such as coal, natural gas, and crude oil. Further uses of fossil fuels will plague the mining industry and create future issues that concern procurement and uses of mining hardware.

3.1.3 Life Cycle of Mining Hardware

Environmental risks of mining stems from the use of fossil fuel to power and cool mining operations, nonetheless, the industry has shown promising signs of reform with renewable energy. This alone does not solve the issue of demand for high levels of computational power. PoW mining requires extensive facilities that compete in a global race to solve cryptographic puzzles for newly mined coins and transaction fees. This is accomplished by using mining facilities that use specialized hardware or ASIC units to increase effiencey and therefore hashrate. To position an operation at the forefront of profitability, miners must constantly upgrade equipment in according with price and trade volume (Ahmed, Leirvik, & Sarkodie, 2022). Once new hardware is required and utilized for at most two years, the device becomes slow and therefore will hinder a miner's profitability (de Vries & Stoll, 2021). This results in an equilibrium where old devices are phased out of the network and become electronic waste or e-waste. Creating a model that defined profitability thresholds of mining efficiency based on power consumption and coins mined per day, de Vries and Stoll found computer hardware used for PoW mining will be phased out within 1.5 years and only have average lifespan of 1.29 years (ASIC units monitored between 2014 and 2022). Furthermore, ASIC units are nearly impossible to repurpose and manufactures such as Bitman, do not have a recycling program. Thinking globally, neither Kazakhstan nor China (countries that rank #2 and #3 in global hashing rate) have comprehensive recycling programs for e-waste (Jiang et al., 2020), leaving the industry in the dark and hoping the free market will resolve the issue.

Fortunately for miners, the industry has been able to achieve greater levels of computational efficiency through upgraded and specialized mining hardware. The gradually upgrade from CPUs to GPUs to ASIC units and FPGAs, has drastically improved hash rates and newer ASICs have been designed to factor in the large power consumption drawbacks of mining. To achieve higher efficiency through ASIC based systems (which are the most efficient and widely used type of mining hardware), manufactures strip down traditional computers and only incorporate components that contribute to solving cryptographic puzzles such as GPUs. The evolution of mining equipment has turned to ASIC based systems that can reach computational levels of 44,000 gigahashes per second compared to 0.01 gigahashes per second from CPUs and 0.2-2.0 gigahashes per second computed by GPUs (Taylor, 2017). This massive efficiency upgrade also is paired with ASICs dramatic decrease in joule (energy consumption) per gigahash at 0.05 which is also a substantial improvement from CPUs and GPUs at 9,000 J/GH and 1,500-400 J/GH respectively. ASIC units have also become more efficient relative to computational power trends (Vranken, 2017). Figure 5 also displays the sustainable energy efficiency improvements through 2017. Although this no doubt improves mining efficiency, it also increases the rate at which units will become obsolete. New ASIC models come to market faster than current lifecycles, which force miners to upgrade equipment without full utilization of an ASIC based mining system.

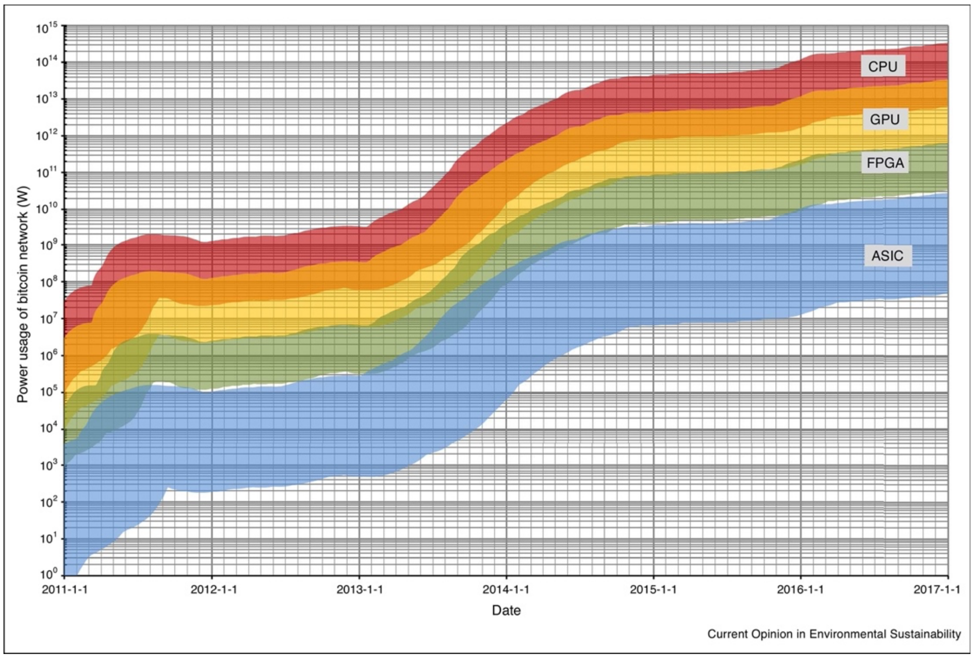

Figure 6. Comparison of Mining Devices and their Energy Consumption (Vranken, 2017)

Despite drastic improvements in computational efficiency and single unit energy efficiency, the mining industry remains plagued with rapidly obsolete technology and continue to upgrade hardware to maintain and/or improve profitability thresholds of devices. Referring to figure 6, presented by Stoll, Klaassen, and Gallersdorfer in their calculation of the carbon footprint, data shows that ASIC based systems are profitable but top manufactures remain very close to the cost of production and price to power consumption of Bitcoin mining.

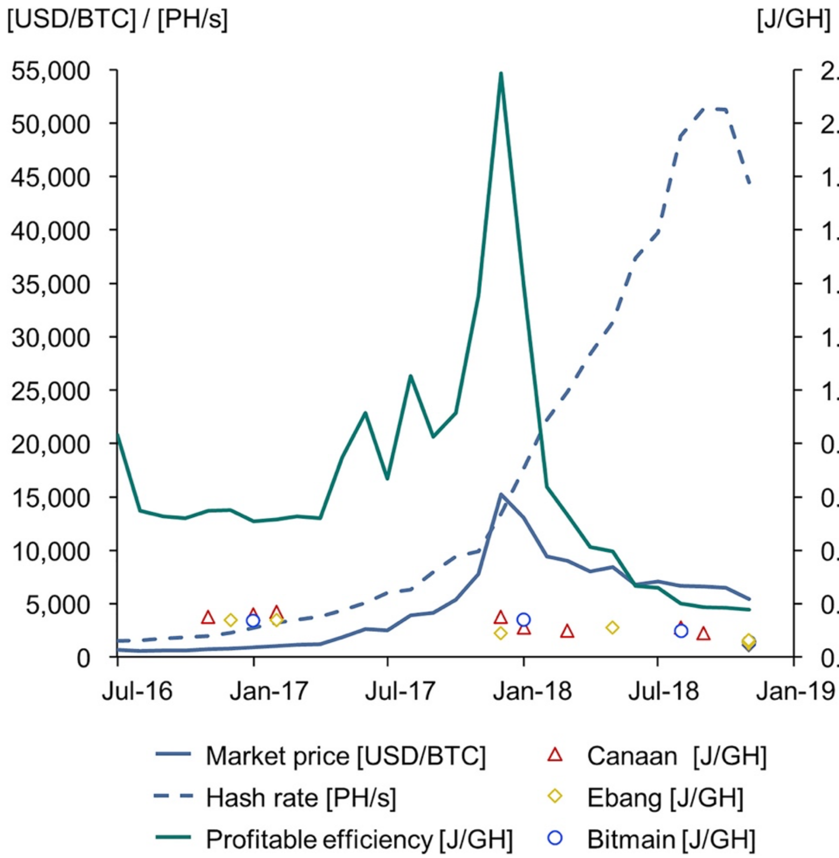

Figure 6. Bitcoin Market Price, Network Hash Rate, Profitable Efficiency, and Hardware Efficiencies of ASIC-Based Mining Systems Released by Major Mining Hardware Producers

The drawback being, ASIC based systems come at the cost of choose 1 of the major manufacturers, Bitmain, Canaan Creative, or Ebang (Tuwiner, 2022). Ironically all 3 of these manufactures have headquarters or produce in China. China infamously has banned the private use of trading and mining of cryptocurrency on environmental grounds, but not has not restricted production or trade of ASIC units. With the current ban in the country, millions of ASIC units must be relocated, repurposed, but fail to be recycled. Stoll and de Vries case study on Bitmain's Antminer S9 reinforces this by exhibiting a shorter average lifespan of 1.29 years but was phased out because of rapidly increasing prices of Bitcoin and the price to efficiency made the model obsolete before a year of being on the market.

E-waste of computer hardware is constituted of toxic chemicals and heavy metals that without proper recycling lifespans will erode soil and exacerbate air pollution (Goodkind, Jones, & Berrens, 2020) and air quality degradation (Erdogan et al., 2022). Bitcoin mining alone has been calculated at e-waste levels of 30.7 Mt with threats of volatility and energy bottlenecks during peak prices can exacerbate the issue up to 64.4 Mt (Stoll, de Vries, 2022). Using initial public offering filing of major hardware manufactures (Bitmain, Canaan, etc.), the authors' study showed that along with exponential trends of power consumption, e-waste and hardware degradation will accelerate under the same economic variables of price volatility and trade volume. Discussed in previous two chapters, the sector dominance of PoW currencies and therefore digital currencies that operate under "mining" rests at around 66%. Bitcoin represents 70% of the market share of PoW currencies is attributed to Bitcoin, which calls for high scrutiny of its carbon footprint and accompanying trends.

3.2 Mitigating *Cryptodamages*

Coinciding with trends of increased participation in the network, PoW mining has evolved into a multi-trillion dollar industry. Now the mining network value chain demands more power than the traditional gold and rare earth minerals industry but will decrease over time in line with Koomey's and Moore's Laws as efficiency (McCook, 2018). Consequently, the emerging industry has displayed large impacts of the negative externalities directly associated with mining. Energy consumption and emissions from fossil fuel continue to plague the industry and fuel negative press from the media, public, and regulators. No longer, does mining have a single cause of concern through its environmental impact. The widespread adoption of PoW cryptocurrencies has spawned many third-party companies that offer financial services such as online cryptocurrency exchanges and even ATMs. Today's value chain of PoW cryptocurrency encompasses far more than the monitoring the process of mining. The Carbon footprint of the industry increases by the year and with price and trade fluctuations. Proponents of digital currency point towards positive trends of renewables entering the industry's energy mix but have less concern over micro-factors such as market incentive for miners to source the cheapest electricity, disruption of supply chains (Wu, Savov, & Mochizuiki, 2021), diversion of renewables from public expenditure projects (Finansinspektionen, 2021), GHG emissions, and the growing concern of obsolete mining equipment.

3.2.1 Miners Decarbonizing Efforts

Despite positive trends of investment into renewables, total decarbonization of the mining industry seems improbable under PoW (de Vries, 2019). The inception of PoW mining had very little environmental consideration attached to the design process. This is noted not to discount blockchain technology, which could provide countless innovation measures to other sectors and industries, but in fact raises the question of the feasibility of decarbonization in the mining industry. The underlying assurance of decentralization is in fact why the PoW protocol is the prominent architecture not solely because it was the original consensus mechanism but maintains security features that are essential for the libertarian promise of a payment method without oversight that was outlined in Nakamoto's white paper. Unfortunately, PoW mining, which currently lacks an international consensus on how to mitigating the damages, has a fractured regulatory approach. Without proper guidance or regulation from monetary and environmental authorities, the industry lacks free market mechanisms that would help curb negative externalities. The industry itself has made extensive strides in factoring in renewable energy to its profile, but has yet to answer the to the feasibility of total decarbonization and if future models could solve PoW's issues?

Negative externalities associated with climate change are the result of the market's failure to solve issues around mining (Truby, 2018). Currently the Bitcoin and Ethereum Sustainability Indexes mark the carbon footprint of the digital currencies at 114.06 Mt CO2 and 52.42 Mt CO2. These marks are increases from previous years as the carbon footprint illustrates that emissions are growing alongside demand and increased participation in the mining network (Stoll et al., 2019). PoW's energy intensive demands have provided more challenges for the emerging industry rather than finding alternatives to tradition and dirty currencies. Unfortunately, the resource-intensive nature of PoW mining has contributed to an environmentally harmful process, despite the emerging industry that has been produced from its model. Intervention in financial markets, especially those without proper taxation and consumer protection, is and will always be a difficult decision to navigate for regulators. In the case of PoW mining, the free market will not correct itself from unsustainable practices because of the industry wide incentive to pursue said practices of purchasing the cheapest electricity available to maximize computational power and subsequently increases the negative externalities of mining. To make comprehensive legislation that protects the market and its producers and consumers, a practical decision must weigh the feasibility of curbing said practices without an industry wide ban. Despite China's ban driving Crypto market prices up (Jennings, 2021) the ban displaced the issues associated with cryptocurrency's carbon footprint onto neighboring countries who also carry a burden of sustainability.

The impact of PoW operations on the environment cannot solely be attributed to the mining industry. For mining facilities to operate, they require power. Power purchased by miners derives state owned energy departments generated by state- or privately-owned power grids. Power purchased by miners is and will be dependent on which state or region is providing easy access to cheap electricity prices per kilowatt hour (kWh). Before China's 2021 ban on mining and trading, China was the global leader in hashrate yet, the Asia Region was reported by Cable UK to be midtable when referring to energy prices. China specifically had an advantage through hydroelectricity production which would surge during rainy seasons and further subsidize power prices through production surpluses. Miners in China at its peak dominated 75.5% of the global hashrate (Sparkes, 2021) of Bitcoin and were powered by a mix of coal and hydroelectricity. Now after its ban, mining has moved across the globe and remains dependent on a chosen country's energy mix of renewables to maintain a green transition for the industry. In its current state, the mining industry will continue to choose cheap electricity because there is no incentive to by the free market to move to the use of renewables. Analyzing mining sites in a post 2021 Chinese ban world, use of problematic fossil fuel sites in Canada (Black Rock Petroleum, 2021), Kazakhstan, and the United States remain large contributors to the global hashrate. This will be discussed further in Chapter 4 under the framing of the consequences of the Great Mining Migration post China's 2021 ban on mining and trading.

Overall, the effort to decarbonize a PoW mining network is hindered by the duality of the state producing and providing renewable energy and miners purchasing said energy to incorporate into an energy mix that does not produce carbon emissions. A green currency to significantly lighten the negative externalities of mining, but a new model must come to fruition. PoW indirectly incentives the use of electricity produced by fossil fuels and its resource intensively has led to a carbon intensive mining process.

3.2.2 Mining Activity and Social Impact

Despite negative externalities associated with the environment, advocates of the cryptocurrency revolution have underlined blockchain technology as an enormous improving on outdate and dirty technologies and provides new opportunity through technological innovation (McCook, 2018). Research from the field of social science sees the blockchain technology and cryptocurrency as independent phenomena and should be managed as such. Cryptocurrency and its mining process powered by PoW have been linked to myriad of potential social issues.

Sentiments around cryptocurrency are changing rapidly amid large spikes and drops in pricing. Finansinspektionen (Swedish Financial Supervisory Authority) famously called for a ban on PoW mining and the noble prize winner Joseph Stiglitz who has called for bitcoin to be banned because it's, "successful only because of its potential for circumvention [and] lack of oversight (Davis, 2019)." Critiques and reports claim that over half of cryptocurrencies provide no function or use for its userbase (Bardinelli & Frumkin, 2018). These concerns expressed have been validated by various social science papers. Alex de Vries has spearheaded this concern by making the connection between environmental demands of and public needs. Using research from Goodkind, Jones, and Berrens', the calculation of value created through energy use versus cost to mitigate damages of energy use has reached a ratio of $1 to $0.49 (Goodkind, Jones, & Berrens, 2020). The authors then were able to correlate this data into a cost-benefit analysis of mining cryptocurrency in the United States. Using price of BTC over time, compared with the increasing complexity of mining over time, the authors illustrated that environmental and social cost of mining has increased whereas the price and therefore value of BTC has fallen relative to increased trends of electricity consumption. This also aligns with what is discussed in Chapter two of this paper that points towards the inherent inefficiency of PoW as the culprit for increased consumption and worsening of negative environmental externalities.

De Vries then points to lack of international alignment of the industry as a problem of exploitation. Using the example of mining in the Navajo Territory in New Mexico, the author notes that the Canadian cryptocurrency mining company Westblock Capital operates in said area has signed Crypto Climate Accord. The agreement unites cryptocurrency miners transition to a greener digital currency through the implantation of renewable energy profile but continues operations in Navajo Territory that is fuel by coal (Ottenhof, 2021). The project is frame by the company to economic independence and job creation within the sovereign territory. In actuality, the project operates in a territory where % of citizens lack basic utilities. Westblock and other companies operating in this space display a trend of exploitation of weak regulatory bodies that provide cheap energy. Vice reported that the mining facilities generate up to $1.6 million per month, and only pay $60,000 in annual land leasing rights and $48,000 annually in energy costs. The energy cost of operate is on average 1/10th of what an average citizen the territory would pay for utilities. 15% of the territory remains in extreme poverty and many homes are without water and power lines. This is not an exclusive case, as trends of exploitation and resource diversion from quality-of-life improvements can be seen even just miles northwest in Chelan County of Washington State (Samford & Domingo, 2019), El Salvador, and Black Sea Territory of Abkhazia.

Municipal and regional energy departments seek emerging industries and business to grow the local economy. Turing electricity production into currency is the promise that mining facilities can make to local governments but, mining operations does not offer socioeconomic benefits that outweigh the political, environmental, and social risks. Power consumption demands of mining operations require the use of renewables, which depletes the supply of clean energy way from public expenditure projects and other industry's that drastically need to decarbonize but also provide massive societal impacts. Regulators at the national and international level must assist in the transition and expansion of mining operations to new locations. The 3rd Global Cryptoasset Benchmarking Study found that of the 28% of miners that receive subsidizes from state departments or state-owned enterprises, 75% of that financial support comes from local governments (Greenberg & Bugden, 2019). This runs in stark parallel which has been displayed between exploitation of low income and marginalized communities that produce cheap electricity and weak agencies and local regulators prioritizing subsidized fossil fuel energy to mining facilities over citizens that lack basic utilities, creates a need for an authority that specializes in mitigating *cryptodamages*.

Chapter 4: The Great Mining Migration: Does Banning Proof of Work Mining and Trading Solve Sustainability Issues?

The call of industry regulation of cryptocurrency trading and mining has been propelled into the public and regulatory spheres through media scrutiny over a growing negative public perception. Impact on the environment, sentiments towards the feasibility of crypto as a "real" currency, and concern over fraud has come to the forefront of the regulatory discussion. Policy makers around the world are involving central banks and regulatory bodies to ensure proper consumer protections. In addition, governments are concerned about the energy dependency the industry operates within. Under a proof of work consensus algorithm, volatility in price along with the price of electricity has dictated the profitability of cryptocurrency mining and states will begin to weigh the public benefit of housing the industry within its borders. This chapter will aim to answer the initial research question which asks if nationwide bans of PoW cryptocurrency operations quell socio-environmental impacts of mining and trading. Analysis will utilize the use of energy mix and infrastructure capacity statistics of China, Kazakhstan, and the United States to illustrate how the 2021 mining and trading ban has levied negative externalities on to countries that lack a modern power grid and modern infrastructure to house large scale mining operations.

4.1 The People's Republic of China

Once a pioneer and domain force the in PoW cryptocurrency space, China shifted the landscape through an industry ban of mining and trading in September of 2021. Beginning in 2011, China had become the global leader in proof of work cryptocurrency mining and global trading volumes of Bitcoin boasting 76% of the Bitcoin hashrate (Armstrong, 2022). This made China an extremely popular destination for miners and their facilities. Overproduction of energy in many regions, such as Sichuan, attracted miners looking for cost effective strategies to tie their geographically bound business. This is no longer the case as many miners are now leaving China for Scandinavia, Russia, and the United States which is in part due to the better broadband infrastructures, cheap electricity, and most importantly friendlier regulation (Parrer, 2019). China has taken what many consider to be a hostile stance towards the entire cryptocurrency industry and not just proof of work mining facilities. To reach the outright illegal exchange of privately owned cryptocurrencies in China, the regulatory road has required multiple actions against all facets of the industry.

4.1.1 Timeline of Actions

Starting in December of 2013, the Chinese Government took hardline action against the People's Bank of China (PBoC) and other financial ministries within the country. A notice containing restrictions on the bank's involvement in cryptocurrency transactions, came only 5 years after the Nakamoto white paper and shocked the mining industry. A collaboration between the PBoC and other ministries produced the "Notice Concerning the Prevention of Risk Related to Bitcoin." This notices what the first of many hardline stances against the decentralized cryptocurrency market as the Chinese government began to doubt its ability to control the market and therefore the fiscal and monetary policy, including evidence of capital flight (Ju, Lu, & Tu, 2015). In late 2013, Bitcoin had surpassed a $1,000 USD valuation for the first time and reportedly lost around 30% of its valuation 10 days after the restrictions levied by the Chinese government in December (Sergeenkov, 2021). The PBoC declared that cryptocurrency and specifically bitcoin, is not a currency. In their 2013 statement (which has now been removed from the PBoC's website), the position of cryptocurrency exchange and digital tokens in the domestic market would now be under the classification of "virtual asset and digital commodity." This restriction completely banned central monetary authorities and payment companies from dealing in bitcoin related transactions (Xie, 2019). This did not explicitly bar private citizens from participating in exchanges, as the restrictions in place during 2013 did not outlaw exchange websites.

As the initial step of cryptocurrency regulation in China, The PBoC and collaborating ministries only explicitly banned financial institutions and payment companies from interacting and accepting cryptocurrency as legal tender. Firstly, the Chinese Government sited cryptocurrency as a “speculative asset.” Bitcoin and other cryptocurrencies alike weaken the state’s ability to monitor and maintain monetary and fiscal control because the volatility of the asset is related to the untethered valuation of cryptocurrencies. Secondly, the notice did not ban the trading of bitcoin and was explained by an explanatory note that the trading of bitcoin by citizens comes at personal risk (Wang J., 2013). At the time, this gave merchants and miners hope that regulation in the future would follow a similar approach that would align with the PBoC’s of risk mitigation rather than outright banning a market still in its infancy.

However, fast forwarding to 2017, there is an echoed sentiment from the 2013 restriction notice from Chinese monetary authorities in the banning of cryptocurrency exchanges. On 4 September 2017, made an announcement that all financing through cryptocurrencies were now illegal. Meaning that exchanges that participated in Initial Coin Offerings (ICOs) had now been barred from the activity and were even mandated to payout registered private accounts within 6 months of the 2017 notice. The notice also contained phrasing that cast an illicit perception around the use of bitcoin stating that, “suspected of [being involved] in the illegal sale of coins, illegal issuance of securities, illegal fundraising, financial fraud, pyramid sale and other illegal and criminal activities (Rizzo, 2017)."

This notice also reaffirmed the strong position that the PBoC took in 2013. It restated that cryptocurrency was not to be considered “legal tender” and merchants are not mandated to accept payment in the form of cryptocurrencies. To cement this the 2017 notice went one step further and outlawed bitcoin as coin substitution. Where many countries including the United States and Iceland have opted to classify the currency as flexible substitute rather than a coin substitute. This would allow for some oversight around the trading and pricing of coins and their ICOs. China and the PBoC instead choose “coin substitution” to force exchanges to relinquish control of the ICOs. Coin substitution and therefore is subsequent circulation and exchange between fiat currencies had been banned over bitcoins ability to circumvent traditional Chinese monetary policy enforcement mechanisms (Hu et al., 2021). By banning ICO’s through reclassification of bitcoin and cryptocurrencies as coin substitutes, the notice was then able to bar exchanges from any financing activities or services involving cryptocurrencies. By crippling cryptocurrency exchanges from participating in ICOs or financing activities, exchanges have lost a level of legitimacy. Now exchanges were completely unable to participate in pricing (from the 2013 notice) and now includes trading and acting as a primary agent for financing and financial services operating within the cryptocurrency market.

Tracking the buildup to the eventual 2021 ban of private cryptocurrency, the PBoC had only sited financial reasoning for the action against the industry. Now in 2017 the field had evolved to incorporate stricter punishments such as the clause that stated if a financial exchange or institution were to violate the 2017 notice, it would lose its business license. Although harsh for many financial institutions, legal compliance from the notice only appeared to effect businesses classified as a financial institution. Still the position on mining in the state was unclear as no regulations at that point had been put forth to mitigate the known damages of fossil fuel proof of work cryptocurrency mining.

Due to the 2017 ban on ICOs, domestic websites had been forced to shut down because of the PBoC fear of capital flight (Aysan & Kayani, 2022). Although not explicitly stated as their intention, large exchanges such as BTC China were forced to relocate trading operations as well as reassess its ability to continue mining operations within China.

Coming to 2020, PBoC continued paternalistic intervention in the market and began its full ban on cryptocurrency operations including mining. By late 2020, the state had begun the rollout of the Digital Renminbi or Yuan which started development in 2014. This effort was directly associated with combating the uncertainty of the cryptocurrency market, issues of capital flight through cryptocurrency, lack of financial oversight, and finally the issue of mining. For the PBoC, this meant that maintaining sovereignty rights over economic freedom offered by cryptocurrency was of the upmost importance. Rollout testing of the digital Yuan had begun to overlap with the larger ban on all operations and financial transactions involving private cryptocurrency. At the time, over 2/3rds of global (reaching

76% at its peak) bitcoin mining hashrate was validated by Chinese mining facilities (Davies, 2022). To the state and notice posted by the PBoC, Bitcoin and other private cryptocurrencies were being issued by "non-monetary authorities." This further invalidated the exchanges and therefore mining operations within the state because now the currency was not legal tender nor was it allowed to be produced within the country due to is decentralized and upregulated nature. The notice also put a ban on provincial mining in regions associated with renewable energy production for cryptocurrency mining. This was the final straw for many private exchanges and mining facilities as many were forced to relocate to more suitable environments such as Russia, Kazakhstan, and the United States.

4.1.2 Sentiment and Reasoning

Statements made by the PBoC from 2021 differ from reasoning associated with the 2013 and 2017 bans. Restrictions from earlier bans focused on classifying cryptocurrency to maintain monetary control over the decentralized assets. Amid an already complex mining environment, miners felt that the regulatory pressure that was being exerted by the PBoC would hinder hashrate. Ultimately the 2021 trading and mining ban resulted from two major sentiments. Firstly, regions such as Shanxi, Guizhou, Xinjiang, Sichuan, and Inner Mongolia, were all top ten mining areas in terms of hashrate before the 2021 ban, but after multiple coal mining incidents that endangered the lives of coal miners, local legislation suspended coal mining production in multiple locations. This bottlenecked Bitcoin mining and resulted in a 30% decrease in hashrate and pushed transaction fees to all-time highs (Pan, 2021). Secondly, and most surprisingly, the State Council had declared trading and mining of cryptocurrency detrimental to achieve decarbonization goals and attributed the energy-intensiveness nature of mining as deferential contributor despite lack of domestic environmental regulation for use of fossil fuels for digital and traditional mining (Li et al., 2022). For instance, the Bitcoin mining facilities in China were heavily dependent on coal-based power, which accounted for ~63% of energy used for PoW mining operations (Mellor, 2021). In May mining operations had been restricted and by September both trading and mining had been banned from private operation.

Outside of the proclaimed reasoning of the 2021 ban, researchers and proponents of cryptocurrency feared that China was overregulating the industry to quell issues of capital flight through Bitcoin by utilizing online exchange platforms. In 2015, Ju, Lu, and Tu found that before the 2013 Chinese restrictions trading strong evidence that capital flight was not only present in cryptocurrency exchanges but in fact was significantly hindered after the ban. Domestically, restrictions have been a success in identifying proper channels to reduce legal risk. The unique structure of the Communist Party of China has positioned the party in opposition to the decentralized nature of cryptocurrency and has forced the hand of regulation from the worlds hashrate leader.

4.1.3 Regulatory Outcomes

The 2021 Chinese ban on trading and mining cryptocurrency had outlined provisions that (1) deemed all crypto transactions, trading, and investments as illegal, whether executed via local or foreign platforms, (2) All Chinese nationals who worked in marketing or tech support roles for foreign exchanges would then be subject to legal prosecution, and (3) enabled the NDRC to set out plans to ban cryptocurrency mining by serving investment in the sector by increasing electricity costs and blocking new companies from entering the industry. Prior to this ban, China had accounted for 46% of the global bitcoin hashrate and was largely contributing to this production through dirty energy mixes fueled by coal. Despite and increasing use and implementation of renewable energy projects with hydroelectricity in mining operations, the seasonal dependency of hydropower left mining operations no choice but to use coal during dry seasons. The NDRC and PBoC felt the responsibility to address the problematic nature that cryptocurrency activities have on the environment and financial system.

Since the 2021 ban, hashrate in China has drastically fallen and is currently the second most efficient country in terms of hashrate. According to Cambridge Bitcoin Electricity Consumption Index the United States accounts for 37.84% and China now accounts for

21.11% (Cambridge Bitcoin Consumption Index, 2022). This is due to the spillover effect of a national ban, that has displaced large scale mining operations. Moving to a complete ban of private cryptocurrency activities appears to be a logical approach to reduce the negative externalities of mining on the environment, however the 2021 ban has only pushed the consequences outside of their boarder.

Nationally the problem has not receded, as 21.11% of the hashrate of Bitcoin is still attributed to operations within China's boarders. Spillover effect directly associated with the national ban on trading mining can be represented through the new incentive of available mining share. With a rapidly decreasing hashrate, large scale mining facilities and even newcomers in the industry have a larger share to gain for their individual operation. This will require an increase in computational power, which means, more energy, new mining hardware, and environmental impact will all be greater. However, the 2021 ban on mining and trade left miners with little to no alternatives. Miners either sold off equipment (Black Rock Petroleum, 2021) or moved to countries with cheap electricity and favorable regulatory policies such as the United States, Russia, Canada, and Kazakhstan.
The difference being the displacement of existing miners that were profitable will need to seek new a profitable location which means miners will continue the exploitation of local agencies to implement the cheapest power available. On an international level, the national ban has added a layer of complexity to the Great Migration and asks if banning PoW mining is the answer the reducing negative externalities.

China refused to sit back and wait for other countries to act on regulating cryptocurrency. Instead, choosing to ban trading and mining of publicly accessed blockchains such as Bitcoin and Ethereum, has pivoted into a pilot program and later fully scale rollout of the digital Yuan. Choosing to launch the program in regions with positive dispositions to mining such as distributing new coins to 50,000 residents in Shenzhen and 100,000 residents in Suzhou receive a distribution of 200 digital Yuan. This would be the world's first sovereign digital currency, that would allow for the implementation of blockchain technology to be spearheaded by the state government. Although this measure appears to be somewhat of a compromise for the PBoC, the initiative is still oppressing the freedom from the state represented in publicly accessed blockchains. Despite efforts of Chinese courts to recognize public digital currencies as legal property but have been overruled by the PBoC wide ban on trading and mining. This left individual citizens without consumer protections who could not offload their investments in now banned exchanges and in turn took massive losses on illicit PoW cryptocurrencies.

4.2 The Great Mining Migration

International frameworks for green transition of the industry exist in the form of the Crypto Climate Accords. The accord's mission states:

> "Surging demand for cryptocurrencies and accelerating adoption of blockchain-based solutions have highlighted an important issue: the technology's growing energy consumption and its impact on our climate. That's why we're working collaboratively with the crypto and blockchain industry to accelerate the development of digital #ProofOfGreen solutions and set a new standard for other industries to follow. Inspired by the Paris Climate Agreement, the CCA is a private sector-led initiative for the entire crypto community focused on decarbonizing the cryptocurrency and blockchain industry in record time. Together, we will #MakeCryptoGreen." (Crypto Climate Accord, 2022)

However, the authoritative power is less than desirable as the accord is only a voluntary agreement for decarbonization by 2030. Lack of oversight on decarbonization efforts is illustrate in the rapid rise of mining in Kazakhstan and expansion of mining in individual states in the U.S. that have overreliance on fossil fuels. When examining the migration of the industry it's important to note not only the incentive to choose cheap power resources but also choosing agencies that have beneficial tax frameworks, positive cryptocurrency perspectives,

4.2.1 Spillover in Kazakhstan

The rapid emergence of Kazakhstan as a cryptocurrency mining location is directly caused by the 2021 ban in China. Increase in share of global hashrate of Bitcoin now total 13.22% which is down from the 18.1% immediately post Chinese 2021 September ban but has netted a 5.02% hashrate improvement compared to its former rate prior to the ban (Blandin et al., 2020). Data also estimates that a fifth of global Bitcoin mining production was migrated to the country (Fintech Perspective, 2022). These numbers appear to give the impression that the mining industry had found a suitable home and would remain in Asia. This perception does not display how failing power grid infrastructure in Kazakhstan would jeopardize the mining industry and be partially responsible for energy consumption increases that would cut off many citizens' accesses to power.

Kazakhstan's state power grid's energy profile mix is extremely disproportionate to the trend seen in mining industry. Renewable energy uses its not only and initiative by energy conscious miners but benefits the business model of PoW mining with cheap power such as hydroelectricity. The case of Kazakhstan is drastically different where only 1.4% of the energy mix of the state comes from renewables (EIA, 2020). EIA reportedly found that fossil fuel generation comes from coal generates 54% of the energy mix followed by natural gas and oil that amount to 25%. Kazakhstan also boasts the worlds 5th largest crude oil reserve and export $25.2B in Crude Petroleum, making it the 9th largest exporter in the world (OEC, 2021). Kazakhstan as a nation is economically dependent on this fact, but its citizens are much more dependent on fossil fuels than cryptocurrency mining rivaling countries. The Green Economy Concept is an initiative started in 2013 that pledges most of the energy production will come from other sources than coal and crude oil (PAGE, 2020). Although a noble mission, this alarming disproportion of fossil fuels has led to the inability to a commit to a green transformation. For the emerging cryptocurrency mining industry, that has received negative public backlash for its "dirty" process, migration into Kazakhstan has manufactured other issues.

Power grid technology in Kazakhstan today is the remnants of Soviet Era technology. Crumbling infrastructure of the power grid is due simply to wear and tear of a system that has been in use for over 40 years. President of the country Kassym-Jomart Tokayev claimed that “age-related damage had led to 4,458 technological breakdowns in 2020 alone (Bisenov and Tobin, 2022). Cryptocurrency is of course dependent on power production of the grid that its purchasing from and the state of the Kazakhstani grid raises questions of stability. January marked a new dilemma for regulators as rising fuel prices (through a market price cap removal) acted as the catalyst for riots with reports of looting (NPR, 2022). Within this metaphorical power struggle, a literal case emerged as authorities decided to shut off internet access to quell efforts of citizen organization. This has had massive consequences on miners who had already been exacerbating environmental externalities through use of fossil fuels. Fallout from the broadband access blackout for six days, miners lost an estimate 20.8 million USD of potential transaction fees and mining rewards. The country had originally embraced the migration of minors post September 2021 (Sparkes, 2021) but were trust into the myriad challenges that come with mitigating damages of cryptocurrency. Adapting warehouses, powering mining facility hardware, and brokering private consumption deals with miners was a good step for the energy ministry but failed to account for outdated power grid infrastructure that could not withstand the exogenous shocks of the global energy market.

Within the country’s own energy consumption increase, Kazakhstani Energy Department identified the issues of “white” (registered) and “grey” (unregistered) miners as the culprit of the energy increase across the country. Authorities then mobilized search groups, a WhatsApp hotline for citizens, and a creation of a Facebook reporting page by the digital ministry to help energy authorities crack down on unregistered mining. With current blackouts and instability issues around power infrastructure, miners have not been able to properly operate since October and have suffered greatly through the January fuel price riots. When miners do operate, they are drastically increasing power consumption that diverts power away from a grid that can’t fully power homes of its citizens and continues to operate on an unsustainable energy mix. China’s 2021 ban has displaced miners into unfavorable locations that will exhibit higher levels of negative externalities of e-waste, energy consumption, and socio-economic imbalances through privately brokered deals with energy suppliers. Additionally, the ban has not solved the socio-economic issues exhibited in China, but in perpetuated further uncertainty of the possible of a subsequent migration away from Kazakhstan. Further migration would perpetuate the cycle of exploitation of local and even lax national energy regulation, use of fossil fuels, and negative consequences for marginalized citizens, which would greatly offset any environmental benefit gained from the 2021 Chinese ban (Sang et al., 2022).

4.3 Convergence in the United States of America: Wyoming and Texas

Fortunately for the mining industry, not all alternative hash rate locations exhibit weak regulatory agencies. The United States has embraced the cryptocurrency revolution in its regulatory approach and has this been coupled with cheap and a surplus of energy. Before the 2021 Chinese trading and mining ban, the United States firmly positioned itself as the worlds 2nd largest contributor to hashrate. Since the ban, the U.S. has become the dominant market force, commanding 37.84% average of the monthly hashrate share (Cambridge Bitcoin Electricity Consumption Index, 2022). There has been widespread convergence of new mining operations across the country. Regulation in the country has centered itself on the issues pertaining the currency as a security, to make taxation and classification feasible. In hopes to not hinder the innovation that blockchain technology could bring to U.S. infrastructure (Xie, 2019). The fractured approach at the international level analogous to the federalist system of the United States that has allowed for various approaches by state legislatures. For example, Plattsburg, New York became the first and only city in the United States to ban cryptocurrency and specifically mining. This ban does not apply to New York State and widened the fissure of regulatory approaches. Beyond this, the incentive for mining operations to relocate in the United States is no exception to the market incentives seen in China prior to 2021 and now in Kazakhstan. Lacking a uniform approach, cryptocurrency mining will circumvent policy that hinder production and seek locations that are prone to the negative externalities associated with the process.

4.3.1 Open Arms of Wyoming

Assessing the capaicty of the United States' energy infrastructure to accommodate a large increase will start with analyzing which of the 50 states miners are choosing to operate in. Coinshares annual report found that three states have a dense concentration of mining activities and for similar reasons. The State of Wyoming has embraced the industry by enacting lax security regulation, has access to energy priced well below the national average, and has ample space for new facilities and facility expansion. Wyoming has become the epicenter of pro-cryptocurrency regulation as the state legislature has enacted HB0043 that defines a digital asset as an intangible under UCC Article 9 (Sixty-sixth Legislature of the State of Wyoming, 2021.). This further categorizes cryptocurrency into three distinct personal property assets. The state also enacted a law that created a further LLC filing for blockchain technology companies called Decentralized Autonomous Organizations (DAOs). Thirdly, the state has allowed for banks to operate with and provide financial services pertaining to uses of cryptocurrency. This provides a plethora of consumer protections and state regulators hope that by demystifying the legal uncertainty consumers will be more likely to invest into the market (Pereira, 2021). Wyoming's embrace of the innovative market will set a ripple effect for states looking to integrate the industry but has ultimately failed to mitigate the negative externalities with legislation and has opened itself up to socio-economic vulnerabilities of mining. For instance, Wyoming is a large producer of surplus energy, and the EIA calculates the state produces 13 times more energy than it consumes. The drawback of this pertains to environmental risk, as the state only incorporates 22% of its energy from renewable resources and is the nation's largest coal producer (EIA Wyoming State Profile, 2022). The state also lacks a Renewable Portfolio Standard (RPS), which is a requirement by national legislatures to generate a set amount of electricity through use of renewable energy, despite having ample capacity and resources in solar and hydropower. For example, energy production accounts for 55-65% of State revenue that is specifically generated from fossil fuel production, but without a RPS the local governments and business have no threshold for renewables to be factored into the state's energy mix (Wyoming Outdoor Council, 2021). In fact, Hydropower only accounts for 2% of the state's energy mix despite being the statistically preferred choice for mining operations. Wyoming exhibits a carbon intensity well above the national average of 420 g/kWh that has reach levels of 830 g/kWh (Coinshares Annual Report, 2021). Figures 7 and 8 display the average carbon intensities in mining regions across the world and across North America respectively.

Region	Carbon Intensity (g/kWh)
Azerbaijan	638
Canada	234
China	318
Georgia	95
Global	492
Iceland	0
Iran	507
Kazakhstan	787
Malaysia	589
Norway	7
Russia	477
Sweden	19
United States	447
Weighted Average	**466**

Region	Carbon Intensity (g/kWh)
Alabama	360
Alberta	614
British Columbia	33
Manitoba	1
Ontario	35
Quebec	4
Georgia	381
Kentucky	810
Minnesota	391
Montana	791
Nebraska	566
Nevada	336
New York	156
North Carolina	356
US Other	398
Pennsylvania	349
South Dakota	179
Texas	411
Washington	130
Wisconsin	586
Wyoming	830
Weighted Average	**420**

Figure 7 Carbon Intensity of Region by Countries with mining operations

Figure 8. Carbon Intensity of North American Regions with mining operations

Wyoming uniquely positions itself against other mining intensive states because of its energy production surplus, availability for facility expansion, and relatively cool temperatures. The Wyoming energy authority claims that the state is prone to the most days in a calendar year that register below 85°F or 30°C (WEA, 2021). Coupled with the fact that Wyoming ranks well below national average for national disaster risk, the State has fostered a sustainable financial environment for mining with the exception being its problematic energy mix. Power consumption is relatively a non-issue as even Native Reservation lands are better connected through private land leasing deals totally $157 million to local tribes that have netted improvements in the power grid (WEA, 2021). Security regulations and legal definitions have also positioned the state to become a global leader in the industry as state regulators aim to achieve 5% of the global hashrate of PoW cryptocurrencies by 2024 where supply will be cut in halve yet again (Bitcoin Clock, 2021).

4.3.2 Texas and Privatized Power Infrastructure

Regions and individual states across the nation lack holistic approaches that factor in risks from multiple dimensions. Exhibiting lack of regulatory oversight, but fostering healthy financial environments, Texas has become a hotbed for mining operations. Texas became the second state to adopt a legal definition of cryptocurrencies through the enactment of 87(R) HB4474 or the Virtual Currency Bill. Defined as

> [“Virtual Currency” means a digital representation of value that functions as a medium of exchange, unit of account and/or store of value and is often secured using blockchain technology.] (Virtual Currency Bill 87(R) HB4474, 2019)

Implementation of the Virtual Currency Bill has morphed Texas into emerging opportunity for cryptocurrency miners and has provided investors with consumer protections other than national legislation classifying cryptocurrency as property. Prior to the bill’s enactment, the State of Texas had begun massive renewable energy investment projects that now account for 14% of the entire nation’s electricity generated from renewables (EIA Texas Profile, 2022). On the state level, 25% of all electricity generated in Texas comes from renewables, with a large majority being generated by solar and wind resources. Wind accounts for over 80% of electricity generated by renewables (EIA Texas Profile, 2021) and is the nation’s second largest producer of solar energy behind California. Even with such a high energy mix of wind power, solar potential is said to be growing with total Megawatt production reaching 10,329 in December of 2021 which is almost double what production was a calendar year prior at 5,987 MW. Despite this capacity and renewable energy potential

Texas remains the nation's largest net energy supplier which is dominated by natural gas and crude oil. At the time of writing, rising fuel prices across the globe are altering energy infrastructure landscapes and Texas has seen a price increase of 1.883% for kWh but remains in the top 10 cheapest electricity price per 50 states (Electric Choice, 2021).

Despite an improving energy mix with high potential for renewables such as solar energy, Texas suffered a cataphoric energy infrastructure crisis in 2021. During February of 2021, more than 4.3 million homes and business were without power consequently from a deep freeze and record low temperatures in the state (Sulivan and Malik, 2021). The storm had frozen wind turbines that had failed to be "winterized" which causes massive energy strains on remaining resources. Solar power only generates 4% of the state's renewable electricity and while the state is experiencing massive levels of drought the geographic location limits hydroelectric production to 0.3% of the state's total energy production. Only 23 dams remain in Texas, with less than 12 being active at any given point (EIA, 2022). This left fossil fuels as the main production resource, which failed highlights the vulnerabilities and lack of capacity of Texas's power grid. The New York Times reported that even though wind turbines had failed to be winterized the overreliance on natural gas was the real culprit, as major pipelines had been found frozen solid and unable to transport fuel. Official reports by the Department of Health and Human serves found that 246 citizens perished during the energy crisis (Texas Department of Health Services, 2021). Linking the emerging cryptocurrency mining to the energy crisis does not have a direct correlation or causation but does illustrate how regions and areas with failing power infrastructures already display negative effects on its population. The state of mining today displays negative externalities that effect the environment and display varying societal impacts dependent on existing infrastructure prior to mining industry expansion or entry.

4.4 Lasting Effects of Migration

After the Chinese 2021 Ban on Cryptocurrency trading and mining, the industry was left in flux and desperately needed to find alternatives for operations based in China. Miners took approaches of; (1) selling off equipment and shutting down operations, (2) relocation of operations to regions and countries that possess friendly regulations or dispositions to mining, or (3) remaing to China and operating illegal mining operations. All of which exacerbate the negative socio-economic externalities defined by researchers and academics.

The case of Kazakhstan shows how an emerging industry that seeks friendly regulations will exploit and directly cause increases in energy consumption. 20th century energy infrastructure was unable to keep up with the demands of a PoW mining operation expansion and has been cited as the reason of energy consumption increases. Multiple government officials including the country's president have backtracked on these statements and hope that externalities of the fuel riots have subsided, and energy production will return to normal. Kazakhstan lacked major oversight over cryptocurrency production as energy consumption problems began in October of 2021, which was less than a month after the September mining and trading ban in China. Kazakhstan has a 15% tax on mining operations (Freeman Law, 2021) in hopes that mining facilities provided jobs and in turn diversify its economy from oil production. Instead, exploitation of the overdependence on oil led to extremely negative social externalities and put a strain on mining operations whose main energy resource was oil. Profitability sank and large-scale operations are prone to seek a more stable environment which opens for potential migration and displacement of negative mining externalities.

The Great Migration of miners also discovered a lifeline in the United States who has taken on the challenge of classifying cryptocurrency with making digital currencies legal tender. Within the federalist system, individual states have taken steps to foster financially safe environments for miner profitability and consumer protections. Despite good faith decisions by local and state governments, infrastructure capacity issues and unbalanced energy mixes will reverse positive trends seen across the mining industry. Lack of hydropower in both Texas and Wyoming (the first two states to enact legislation protecting digital assets) as well as geographic reliance on fossil fuels, pose uphill battles for renewable integration. Texas is the nation's top supplier in net energy production (64.8%)

(BLS Report, 2021) and will continue to export fossil fuels to maintain their exporting revenues which total $100.5 billion. Mining will continue regardless of state energy mixes because Wyoming and Texas both have room for expansion as well as rank in the top 10 of cheapest electricity prices per kilowatt hour. Texas's capacity to accommodate an influx of mining operations is highlighted by its solar energy production potential and high wind power production. It is then plagued with overreliance on fossil fuels and a privatized power grid that relies on the free market to determine what citizens will use to power their homes and businesses. The free-market lacks correction mechanisms for clean energy and incentives cheap energy over all resources. Generally fossil fuels maintain cheaper prices than renewables because of the infrastructure upgrades to build out renewable energy capture technology. Conversely, after upgrading and integrating renewables into the power grid, renewable energy prices are now rivaling fossil fuel electricity prices (Masterson, 2021). Wyoming aims to hold a global hashrate share of 5% of PoW cryptocurrencies soon, but also suffer from lax environmental consideration and high use of fossil fuels. To its credit, the state has fostered a relatively safer environment for investors in hopes of igniting an emerging industry within the state. However, Wyoming legislatures have spawned a ripple effect of state legislation that is (1) fractured from state to state and (2) lacks socio-economic fallout consideration. Both states can attribute the benefits of blockchain technology to future infrastructure improvements but mining in its current state is crippling the already flawed infrastructure seen mining dense regions in the United States.

Negative trends of emissions, e-waste, and social exploitation will continue to hurt the mining industry if regulatory oversight is not administered. Case of the United States and more so Kazakhstan illustrates how immediate the negative externalities will affect local environments. Here the catalyst for it all has been China's independent decision to ban PoW activities surrounding mining and trading. The decentralized architecture behind mining (PoW) has exhaserbated the negative externalities documented by researchers and banning such activities has not solved the various issues. China has seen a resurgence in illegal mining activity that is operating through problematic energy mixes, and the displacement of "white" miners across Kazakhstan has put large strains on fuel prices, availability of energy, and incentivized operations to utilize cheap and dirty energy. Across the Pacific, the United States has become the dominate force in global hashrate share but examining locations of mining density in the states of Texas and Wyoming show that regulation only has come in forms of security regulations and legal definitions. Without proper federal guidance the states have fostered their own “crypto-friendly” havens while ignoring the environmental impacts on an already vulnerable environment and power infrastructure. Banning PoW cryptocurrency activities, without internationally agreed upon framework, migrates socio-economic externalities and does not fully quell the operations within a given country than bans such activities.

Conclusion and Policy Recommendations

A shifting landscape due to a great Mining Migration has shed light on the true socio-environmental impacts of cryptocurrency mining. The most prominent form of crypto mining today operates under the Proof of Work consensus mechanism. Miners participate in a PoW "arms race" (Howson & de Vries, 2022) to solve cryptographic puzzles that involve trial and error guessing of the SHA-256 hashing sequence (Vranken, 2017). The largest resulting cryptocurrencies today are the original PoW digital currency Bitcoin and Ethereum that accounts for 66% traded cryptocurrency (Adejumo, O.A. et al., 2022). New blocks are chained to the blockchain every 10 minutes for Bitcoin (de Vries, 2022) and 10 to 20 seconds for Ethereum (Etherscan, 2022). However, the decentralized architecture behind PoW requires high computing power (Schinickus, 2021) to solve the puzzles faster than competing mining facilities. Additionally, when new miners enter the network, solving cryptographic puzzles for computers becomes increasingly difficult (Schinckus, 2021). This is reflected by industry-wide increasing energy demands (Truby, 2018) to maintain large mining facilities that house thousands of specialized mining equipment known as ASIC units (Stoll, Klassen, & Gallersdorfer, 2019). Conversely, energy demands increase despite difficulty in mining as well as price and trading fluctuations (Ahmed, Leirvik, & Sarkodie, 2022). Miners leaving the network for profitability or regulatory reasons garner larger shares of the hash rate to be earned by miners remaining on the network. Bitcoin, unlike Ethereum, has an extra dimension of mining complexity because it has a finite amount of coin supply to be mined with less than 2 million Bitcoin remaining of the original 21 million (Adejumo, O.A. et al., 2020). This causes the PoW algorithm to increase in difficulty regardless of change of total miners on the network. Energy consumption demands will exponentially increase over time because of these dimensions and 341 PoW currently in circulation, mining will find new avenues for revenue.

Energy consumption of mining also finds problematic dimensions because profitability is dictated by efficiency to the price of electricity. To cool and power mining equipment Bitcoin and Ethereum consume to 286.09 TWh of electricity that results in a combined carbon footprint of 159.57 Mt CO2 annually (Digiconomist, 2022) (Digiconomist, 2021). The global green transition to renewables has brought the once expensive resources down to competitive prices. Crypto miners have been at the forefront of this transition and boast industry renewable energy mixes up to 56% (Blandin et Al., 2020). This has its own drawbacks, as the primary renewable power preference has been hydroelectricity across all regions which is then followed by fossil fuels of natural gas, coal, and crude oil. Prices will remain low during the infancy of the world's green transition so miners will continue to choose fossil fuels in crypto friendly regions. Additionally mining has a mounting e-waste problem; Bitcoin produces more e-waste from obsolete mining equipment than the Netherlands (34.98 Kt) (Digiconomist, 2022). Specialized mining equipment known as ASIC units have become the only profitable large scale mining system (Vranken, 2017) amid the current complexity of competition in the PoW "arms race." This specialization however comes at the cost of low average lifespans of mining hardware (Howson & de Vries, 2022) and failure of manufacturers to provide recycling programs (Jiang et al., 2020). If let untended to, e-waste I linked to degradation of land and soil through leakage of toxic chemicals in ASIC units. If energy consumption will exponentially rise, it is safe to assume e-waste will grow alongside increased complexity of mining.

Thin margins of profitability and lack of environment regulation has promoted the discussion over banning PoW operations all together. Regulators must look to mitigate *cryptodamages* (Goodkind, Jones & Berrens, 2020) at the international level. A fracture approach to action or inaction of mining regulation has cause massive spillover seen by the PBoC 2021 Ban on mining and trading of publicly accessed blockchains. Regulators hoped and claimed this action would curb the environmental risks of mining that would offset China's 2050 carbon neutrality goal. After this ban, miners were forced to relocate and sell equipment or face prosecution from the state. Reflected in the sharp decline of hash rate from the once global giant [76% of Bitcoin mining feel to 22.11% (Cambridge Bitcoin Consumption Index, 2022) was a redistribution of mining operations in Kazakhstan and the United States. Kazakhstan's weak power infrastructure took record high demands attributed to mining operations only one month after the September ban in China. Rising fuel prices caused domestic riots and harmed the mining industry for 6 days due to power blackouts to quell riot participates. The United States on the other hand looks poised to remain the global leader in PoW mining and now boasts 34.56% of the Bitcoin hashing rate (Cambridge Bitcoin Consumption Index, 2022). Mining dense states of Wyoming and Texas have opened their arms to the industry by altering security regulations to classify digital currencies as protected assets (Freeman, 2022) (Sixty-sixth Legislature of the State of Wyoming, 2022). Unfortunately, each state's energy profile is dependent on fossil fuels for energy and exports. This is also not reflective of industries crypto climate accord agreement and will hurt the efforts to decarbonize the industries renewable energy mix. Federal regulation in the country only serves fiscal purposes of classification of digital assets and has little to no focus on taxation of mining nor litigating *cryptodamages*.

Fractured approaches leave the industry to free market mechanisms that have only pushed the industry further into flux. Multitude of variables affect mining production and therefore the damage that an unregulated industry can have on its environment. International approaches are beginning to emerge in the EU with Swedish officials recently calling for a ban specifically on PoW mining, but regulation continues to focus on security regulations to define what is admittedly much needed consumer protections. Carbon offsetting has been seen as a possible avenue but will not solve the issue of e-waste caused by short lifespans of mining hardware (de Vries, 2019). Banning PoW will only mitigate *cryptodamages* if a unilateral agreement is made across continents. This would still harm investors who have become stakeholders in cryptocurrency's value. Instead, regulators must collaborate to offset environmental challenges by incentivizing greener consensus mechanisms such as Proof of Stake. PoW has created a revolution for decentralized payment methods and brought to light the importance of a future that in operate a blockchain technology for increased and automated security protocols, such as the digital ledger (Matsuura, 2016). Unfortunately, PoW protocol in mining has created extremely negative socio-environmental externalities that already have costs of half of the value of Bitcoin (Goodkind, Jones & Berrens).

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