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Externalities and market failures of cryptocurrencies

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Abstract

This paper discusses the externalities and market failures in cryptocurrency markets. In particular, I highlight the significant environmental externalities created by Proof-of-Work (PoW) cryptocurrencies, the most prominent of which is Bitcoin. The main goals of this paper are to quantify these externalities, illustrate the mechanisms by which they arise, and finally discuss feasible mechanisms to regulate them. Latest estimates show that Bitcoin mining consumes roughly the same amount of electricity as Argentina or Sweden, with commensurate carbon dioxide emissions. The two main factors driving these externalities are Bitcoin's electricity-intensive consensus protocol and Bitcoin prices, which directly influence mining incentives. Efficient supply-side regulation of these externalities is hamstrung by the internationally mobile nature of Bitcoin miners, creating a risk of carbon leakage and regulatory arbitrage in the absence of a global carbon tax. Moreover, the cryptocurrency market and exchanges themselves are to a high degree unregulated and opaque. This exacerbates the situation since cryptocurrency prices are directly linked to mining incentives. Instead of regulating the miners i.e. the supply side of the market, as the literature has broadly suggested, I recommend focusing on regulating the demand side, the exchanges and marketplaces, as a reasonable first step in the comprehensive regulation of cryptocurrencies. Cross-border coordination is likely to be a crucial aspect in mitigating the environmental externalities of cryptocurrencies.

Keywords: bitcoin, cryptocurrency, externalities, crypto mining.
JEL codes: D62, E42, H23, Q54, Q58.

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26.10.2023

(The opinions presented in this paper represent the author's own views and not necessarily those of the Bank of Finland. For correspondence, please contact topi.hokkanen@bof.fi)

Abstract

This paper discusses the externalities and market failures in cryptocurrency markets. In particular, I highlight the significant environmental externalities created by Proof-of-Work (PoW) cryptocurrencies, the most prominent of which is Bitcoin. The main goals of this paper are to quantify these externalities, illustrate the mechanisms by which they arise, and finally discuss feasible mechanisms to regulate them. Latest estimates show that Bitcoin mining consumes roughly the same amount of electricity as Argentina or Sweden, with commensurate carbon dioxide emissions. The two main factors driving these externalities are Bitcoin's electricity-intensive consensus protocol and Bitcoin prices, which directly influence mining incentives. Efficient supply-side regulation of these externalities is hamstrung by the internationally mobile nature of Bitcoin miners, creating a risk of carbon leakage and regulatory arbitrage in the absence of a global carbon tax. Moreover, the cryptocurrency market and exchanges themselves are to a high degree unregulated and opaque. This exacerbates the situation since cryptocurrency prices are directly linked to mining incentives. Instead of regulating the miners i.e. the supply side of the market, as the literature has broadly suggested, I recommend focusing on regulating the demand side, the exchanges and marketplaces, as a reasonable first step in the comprehensive regulation of cryptocurrencies. Cross-border coordination is likely to be a crucial aspect in mitigating the environmental externalities of cryptocurrencies.

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1. Introduction

Cryptocurrencies are no longer mere upstarts in the financial world. The first and most widespread cryptocurrency, Bitcoin, has now existed for 14 years, and various other cryptocurrencies available today number in the hundreds, if not thousands. The popularity of the most used and traded cryptocurrencies has increased dramatically, as evidenced by the excessive volatility of their prices and the emergence of an entire ecosystem of start-ups, companies, and financial entrepreneurs that deal either directly with the cryptocurrencies or develop second-layer solutions for them.

The energy consumption of cryptocurrencies has also increased markedly, causing ever more global environmental externalities in the form of carbon dioxide emissions. In this paper, I briefly discuss the global externalities that cryptocurrencies and their mining generate and consider ways to regulate them. I focus on the economic aspects of those externalities rather than on their technological aspects. Therefore, this paper intends to be a professional economist's view of both the incentive structure and externalities of cryptocurrencies and the research literature on this topic. For an excellent exposition on the economics of cryptocurrencies, especially the incentive structure inherent in their mining, I refer the reader to Halaburda et al. (2022). For a similarly extensive survey of the literature regarding the environmental externalities of cryptocurrencies, Wendl et al. (2023) is an excellent choice. In this paper I aim to cover both aspects, hopefully shedding some light onto how they interconnect and affect the issue of regulating these cryptocurrencies.

Mine is far from the first paper, or indeed piece of legislation to suggest regulating cryptocurrencies. The current regulatory push for cryptocurrencies in the European Union (see ESRB (2023), Nurminen et al. (2023)) has recognized this need, however with the distinct difference that this regulation mostly addresses the concerns cryptocurrencies create for financial and macroeconomic stability, while remaining silent on the environmental externalities and their regulation. Therefore, my paper augments the rapidly expanding literature on the environmental externalities of cryptocurrencies, highlighting yet another key aspect that warrants regulatory concern while complementing literature that calls for cryptocurrency regulation from a financial stability standpoint.

As the first and best known of the so-called Proof-of-Work (PoW) cryptocurrencies, I will mostly focus on Bitcoin. There are good reasons to focus on Bitcoin: firstly, it uses a specific consensus mechanism (called Proof-of-Work) that consumes a significant amount of electricity and is therefore a source of major environmental externalities. Secondly, the economic agents involved in performing this computational work, i.e. Bitcoin miners, are internationally mobile, difficult to locate and hence also difficult to regulate using standard instruments such as targeted Pigouvian taxes. This creates a rather devious one-two punch of a problem for efficient regulation, since neither first-best methods (Pigouvian taxation) nor targeted instruments are likely to be implementable.

I find that instead of trying to regulate miners and mining pools by way of Pigouvian taxation, more emphasis should be put on regulating the demand side of the Bitcoin market, i.e., the marketplaces and crypto exchanges. These conclusions echo the sentiments of Wendl et al. (2023) who suggest that the environmental externalities of Proof-of-Work cryptocurrencies are best tackled by (demand side) policies that demotivate investments in these currencies, thereby constraining mining incentives through prices.

Since the externalities of Bitcoin arise due to both demand and supply side issues, in the following I will start by giving a brief, non-technical overview of Bitcoin and the technology it uses, and continue with the particularities of its demand and supply, primarily based on received literature. I will then present the current estimates of both the electricity consumption and carbon emissions of Bitcoin and discuss the caveats of these estimates and the implications on effective regulation. Finally, I will present my conclusions and give my policy recommendations.

2. Bitcoin and Proof-of-Work cryptocurrencies in a nutshell

Bitcoin was invented in 2008 by the pseudonymous Satoshi Nakamoto, purportedly as a peer-to-peer electronic cash system (Nakamoto, 2008). In its most fundamental form, it is a decentralized ledger system that uses a specific consensus algorithm called Proof-of-Work (PoW) to write transactions into a public ledger called the *blockchain.* The ledger keeps account of virtual tokens which are called *Bitcoins*. These tokens are transacted with in a cash-like manner, at least according to Bitcoin's design philosophy. However, every Bitcoin transaction needs to be validated by the network and recorded in the decentralized ledger. Therefore, the network needs constant upkeep.

The economic agents doing this work are called *miners*. The miners compete with one another for the right to add new transactions, collected into blocks, into the blockchain. As the name of the blockchain suggests, blocks are cryptographically linked to one another. The right to add a new block is determined by committing computational capacity and solving a cryptographic puzzle using brute force guessing (hence Proof-of-Work).

The winner (the agent providing the correct guess) earns the right to add a new block to the chain. Upon success, the winning agent is rewarded with *a mining (or block) reward*, consisting of both a *transaction fee* and *newly minted Bitcoin*. This is the primary reason these agents are called miners, as they are mining new coins. In the Bitcoin payment system, they act as agents doing the clearing and settlement (Williamson, 2018). Finally, the transaction fees are paid by users wishing to make a transaction with Bitcoin.

Mining rewards are the primary incentive for miners to do their work. However, they are provided in the form of Bitcoin (i.e. native tokens). The total supply of Bitcoin is fixed and set by the PoW algorithm. In other words, more mining does not produce more Bitcoins. Bitcoin supply is essentially capped at 21 million units, with miners eventually exhausting this cap with their operations. The algorithm adjusts the difficulty of the computational puzzle so that a new block (along with its included transactions) is added to the Blockchain approximately once every 10 minutes. What makes Bitcoin's consensus protocol unique is that the resource usage inherent in it (the guesses) is an integral component of its design, maintaining the security of the Blockchain. This is established by way of physical resource constraints, such that a potential attacker wishing to corrupt the ledger would need to essentially redo a majority of the computational effort by replicating the longest interlinked Blockchain (or longest fork), which they will be unable to do unless they hold the majority of the computing power in the network.

The primary issue with Bitcoin from an environmental standpoint is its significant consumption of electricity and other resources. The PoW algorithm essentially functions as an *all-pay auction*, where miners compete against each other in a Tullockian (1980) way. Unlike its more familiar auction brethren, though, in an all-pay auction every bidder, not just the winner, pays their own bid. In Bitcoin's case, these bids are committed computational capacity; guesses that have been made. Therefore, each bid comes with social damages, namely the carbon dioxide emissions of the electricity production.

State of play in cryptocurrency markets

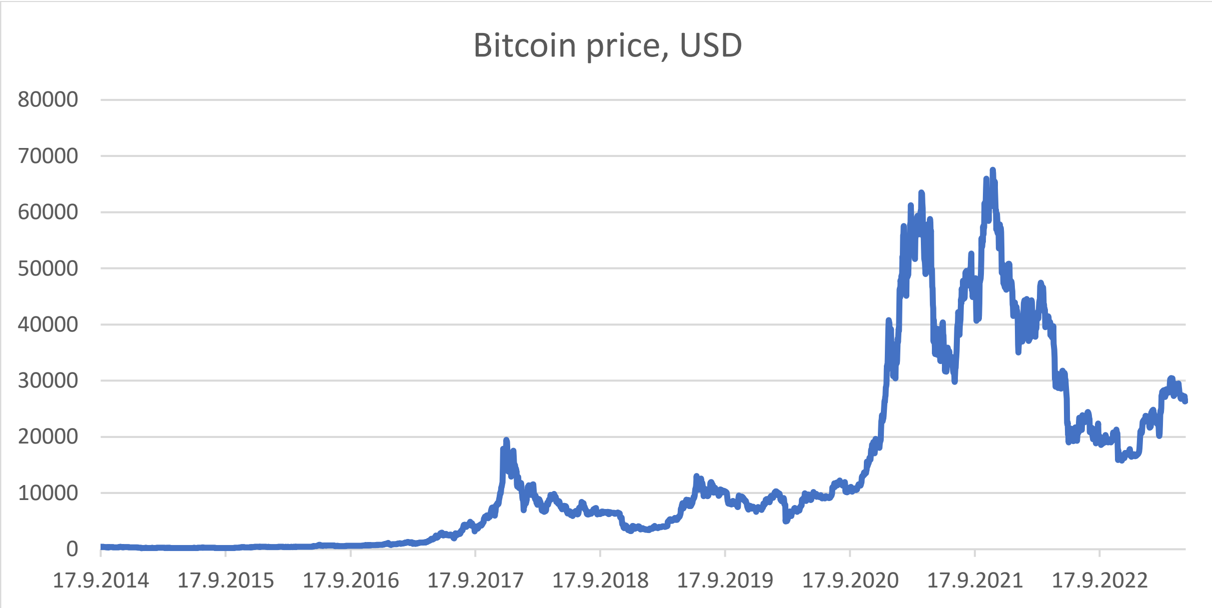

Figure 1: Bitcoin price in USD, source: Yahoo Finance (https://finance.yahoo.com/quote/BTC-USD/history?p=BTC-USD).

As Figure 1 illustrates, after a rather lengthy period of relative inactivity, the market price of Bitcoin has been very volatile starting from 2017 onwards. The largest price movements have happened in recent years, with very sharp price increases and decreases occurring, particularly during the COVID-19 pandemic. From the very beginning, though, Bitcoin and Bitcoin markets have been marked with controversies and scandals. These include (but are not limited to) the seizure of the darknet marketplace Silk Road, and the ensuing controversy regarding the primary use of Bitcoin as payment for illicit transactions, fraudulent marketplaces such as the Mt. Gox scandal in 2014. A more recent example of fraudulent marketplace activities is the rather cataclysmic implosion and bankruptcy of the crypto exchange FTX in 2021 alongside the ensuing "crypto winter" of 2021-2022.

The social costs of Bitcoin mining

Bitcoin mining is fundamentally a competition where each entrant uses their own computational capacity to provide guesses ("hashes") to solve a cryptographic problem. Whoever provides the right guess is the winning miner, and they are rewarded for it with Bitcoin, both in the form of newly minted Bitcoins and the transaction fees of queuing users.

In economics, this form of competition the miners are involved in is called a Tullock (1980) contest (ironically enough originally used to model rent-seeking activity). To give a practical example of a particular Tullock contest, one may think of lottery draws at a festival. One participates by buying a ticket, and one's probability of winning the grand prize increases in the number of tickets bought. In finite lotteries, one can naturally then guarantee a win with probability one by simply purchasing all the tickets, however lotteries are (usually) designed in a way to make this unprofitable. The Bitcoin Proof-of-Work consensus mechanism can be thought of as a stochastic Tullock competition, where the total amount of lottery tickets, or total committed computational effort is unknown since it is essentially set by external market forces, such as the price of Bitcoin, the efficiency of the hardware and miner free entry. The same logic still applies, though, so that the probability of a win (right guess) increases in the miner's own computational capacity. Naturally, as with the finite lottery case, this winning probability decreases in the other players' (miners') efforts.

A second, equivalent way of thinking of Bitcoin mining is as an *all-pay auction* (see Riley and Samuelson, 1981). This auction type differs from other, more familiar auctions in one important way; in an all-pay auction every bidder regardless of whether they win the item, *pays their own bid*. This is very similar to a Bitcoin miner having to spend resources - electricity and money, to operate their mining hardware to provide guesses with only one miner winning and yielding new Bitcoin. Tullock competitions and all-pay auctions are both extensively used in economics to study a particular type of behavior, called rent-seeking behavior, and not without cause (see, for instance, Siegel, 2009). They are used in this manner since they both induce a particular type of externality which other auction or competition formats generally do not, called *effort duplication or overinvestment*[1]. What this essentially means is that in both types of mechanisms, the agents, be they bidders or buyers of lottery tickets end up bidding more than would be socially optimal.

In other settings, these wasted efforts or resources might be rather unproblematic, since why would a social planner or regulator care that a bidder overpays or provides too much effort? After all, it is the bidder or agent that bears the private costs of this overprovision. In Bitcoin's case, though, this is dead wrong. Every miner, when providing their guesses incurs *social costs* in the form of climate damages that affect not only the miner privately but everyone on the planet. Therefore, Bitcoin mining, given the PoW consensus protocol is an *all-pay auction with global externalities*. In essence, Bitcoin manages to combine two separate forms of externalities in a harmful way by coupling a consensus mechanism that induces overinvestment with a form of effort (guesses, "hashes") that creates global externalities.

[1] In fact, the all-pay auction may revenue dominate other, more standard auction types in auction settings outside the independent private values (IPV) -setting (see Krishna and Morgan, 1997 and Goeree et al., 2005).

A third consideration is that successful miners are rewarded with Bitcoin, with the price of the cryptocurrency being determined in the marketplace and on crypto exchanges. This creates an indirect connection between miners, crypto exchanges and Bitcoin prices, as higher Bitcoin prices induce more mining effort, and more miner entry due to the mining market having (in theory) free entry.

A standard solution in economics for such an externality problem would be to levy a Pigouvian tax on the miners, equivalent to their marginal social damages. Such a tax, when optimally designed, essentially increases the private costs of the miners to coincide with the social costs, which then results in a socially optimal production (mining) level, given individual miner optimization. The real problem with this instrument in Bitcoin's case is that the miners themselves are mobile and difficult to locate. Moreover, a harmonized and targeted Pigouvian tax would require a high level of cross-border coordination, a situation that to this day remains elusive in environmental regulation.

Of note is also the fact that Pigouvian taxation can, in principle be implemented by using some other instrument at the regulator's disposal, *given that the induced equilibrium response of the miners is equivalent to one under a Pigouvian tax.* In other words, this means that if corrective taxation cannot be levied directly on the agents causing the externalities, then some other avenue may be used to get results resembling the Pigouvian outcome. The relevant question then becomes: what would be a realistic way to regulate Bitcoin in such a way as to implement an outcome sufficiently close to a Pigouvian tax on the miners?

3. Bitcoin demand and price formation

Bitcoin as a payment system

Bitcoin's stated aim is to be an electronic form of cash. In economics, money (of which cash is but one form) has several important roles. It serves as a store of value, unit of account and as a medium of exchange. Moreover, a subtler point emphasized by, for example Kiyotaki and Wright (1989) is that the medium of exchange role is one that most strongly characterizes money in equilibrium. In other words, many things have the propensity to be (either commodity or fiat) monies, but the critical criterion is whether they are accepted as medium of exchange, which depends wholly on the economy and society at large, since it is a co-ordination problem. At present, Bitcoin, by these criteria is not money (for a detailed analysis, see Grym, 2018) since it fails in most, if not in all of the three roles mentioned above. However, in a Kiyotaki-Wright world of endogenous money, cryptocurrencies do indeed possess many of the desirable characteristics which increase the probability of something being adopted as money in equilibrium such as storability, non-perishability, transportability etc. However, Bitcoin and other cryptocurrencies have yet to establish their acceptance by the society at large, therefore largely failing the co-ordination aspect of moneyness established by Kiyotaki and Wright (1989).

Regarding this latter point, Hinzen et al. (2022) investigate the adoption of Bitcoin as a payment system and show that Bitcoin suffers from a limited adoption problem in equilibrium whenever alternative and faster clearing means of payment are available. This results from the settlement delay inherent in Bitcoin, where the transaction rate is essentially capped at a certain level due to the PoW consensus mechanism. As a particularly useful comparative static, they derive the result that the limited adoption problem vanishes when there is no network delay. To put their results in practical context, they consider a thought experiment of ramping up Bitcoin's transaction rate to 150 million transactions per day (equal to Visa's daily US transaction volume), which in their model leads to Bitcoin transaction processing times of upwards of one year.

If not money, could Bitcoin then still be a viable payment system or investment? So far the only evidence of Bitcoin as a full-scale payment system comes from El Salvador, which experimented with giving Bitcoin legal tender status. Alvarez et al. (2022) report that this experiment has been an almost unequivocal failure. They show that even with a substantial incentive scheme supporting the adoption of Bitcoin, in this case the creation of Chivo wallets for every citizen alongside a $30 payment for anyone downloading it, Bitcoin has not been adopted as a primary payment system in the country. Most users simply traded in their government allotted Bitcoin for fiat currency and never looked back.

Crypto exchanges and their (lack of) transparency

Bitcoin nowadays has a well-developed secondary market in which those holding Bitcoins can amongst other things exchange their holdings for fiat currency or alternatively purchase any of the other various cryptocurrencies in use today. These entities are called crypto exchanges, functioning, ironically enough, as centralized, trusted entities that handle cryptocurrency transactions. In this regard they are not very different from standard financial intermediaries.

One of the well-known issues in studying Bitcoin transactions using the publicly available blockchain data is that many transactions recorded on the Blockchain are not economically meaningful. In other words, they do not represent actual trading or use of the currency. These transaction data include (but are not limited to) wash trading by the exchanges and transactions aimed at obfuscating the origin of the funds. Therefore, if one were to look at pure transaction volumes, the numbers would be highly inflated. Makarov and Schoar (2022) use a novel approach to analyze the Blockchain data, devising an algorithmic method of filtering out the obfuscating transactions, which they dub spurious volume. Using data between 2015-2021, they find that *"the vast majority of real transactions between real entities are for trading and speculative purposes".* Moreover, the authors find that 90% of the observed transaction volume is not economically meaningful, but rather simply due to the design of Bitcoin and the preference for many users for anonymity, meaning that a significant amount of transaction volume is coming from various "mixers", which serve to split and recombine incoming transactions to obfuscate their origins. In contrast to Foley et al. (2019), only 3% of the real transaction volume could be directly linked to illegal activities, or darknet hubs. The second major contribution of this paper is the authors' mapping out of the Bitcoin ecosystem and trading network, showing that Bitcoin transactions concentrate around a few big players, namely the centralized crypto exchanges.

Focusing on the crypto exchanges themselves, Cong et al. (2022) use the transaction data from the known crypto exchanges and analyze the transaction volumes of both regulated and unregulated exchanges from July to November 2019, using statistical detection methods for falsified data. They find that by and far, the regulated exchanges don't engage in wash trading, while a significant number of unregulated exchanges do with proportions of wash trading as high as 80-90% of all transactions in a given exchange. However, the price impact of this wash trading seems to be transitory, with market arbitrageurs stabilizing prices across the regulated and unregulated exchanges relatively quickly.

The authors suggest that one key reason for the exchanges engaging in this activity is to manipulate the market information about the exchange itself to boost their visibility on ranking websites (such as CoinMarketCap etc.) that rank exchanges partly by volume of trades. By fraudulently inflating trade volume, the exchanges draw in more clients and customers. Amiram et al. (2022) confirm the market manipulation incentives of unregulated exchanges, demonstrating that wash trading indeed has short-term benefits for the exchanges by drawing in more customers at the cost of long-term reputational concerns. This might not be problematic, if the transaction volume on regulated exchanges would dwarf that of unregulated ones, but regulated exchanges still represent only a fraction of the volume traded in other exchanges, indicating that wash trading is prevalent and rampant in the Bitcoin market in general.

Bitcoin price determination and market efficiency

There exists a vast literature analyzing the prices of Bitcoin, either with time series methods, or alternatively using general equilibrium models to theoretically model cryptocurrency prices in equilibrium. Along the first line of inquiry, papers testing the efficiency of the Bitcoin market in terms of the Efficient Market Hypothesis or news shocks include, for instance Urquhart (2016), Makarov and Schoar (2020), Borri and Shakhnov (2022) or Corbet et al. (2019). This literature broadly suggests that while the exchanges themselves do have significant and detectable price dispersion across currency pairs and exchanges, arbitrage opportunities are still somewhat limited due to capital controls and other restrictions. However, this analysis obviously does not extend into the OTC markets and transactions that stay off the known exchanges. The second line of inquiry, general equilibrium modelling of cryptocurrency prices usually involves embedding a cryptocurrency, such as Bitcoin into an OLG or DSGE model (see e.g., Schilling and Uhlig, 2019, Biais et al., 2022 or Choi and Rocheteau, 2021). In these models the prices of cryptocurrencies are primarily determined analogously to other financial assets as a discounted sum of the benefits the asset generates, the difference here being that whereas financial assets create cashflow in the form of dividends, with Bitcoin these streams represent the net transaction benefits of the cryptocurrency, possibly realizing only far in the future.

Theoretical models of Bitcoin pricing generally predict the existence of multiple equilibria, with boom-and-bust cycles and excess price volatility. The acceptance of Bitcoin as a valid method of payment or legal tender is scarce, with the only such experiments being almost complete failures (cf. Alvarez et al., 2022). As Bitcoin performs poorly as a hedge or a component of a well-diversified portfolio (European Systemic Risk Board, 2023), the remaining sources of demand seem to be trading, speculation, and activities where anonymous transactions are highly valued, including, for example tax avoidance, illegal activities, or other less savory dealings. The volume of these trades is documented to be as high as 46% of total activity in Foley et al. (2019), whereas Makarov and Schoar (2022) put the number at one order of magnitude lower at less than 3% of *real* volume.

Bitcoin as an investment?

The investment case for Bitcoin and other cryptocurrencies seems to arise mainly out of speculative interest, since Bitcoin performs poorly in most other roles in a well-diversified portfolio (see ESRB, 2023, FSB, 2022). Auer et al. (2023) exploit a fresh dataset of cryptocurrency prices and two external shocks to shed some light on this question. The authors investigate the correlation between the use of cryptocurrency trading applications, Bitcoin prices and other background covariates. They find that the most important driver of new users are Bitcoin prices, even when controlling for other factors such as macroeconomic conditions. Moreover, they use two exogenous shocks for Bitcoin prices, namely China's crypto mining ban of 2021 and the social unrest in Kazakhstan (these being two very active locations for Bitcoin mining) to confirm that new Bitcoin investment seems to mainly be driven by the prices of Bitcoin itself. Most alarmingly, though, the authors' data indicates that at the time of rising Bitcoin prices – and hence during a significant inflow of new Bitcoin investors – large holders of Bitcoin were simultaneously offloading their Bitcoin positions, essentially profiting from the entry of new investors into the cryptocurrency. This activity is not so very different to that which happens in asset price bubbles, or in the extreme, those that happen in a Ponzi scheme.

Financial speculation, of course, is not a new economic phenomenon – far from it. Speculators and arbitrageurs have existed for as long as there have been financial markets, and from an efficiency standpoint they both serve a useful purpose in keeping the markets efficient and aiding in price discovery. However, speculation in Bitcoin is to some degree unique when compared to speculation in, say, commodities or other financial assets. One may speculate in gold or oil, even to the degree that one is driving the market price of said commodities up on the financial markets. Extraction of these assets may even cause environmental externalities like Bitcoin does, but these assets or commodities differ from Bitcoin in one crucial way: they have a use beyond their speculative value. Oil is used in heating, in making plastic, the chemical energy contained within is used to power our cars and airplanes. Gold is used in electronics for its superior conductance characteristics. And the list goes on.

But Bitcoin, apparently, is not really used for much else other than speculation. It has so far failed as a payment system everywhere it's been tried, while the literature cited above contains ample evidence of it being used for unsavory means. Moreover, its very design incorporates aspects that diminish its viability as a payment system, as noted by Hinzen et al. (2022). Yet the carbon dioxide from its mining is emitted to the atmosphere, causing global environmental externalities, and exacerbating climate change. Therefore, speculation in Bitcoin is an activity that causes global harm, while the benefits of the cryptocurrency remain unclear.

4. Bitcoin supply and miner incentives

The mining of Bitcoin has evolved from being simply a hobby for the general tech-savvy enthusiast done on laptop CPUs, to a professional endeavor undertaken by profit-seeking agents using purpose-built and highly specific hardware, called application-specific integrated circuits (ASICs). In stark contrast to its stated goal of decentralization, most Bitcoin mining is nowadays heavily centralized, taking place in large *mining pools*, in which individual miners pool their computing power (and hence, also probability of success), sharing the transaction fees and newly minted Bitcoin from their activities. Figure 2 below presents the largest mining pools active today by the total number of guesses they provide, or as it is more often referred to, *the network hashrate*.

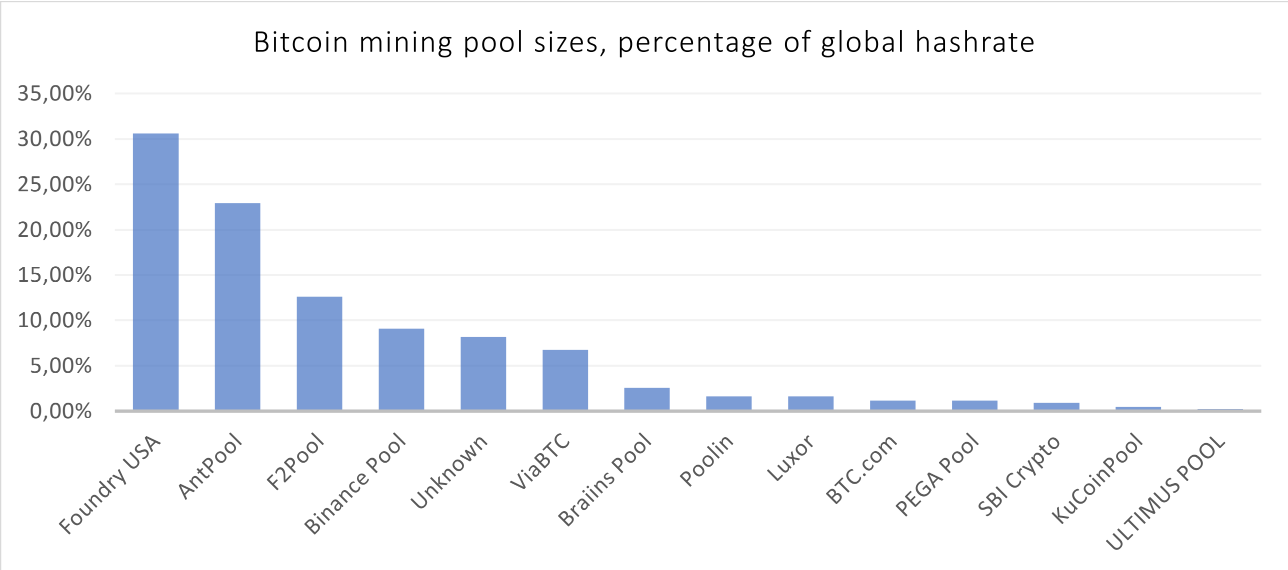

Figure 2: Bitcoin hashrate by pool, May 2023 (source: BTC.com, https://explorer.btc.com/stats/pool)

The effects of this miner centralization have been of particular interest in the literature, as highly centralized markets can be harmful to competition due to, for instance, collusion. In Bitcoin's case increased centralization of the miners also increases the risks of a majority attack, where a malicious actor can try and subvert the Blockchain for their own personal gain (Makarov and Schoar, 2022).

Cong et al. (2021) highlight the ambivalent effects of miner centralization. Mining pools allow risk-sharing between the pool members, and hence miner risk-aversion contributes to the formation of mining pools in equilibrium. Curiously though, while larger mining pools internalize the effort duplication externalities better and grow at a slower rate than smaller pools (which, from an environmental externality point of view, is good!), they regardless contribute significantly to overall electricity use. They also document the extensive centralization that has taken place in the Bitcoin mining market during the years 2011-2018. During this time, the number of active pools grew from seven to forty, with a 70% market share of the five largest firms in 2018, meaning that the mining market became extremely centralized.

Surprisingly, even individual miner incentives clash with Bitcoin's goals of being an efficient payment system, especially when it comes to settlement and network delay. For instance, Soria and Mohazab (2021) show that miners have incentives to restrict the numbers of transactions written to new blocks, essentially creating artificial bottlenecks in Bitcoin and similar PoW- cryptocurrencies, slowing down the transaction rate. They do this to increase transaction fee revenues, essentially creating an auction setting since the users of Bitcoin bid a transaction fee when they submit their transaction to be added to the blockchain. As higher fees get higher preference, restricting transaction supply has the effect of shifting the bids up, therefore extracting more rents from the users. Same qualitative outcomes of transaction delays arise in Huberman, Leshno, and Moallemi (2021), where the Bitcoin Payment System essentially operates as a market for transaction processing speed and in Hinzen et al. (2022), where it is dubbed endogenous network delay.

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Prat and Walter (2021) analyze the long-run carbon footprint of Bitcoin mining and note that if mining rewards (Bitcoin prices or transaction fees) do not increase commensurately, technological progress alone should shrink the electricity consumption of Bitcoin in the long run. However, the estimates of electricity consumption presented earlier don't seem to imply this to be the case, and one reason for that may be that while the block rewards themselves decrease according to a predetermined schedule[2], Bitcoin prices (cf. Figure 1) have likely more than compensated for the diminished revenue due to halvings. Therefore, these papers point to a Bitcoin that functions as an inefficient payment system, given the actual supply side incentives. Regardless of the motivation of the user to hold Bitcoin, if it is to be transacted with in any meaningful way beyond a virtual prestige token, there must exist a link between the cryptocurrency and fiat currencies. This is where crypto exchanges and their services come in, creating a crucial link which allows users on their platform to transfer money into and out of Bitcoin holdings, to purchase other cryptocurrencies, and engage in other trading activity.

Strikingly, given the all-pay auction-like effort duplication inherent in Bitcoin's PoW consensus protocol, from the climate damage standpoint the socially optimal mining market structure for Bitcoin would be a *monopoly*. A monopolist miner will still consume electricity, but with a single miner the harmful effort duplication (the primary source of the environmental externalities) would be minimized. In fact, Ma et al. (2019) suggest this, noting that a monopolist miner will choose the minimal level of technology to solve the computational task (this is called technology in their model, but for our purposes we may as well call it electricity or computational capacity), with competition increasing the collective resource usage from the monopolist's cost-minimizing input choice. Similar results arise in Prat and Walter's (2021) model as well, where the environmental externalities (resource consumption) of Bitcoin mining are increasing in the degree of competitiveness in the mining market.

A takeaway from reasoning of this kind is that the problem in Bitcoin mining isn't that it's centralized, but that it isn't centralized *enough.* And perhaps therein lies a source of concern with mining pools as well: on the one hand, miner centralization is socially beneficial since the larger the pools become, the more they internalize the harmful effort duplication externalities leading to environmental externalities. However, this analysis neglects the fact that the mining market has free entry so in theory anyone with access to a computer and electricity can become a Bitcoin miner. And this entry is primarily driven by Bitcoin prices, which – as the previous chapter documents – seem to be set by inefficient, opaque, and volatile marketplaces.

[2] At present, the next such "halving", where the block reward is halved is estimated to happen in 2024, where the block reward is to be reduced to 3.125 Bitcoin.

Moreover, while miner centralization abates the environmental externalities for the above-mentioned reasons, it also simultaneously violates one of the basic tenets and design principles of Bitcoin, decentralization. This seems to suggest a somewhat unfortunate tradeoff inherent in Bitcoin, and in Proof-of-Work cryptocurrencies more generally: the social costs to be paid for their necessary decentralization seem to be the significant (and global) environmental externalities they create.

5. The direct and indirect externalities of Bitcoin

Bitcoin, as discussed previously, requires maintaining a peer-to-peer network to function and record transactions in the blockchain. This activity is at the heart of the Bitcoin proof-of-work design (Nakamoto, 2008), but it is also extremely energy-intensive, inducing essentially an electricity use competition between the miners, with the winner reaping new Bitcoin. This in term incentivizes Bitcoin miners (and mining pools) to locate in countries and jurisdictions that offer reliable access to cheap electricity (cf. CCAF, 2023 and Makarov and Schoar, 2022). The high electricity consumption creates significant climate externalities in the form of carbon dioxide emissions. As I will argue in the following, these externalities alone are likely to be substantial, although very difficult to estimate (mainly due to data availability). Furthermore, the local and indirect externalities of Bitcoin mining are likely substantial as well.

5.1 Bitcoin mining consumes a significant amount of electricity every year

According to the Bitcoin Electricity Consumption Index (BECI) developed by the Cambridge Center for Alternative Finance (CCAF, 2023) and Jones et al. (2022) the yearly electricity consumption of Bitcoin mining lies somewhere in the range of 43-124 TWh, depending on the specific assumptions of miners' energy efficiency. To give some context for these numbers, according to EIA (2023), for instance Finland's yearly consumption was roughly 84 TWh in 2021. Figure 1 below plots the yearly estimates from the BECI. In contrast to the early years of Bitcoin, where electricity consumption was low, from 2017 onwards the yearly electricity consumption of mining has been on an increasing trend.

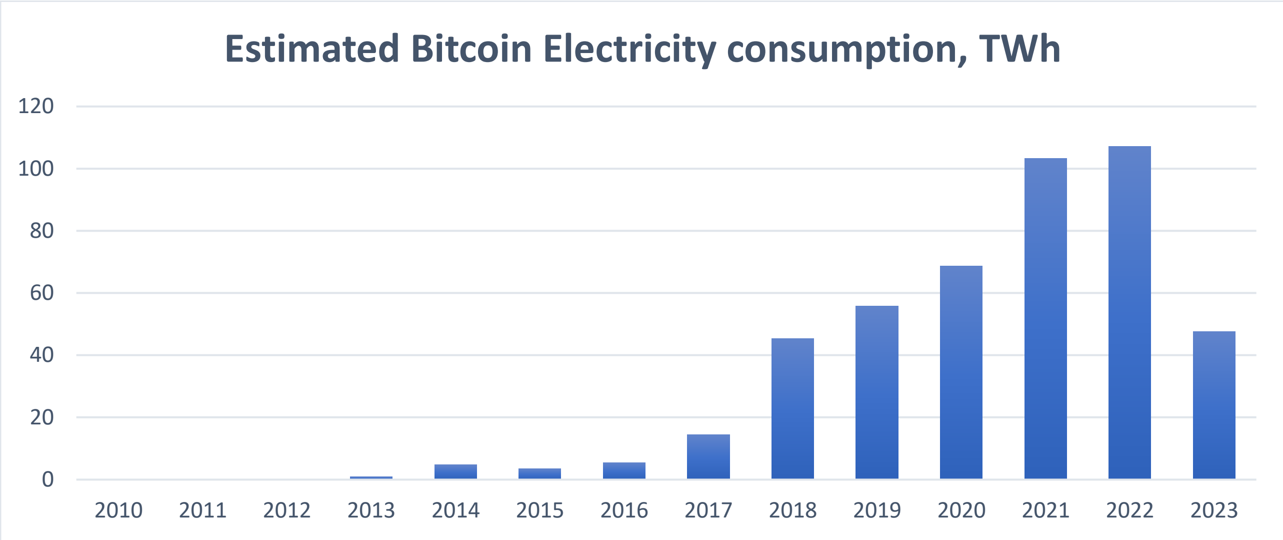

Figure 3: Estimated Bitcoin electricity consumption, 2010-2023. Source: CCAF BECI (https://ccaf.io/cbnsi/cbeci). The values are yearly best estimates of the electricity consumption of Bitcoin mining operations.

Wendl et al. (2023) survey the cryptocurrency research literature, summarizing results related to the environmental externalities of PoW and PoS cryptocurrencies (leading examples being Bitcoin and Ethereum, respectively), focusing on four aspects of externalities that they create. These categories are the resource use, electricity consumption, the electronic waste produced and other environment-related aspects. The survey places the energy expenditure of Bitcoin at roughly the same magnitude as Jones et al. (2022) and the CCAF BECI graphed above. As per the electronic waste generated by PoW cryptocurrencies (mainly Bitcoin), the surveyed literature suggests that Bitcoin generates roughly four orders of magnitude greater amounts of electronic waste per transaction than, for instance, a payment card system like VISA does. OECD (2022) estimates that a single Bitcoin transaction has a carbon footprint of 670 kg CO2 – for comparison this is roughly equivalent of a single-passenger transatlantic flight from Amsterdam to New York. Digiconomist (2023) computes that the equivalent footprint for a single VISA transaction is roughly three orders of magnitude lower at 0.45 *g* CO2 per transaction.

Based on the literature surveyed, the authors recommend shifting focus from regulating miners (which, as previously argued, is exceedingly difficult) towards regulating the centralized exchanges where the cryptocurrency trading and speculation takes place. In a similar vein, they recommend increasing market awareness of the environmental impacts of PoW cryptocurrencies to incentivize investors and users towards favoring greener cryptocurrencies.

5.2 Miner locations and carbon leakage

Figure 4 below plots the distribution of the global hashrate by country, based on miner location data from CCAF (2023). The methodology that CCAF uses for this geolocation of miners relies on pool self-reporting, and so assumes that this location data is correct and not disguised by, say, VPN use. Makarov and Schoar (2022), in contrast, geolocate the miners in their paper by assuming that miners cash out their Bitcoin rewards for fiat currency at their nearest centralized exchange. Their data only extends up to 2021, so they do not observe the mass exodus of miners from China, but up until that point they place most miners in China, as does CCAF[3] in the figure below.

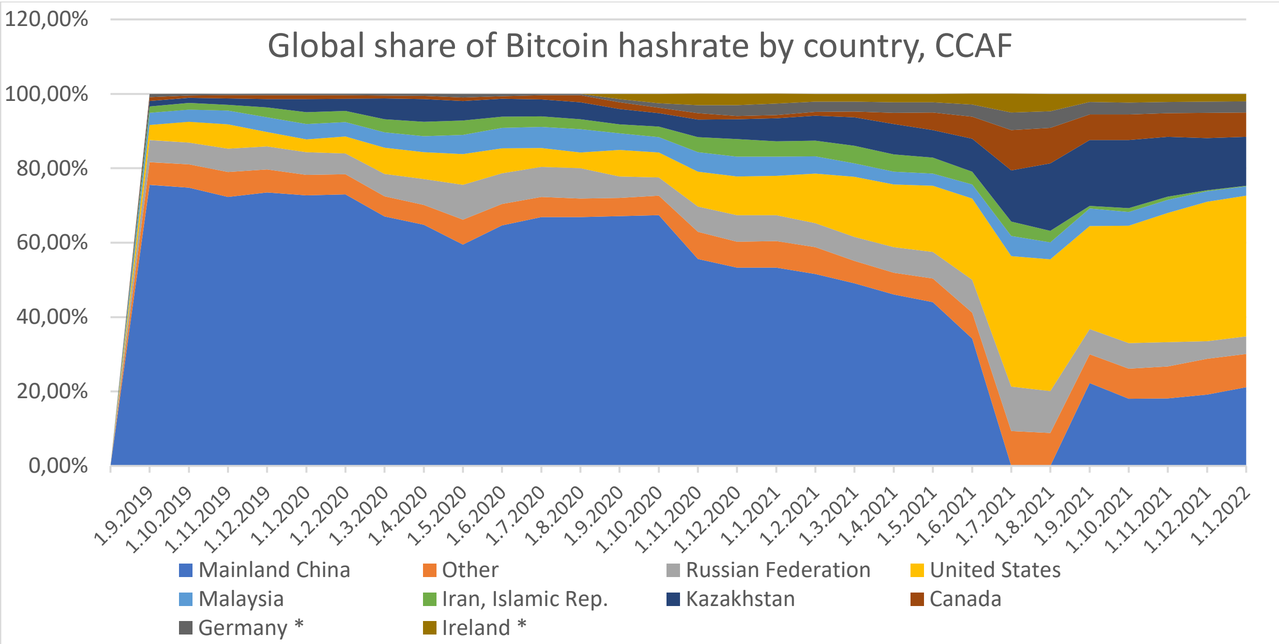

Figure 4: Share of global hashrate by country, source: CCAF Mining map (https://ccaf.io/cbnsi/cbeci/mining_map).

Most miners operated in China up until 2021, when China imposed a unilateral ban on Bitcoin mining. The resulting exodus seems to have driven a significant share of miners to the United States and Kazakhstan. However, while this unilateral action did have its intended consequence of driving miners away from China, an unintended consequence may have been the induced *carbon leakage*, since Chinese miners had access to significant hydropower electricity generation, whereas the United States still heavily relies on fossil fuels (De Vries et al., 2022).

[3] https://ccaf.io/cbeci/mining_map/methodology. Moreover, the market coverage of their self-reporting geolocation represents *"less than half of global hashrate"*, so it is unclear whether it is representative of miner location globally.

Carbon leakage refers to the unintended consequences of unilateral environmental regulation, where stringent regulation imposed on firms in one area or country may induce either a relocation of firms (as happened in this case) or some their activities to regions and countries where they face less regulation. Due to this looser regulation at the firms' alternative locations, the induced result may be that global emissions and hence externalities increase due to unilateral regulation. Leakage of this sort has been and continues to be a main factor influencing environmental regulation, such as the EU-ETS. In the case of Bitcoin, the result of China's unilateral mining ban may have ended up increasing the global CO2 emissions of Bitcoin mining, since the primary locations for the exiled miners were Kazakhstan and the United States, both countries known for their heavy fossil fuel reliance. The mobile nature of Bitcoin miners renders the carbon leakage risk of curtailing Bitcoin's carbon emissions high, complicating the regulators' problem.

Optimal environmental regulation under such carbon leakage risk is an active area of research[4] in industrial organization and microeconomic theory. While classic incentive regulation literature along the lines of Laffont and Tirole (1993, 1996) generally implies that regulation will be distorted below the socially optimal level due to asymmetric information and incentive compatibility, firm mobility and especially the multilateral externalities caused by carbon leakage render at least some of these insights moot. For instance, in Ahlvik and Liski (2022) optimal regulation under carbon leakage risk may be stricter than first-best, necessitating stricter regulation than would otherwise be implemented.

6. Climate externalities of Bitcoin mining

The climate externalities of Bitcoin primarily arise out of its heavy electricity consumption. Therefore, the damage estimates that follow typically use the following methodology: As a first step, the researcher estimates the electricity consumption using the *network hashrate* (the number of guesses) and the (assumed) efficiency of the mining rigs. Publicly available data on mining pools and their hashrates allows the researcher to pin down the electricity consumption of the major pools. Multiple sources exist for this computation, and due to Bitcoin's fixed supply policy, this part of the estimation can be considered as the most accurate.

The next step is to estimate the carbon dioxide emissions based on the electricity consumption. For this, the researcher optimally would have access to detailed data on electricity production to arrive at an unbiased estimate. Herein lie the two most relevant caveats of the emission estimates: the first being that the mining pools are generally difficult to locate, and the second that electricity production data is usually unavailable

[4] A recent and thorough survey of the carbon leakage literature is Timilsina (2022).

to the researcher at the desired level, forcing the use of aggregate data, say, at the country level. As an example, let's assume that Pool XYZ is observed to generate 20% of the global network hashrate at some point in time. The researcher, interested in estimating the pool's emissions is then faced with the issues of placing the operations of XYZ somewhere on the planet and procuring data on what production methods are used to generate the electricity it consumes. Furthermore, since electricity production methods have widely varied carbon emissions, this fact alone creates significant variance in in the estimates themselves.

The following graph illustrates the CCAF (2023) estimates for Bitcoin's carbon dioxide emissions, computed for three scenarios: the lowest scenario assumes that all the electricity consumed was produced with hydro power, the highest estimate on the other hand assumes it to be produced with coal. The best-guess scenario uses the miner's self-reported location data and pairs that up with the available electricity production mix for a given miner's location, producing the best estimate of mining emissions given current data restrictions.

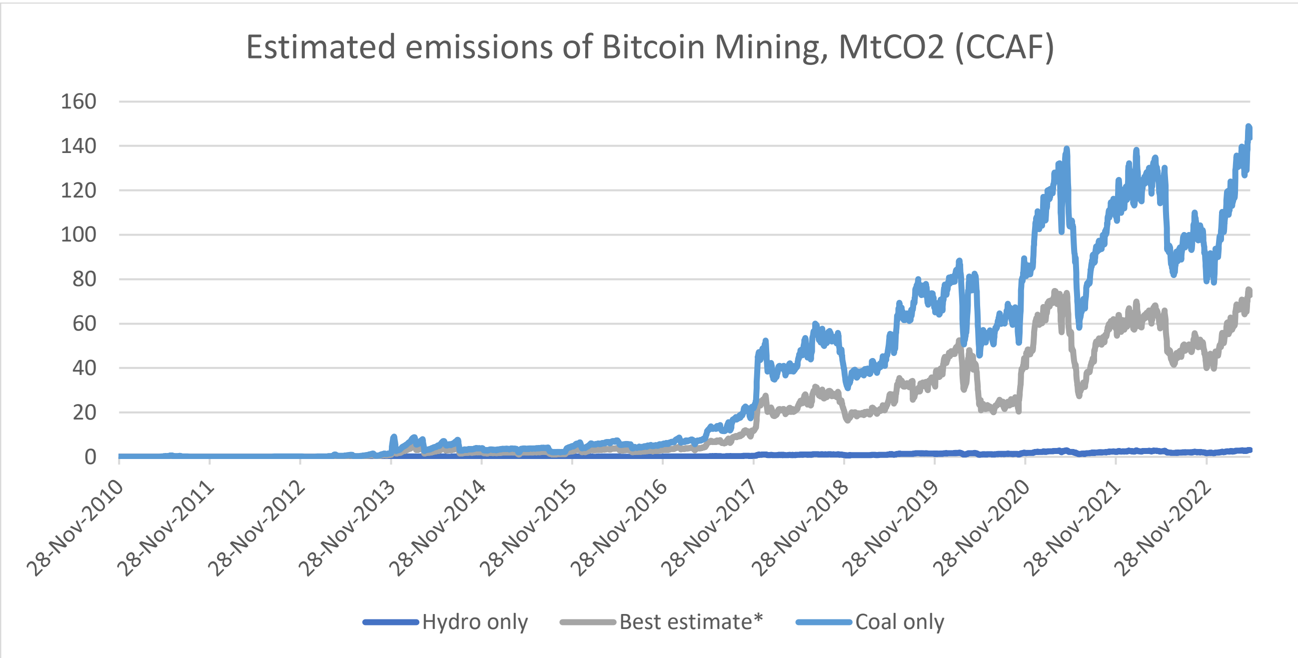

Figure 5: Estimates of CO2 emissions of Bitcoin mining, three scenarios. Source: CCAF BECI (2023). https://ccaf.io/cbnsi/cbeci/ghg.

Emissions under a hydro power only -scenario are virtually nil, while coal production unsurprisingly produces substantial carbon dioxide emissions. Most notably, however, mining emissions are on a rising trend, mirroring the rise in Bitcoin price and activity in the cryptocurrency. The latest best guess estimate for 2023 sits somewhere in the range of 70-80 $MtCO_2$, which is roughly comparable to the yearly emissions of Austria or New Zealand.

Jones et al. (2022) estimate the climate externalities of Bitcoin mining for 2016-2021. They estimate that in 2020 Bitcoin mining used 75.4 TWh of electricity, which places Bitcoin slightly above Austria in yearly electricity consumption. Using similar methodology, and the geolocation data from CCAF (2023), they estimate the emissions of Bitcoin mining and compare these climate damages to the production of other commodities. Their comparison puts Bitcoin mining on par with commodities such as beef production, natural gas production and gasoline production, prompting them to dub Bitcoin digital crude, at least in terms of the mining emissions.

Hebous and Vernon (2023) estimate the carbon emissions of Bitcoin mining and suggest levels of Pigouvian taxes that should be imposed on the miners to correct for their environmental externalities. According to their estimates, global Bitcoin mining produces roughly 0.3% of the world's carbon dioxide emissions, with that proportion projected to rise to 0.9% in 2027. They find that the electricity spent authenticating a *single* Bitcoin transaction in 2021 (the peak year for Bitcoin prices) was equivalent to a typical German citizens three-month electricity consumption. Their optimal Pigouvian tax levied on Bitcoin mining is in the range of USD 0.045-0.087 per kWh of electricity used for mining. However, the instrument by which they propose this tax to be implemented are sector-specific tax rates specifically targeting Bitcoin miners, akin to the suggestions fielded in the U.S. (OSTP, 2022). As a unilateral measure, instruments like this, however, run the risk of miner relocation and carbon leakage.

All these sources document the fact that Bitcoin mining is extremely energy-intensive, and its electricity consumption seems to be increasing. This is perhaps not surprising, given the significant increase in Bitcoin prices and the fact that miners' incentives to mine Bitcoin are directly affected by the price of Bitcoin through their block rewards and transaction fees. However, there are several caveats to keep in mind when considering the estimations and numbers presented above. The first caveat is that geolocating miners is not trivial. For instance, CCAF (2023) and Jones et al. (2022) rely on essentially the same methodology to pinpoint the location of Bitcoin miners, which is pool self-reporting. Moreover, this location data is a key step in the estimation of climate externalities, so any inaccuracies will work to compound the estimation error for emissions. Hence, while we can confidently say that Bitcoin mining consumes a significant amount of electricity, the global negative externalities created are much tougher to pin down.

Local and indirect externalities of cryptomining

Thus far, we've only considered the global externalities of Bitcoin mining, but this activity has significant local and indirect externalities to consider as well. Perhaps the most prevalent indirect effect of mining is that it shifts out the local electricity demand due to electricity-intensive operations. In a flexible, marginal cost-based electricity market this directly diminishes consumer surplus, as residential consumers will face steeper prices for their electricity. In upstate New York, Benetton et al. (2022) investigate the local effects on electricity markets of cryptomining activities, finding that upon a miner's location to a municipality, the energy-intensive mining shifts the electricity demand curve in the region, and therefore leads to significantly higher electricity prices paid by the consumers and small businesses in the region. Even accounting for the increased tax revenues that miners bring with them (assuming the municipality indeed has a way to set differentiated tax rates for miners), they compute that the entry of cryptominers led to a significant consumer surplus loss of $241 million via higher equilibrium electricity prices.

The authors investigate these effects also in China, where local electricity markets are not as flexible as in the United States and find that similar demand shocks caused by incoming cryptominers presumably led to blackouts in the affected grid and municipality[5]. The results of this paper, however, would also apply to the entry effects of some other energy-intensive operator of similar stature, such as a data center for Amazon Web Services. The main difference, however, is the fact that in the case of the Amazon data center, we have a much clearer picture of the benefits it creates, whereas with cryptocurrency mining operations, these benefits (and indeed their allocation) is unclear.

One might think that the best-case scenario for Bitcoin mining would have the miners use purely renewable energy sources, or to have the mining pools serve as stabilizers in the electricity production grid, consuming electricity that would otherwise need to be disposed of somehow, or perhaps even both. Regarding the first point, even mining that would be fully committed to renewable energy sources would still cause indirect externalities. This is due to the miners' renewable energy demand crowding out residual electricity demand (assuming renewable demand was non-zero absent miner entry). In a marginal-cost based electricity market such as the U.S. electricity market in general or Nord Pool here in Finland, this residual demand then shifts to the part of the market where demand is met with higher-marginal cost production which typically is more emission-intensive. The second point may truly be one benefit of Bitcoin miners since their high energy demand would pair well with locating to areas where electricity producers have an excess supply of electricity that cannot be sold to the local grid. However, this particularity of renewable electricity generation (intermittent excess supply) may not be incentive enough for the miners to locate to such areas.

[5] OSTP (2022) report similar incidences in the United States, with mining firms reportedly putting much undue strain on the local electricity grid.

A greener Bitcoin?

The main driver of the sizable environmental externalities of Bitcoin – or, alternatively, the main design innovation of the cryptocurrency – is the Proof-of-Work protocol. In this protocol, committed computational capacity serves as the proverbial "skin in the game" for the participants of the network that forms the Blockchain and DLT, safeguarding its security against corruption and majority attacks. This, however, has the immediate implication that since the competition has a winner-takes-all structure, the computational efforts of everyone *but* the winner are lost. As these efforts come at a significant cost of carbon dioxide emissions, this protocol is very costly from a social welfare point of view.

It is technically possible for Bitcoin to change to an alternative consensus protocol called Proof-of-Stake (PoS), which would essentially eliminate the lost computational effort of the PoW protocol and in doing so greatly diminish the carbon footprint of Bitcoin. This would, however, require that the majority of Bitcoin miners and nodes *agree* to this change, creating what's referred to as a *hard fork* in the Blockchain (Biais et al., 2019a, 2019b), essentially changing the "main branch" of the Blockchain that all miners coordinate on. Such changes, however, would require a majority of miners or mining pools to agree to it, changing the entire blockchain once and for all. Such coordination is naturally easier to achieve when the market is highly centralized, which ironically enough, Bitcoin mining markets are (cf. Figure 3). Although such a change is rather radical for a cryptocurrency, there is precedent in the markets for it. As of today, out of the most prevalent cryptocurrencies at least Ethereum (Ether) has successfully managed transitioning from PoW to PoS, and in doing so lowered its carbon footprint by several orders of magnitude (see e.g. https://ethereum.org/en/energy-consumption/).

There are, however, many caveats to a change like this that one must keep in mind in Bitcoin's case. First, the majority of miners must agree to change the protocol, which may be exceedingly difficult to accomplish for Bitcoin. Secondly, this change would necessarily lead to a higher degree of centralization in the network itself, which may also be something Bitcoin proponents and miners would object to. Beyond protocol changes, there is also some evidence that Bitcoin mining pools themselves are starting to address the issue of negative climate externalities caused by the cryptocurrency. Some mining pools now call themselves "eco-friendly" and use part of their block rewards and transaction fees for carbon offsets, which could alleviate some of the issues discussed previously. At present, though, I am not aware of any of the largest pools publicly engaging in such carbon offsets (it is, of course, possible that individual miners may do this *privately*).

Without the proper regulation in place, though, it is hard to foresee the major mining pools all undertaking such voluntary measures unless they are incentivized to do so, either by way of regulation or due to market forces, such as consumer demand.

7. Conclusions and policy recommendations

While Bitcoin may nowadays be many things to many people, it certainly wasn't designed with the climate in mind. At the time of its launch, the climate externalities of its protocol might have seemed like a secondary concern. In this paper, I've argued that this is no longer the case and that Bitcoin's climate externalities are likely very substantial. Worse still, no simple regulatory solutions loom on the horizon to correct this.

I have focused on laying out the externalities and market failures of the most prominent cryptocurrency, Bitcoin. The literature reviewed implies that, at present, the stated goal of Bitcoin to be a peer-to-peer version of electronic cash (Nakamoto, 2008) has not materialized – at least if that goal is understood to mean anything resembling an efficient payment system, store of value, unit of account or legal tender. Instead, Bitcoin is being used for various other purposes, a significant one being speculation. Bitcoin mining is extremely electricity-intensive, with miners having strong incentives to create endogenous network delay in the processing of payments to increase their own revenues. Furthermore, the marketplaces for this cryptocurrency are opaque and to a large degree unregulated[6]. One may argue that all these things are simply hiccups that any emerging technology may face before its eventual adoption and the final realization of its benefits. However, the benefits of Bitcoin loom far in the future, while the global damages of Bitcoin are materializing now. Since these damages may be substantial, the relevant question then is how can they be regulated?

The first-best solution for this issue would be a global Pigouvian tax on carbon dioxide emissions. It would address the environmental externalities caused by Bitcoin mining, but it does so in a highly non-specific manner since it would essentially rectify *most, if not all* climate externality issues in one fell swoop, not just ones caused by Bitcoin miners. Moreover, apart from being non-specific to the extreme, the larger problem with such a policy is coordination. Successful implementation of such a tax would, in essence, require solving the coordination and free-riding issues that have plagued climate policies since their very inception. Therefore, it behooves us to think about *second-best policies*.

If a global carbon tax is infeasible, one might think that the next best thing would be to regulate the cryptocurrency miners themselves, either by taxation or by a suitable quantity-based mechanism such as an emissions trading scheme not unlike the EU-ETS. However, as the preceding analysis implies, this is likely to be difficult since miners are both internationally mobile and difficult to geolocate. Furthermore, trying to

[6] For a recent perspective, the Financial Times reached out to the 21 largest crypto exchanges with a series of questions regarding basic corporate governance, such as their location, primary regulator, identities of key corporate officers etc. Disturbingly, only one disclosed this basic information, with most refusing to disclose them or providing only partial answers (Muir, 2023).

directly regulate their input usage by, for instance, taxing the mining-specific hardware or implementing coordinated Pigouvian taxation on their electricity consumption would create legal and practical difficulties, not to mention a massive monitoring burden.

Without a global carbon tax or a viable regulatory instrument specific to the miners, this then brings us to the third and likely the most viable option which is to regulate the demand side of the market, i.e., the crypto exchanges. These marketplaces serve as both the on-ramps and off-ramps for Bitcoin/fiat transactions and are the key market makers for Bitcoin, enabling much of the Bitcoin trading activity and transactions. Yet they have received relatively little attention thus far. Therefore, in my view, it would be prudent to focus on efficient regulation of the crypto exchanges, first by regulating them in the same way as other financial intermediaries are and moreover investigating the possibility of implementing transaction based Pigouvian taxation within these marketplaces. In essence, this would mean recognizing that the most feasible means of environmental regulation is via the marketplace, with an instrument that would optimally implement a Pigouvian tax on the miners. Regardless of the policies chosen, however, there is a clear need for international cross-border coordination, as unilateral policy measures (such as mining bans) may end up dissipating welfare even more due to miner relocation and the induced carbon leakage.

The European Union has already recognized the need to regulate cryptocurrencies, as evidenced by the current Markets in Cryptocurrency Assets Regulation (MiCA) that entered into force in June 2023 and will start to apply in the markets during 2024 (see Nurminen et al., 2023). This regulation is broadly similar to suggestions fielded by the Financial Stability Board (2022) and the European Systemic Risk Board (2023) and aims to provide comprehensive regulation of cryptocurrencies and crypto assets. This regulatory push, however, addresses mostly the concerns cryptocurrencies create for financial stability and transparency, while remaining silent on their environmental externalities, the focus of this paper.

As concerns over the sustainability of cryptocurrencies are emerging, one hopes that solutions to the externality problem might rise endogenously from within the crypto ecosystem. It is becoming more widely understood by investors, entrepreneurs, financiers, and enthusiasts alike that PoW cryptocurrencies, such as Bitcoin have massive carbon footprints. Some cryptocurrencies, such as Ethereum, have made the shift to alternative consensus protocols to reduce their electricity consumption, so one may ask if Bitcoin would be able to do the same one day? Perhaps the crypto entrepreneurs will shift away from Bitcoin to favor other, greener and less energy intensive cryptocurrencies[7]. However, the current market shows little signs of this happening, with Bitcoin still being the most prevalent cryptocurrency in use today.

In the absence of these market developments, it is in the public interest that regulators step in to curtail the negative externalities of PoW cryptocurrencies. The regulation of Bitcoin, however, faces many of the same obstacles as traditional environmental regulation with a threat of carbon leakage and regulatory arbitrage. In contrast with targeting the mobile miners, which may prove to be extremely costly and fraught with difficulty, I propose refocusing regulatory efforts on the demand side of Bitcoin, i.e. the marketplaces and crypto exchanges. This task may be very difficult, but the European Union has historically proven itself capable of leading by example in regulation, so perhaps it is now time to do the same when it comes to the comprehensive environmental regulation of cryptocurrencies as well.

[7] Wendl et al. (2023) recommend, for instance, targeted information campaigns for Bitcoin investors in order to spread awareness of its high electricity use. However, websites such as Digiconomist (https://digiconomist.net/) and the CCAF's Bitcoin Electricity Consumption Index (https://ccaf.io/cbnsi/cbeci) have already been in operation for quite some time (not to mention the extensive news coverage of Bitcoin's unsustainable carbon footprint), so it seems improbable that the median Bitcoin investor would be wholly unaware of these issues with their chosen cryptocurrency.

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