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Sustainable Finance in the Digital Age: An Analysis of Cryptocurrencies and CBDCs

Bachelor's Thesis

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Year of the defence: 2024

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In Prague on 31.7.2024 Jan Tůma

References

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Abstract

The advent of digital currencies has revolutionized the financial landscape, introducing new opportunities and challenges. Cryptocurrencies, led by Bitcoin, are lauded for their decentralized nature and robust security but face criticism for their immense energy consumption and carbon footprint, among other boons and banes. Central Bank Digital Currencies (CBDCs), on the contrary, are issued by central banks or governments and promise stability and higher efficiency but raise concerns about privacy and centralized control. On top of that, both of these digital assets pledge enhanced financial inclusion. This study approaches digital currencies from almost every angle imaginable, however, the emphasis is placed on the environmental impact. Our study aims to be a comprehensive resource for those interested in digital currencies, particularly concerning sustainability. Next, we attempt to answer questions regarding the connectedness of Bitcoin's volatility and energy consumption or the potential relation between its hash rate and share of renewable energy. We even mention a possible solution how to make cryptocurrencies more green. So, while many countries are researching or even launching their CBDCs, and others are toying with cryptocurrencies, it is time to look into what is all this fuss about.

Keywords

cryptocurrencies, CBDC, sustainability, environment, energy

Title

Sustainable Finance in the Digital Age: An Analysis of Cryptocurrencies and CBDCs

Abstrakt

Příchod digitálních měn způsobil revoluci ve finančním sektoru a přinesl nové příležitosti i výzvy. Kryptoměny, v čele s bitcoinem, jsou vyzdvihovány pro svou decentralizovanou povahu a silné zabezpečení, ale čelí kritice mimo jiné kvůli enormní spotřebě energie a uhlíkové stopě. Digitální měny centrálních bank (CBDC) jsou naopak vydávány centrálními bankami nebo vládami a slibují stabilitu a vyšší efektivitu, ale vzbuzují obavy ohledně soukromí a centrální kontroly. Kromě toho obě tato digitální aktiva slibují větší finanční začlenění. Tato studie přistupuje k digitálním měnám téměř ze všech myslitelných úhlů, důraz je však kladen na dopad na životní prostředí. Naše studie si klade za cíl být komplexním zdrojem informací pro ty, co mají zájem o digitální měny, zejména pokud jde o udržitelnost. Dále se snažíme odpovědět na otázky týkající se souvislosti volatility bitcoinu a spotřeby energie nebo potenciálního vztahu mezi jeho hash rate a podílem obnovitelné energie. Zmiňujeme se i o možném řešení, jak kryptoměny učinit ekologičtějšími. Zatímco tedy mnoho zemí zkoumá nebo dokonce spouští své CBDC a další si pohrávají s kryptoměnami, je na čase podívat se, proč je kolem toho všeho takový rozruch.

Klíčová slova

kryptoměny, CBDC, udržitelnost, životní prostředí, energie

Název práce

Udržitelné finance v digitálním věku: Analýza kryptoměn a CBDCs

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Introduction

The global financial landscape is rapidly evolving and digital currencies are the leading innovation. Since 2008, when an unknown entity under the pseudonym Satoshi Nakamoto conceived a decentralized middleman-free digital currency utilizing cryptography called Bitcoin, thousands of other cryptocurrencies, referred to as altcoins, have been created. While Bitcoin's price and popularity have grown exponentially, so has its criticism. Albeit having many advantages, such as strong security, transparency, reasonable privacy, and global accessibility, it faces objections because of its extreme price fluctuations, limited transaction throughput, regulatory challenges, and environmental impact. Another kind of digital currency is the Central Bank Digital Currencies (CBDCs), which are, conversely, issued by a central authority, and act as a digital extension of fiat currencies. Furthermore, they strive for enhanced financial inclusion, higher efficiency, more straightforward monetary policy implementations and to prevent fraudulent activities. However, they raise concerns about privacy, data security, vulnerability to cyber-attacks, and centralized control. This study focuses on cryptocurrencies and CBDCs and can be divided into two big parts, the first being devoted more to the environmental aspects of digital currencies and the second one more to their other features, since viewing them only from the sustainability standpoint would leave out many other important factors. Our study aims to be as comprehensive as possible as a guide for those interested in digital currencies, especially those worried about environmental impact.

The first part consists of the literature review, methodology section, and results and discussion. In the literature review, we go over the important research that has been carried out so far, while explaining the underlying technologies of digital currencies and mentioning possible solutions for Bitcoin's immense electricity demand. In the end, we identify some gaps in the existing literature. In the methodology section, we mention the methods used and briefly describe them. In the results and discussion chapter, we test three hypotheses, that are indicated later on, discuss their results, and specify the origins of the data we used.

The second part corresponds to the comparative study chapter, where we discuss technological infrastructure, security, privacy, accessibility and inclusivity, economic impacts, and regulatory frameworks of digital currencies and, in some cases, fiat. Finally, we summarize our findings, admit limitations, and think of further research possibilities in the conclusion.

Apart from contributing to the existing body of literature with a comprehensive guide to digital currencies, we also aspire to answer the following questions. First, is Bitcoin's volatility correlated with its higher energy consumption? Second, is a higher hash rate associated with a lower share of renewable energy? And third, do different consensus mechanisms necessitate different amounts of electricity?

The fact that cryptocurrencies have existed longer than CBDCs reflects that more research has been done on cryptocurrencies than CBDCs and the same applies to data availability. Hence this thesis naturally revolves more around cryptocurrencies. Often when we talk about Bitcoin, the same applies to other cryptocurrencies as well.

In the following section, we introduce digital currencies slightly more by going over the fundamental attributes of both cryptocurrencies and CBDCs.

Introduction to digital currencies

Cryptocurrencies

Cryptocurrencies are digital currencies that do not rely on central authorities, like banks, to verify transactions. Instead, the majority of cryptocurrencies employ a distributed ledger technology (DLT), typically a blockchain, a record of all transactions, that is shared among many computers preventing it from being altered by a hacker attack.
Key features of cryptocurrencies include:

Decentralization: as mentioned above, most cryptocurrencies operate on a decentralized network using blockchain technology. This ensures that no single entity controls the currency, promoting a democratic and transparent financial system.

Security: the usage of cryptography to secure transactions and control the creation of new units, transactions being verified by a network of computers (nodes), and transparent and publicly accessible blockchains together with the fact that transactions are immutable once they are added to the blockchain, all contribute to rendering cryptocurrencies resistant to fraud, tampering and unauthorized changes.

Anonymity: even though ledgers of transactions are publicly accessible, cryptocurrencies maintain a certain level of anonymity.

Accessibility: cryptocurrencies operate without regard to borders, making internet connection the only requirement for anyone to access.

Despite their benefits, cryptocurrencies face criticism because of their volatility, lack of regulation, usage for illicit activities, and most importantly for the sake of this thesis, their energy-intensive mining processes.

CBDCs

Central bank digital currencies (CBDCs) are another form of digital currency, but unlike cryptocurrencies, they are issued by a nation's monetary authority, a central bank, or a government, and their value is fixed and equivalent to the country's fiat currency.

Key features of CBDCs include:

Centralization: CBDCs are controlled by a central authority, and considering they are carefully designed and implemented, they can become stable and reliable currencies.

Legal tender: as an extension of a country's fiat currency, CBDCs are designed to be a legal tender.

Financial inclusion: even though CBDCs are no panacea to financial inclusion, they still might offer higher accessibility for the unbanked than the current banking infrastructure.

Efficiency: by employing digital technology, CBDCs strive for better efficiency, meaning they could provide reduced transaction costs and times.

To this day, several countries have already implemented CBDCs and many more are in various stages of exploration. And while their potential to change finance is enormous, they also raise concerns regarding privacy, data security, and increased central bank control over the economy.

1. Literature review

1.1 Environmental impact of cryptocurrencies

Cryptocurrencies with their growing popularity have already attracted the attention of many researchers studying their impact on the environment (e.g., Bublyk et al., 2023; Howson, 2021; Krause & Tolaymat, 2018). Bitcoin, being the largest cryptocurrency, earned paramount focus. Bitcoin uses the proof of work (PoW) process, a blockchain consensus mechanism, where transactions, that are added to the blockchain, are verified using computing power. Users that verify these transactions (miners), use specialized powerful computers to solve complex mathematical puzzles and compete against each other who wins the next block reward. With the increasing number of Bitcoins mined, the puzzles are getting more difficult, therefore more and more energy is required to run the growing amount of computers. Approximately every 4 years, the reward for mining a new block is reduced by half in the event of Bitcoin halving. The total Bitcoin supply is capped at 21 million and at the time of writing this thesis, more than 93.5% has already been mined.

As cryptocurrencies get employed to a greater extent, the issue might not only be the increased energy usage the mining processes require but also the need to regularly replace outdated computing units with newer and more powerful ones to even stand a chance against the competition. Therefore cryptocurrency mining, Bitcoin in particular, naturally raises concerns about its impact on the environment.

It's not uncommon in studies (e.g., Kohli et al., 2023) to come across comparisons between the energy or electricity used by mining Bitcoin and that of developed countries, but while it may be interesting, it cannot generally be considered meaningful comparison for a multitude of reasons, including different purposes, economic impacts and context.

In addition to the high energy consumption, many studies (e.g., Corbet et al., 2019) have shown that Bitcoin mining also generates copious amounts of CO2. According to Jiang et al. (2021), Bitcoin mining was responsible for approximately 1% of the global CO_2 emissions. Stoll et al. (2019) provide an in-depth analysis of the power consumption and carbon footprint of Bitcoin and emphasize the need for regulatory intervention to address the effects and secure sustainable adoption of blockchain technology. Badea & Mungiu-Pupazan (2021) mention challenges such as competition for cheap electricity and negative impacts on local communities and highlight the potential of renewable energy sources to diminish environmental effects.

According to the Cambridge Bitcoin Electricity Consumption Index (CBECI), China used to account for around 75% of the world's hash rate back in 2019 because of its cheap electricity, and since most of China's electricity comes from coal, its air pollution was escalating. That changed with the Chinese government banning Bitcoin mining in 2021, after which China's hash rate plunged to about 20%. Nowadays, the USA has the largest share of the world's hash rate, with its biggest mining pool called Foundry, accounting for approximately 32%. According to their webpage, 71% of their hash rate comes from ESG-positive energy sources.

According to OSTP (2022), the crypto asset industry can potentially use stranded methane gas to generate electricity for mining. Methane is a potent greenhouse gas, that has 28 to 36 times higher global warming potential than carbon dioxide over a 100-year time frame and is about 85 times more powerful than carbon dioxide over a 20-year time frame (IEA, 2021). Transporting this methane or electricity generated by it from remote gas and oil wells to the end-users would mean building pipelines or electricity transmissions for exorbitant costs. Cryptocurrency miners, on the other hand, can set up mining farms much more easily, making it a win-win solution. Reducing methane emissions can decelerate climate warming. Batten (2023a), the co-founder of CH4Capital, goes even further and claims, that the Bitcoin network may go carbon-negative in the near future by utilizing landfill gas. Compared to the long history of traditional currencies and centralized finance, cryptocurrencies are still a nascent technology. In such an early phase, the expansion of decentralized finance (DeFi) tends to exacerbate the pollution levels (Zhang et al., 2023). According to their study, the period, where Bitcoin market development can aid in decreasing carbon dioxide emission levels has yet to come and the potential of DeFi to mitigate environmental degradation has yet to be realized.

1.2 Sustainable finance principles and ESG considerations in digital currencies

As reported by Batten (2023b), Bitcoin mining can also help water scarcity. The majority of the world's most water-stressed countries are located in the Middle East and North Africa. Rich countries like the UAE use desalination to tackle water scarcity. Water desalination is highly energy intensive and 78% of energy the UAE uses for that purpose comes from fossil fuels. Often, heat is used for desalination, and this is where Bitcoin mining comes into play because almost 100% of the energy used by mining rigs is transferred into heat. Therefore desalination plants can use the waste heat that mining computers create and get rewarded with bitcoins, thus desalinating water more profitably.

At the time of writing this thesis, 3 countries, the Bahamas, Jamaica, and Nigeria, have already launched their CBDCs, and 36 are executing pilot programs (Atlantic Council, 2024). However, implementing CBDCs is not equally favorable in all countries (Náñez Alonso et al., 2021). As indicated by Auer et al. (2021), convenient and low-cost access to other currencies for remittances, travel, and trade could provide users with more incentives to adopt CBDCs. They also point out that these benefits would matter the most for developing countries where notable parts of the population are unbanked or underbanked. As observed by Náñez Alonso (2023), the environmental impact of CBDCs depends on what sources of energy are used to operate them, regardless of them being based on DLT or not. Therefore, the impact can be diminished if the energy is sourced by green and sustainable methods, securing a more enduring economic prosperity. Chen (2018) suggests that employing CBDCs could play a role in decarbonizing the economy, and Yang et al. (2023) argue that CBDCs could provide a way to lower emissions of polluting gases and that embedding sustainable finance principles into the use of CBDCs should be imperative, as reinforced by Ren et al. (2023). Nonetheless, citizens often do not consider environmental sustainability as a priority for the acceptance and use of CBDCs as observed by Liu et al. (2022). According to Agur et al. (2023), they have the potential to consume less energy for basic processing functions, compared to traditional payment methods and cryptocurrencies. Sedlmeir et al. (2020) found out that despite cryptocurrencies' immense energy consumption, they do not pose a significant threat to the climate, chiefly due to the fact, that the energy usage of PoW blockchains does not elevate eminently when they process more transactions.

1.3 Consensus mechanisms and energy consumption

A consensus mechanism is a program used in blockchain systems to achieve agreement among all participants in a network, hereby validating transactions and the state of the ledger. This automated process secures the network and protects it from threats such as double-spending or Sybil attacks. Bitcoin and a host of altcoins use the Proof of Work consensus. As discussed above, PoW faces critique due to its power-intensive nature.

Over time, other more innovative consensus mechanisms have been introduced. The most prominent one of them is Proof of Stake (PoS), where validators (also called stakers) are selected which one gets to create a new block, based on the number of coins they hold and are willing to stake as collateral. Since no specialized mining hardware is required for PoS, anyone with a device with an internet connection can become a validator (de Vries & Stoll, 2021), and thus there is no additional electronic waste anticipated. And because PoS is not competitive in the same way as PoW, this mechanism necessitates far less energy. As estimated by Truby et al. (2022), the carbon emissions of PoS are thousand-fold lower compared to PoW. Additionally, PoS is easily scalable and able to handle larger volumes without aggravating the environmental impact (Milunovich, 2022). This was the main reason, why several blockchains, most notably Ethereum, transitioned from PoW to PoS. On the day of this transition (called The Merge), Ethereum's electricity usage decreased by 99.99% (CBNSI). But PoS also has its drawbacks. For instance, it might suffer from centralization, because if an entity stakes a massive deal of assets, it could gain a disproportionate influence over the network decisions or it may be able to act maliciously with greater ease. Because of this centralization concern, superior security of PoW, technical challenges and risks, and philosophical reasons, it is unthinkable that Bitcoin would also transition to PoS. As illustrated by Sedlmeir et al. (2020), because of consensus and inherent redundancy, blockchain technologies in general still require more energy than centralized structures.

1.4 Gaps in literature

Ever since their introduction, there has been a growing interest in studying cryptocurrencies and their impact on the environment. But all the studies revolve mainly around Bitcoin. Corbet et al. (2019) call for further research on environmental sustainability, specifically on other crypto assets. Different cryptocurrencies may have various levels of energy consumption and carbon footprints as well as similar or distinct use cases as Bitcoin. It is essential to analyze whether cryptocurrencies as a whole are sustainable regarding their energy demands and evaluate their impact on climate change. As pointed out by Sedlmeir et al. (2020) and Wendl et al. (2023), there is a lack of studies that explicitly address the environmental impact of cryptocurrencies using PoS or other consensus mechanisms. Yang et al. (2023) identify gaps in the literature concerning the sustainability of CBDCs and comprehensive studies that investigate the environmental impact of CBDCs in comparison to cryptocurrencies and traditional banking systems.

2. Methodology

This chapter sets the scene for the analytical part of this study examining the environmental impact of digital currencies. Since CBDCs are still mostly being researched, and developed, few are being tested and even fewer have already been launched, there is not much data regarding their energy usage and carbon footprint available. Therefore, our investigation revolves around cryptocurrencies. By implementing a quantitative research approach, our study has attempted to find answers to the three following questions. First, is increased Bitcoin price volatility associated with higher energy consumption? Second, is a higher network hash rate connected with a lower share of renewable energy due to increased energy demands being met by non-renewable sources? And third, does the choice of different consensus mechanisms affect its electricity consumption significantly?

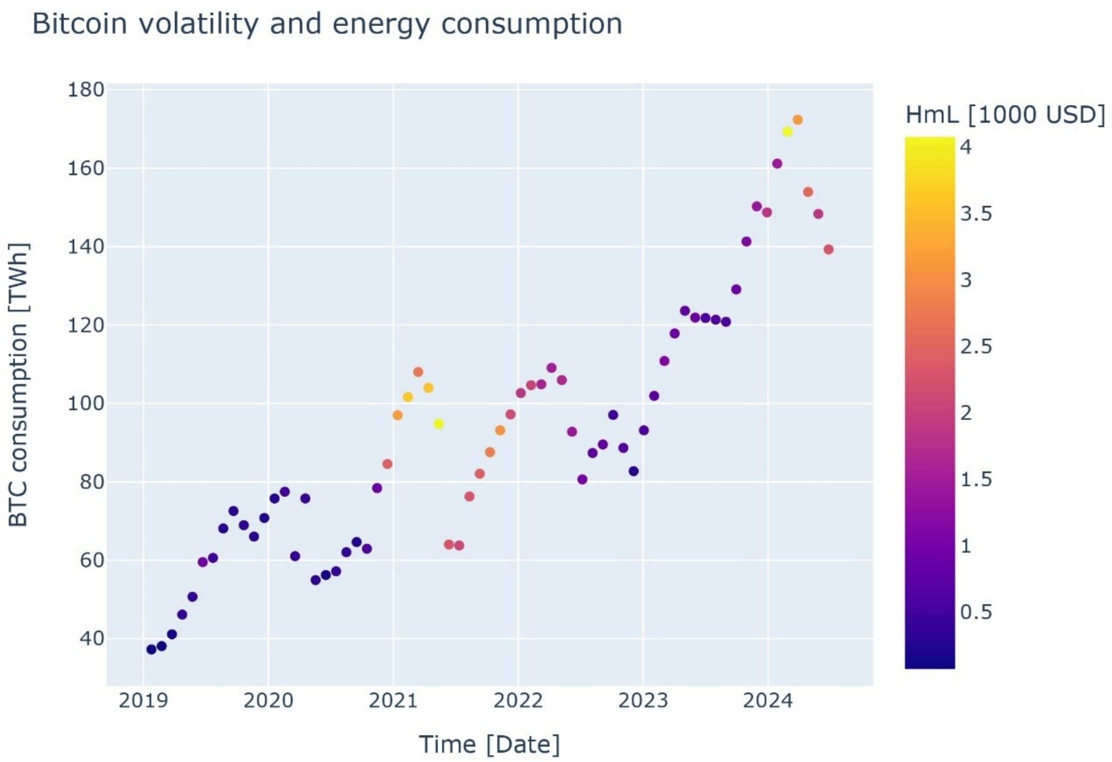
The origins of data we collected are described under each hypothesis and similarly, the methods used are listed and briefly explained when they are applied.

3. Results and discussion

3.1 Hypothesis 1

Null hypothesis: There is no significant relationship between Bitcoin price volatility and energy consumption.
Alternative hypothesis: Increased Bitcoin price volatility is associated with higher energy consumption.

Data on the price of Bitcoin are taken from Yahoo Finance, originally sourced from CoinMarketCap and energy consumption from the Cambridge Bitcoin Electricity Consumption Index (CBECI). CBECI website, renowned for its comprehensive and up-to-date data on Bitcoin and Ethereum energy use as well as carbon footprint, serves as a primary data source throughout this thesis. The volatility of Bitcoin price is computed as a difference between the highest and lowest price point of each day, denoted by the variable HmL (High minus Low) and standardized so its unit is 1,000 USD. Volume, the total amount of bitcoins traded within a particular day, is presented in millions of bitcoins (i.e., the reported volume is divided by 1,000,000). Both HmL and BTC (Bitcoin) consumption data are aggregated to monthly frequency to smooth out the noise of daily HmL. 5 number summary, a set of descriptive statistics consisting of the minimum, first quartile, median, third quartile, and maximum, is applied to both HmL and BTC consumption. Since the energy consumption prior to 2019 is orders of magnitude lower, it is irrelevant to the problem at hand, therefore the analysis considers data since January 2019.



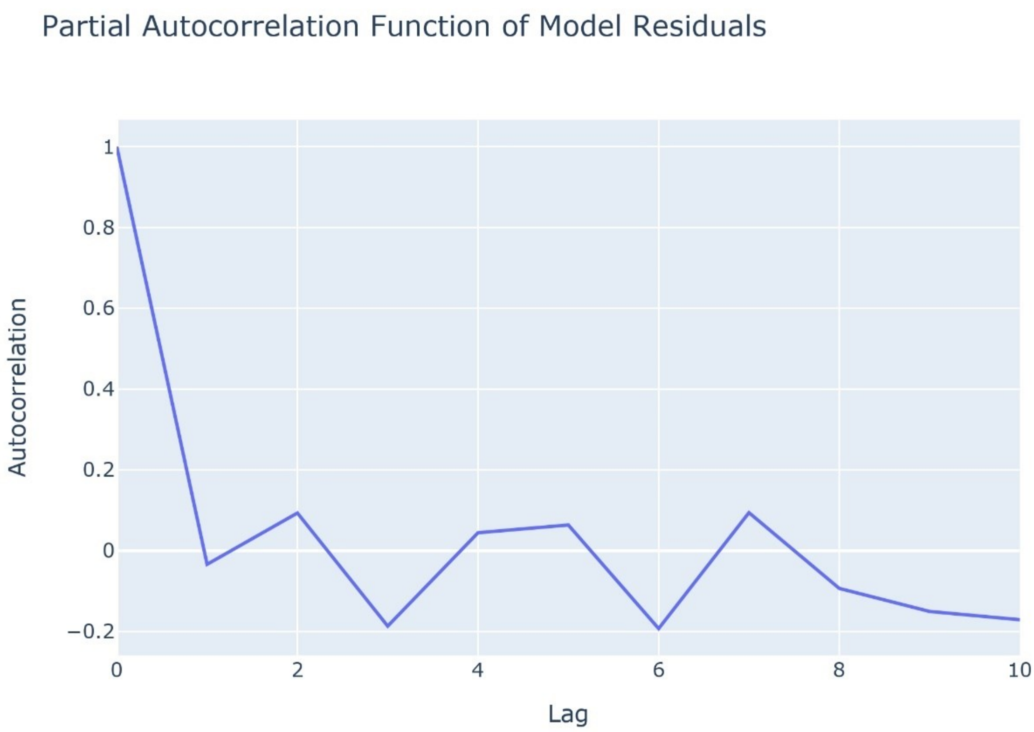
In the graph above, one can notice that for times with higher HmL values, the energy consumption is also higher. Due to the high autocorrelation of BTC energy consumption and non-stationarity in the model, the hypothesis is formally tested using an ARIMA model. ARIMA stands for Autoregressive (AR) Integrated (I) Moving Average (MA) and it is a statistical method combining AR features with those of MA, while I denotes differencing, by which a non-stationary time series is transformed into a stationary one. ARIMA is also good for short-term forecasting and we will attempt to forecast the BTC energy consumption one step ahead, which should not be too difficult because of the strong autocorrelation being present. For this reason, data are split into a training set and a testing set. Using the KPSS (Kwiatkowski-Phillips-Schmidt-Shin) test, a test that assesses the stationarity of a time series by testing the null hypothesis that the series is stationary around a deterministic trend, it is discovered that differencing of order one is sufficient to make the series stationary. Thus in this case, the ARIMA parameters are (0,1,0), meaning that stationarity is achieved only by differencing the data once, without including AR or MA components. We then infer that HmL as a volatility measure is indeed a statistically significant driver of BTC energy consumption, as handling a higher volume of trades requires more energy, with $p < 0.001$. One possible explanation for it is that when the price is high and volatile, more miners are incentivized to join the network to take advantage of potential profits, which leads to increased energy consumption.

	coef	std err	z	P>|z|	[0.025	0.975]
HmL [1000 USD]	6.9617	1.756	3.964	0.000	3.520	10.404
sigma2	65.8472	14.981	4.395	0.000	36.484	95.210

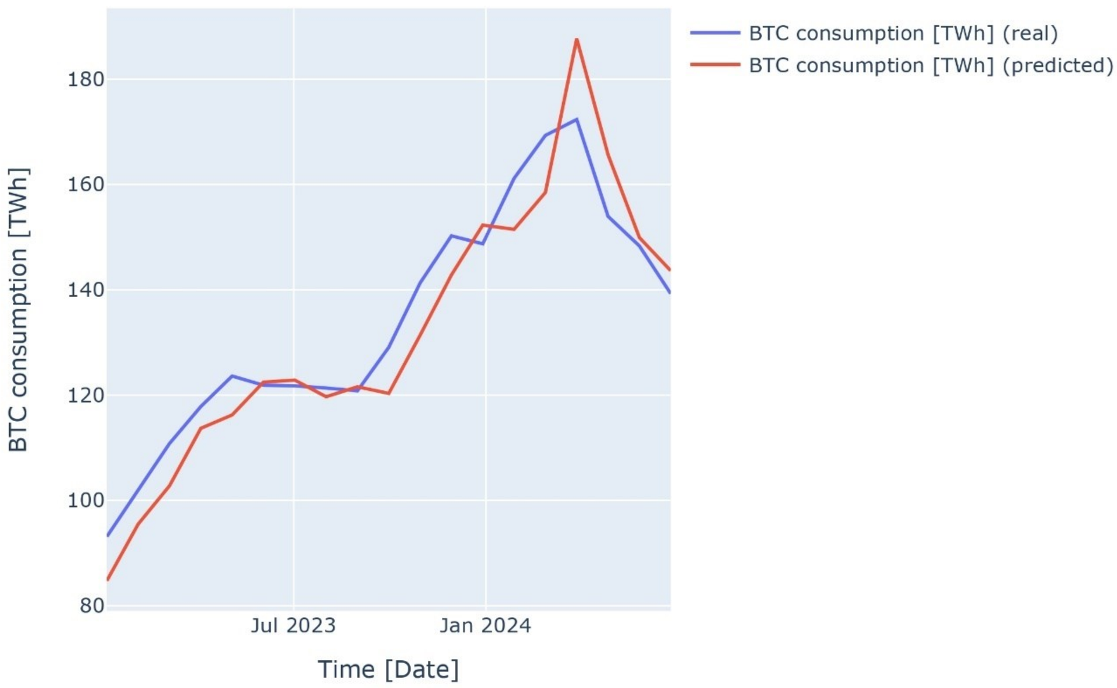
Our dependent variable y is equal to the BTC consumption and our differenced model looks as follows.

$$y_t - y_{t-1} = \beta_{HmL} HmL + \varepsilon_t, \quad \varepsilon_t \sim N(0, \sigma^2)$$

By applying the partial autocorrelation function (PACF) on the model residuals, it can be verified that the correlation structure is specified correctly. The PACF, in essence, clarifies the direct correlation between a variable and its lagged values, excluding the influence of intermediate time steps.



Finally, one step ahead prediction of BTC energy consumption is computed, and as anticipated, it is indeed an accurate prediction, mostly due to the present autocorrelation.

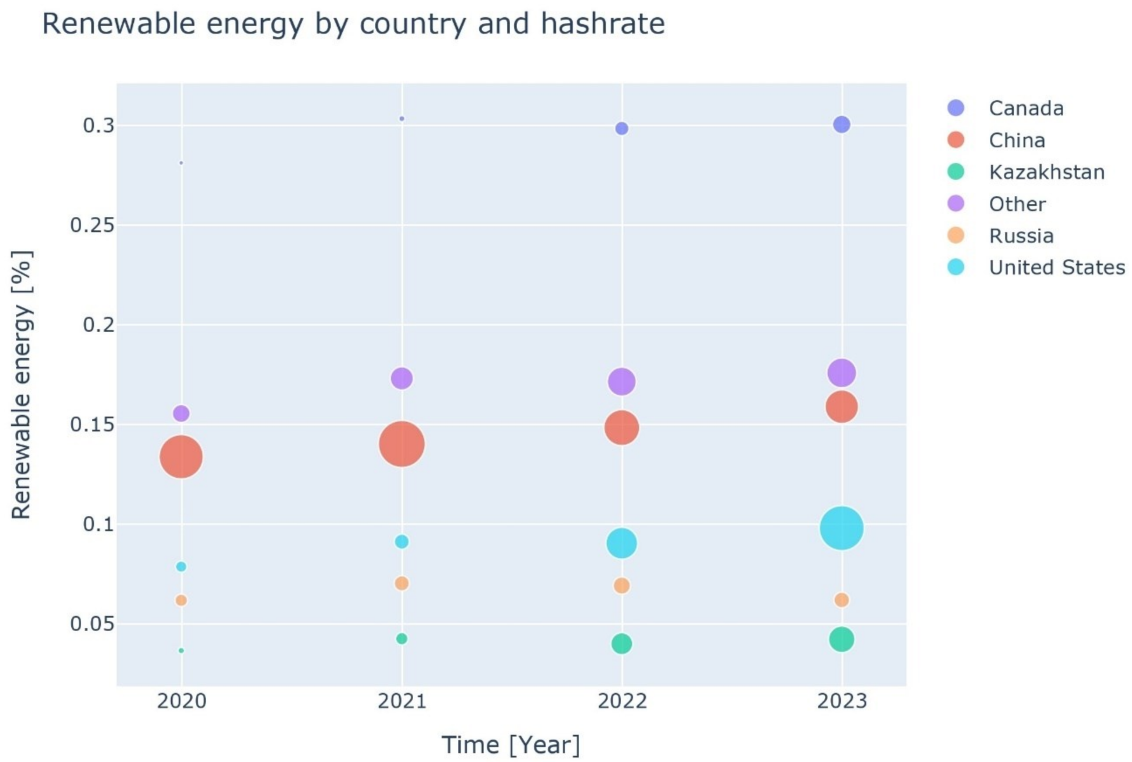


3.2 Hypothesis 2

Null hypothesis: Higher Bitcoin network hash rate is not associated with a lower share of renewable energy.

Alternative hypothesis: Higher Bitcoin network hash rate is associated with a lower share of renewable energy.

Data needed to test this hypothesis are primary energy consumption per capita by source and the evolution of the Bitcoin network hash rate. Data on the share of renewable energy (energy_mix) are sourced from the Energy Institute and data on the evolution of the network hash rate (hash) come from CBECI's Mining Map. Since energy_mix data are provided on a yearly basis, hash data have to be resampled so that both datasets have the same frequency. As the names of some of the countries in one dataset do not match those in the other, they have to be renamed. Out of all the countries for which data were available, five with the largest share of hash rate, United States, China, Kazakhstan, Canada and Russia, were chosen and the rest of the world is included in Other. Non-renewable sources consist of coal, oil, gas, and nuclear, whereas hydropower, wind, and solar are considered renewable.

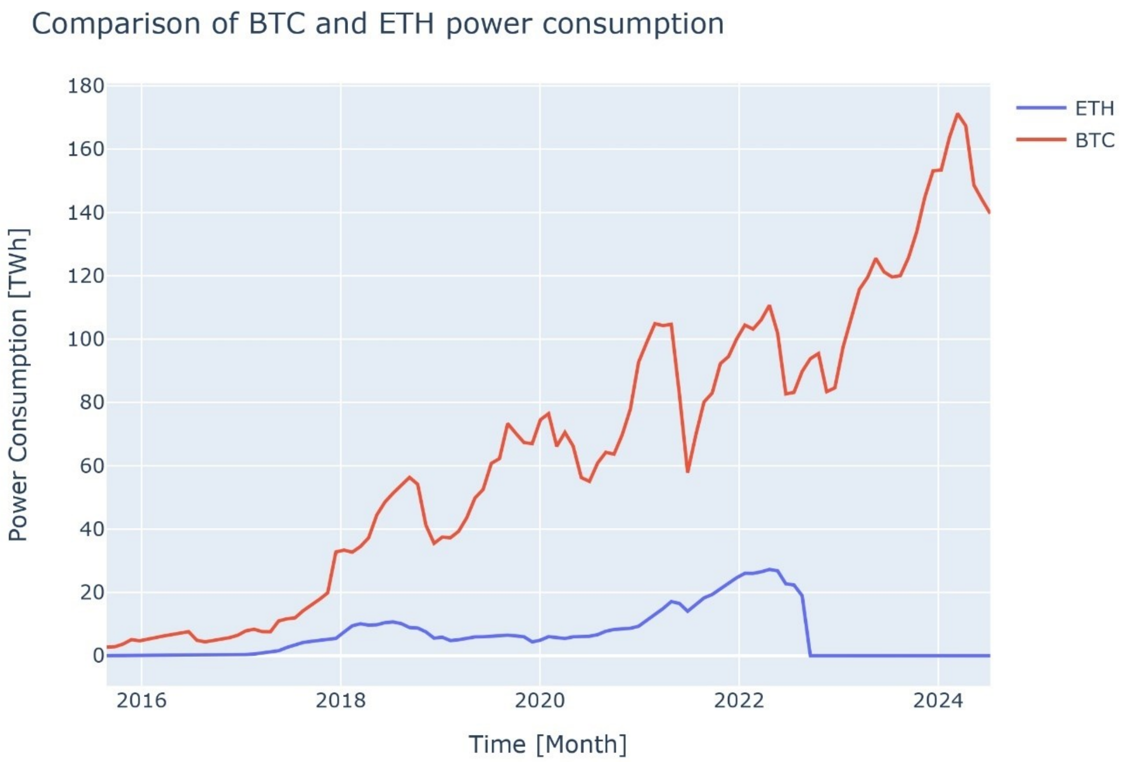


The hash rate share of the US has increased in the last years and the one of China has decreased, while both of the countries shifted their energy usage towards renewable sources. The correlation is thus rather spurious, the changes in the energy mix are driven by different factors than Bitcoin mining as well as shifts in the hash rate shares may be influenced for instance by various regulations. Bitcoin energy consumption accounts for a mere 0.22% of the world's total energy consumption (CBECI).

3.3 Hypothesis 3

Null hypothesis: The consensus mechanisms used in cryptocurrencies do not contribute significantly to their environmental impact.
Alternative hypothesis: The consensus mechanisms used in cryptocurrencies contribute significantly to their environmental impact.

Because Ethereum is the most prominent cryptocurrency that underwent a change of its consensus mechanism, it will serve as an example of both PoW (before the Merge, happening on 15 September 2022) and PoS mechanism (after the Merge). Data for annualized electricity consumption for both periods are extracted from the Cambridge Blockchain Network Sustainability Index (CBNSI) and the graph is complemented with annualized electricity consumption of Bitcoin (CBECI) for comparison.



In the plot, one can notice a substantial plunge in the electricity consumption of ETH in September 2022 on the day of the Merge. Now, the idea that the proof of stake consensus mechanism helped ETH reduce electricity consumption significantly will be tested in a formal manner. No differencing is formally required but we still perform it due to the high autocorrelation of ETH electricity consumption. According to the KPSS test, one differencing suffices, thus the ARIMA parameters are (0,1,1)

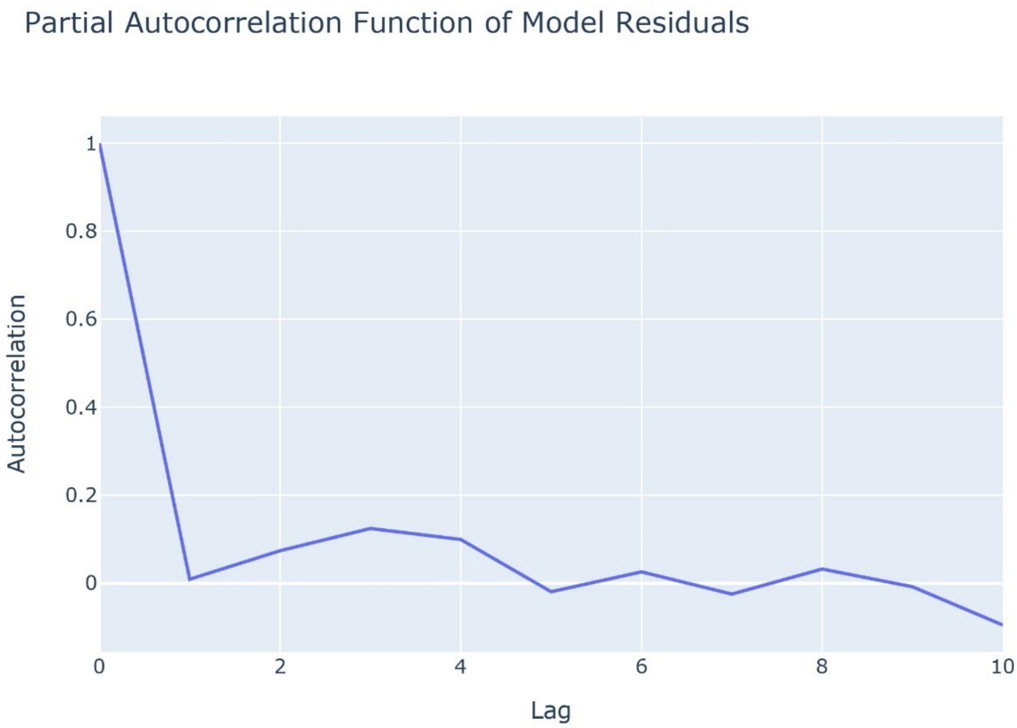
It is clear that post-merge, the ETH electricity consumption became much lower with $p < 0.001$, and therefore the null hypothesis is rejected.

ETH electricity consumption is denoted by the variable y and our differenced equation is presented below.

$$y_t - y_{t-1} = \beta_{post\_merge} I(date \geq 2022-09-15) + \varepsilon_t + \theta_{ma.L1}\varepsilon_{t-1}, \quad \varepsilon_t \sim N(0, \sigma^2)$$

	coef	std err	z	P>|z|	[0.025	0.975]
post_merge	-21.2981	3.080	-6.915	0.000	-27.335	-15.261
ma.L1	0.5020	0.064	7.859	0.000	0.377	0.627
sigma2	0.6473	0.048	13.612	0.000	0.554	0.740

A partial autocorrelation function is used to check that the correlation structure was specified correctly.



4. Comparative study

Over the course of most of human history, two ways of holding money have existed: owning physical items and having a trusted institution keep track of how much money one has. But neither of those systems comes without its flaws. Tangible forms of money cannot be used for online or long-distance transactions, they are easier to be stolen or counterfeit and impractical to transport and store. To tackle these issues, people have invented intangible money controlled by a trusted third party. This kind of money solves the aforementioned problems but comes with a set of problems of its own. Since every transaction has to be completed via a middleman, they tend to charge fees for their work. Another issue is a lack of accessibility. As in most cases, the middleman is a bank, and as of 2021, there were 1.4 billion adults unbanked globally (Demirgüç-Kunt et al., 2022), these people do not have access to this form of money. Furthermore, using a trusted third party means entrusting them with one's money and personal data. And while money is usually insured and thus one can get it back even after a bank failure, the same cannot be said about data theft. For instance, personal data including Social Security Numbers of nearly 148 million Americans were stolen from Equifax in 2017 (CNET, 2018). To sum it up, most issues of tangible money are solved by intangible money and several of their own problems stem from trusting a middleman. So what if there was a form of money that was both intangible and middleman-free? Turns out that such currency was invented centuries ago. On the Micronesian island of Yap, people for centuries used giant circular stone discs, known as rai stones, as their currency (Poole, 2018). Even though they can be touched, most of them are too heavy to be carried around. Instead, the Yapese keep a mental log of who owns each stone. Therefore transactions can occur without the stones physically moving, much like online transactions, making it a sort of intangible currency. On account of the transaction history being shared among other villagers, the trust is not concentrated into a single entity, it is also middleman-free. In the words of Mehta et al. (2019), „We don't know if Satoshi studied Yap while developing Bitcoin, but it is a modern, internet-friendly version of rai stones". This section is devoted to comparing cryptocurrencies, CBDCs, and fiat currencies from various angles, analyzing their advantages and shortcomings, and deciding what are they suited for the most.

4.1 Technological infrastructure

Unlike cryptocurrencies, many CBDC projects tend to opt for using a permissioned blockchain, which is a distributed ledger that is private and can be accessed only by users with permission. Such systems would be operated under the direct supervision of a central bank. This modernization of the current financial setup is meant to reduce transaction speeds, improve scalability, and potentially mitigate environmental impact.

Fiat currencies have evolved from solely physical forms to complex digital transaction systems like the Society for Worldwide Interbank Financial Telecommunication (SWIFT) and Real-Time Gross Settlement (RTGS), which facilitate fast and secure transactions but also require energy to maintain data centers and network infrastructure.

4.2 Security

The decentralized nature of cryptocurrencies and the cryptography behind them pledge enhanced security. There is a possibility of a 51% attack, where a single entity, if they had more than half of the total network's mining power, could for instance reverse non-confirmed transactions and double-spend coins. Such an attack would be prohibitively expensive for Bitcoin, and unless the attacker controls over 50% of the total hash power, they would have no chance of tampering with the blockchain (Mehta et al., 2019). But the smaller the network, the more prone it is to be a target of a 51% attack.

CBDCs are typically designed with a high emphasis on security, however, the fact that they are centralized also means that there is a central target for cyber criminals to focus on. Security protocols must therefore be extremely robust with regular updates.

Counterfeiting banknotes is becoming increasingly difficult with a host of advanced security features including watermarks and holograms and better verification tools, but there still are cases of banknote counterfeiters (Europol, 2020). Digital fiat transactions are safeguarded by encrypted banking systems and secure payment gateways, but they are still to a degree susceptible to cyber-attacks and data breaches.

4.3 Privacy

Originally, cryptocurrencies like Bitcoin were perceived as highly anonymous, but in reality, they only provide pseudonymity. Identities cannot be directly determined from their Bitcoin addresses which are publicly accessible, but there are several methods that can present valuable insights and lead to successful investigations. Such investigation may include the following steps: Reviewing the narrative of events and setting a timeline, tracing cryptocurrency transactions, forensic analysis and blockchain intelligence tools, digital forensics, where email metadata, domain servers, and IP addresses are analyzed, and legal discovery through subpoenas or warrants (CNC Intelligence, 2022). But Bitcoin is not the most privacy-oriented cryptocurrency, for this purpose, coins like Monero and Zcash were developed. Monero employs ring signatures, to create a ring of possible signers to obfuscate the origin of the transaction, stealth addresses, to hide the recipient's address, and ring confidential transactions to conceal the transaction amount. Zcash utilizes a technology called zk-SNARK (Zero-Knowledge Succinct Non-Interactive Argument of Knowledge) and allows for opting between a transparent and a shielded address. Choosing the transparent option makes the user's holdings and history publicly accessible like in Bitcoin's case and the shielded option renders wallet balance and history untraceable, similar to Monero's case. These enhanced privacy features therefore appeal also to users committing illicit activities and thus pose challenges to regulators, concerning anti-money laundering for instance.

According to the European Central Bank (ECB, 2021), what people would want the most from the digital euro is privacy (43%), followed by security (18%), the ability to pay across the euro area (11%), no additional costs (9%) and offline usability (8%). CBDCs can be programmable or not, but in the latter case, they would function similarly to traditional digital money, lacking the advanced features they were developed to have in the first place. These features of programmable CBDCs may include smart contracts, which would let a transaction take place if certain conditions were met, spending limits, curbing amounts that can be spent within a certain timeframe or for specific types of goods, geographic restrictions, automated tax collection, deducting taxes in real-time, or setting an expiration date on the money. The incentive behind this would be to increase the velocity of money and thus lead to higher levels of economic activity, but at the same time, it would warrant the issuing government greater control over its citizens' money and thwart their endeavors to save. Meanwhile, the advantages of programmable CDBCs would be, above all, for governments, allowing them to monitor economic factors in real-time and adjust monetary policies accordingly (Ozili & Náñez Alonso, 2024), for many citizens they would be a major invasion of privacy. "There have to be some safeguards ... the money flows of average citizens need to be private to ensure civil movements can be crowdfunded", warns Andrés Arauz, former general director at Ecuador's central bank and architect of the world's first CBDC, that was discontinued after low adoption rates and technical issues, as he is concerned that CBDCs could become an effective addition to goverments' surveillance arsenal (Smith-Meyer, 2022). To prevent operations of people with nefarious intentions, central banks should have KYC (Know Your Customer) systems in place, to identify and verify the identity of a CBDC user through a series of controls and checks involving the user's ID card, driver's license, passport, phone number, documents indicating address or two-factor identification. This image of security is to increase their acceptance (Tronnier et al., 2022).

Physical cash remains the most private form of currency, offering complete anonymity and untraceability of transactions. Hence cash is still the prevailing choice of currency for criminals (Department of the Treasury, 2024). Digital fiat transactions, on the other hand, are traceable, and financial institutions are required to monitor them and report suspicious activities for anti-money laundering and counter-terrorism financing purposes.

4.4 Accessibility and inclusivity

Cryptocurrencies present an unparalleled opportunity to move funds globally. No bank account is required, only a device with an internet connection and a digital wallet. This could be a tremendous help for people in certain unbanked regions, yet in some others, having an internet connection and a smart device still poses a barrier to entry. Cryptocurrencies have no notion of borders and each transaction regardless of its distance or volume is treated the same. With that said, Bitcoin, for instance, is not cut out to be the number one choice for smaller everyday payments. While Visa handled on average around 8,400 transactions per second (TPS) in 2023 (Statista, 2024a) and is capable of executing more than 65,000 TPS according to their webpage, Bitcoin can only perform 7 TPS (Chainspect, 2024).

Furthermore, the time it takes for a Bitcoin transaction to become permanent in its ledger is 1 hour. To solve this scaling issue, decentralized networks like the Lightning Network have been developed. Lightning enables instant, low-cost transactions by conducting them off-chain, with only the initial and final transactions being settled on the blockchain. Therefore it is capable of executing millions of TPS, but was designed chiefly for micropayments (Lightning Network, 2024). Cryptocurrencies used to be perceived as a domain only for people with technological backgrounds, but they are increasingly becoming user-friendly and accessible to the general public due to advancements and more simplistic designs in platform interfaces.

CBDCs aim to combine features of programmable digital money with the stability and regulation of traditional fiat. They can be designed to function offline, ensuring accessibility in areas with limited internet connection or in case of network outages, and even give payments a level of privacy that is close to that of cash (Panetta, 2023). Therefore they could also help people in unbanked or underbanked regions significantly. Depending on how different countries design their CBDC systems to be interoperable with each other, the time and cost it would take for a cross-border transaction to go through would be reduced (Bank for International Settlements, 2021).

4.5 Economic impact

Cryptocurrencies' decentralized nature grants that monetary policies like interest rate adjustments have no direct influence on them. But it also means that they could not be used to address economic issues in the same manner that fiat is. If a cryptocurrency with a capped total supply like Bitcoin was adopted in a country, it could alleviate the country's inflation but it could introduce the opposite issue - deflation. And Bitcoin's supply is not only fixed, there are several ways how to lose bitcoins forever, thus decreasing the total number of bitcoins that could ever be used again. Even though deflation would be good news for Bitcoin investors, because the scarcer the coins would be, the more valuable they would get, it would imply that the country's economy in general could struggle. Since the money would increase its value over time, people would be less incentivized to spend it, thus lowering money velocity and hence decreasing economic activity. On top of that, Bitcoin's price, just like one of any other altcoin can shed or gain tens of percent within a week. This volatility issue prevents 61% of people who do not own any cryptocurrencies from using them (Kaspersky, 2023). But it does not stop people from using them as an inflation hedge in some areas of the world, where there is a risk of severe inflation. As of November 2023, around 7% of the world's population were identity-verified crypto asset users (Statista, 2024b), and as Bitcoin matures and gets adopted more, it might be assumed that the volatility decreases over time. Krištoufek (2023) supports this narrative under the condition that there is a significant influx of small users into the network, who perform small transfers and are not exchange traders. He, on the other hand, also points out that increasing exchange volume, on-chain transfer value, and the price of Bitcoin by themselves increase its volatility.

CBDCs provide central banks with new opportunities how to implement monetary policies. For instance, central banks could apply interest rate policies more directly and even implement negative interest rates to CBDC holdings to incentivize their holders to spend more during periods of economic contraction (Caccia et al., 2024). If CBDCs were to replace a substantial portion of bank deposits, it could weaken the traditional banking sector's stability by reducing its funding base potentially leading to liquidity issues and heightened risks of bank failures. Furthermore, in the long run, it is expected that the introduction of CBDCs would lead to a decrease in the number of banks and thus greater concentration in the banking sector and increased financial instabilty (Hemingway, 2023). Rehman et al. (2023) indicate that CBDCs do not inherently cause higher inflation while putting financial stability at risk, however, a CBDC introduction may influence the money supply and velocity, which are both important aspects in determining inflation. This would depend on where the CBDC would be introduced, in developed countries such as the United States and the United Kingdom it could actually enhance financial stability by providing a more efficient and innovative financial system without disrupting existing financial and monetary policies. Whether a CBDC implementation will lead to increased financial stability or instability will ultimately rely on how carefully they will be introduced.

4.6 Regulatory framework

Cryptocurrencies pose unique regulatory challenges because of their decentralized nature. In their early years, cryptocurrencies operated under the governments' radar and had been an excellent option for criminals laundering money, drug trafficking, or evading taxes. But as they were becoming more popular, they began getting attention from lawmakers and regulators. The first regulations started in 2013 with the Financial Crimes Enforcement Network's guidelines for virtual currencies and since then, several countries, including Bolivia and Nepal for instance, banned cryptocurrencies completely (Orji, 2022). Even though China used to have dominance in the Bitcoin mining industry as well as producing an ample amount of mining hardware, it has been placing heavier and heavier bans on cryptocurrencies every couple of years (Mehta et al., 2019). The most stringent ban was implemented in September 2021, making all cryptocurrency transactions in the country illegal (Orji, 2022). Cryptocurrencies may also present legitimate use cases and help the economy if handled properly. That is why many other countries, including EU members and the United States, decided to take a more delicate approach and treat crypto assets as innovative financial instruments, implementing various regulatory frameworks that protect the investors and prevent illicit activities. Because cryptocurrencies operate on a global scale, regulations must be international to prevent cross-border financial crimes. In June 2023 the Markets in Crypto Assets Regulation (MiCA) instituted uniform EU market rules for crypto assets, that were not yet regulated (European Securities and Markets Authority, 2023), and in November 2023 International Organization of Securities Commissions (IOSCO) issued 18 policy recommendations for crypto and digital assets markets covering 6 key areas, including cross-border risks and regulatory co-operation (IOSCO, 2023).

CBDCs are developed under the direct oversight of central banks, which grants a clear regulatory framework from the beginning. CBDCs present not only opportunities but also challenges. Main considerations include privacy, data protection, and adherence to Anti-Money Laundering (AML) and Countering the Financing of Terrorism (CFT) regulations. Different design choices will impact users' anonymity and data processing as well as the level of surveillance. Although most current CBDCs do not aim for surveillance, it is hard to ignore privacy concerns, because a less democratic government could redesign their CBDC after it becomes established (Ledger Insights, 2024). Furthermore, as the financial industry is experiencing a significant rise in complexity, frequency, and seriousness of cyber attacks targeting financial institutions and market infrastructures, cybersecurity threats such as breach of data, credential theft, and double-spending pose major risks and must be addressed to gain user trust (Bank for International Settlements, 2023).

Since fiat currencies have existed for decades, their regulatory frameworks are well established. But there is one concept tied to them, that deserves a closer look, and that is stablecoins. Albeit stablecoins are cryptocurrencies, their value is pegged to a reserve asset, often fiat currencies. They were designed this way to minimize price volatility and as such, they bridge the worlds of cryptocurrencies and fiat currencies by combining the fast and global transaction processing and the security of blockchain technology with the stability of traditional currencies. At the same time, these new dynamics that they bring, require innovative regulations that became a priority for large economies due to their potential systemic risks. (Delivorias, 2021) aims to regulate stablecoins by, among others, requiring issuers to be authorized and to publish white papers approved by the national competent authority (ECB, 2021). The vast majority of stablecoins operate on Ethereum and other non-PoW blockchains (CoinMarketCap, 2024), hence their environmental impact is not detrimental.

Conclusion

With our world getting more digitalized every day, money is not to be left out. Digital currencies very well may be the future and as both cryptocurrencies and CBDCs are rather new technologies, they raise many questions and concerns. One of the largest ones, especially with cryptocurrencies, is the impact on the environment, and that is what this study was mostly focused on. While it is true that Bitcoin's energy-intensive nature poses a notable threat to the environment, its final impact will depend on a host of factors. First, Bitcoin mining does less harm, if it is being powered by energy from renewable sources and in areas that have plenty of it. The largest mining pool, for instance, claims to be using energy mostly from ESG-positive sources. Second, it depends to what extent is Bitcoin being used, because it is not the only cryptocurrency, as well as PoW is not the only consensus mechanism. Other consensus mechanisms, e.g. PoS, necessitate negligible amounts of energy compared to PoW and therefore cryptocurrencies as a whole do not imperil the environment as much. Moreover, miners can set up their farms almost anywhere, meaning they also could utilize otherwise economically stranded gases to generate electricity to power their mining rigs. With this approach, Bitcoin could even go carbon-negative. Even though there is not much data on energy consumption and carbon emissions of CBDCs yet, however, if designed carefully, they could lower emissions of polluting gases, despite the fact that sustainability is not the top priority on citizens' lists. Another major concern related to non-stablecoins crypto assets is their volatility. Because of its volatility, Bitcoin, let alone other even more volatile cryptocurrencies, would now struggle to be legal tenders, on the other hand though, their extremely high risk and extremely high reward nature makes them an interesting option for hyper-aggressive investors. In spite of that, Bitcoin has been a legal tender in El Salvador since 2021 and many other countries support its use. In this study, we discovered that Bitcoin's volatility is a statistically significant driver of its energy consumption, as handling a higher volume of trades requires more energy. We also found no discernable relation between the share of renewable energy and higher hash rate.

To sum up the comparative study, we can say that cryptocurrencies offer strong security and privacy features, and are independent of any institution and borders, but pose different risks to their users, such as less legal protection, more difficult mechanisms for dispute resolution, and fraud recovery compared to their centralized counterparts or traditional payment methods. Bitcoin is not the most privacy-oriented coin, there are coins like Monero and Zcash offering complete anonymity. When it comes to the privacy of CBDCs, it will largely depend on their design, which could range from cash-like privacy to complete government surveillance and control. Although they can be programmed to have a multitude of features, many of them being more favorable for the issuing government than the citizens, in democratic countries, they would have to be developed with regard to their inhabitants to increase their adoption, even though they can always be reprogrammed later. Both cryptocurrencies and CBDCs present a tremendous help for the unbanked and underbanked populations as well as a means to move funds globally more seamlessly, however, cryptocurrencies can do it today whereas CBDCs might in the future. While Bitcoin itself is slow and often expensive for everyday use, possible solutions are emerging, such as the Lightning Network. Nevertheless, Bitcoin is at this stage most suitable for two things: high-value or international payments and as a speculative asset. Stablecoins, on the contrary, can revolutionize payment systems, but they cannot exist without strong fiat currencies.

Limitations and further research

The research of this study is limited mainly by data availability. In hypothesis 2, data on the evolution of the Bitcoin network hash rate range from September 2019 to January 2022, and when combined with energy_mix data, only four time points are produced. To perform meaningful research on the sustainability of digital currencies, more data on CBDCs and other cryptocurrencies than Bitcoin is needed. Energy consumption and carbon emissions data on traditional banking are also very scarce. Once there is more data available, a sustainability comparison of various cryptocurrencies operating on different blockchains with CBDCs and traditional payment systems would be needed.

Final thoughts

Cryptocurrencies are probably not going away anytime soon, so the world will have to adapt and cryptocurrencies should adjust to fit in the environment that increasingly cares for sustainability. In an ideal scenario, each cryptocurrency would be used for what it is suited the most, multiple consensus mechanisms would be employed and mining processes for PoW currencies would be fueled mainly by waste gases. To combat their privacy concerns, CBDCs could utilize Zero-Knowledge Proofs (ZKPs), a cryptographic method that allows one party to prove to another that they possess knowledge about a piece of information without actually revealing the information itself.

Shrnutí

Náš svět se každým dnem digitalizuje, a tak ani peníze nesmí zůstat stranou. Digitální měny mohou snadno být budoucností, a protože kryptoměny i CBDC jsou poměrně nové technologie, vyvolávají mnoho otázek a obav. Jednou z těch největších, zejména v případě kryptoměn, je dopad na životní prostředí, a právě na něj se tato studie zaměřila především. Je sice pravda, že energetická náročnost bitcoinu představuje pro životní prostředí znatelnou hrozbu, ale jeho konečný dopad závisí na řadě faktorů. Za prvé, těžba bitcoinů škodí méně, pokud je poháněna energií z obnovitelných zdrojů a v oblastech, které jí mají dostatek. Největší těžební pool například tvrdí, že využívá energii převážně ze zdrojů, které jsou šetrné k životnímu prostředí. Zadruhé záleží na tom, do jaké míry se bitcoin používá, protože to není jediná kryptoměna, stejně tak jako PoW není jediný konsensuální mechanismus. Ostatní konsensuální mechanismy, např. PoS, vyžadují ve srovnání s PoW zanedbatelné množství energie, a proto kryptoměny jako celek nepředstavují pro životní prostředí takovou hrozbu. Těžaři si navíc mohou své farmy zřídit téměř kdekoli, což znamená, že by mohli využívat i jinak ekonomicky ztracené plyny k výrobě elektřiny pro napájení svých těžebních jednotek. Díky tomuto přístupu by bitcoin mohl být dokonce uhlíkově negativní. I když zatím není k dispozici mnoho údajů o spotřebě energie a emisích uhlíku CBDC, při pečlivém navržení by však mohly snížit emise znečišťujících plynů, a to navzdory skutečnosti, že udržitelnost není hlavní prioritou občanů. Další významnou obavou spojenou s kryptoaktivy, která nejsou stablecoiny, je jejich volatilita. Kvůli své volatilitě by se bitcoin, natož jiné ještě volatilnější kryptoměny, nyní jen těžko stávaly zákonnými platidly, na druhou stranu však jejich extrémně vysoká rizikovost a extrémně vysoká výnosnost z nich činí zajímavou možnost pro hyperagresivní investory. Navzdory tomu je bitcoin v Salvadoru od roku 2021 zákonným platidlem a jeho používání podporuje i řada dalších zemí. V této studii jsme zjistili, že volatilita bitcoinu je statisticky významným faktorem jeho spotřeby energie, protože zpracování většího objemu operací vyžaduje více energie. Dále jsme nezjistili žádný zřetelný vztah mezi podílem obnovitelné energie a vyšší mírou hashování.

Shrneme-li tuto srovnávací studii, můžeme říci, že kryptoměny nabízejí silné prvky zabezpečení a ochrany soukromí a jsou nezávislé na jakýchkoli institucích a hranicích, ale představují pro své uživatele různá rizika, jako je menší právní ochrana, obtížnější mechanismy řešení sporů a vymáhání podvodů ve srovnání s jejich centralizovanými protějšky nebo tradičními platebními metodami. Bitcoin není měnou nejvíce zaměřenou na soukromí, existují kryptoměny jako Monero a Zcash, které nabízejí úplnou anonymitu. Pokud jde o soukromí CBDC, bude do značné míry záviset na jejich designu, který by se mohl pohybovat od soukromí podobného hotovosti až po úplný státní dohled a kontrolu. Ačkoli mohou být naprogramovány tak, aby měly množství funkcí, z nichž mnohé jsou výhodnější pro vydávající vládu než pro občany, v demokratických zemích by měly být vyvinuty s ohledem na jejich obyvatele, aby se zvýšilo jejich přijetí, i když je lze vždy přeprogramovat později. Jak kryptoměny, tak CBDC představují obrovskou pomoc pro nedostatečně bankovně zajištěné obyvatelstvo, stejně jako prostředek k bezproblémovějšímu přesunu finančních prostředků po celém světě, nicméně kryptoměny to mohou dělat dnes, zatímco CBDC toho možná budou schopny v budoucnu. Zatímco samotný bitcoin je pomalý a pro každodenní použití často nákladný, objevují se možná řešení, jako například Lightning Network. Bitcoin je nicméně v této fázi nejvhodnější pro dvě věci: pro platby vysoké hodnoty nebo mezinárodní platby a jako spekulativní aktivum. Stablecoiny naopak mohou způsobit revoluci v platebních systémech, ale nemohou existovat bez silných fiat měn.

Omezení a další výzkum

Výzkum této studie je omezen především dostupností dat. V hypotéze 2 se data o vývoji hash rate sítě bitcoinu pohybují od září 2019 do ledna 2022 a v kombinaci s údaji energy_mix vznikají pouze čtyři časové body. K provedení smysluplného výzkumu udržitelnosti digitálních měn je zapotřebí více údajů o CBDC a jiných kryptoměnách než je bitcoin. Údaje o spotřebě energie a emisích uhlíku v tradičním bankovnictví jsou rovněž velmi omezené. Jakmile bude k dispozici více údajů, bylo by třeba provést srovnání udržitelnosti různých kryptoměn fungujících na různých blockchainech s CBDC a tradičními platebními systémy.

Závěrečné poznatky

Kryptoměny pravděpodobně v dohledné době nezmizí, takže se jim svět bude muset adaptovat a kryptoměny by se měly přizpůsobit tak, aby zapadly do prostředí, které stále více dbá na udržitelnost. V ideálním případě by se každá kryptoměna používala k tomu, k čemu se nejvíce hodí, používalo by se více mechanismů konsensu a těžební procesy PoW měn by byly poháněny především odpadními plyny. V boji proti obavám o jejich soukromí by CBDC mohly využívat Zero-Knowledge Proofs (ZKP), což je kryptografická metoda, která umožňuje jedné straně dokázat druhé, že má znalosti o určité informaci, aniž by tuto informaci sama skutečně odhalila.

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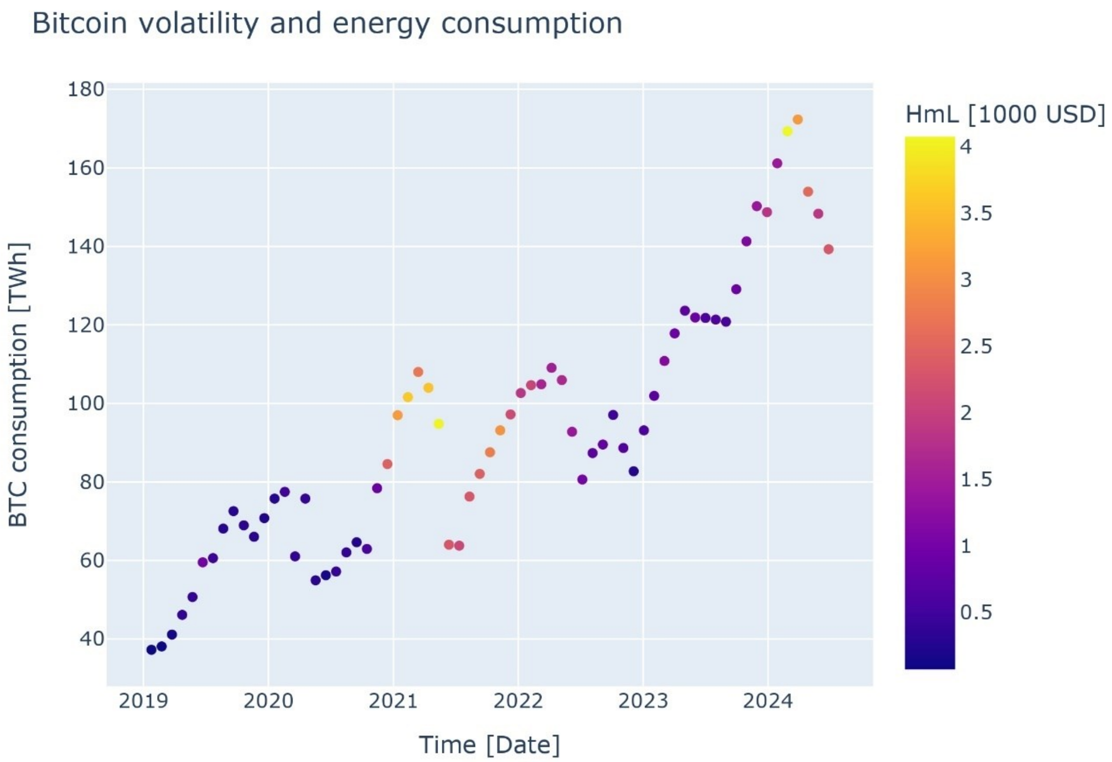
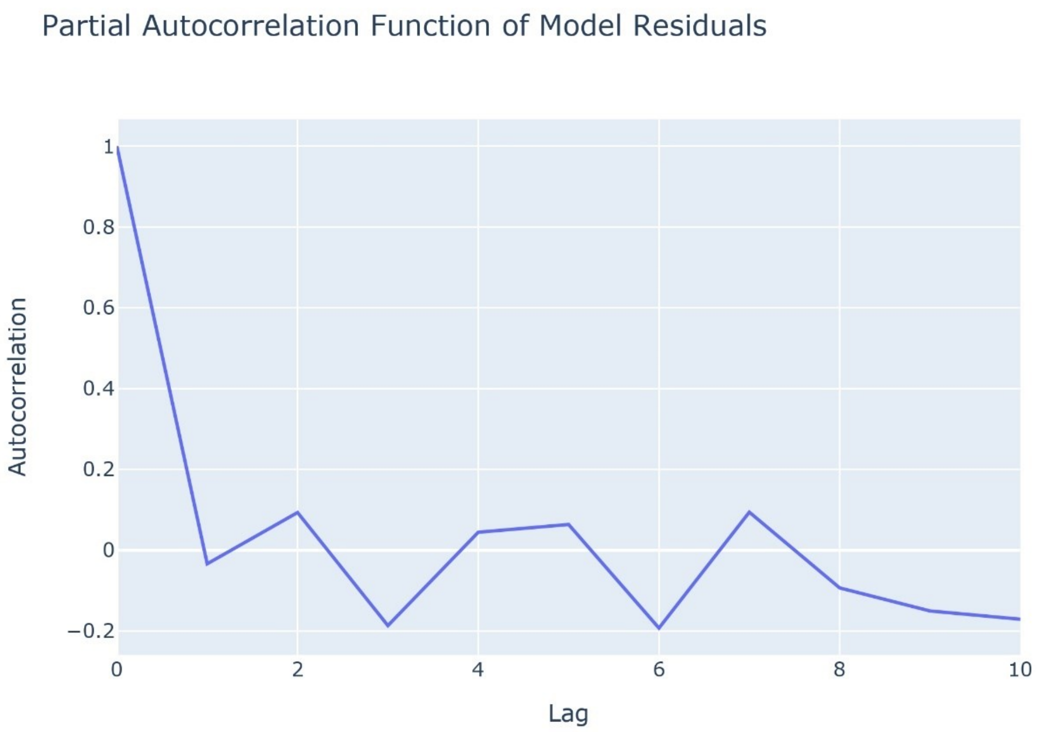
List of Appendices

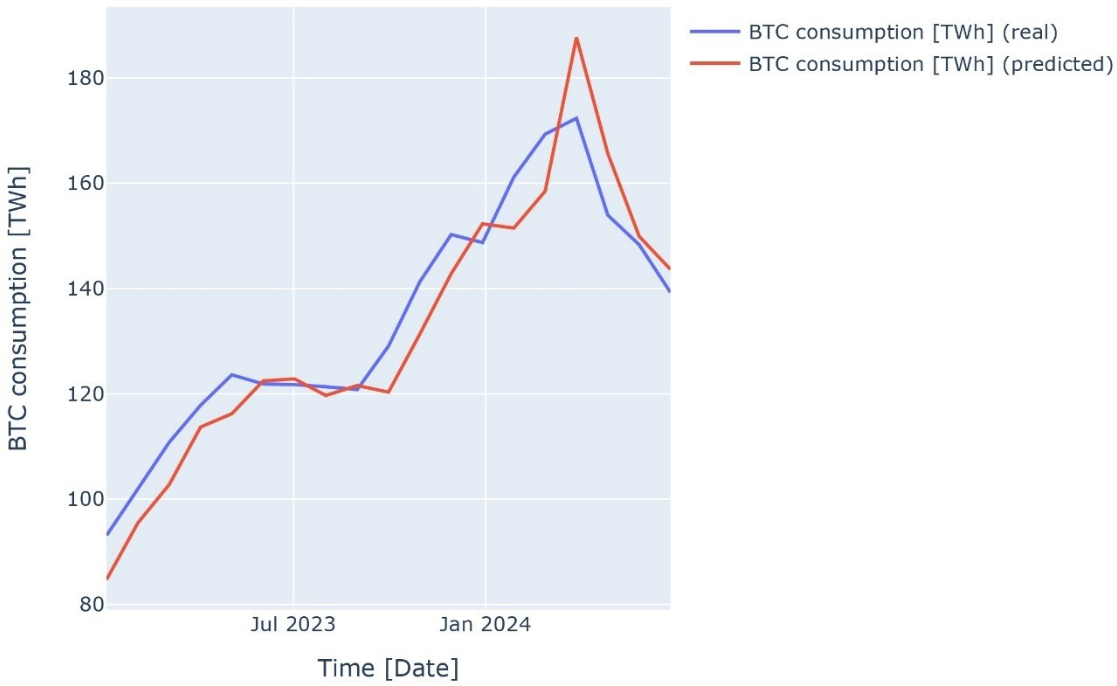
Appendix no. 1: Bitcoin volatility and energy consumption (plot)



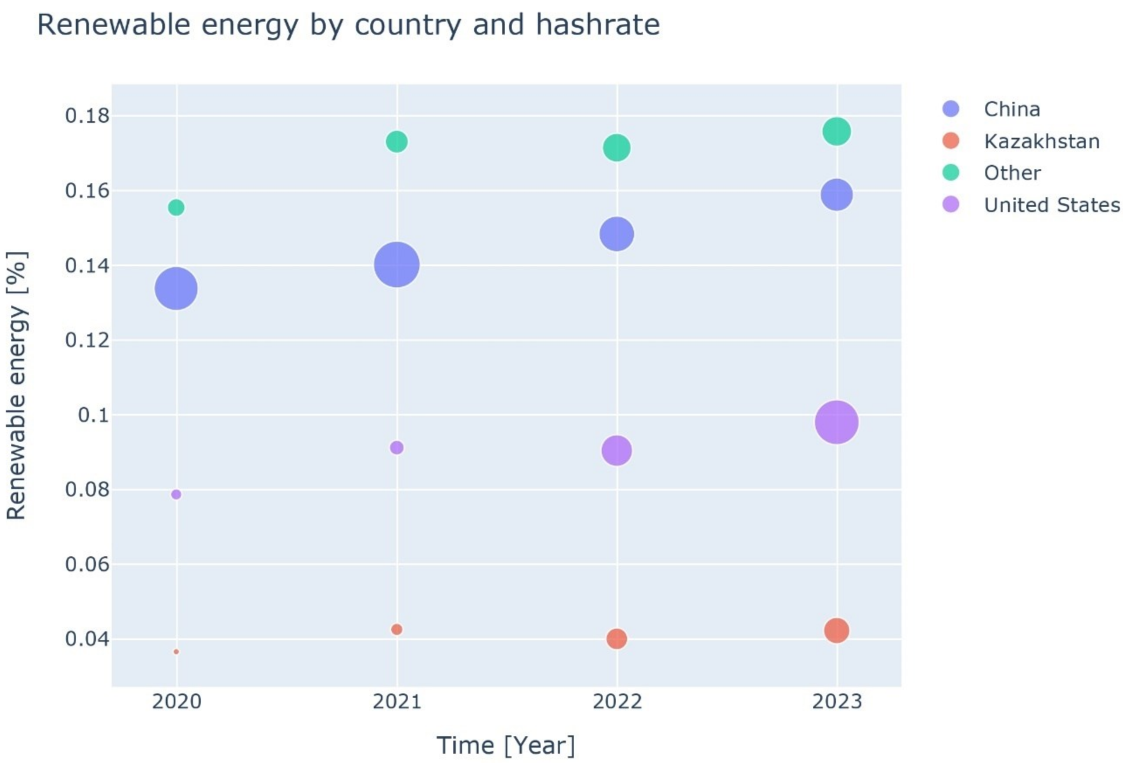
Appendix no. 2: Hypothesis 1 - Partial Autocorrelation Function of Model Residuals (plot)



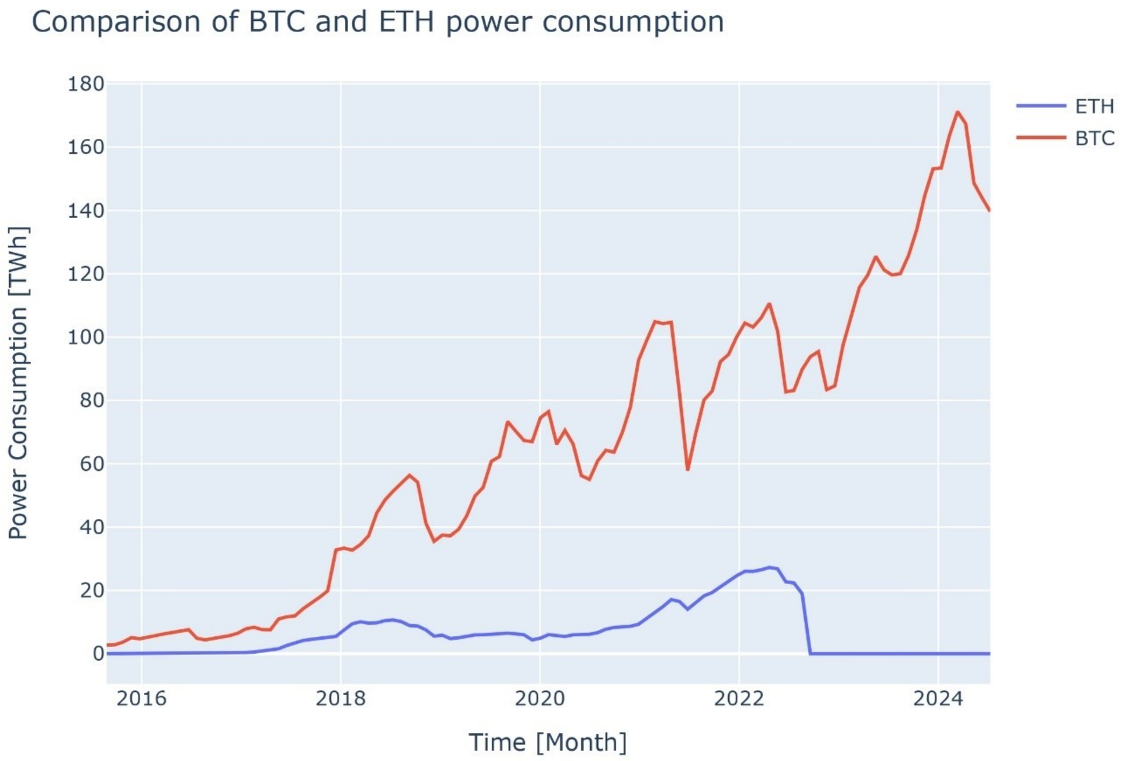
Appendix no. 3: Hypothesis 1 – Bitcoin energy consumption prediction (plot)



Appendix no. 4: Hypothesis 2 – Renewable energy by country and hashrate (plot)



Appendix no. 5: Hypothesis 3 – Comparison of BTC and ETH power consumption (plot)



Appendix no. 6: Hypothesis 3 - Partial Autocorrelation Function of Model Residuals (plot)