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Cryptocurrencies' hashrate and electricity consumption: evidence from mining activities

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Received 28 August 2021
Revised 14 October 2021
24 December 2021
Accepted 22 January 2022

Abstract

Purpose – Given the growing importance of cryptocurrencies and the technique called "SegWit" that allows to compile more transactions in a mined block, the electricity consumed per block might potentially decrease. The purpose of this study is to consider that the difficulty to mine a block might be a better indicator of the Bitcoin\Ether's electricity consumption.

Design/methodology/approach – This study applies the vector error correction model to investigate data related to primary energy consumption and electricity production, supply and consumption for Bitcoin and Ether hashrates from 2016M1 to 2021M5.

Findings – The hashrate (difficulty of solving the cryptographic problem related to the validation of a transaction) is found to have a positive cointegration with energy and electricity consumption. Despite the launch of the Segregation Witness (SegWit) mechanism allowing blocks to handle a higher number of transactions per block, this Bitcoin and Ether growing need in electricity has significantly been increasing since October 2019.

Originality/value – The major contribution of this study is to investigate a more relevant indicator, namely, hashrate (computational difficulty to solve cryptographic enigma associated with cryptocurrencies-related transaction). The approach of this study can be justified by the fact that there exists a technical solution consisting in increasing the number of transactions per blocks so that less electricity might be required to validate a transaction.

Keywords Electricity consumption, Bitcoin, Ether, Hashrate

Paper type Technical paper

1. Introduction

There is an increasing literature investigating the pros and cons of Bitcoin and other cryptocurrencies (Polasik *et al.*, 2015). The technology behind Bitcoin is called blockchain and it offers a decentralized way of managing data (Underwood, 2016; Yli-Huumo *et al.*, 2016; Macrinici *et al.*, 2018; Casino *et al.*, 2019). Even though blockchain is widely recognized as a disruptive innovation, this technology is also paradoxically associated with some important ethical debates such as data integrity or climate change (Harris, 2018).

Canh Phuc Nguyen receives funding from the University of Economics Ho Chi Minh City, Vietnam.

Studies in Economics and Finance
Vol. 39 No. 3, 2022
pp. 524-546
© Emerald Publishing Limited
1086-7376
DOI 10.1108/SEF-08-2021-0342

Several perspectives exist in the literature. Change (2017), for instance, explained that blockchain technology through its way of managing transactions can help in fighting climate change by:

- improving carbon emission trading;
- promoting clean energy trading; and
- enhancing climate finance flows.

Sanderson (2018) wrote that blockchain technology could be a potential solution to encourage the development of green bonds by establishing their credibility in a trustable market.

Precisely, an immutable way of verifying/recording environment standards could ease the implementation of an efficient green bond market aiming at reducing the CO_2 emissions for investors and issuers. In other words, blockchain could promote green investment and indirectly contribute to the fight against climate change. In the same vein, Duchenne (2018) explained that blockchain-based smart contracts can help in the implementation of a frictionless context aiming at supporting all climate change initiatives. However, Duchenne (2018) added that:

> This [novelty] comes at a cost of understanding the real impacts of the disruption this new technology brings, both on the financing side of renewable energy projects, climate finance in general and the various legislative scheme supporting same.

In other words, the technical solutions provided by blockchains to improve environmental issues is not all roses. Precisely, blockchain-based transactions require a validation based on the resolution of a cryptographic problem to be accepted (and recorded) by the whole network. This algorithmic process (labeled proof-of-work or POW) is used to secure the majority of cryptocurrencies. This process offers a secured technological framework requiring a significant level of electricity to ensure the appropriate functioning of the computers working on the cryptographic problem. For security reason (it is the only algorithm offering a high level of cryptographic security), POW is the most commonly implemented algorithmic configuration used in the crypto-world. However, this frame has a drawback – as Schinckus *et al.* (2020) explained that:

> The cryptographic problem to solve is sent to all computer nodes in the network but only one node will solve the problem (through a competition) and will validate the new transaction/record (and then get the reward related to the mining process).

This situation generates a context in which all the other non-mining computers simply consumed energy without any reason/reward.

The majority of the existing works analyze the relationship between the energetic needs of cryptocurrencies and their trading volume. The idea is simple: a higher number of transactions involving Bitcoin and Ether increases significantly the energy/electricity required to validate these transactions. Such perspective has been questioned by some technical works (Dittmar and Praktiknjo, 2019; Masanet *et al.*, 2019; Schinckus *et al.*, 2020, 2021) explaining that the number of transactions can actually be increased in a block computationally validated by the blockchain technology. These studies suggested (but did not provide empirical evidence) to study the electricity consumed by the blockchain technology in relation to the dynamics of its hashrate (i.e. the network's computational power) required to validate these transactions and not in relation to the trading volume – the novelty of this article is to provide an empirical analysis about the potential link between hashrate and energy consumption. The reason to associate the former to the latter is simple:

the more complex the algorithmic validation is, the higher the computational power (and, therefore, electricity) required to validate a transaction is. A way of capturing this complexity is to use the hashrate that refers to how much computing power the network's members are using in the validation process. In other words, if the validation activities are set in such a way that complexity is high, then the needs in computational power are high and the electricity consumption important. In this context, there is a need to study the blockchain technology's electricity consumption through a lens that takes into consideration the algorithmic complexity of the validation process. This different way of measuring the electricity/energy consumption is important, as it suggests that blockchain technology, by increasing the number of transactions in a block, could eventually reduce the system's electricity consumption. This aspect directly influences the current debates on the sustainability of Bitcoin and more generally blockchain technology. Indeed, in the current context, the blockchain-based Bitcoin is said to consume the same level of electricity than a country like Denmark, contributing, therefore, significantly to CO_2 emissions and e-waste (de Vries, 2018). The environmental impact of mining activities is a major issue for cryptocurrencies, as it directly questions their sustainability in the long term. In this context, the key contribution of this paper is to explore alternative and more relevant ways of measuring their environmental impact. Precisely, the vast majority of the existing studies on this topic consider that the number of transactions involving cryptocurrencies is an appropriate indicator to estimate their influence on electricity consumption. The major contribution of this article is to investigate a more relevant indicator, namely, hashrate (computational difficulty to solve cryptographic enigma associated with cryptocurrencies-related transaction). Our approach can be justified by the fact that there exists a technical solution consisting in increasing the number of transactions per blocks so that less electricity might be required to validate a transaction. In other words, the increase of the number of transaction per blocks could imply a reduction of the electricity consumption required for the validation of these blocks. The electricity consumption by cryptocurrencies does not depend on the number of transactions but rather on the number of blocks (in which transaction can be increasingly stored). In this context, the relevant reference to discuss the cryptocurrencies' electricity consumption became the number of blocks to validate in the mining process. The solution consisting in increasing the number of transactions per blocks is called "SegWit" or Segregated Witness and its potential impact on energy consumption has never been properly assessed through an empirical analysis. The contribution of this article is to discuss these aspects and empirically assess the influence of SegWit on the blockchain technology (with Bitcoin as a proxy) electricity consumption.

Even though some articles (Schinckus *et al.*, 2020; Schinckus, 2020, 2021) mentioned the necessity to investigate the blockchain energetic consumption through its hashrate, there are no systematic empirical studies on the topic. The contribution of this article is to provide the first global empirical study on this issue – in this context, we will not use the classical economic perspective associating the electricity consumption with the number of transactions; we will instead adopt a more technical angle based on the hashrate and investigate the relationship between the dynamics of two blockchain technology-based cryptocurrencies' (Bitcoin and Ether) hashrate and their consumption of electricity. Our method offers a new metric to investigate the timely environmental problem of blockchain technology.

The following section provides an overview of the literature work on blockchain and energy consumption, while the third section presents our methodology and data. The fourth section analyses our results, and we end this article with some recommendations in our conclusion.

2. Literature review

The growing importance of cryptocurrencies is at the heart of a lot of discussions (Alvarez-Ramirez *et al.*, 2018; Balcilar *et al.*, 2017; Brandvold *et al.*, 2015; Takaishi, 2018; Vliet, 2018; Brauneis and Mestel, 2018; Jiang *et al.*, 2018; Koutmos, 2018). This paper focuses on the underlying technology implemented in the trading of cryptocurrencies: the blockchain technology. Bitcoin is actually famous for being the first application of this technology which combines decentralized transactions and data management. The core principle of blockchain is that data integrity should not be controlled by a third party but should be trustworthy be checked by a third party (Yli-Huumo *et al.*, 2016). The existing literature mainly focuses on what people know and see: the financial services and how blockchain technology can customize and improve these services – such perspective often leaves the technical background unexplained. Yli-Huumo *et al.* (2016) reviewed 41 primary papers dealing with blockchain and showed that less than 20% mentioned technical details on the way these blockchain applications are actually working. Underwood (2016) listed all the domains in which technology could potentially contribute to national economies – however, these opportunities are still under-investigated because of a lack of understanding about the algorithmic validation that such technology requires. As mentioned in the previous section, this article is the first study to investigate the relation between cryptocurrencies' hashrate and their electricity consumption. Hence, the literature dealing directly or indirectly with this relationship is very limited. Despite this absence of research on this particular relationship, there exists a large literature dealing with environmental consequences related to the use of cryptocurrencies. Given the nature of this article (which can be seen as a sub-set of this literature), this section provides an overview of the existing works on this matter – such overview will aid in emphasizing our contributions.

Through its transparency and data management, blockchain technology has been promoted as the digital solution to ensure a better stakeholders' involvement. Such technological turn creates a lot of business opportunities bringing innovative solutions in several important societal issues: intellectual property; land property; fight against the global warming; etc. For instance, blockchain technology contributed to not only the development of peer-to-peer clean energy-based trade but also the facilitation of transactions to improve carbon emission trading (Andoni *et al.*, 2019). Sanderson (2018) wrote that blockchain technology could be a potential solution to encourage the growth of green bond markets by making this market more transparent and ensuring that all green bonds are really associated with green initiatives. Woodhall (2018) detailed how blockchain and smart contracts can help in easing all initiatives related to climate change. Sikorski *et al.* (2017) studied the use of blockchain to improve the energy consumption of machine-to-machine interactions and improving the electricity use in the chemical industry. Brilliantova and Thurner (2018) provided a study with experts interviews discussing the future of blockchain technology in relation to energy consumption. These authors explained that the major outcome of blockchain technology for now is probably the development of electric vehicles, while, in the long term, blockchains will enable the implementation of peer-to-peer microgrids aiming at optimizing energy consumption. Other studies (Green, 2018; Harnett, 2018) presented how this technology can also contribute to the achievement of several initiatives whose purpose is to solve the climate change problem. Related to this point, Gore (2018) reviewed the first blockchain-based peer-to-peer energy system allowing Brooklyn (New York) residents to sell their surplus of solar energy to the neighborhood via the use of a blockchain-based smart contract. Furthermore, according to Gore (2018), this technology can help consumers to get and manage their energy bills in a more transparent and accurate way – indeed, by offering a better tracking system, for energy generation/distribution, a blockchain-based energy system enhances transparency and all stakeholders benefit from this by having a less centralized tariff system. According to Marke (2018), blockchain technology can contribute to the development of a smarter renewable energy system making all international transfers through a fraud-free emissions management greener and smoother. Through its transparency, blockchains could also enhance community-led/ accountability and reporting paving the way for a large range of technological solutions currently explored by financial industry (Truby, 2018). Zhang *et al.* (2018) listed several examples from China and other countries showing how blockchain can boost climate-related businesses. There is a growing number of projects implementing blockchain to improve the energy consumption (Andoni *et al.* (2019) for a detailed review on this topic). Andoni *et al.* (2019) wrote that:

> The blockchain technology is an emerging technology, which has drawn considerable interest from energy supply firms, startups, technology developers, financial institutions, national governments and the academic community, promises transparent, tamper-proof and secure systems.

In relation to that, these authors reviewed 140 blockchain research projects to understand how blockchain is used to promote green energy – they found that blockchain can actually be found in the development of specific green initiatives such as: decentralized marketplaces, electric vehicles and e-mobility.

Unfortunately, the blockchain technology is not all roses. All projects and initiatives evoked above mainly discuss the impact of blockchain technology on the financial services without mentioning (or discussing) the energy required to fuel this technology. Precisely, the environmental benefit of blockchain can be nuanced simply because this technology also requires a significant level of energy/electricity to operate. The essence of blockchain technology is to encompass all transactions into blocks that are interrelated (chained) so that their immutability and traceability are guaranteed. In this context, the process of adding transaction records (in a block) to the past transactions (i.e. previous block to construct a blockchain) can be implemented through a particular computational work often designed as "mining." A blockchain-based transaction requires a significant level of computational power to solve a cryptographic problem that is usually associated with all new block of transactions in the network. Indeed, an algorithmic enigma is associated to every block to ensure that each record can be validated only by the network's members and not controlled by any potential third party. This algorithmic configuration is ingenious, but it requires a lot of electricity to fuel the computational validation of each new block and ensure the technical security of the network. In terms of negative externalities, Mora *et al.* (2018) or Morris (2018) mentioned that the global temperature could increase by 2°C by 2034 if nothing changes in the way we currently use the technology in the cryptocurrencies. From an economic viewpoint, one can then say that the mining activities related to the validation of Bitcoin generate negative externalities simply because they create a negative effect (contribution to the increase of the global temperature) on an unrelated third party (world population) – even though this aspect has been discussed in the existing literature (Vranken, 2017; de Vries, 2018; Mora *et al.*, 2018; Morris, 2018; Stoll *et al.*, 2019; Goodkind *et al.*, 2020; Schinckus, 2020; Schinckus *et al.*, 2020), all these debates [1] assume that the Bitcoin's use of energy is related to its trading volume. This article directly contributes to these debates by investigating the extent to which a more relevant measure (hashrate) should be considered to estimate the Bitcoin (blockchain) consumption of energy. Given the growing importance of cryptocurrencies and the technique called "SegWit" that allows to compile more transactions in a mined block, the electricity consumed per block might potentially decrease.

In this context, we consider the difficulty to mine a block might be a better indicator of the Bitcoin/Ether's electricity consumption. With this purpose, the following section presents how we study this issue through the lens of the hashrate' dynamics and the idea that number of transactions can actually be increased in each block (through the SegWit mechanism) so that electricity consumption might actually be reduced.

3. Methodology

3.1 Conceptual framework

This study aims at investigating the relationship between mining (validating) activities and electricity consumption. The originality of our study refers to the fact that we use the hashrate as a proxy to characterize the dynamics of mining activities in their relationship with the electricity consumption. The hashrate refers to the computational power required to validate a block of transactions – this point has to be distinguished from the idea that the hashrate could be associated with the computational power required to validate one transaction. Acknowledging that the number of transaction can vary in a block, we claim that the most appropriate measure to estimate the electricity consumption of blockchain-based activities should be the hashrate and not the number of transactions – however, as explained in the previous section, the current studies exclusively focus on the number of blockchain-based transactions to estimate the electricity consumption of this technology. This section details the way we investigate our claim.

The hash can be seen as the numerical fingerprint for a set of data – for example, all transactions included in a block are associated to a particular hash (i.e. specific algorithmic enigma) that has to pass through an algorithm to be encrypted/decrypted. The validation of such a block using a POW algorithm is energy consuming. This situation is because even though all nodes are competing cryptographically to validate a new block, only the validating node gets the reward, while the others have simply consumed energy for nothing. The average time to validate a POW-based block of transactions is about 10 min and the energy required for this validation depends on the hashrate that refers to the number of hashes that can be treated every second by the miners (network's members) working on the validation. In other words, the hashrate is related to the amount of computational effort that is needed to deal with the hash of a block of transactions. It is worth mentioning that because, in a blockchain, all blocks are added on the previous one, there is an increasing need in the power required to deal with new hashes. For instance, Kent and Bain (2020) explained that the validation of a Bitcoin transaction in 2020 is 6.7 trillion times harder to solve than the validation of the very first Bitcoin transaction. To solve this issue, the Bitcoin network re-adjusts the difficulty every 2016 blocks defining, therefore, what is called as the "bitcoin mining difficulty epoch." The difficulty of validating a new block of transactions is increasing until the 2016th block after which the difficulty is re-adjusted (decrease to a lower level) so that the difficulty of the last (2016th) block in each difficulty epoch has a minor effect on the difficulty of the first block of the following epoch. In this context, it is important to understand the two parts of the reasoning:

(1) the hashrate that refers to the difficulty of the algorithmic validation or, in other words, the number of computational iterations that the network can do in 1 s; and

(2) the 10 min that is the average time required to validate a sequence of 2016 blocks because of the high difficulty.

This situation can be roughly described in Figure 1.

Unfortunately, this technical solution is not simple enough because, because of the enthusiasm generated by Bitcoin, 2016 blocks are created on average quicker than the 10

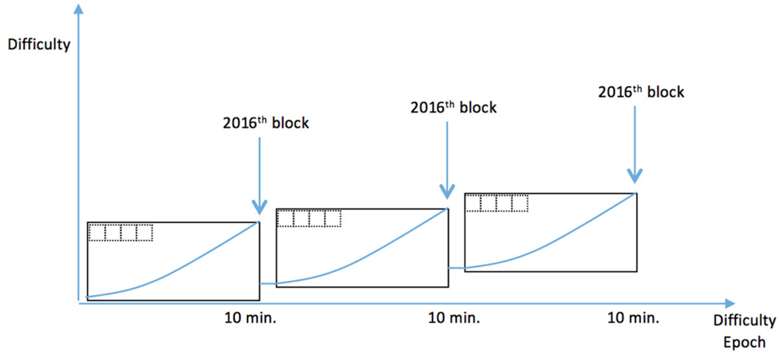


Figure 1.
Bitcoin's difficulty epoch

Source: Authors

min required to validate these blocks (of transactions) implying that the difficulty is increasing quicker than the number of blocks as illustrated in Figure 2.

Figure 2 shows that, when the first 2016 blocks are validated (after 10 min), other sequences of 2016 blocks have already been initiated so that the hashrate of the Bitcoin's activities is much higher than in Figure 1 because of the increased use of computational power of the network. These parallel sequences are because of a high number of activities – even though, there is still a re-adjustment of the difficulty after each sequence of 2016 blocks validated, the fact that several parallel sequences are involved in mining activities leads the difficulty to rise sharply. There exist debates about the potential effect of what is called "halving" on the energy consumption/hashrate of Bitcoin. Bitcoin halving describes the situation in which the reward for mining Bitcoin transaction is cut in half. This is related to the limited amount of Bitcoin whose supply has been fixed at 21m – when this amount is reached, the creation of new Bitcoin will cease. Halving is a process ensuring that "the amount of Bitcoin that can be mined with each block decreases making Bitcoin more scarce and ultimately more valuable" (CFI, 2021). By making Bitcoin scare, this process supports its high (growing trend in its) price so that halving offers miners more incentive to mine even though their rewards have been halved. This influence contributes to the competition

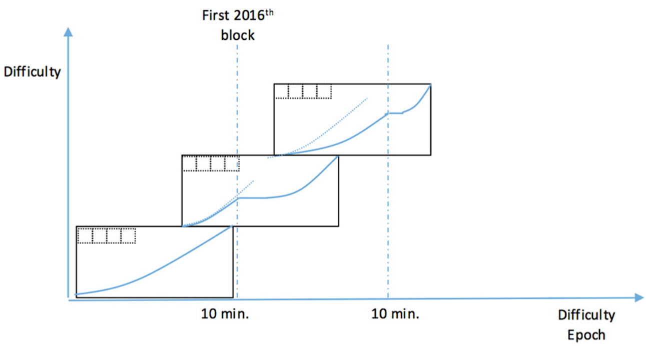


Figure 2.
Bitcoin's difficulty epoch with several parallel sequences of 2016 blocks

Source: Authors

in mining activities, and it, therefore, affects positively the electricity consumption [2]. In this context, one can expect that mining activities (i.e. validation of a block of transactions) are strongly related to the hashrate, as the higher hashrate, the higher computational power required for a new block to be mined\validated is. In other words, a higher hashrate implies a higher electricity consumption (Dittmar and Praktiknjo, 2019; Masanet *et al.*, 2019) so that the baseline function can be summarized as follows:

$$\mathrm{f(energy\ consumption)} = \mathrm{f(hashrate)} \tag{1}$$

This baseline function results from a particular assumption: the key determinant of the blockchain based systems' consumption of electricity is their hashrate and not their trading volume (number of transactions). Even though hashrate and trading volume might be, at first sight, related, it is important to distinguish them simply because the number of transactions refers to the number of inputs that can be added in a block, while the hashrate rather refers to the computational power required to validate (mine) a block. This configuration implies we could easily increase the number of transactions without increasing the hashrate. The following section explores and discusses by explaining how we test the above relationship for two key cryptocurrencies using blockchain-based technology: Bitcoin and Ether.

3.2 Data description

Our study collects four different kinds of energy consumption including total primary energy consumption (PriEn), total electricity production (Eprod), total electricity supply (Esup) and total electricity consumption (Econ) to proxy for energy consumption. The use of four proxies is to ensure the robustness of our results. The primary energy consumption is collected from the US Energy Information Administration (https://www.eia.gov/totalenergy/) and the electricity data are collected from the International Energy Agency [3] (https://www.iea.org/data-and-statistics/data-product/monthly-electricity-statistics). Two data sets are available in monthly forms, whereas primary energy consumption is available until May 2021. The hashrate of Bitcoin (BTChr) and Ether (ETHhr) have been collected in their monthly form as well from two websites that are well-known for monitoring the activities of these two cryptocurrencies: https://www.blockchain.com/charts/hash-rate and https://etherscan.io/chart/hashrate. The description of our variables, their sources and description are presented in Table A1, Appendix.

In this study, we analyze the data starting from 2016. This choice is motivated by the fact that blockchain technology has been growly used since then and that this growing use directly impacts the hashrate (i.e. the level of difficulty to mine blocks) and, therefore, the electricity consumption – in that context, starting our analysis on that year is the most suitable period for an empirical study on the impact of the hashrate on the energy consumption. We use the monthly data from 2016M1 to 2021M5 for our empirical investigation, as data of energy and electricity are available until 2021M5. Because we use monthly data, we might face some seasonal effects such as seasonality (i.e. stability, moving seasonality and residual seasonality) (Geuder *et al.*, 2019; Kinateder and Papavassiliou, 2021). To solve this issue, we use the X-12 monthly seasonal adjustment method (proposed by the US Department of Commerce and the US Census Bureau [4]) to check and adjust these seasonal effects. The X-12 method is developed from the X-11 tool, which is presented as an advancement in adjusting the seasonality (De Gooijer and Franses, 1997). The results of X-12 tests show that we have the seasonal effects in all our variables (Table A1, Appendix). In this methodological context, we use the seasonally adjusted data for our variables.

In accordance with the conventional method in time series data analysis, all variables are taken in logarithm to normalize data – the coefficients of our estimations can, therefore, be considered as the elasticity of the energy consumption to the change of the hashrate.

Data, calculation and data description of transformed variables are presented in Table 1, thereafter. In the current crypto-world, Bitcoin and Ether are the two biggest cryptocurrencies using the POW algorithm implying a high level of security [5]. The growing popularity of these two cryptocurrencies can be illustrated by Figures 3(a)–Figures 3(b) showing a sharp increase in their price and market capitalization for both Bitcoin and Ether during these past years.

This growing popularity of Ether and Bitcoin generated an increase in the number of blocks (of transactions) to be validated so that the hashrate of these crypto-assets increased as well – as illustrated in Figure 4.

These trends result from what we explained in the previous section: because of their popularity, there is an increasing number of transactions implying an increasing need in creating blocks so that, in 10 min, several sequences of 2016 blocks are launched simultaneously implying a sharp increase of the hashrate. The next sub-section provides the empirical analysis of our empirical data.

3.3 Data analysis

For our empirical estimations, the study recruits the Dickey–Fuller unit root test to check the stationarity of all variables. The results are shown in Table 2. Table 2 shows that except the Bitcoin's hashrate, all variables are stationary at every levels.

The unit root tests indicate a stationarity for all variables. The unconditional correlation matrix in this table also suggests that Bitcoin and Ether have a significant positive correlation with all four proxies of energy consumption. Afterwards, our study recruits the Granger causality test (Granger, 1969) and we test the existence of a potential break date for all variables by using the Wald test. All results are reported in Table 3.

The results in Table 3 above summarizes the statistical relations between Ether, Bitcoin and energy – it shows a long-term cointegration between Bitcoin/Ether hashrate and energy consumption.

The results of the cumulative sum test for the parameter stability show the existence of structural breaks for the variables (e.g. *PriEn, Eprod, Esup, BTChr* and *ETHhr*). We also conducted a LM test that indicates the existence of an ARCH disturbance in BTChr and ETHhr. Finally, the Granger causality test also shows insignificant causalities from the hashrates of Bitcoin and Ether on our four proxies of energy consumption. As the data may have a structural break, this study recruits both the Johansen cointegration test (Johansen, 1991) and the Gregory–Hansen Test for Cointegration with Regime Shifts (Gregory and Hansen, 1996) to examine the cointegration between Bitcoin and Ether hashrate, respectively, for each variable of energy consumption.

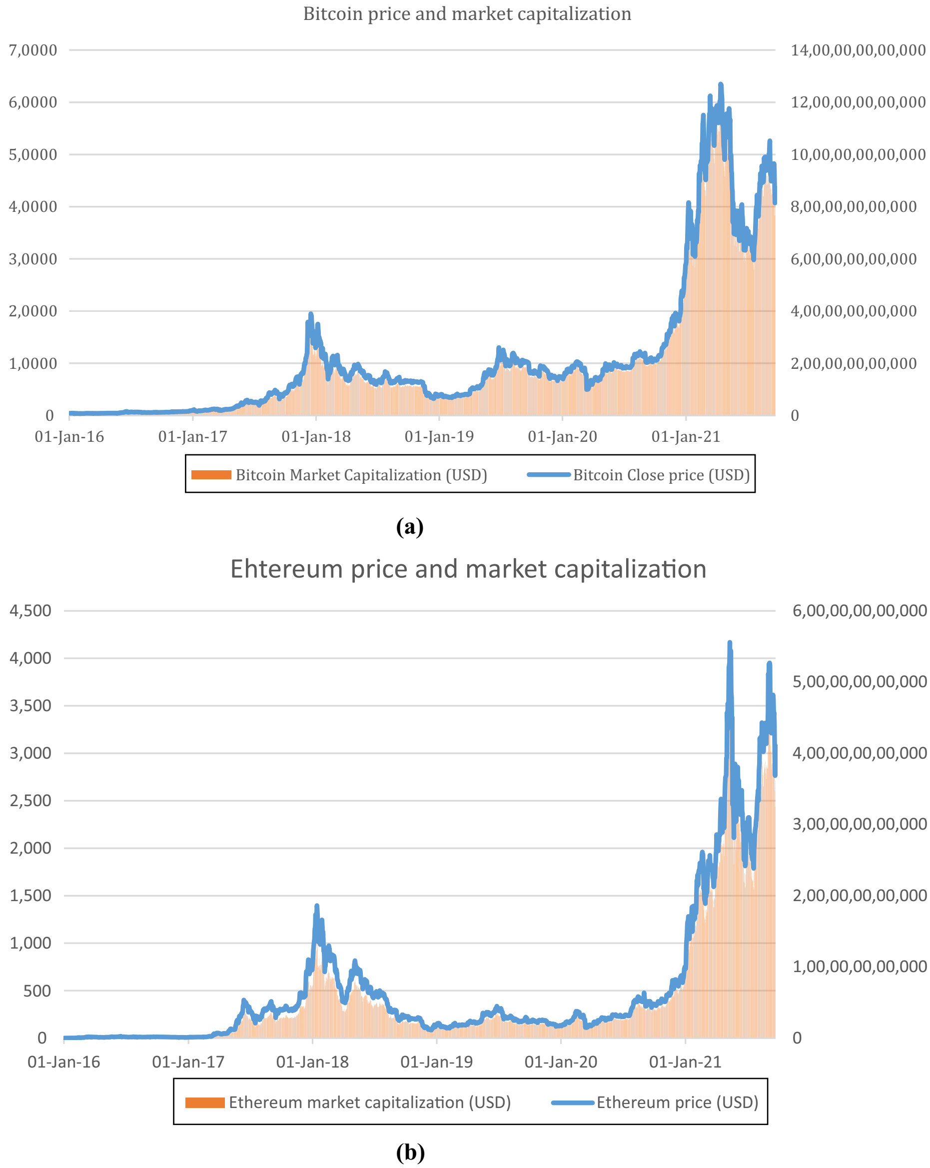
Overall, our data show stationary characteristics and there is a long-term cointegration among our variables, while variables appear to be stationary at a level so that this study uses the vector error correction model (VECM) [6] (Engle and Granger, 1987).

Finally, the Gregory–Hansen Test for Cointegration with Regime Shifts indicates the existence of a structural break in the cointegration between Bitcoin/Ether hashrate and energy consumption in 2017M10. In this context, the study divides sample into two periods: 2016M1–2017M9 and 2017M10–2019M9 to examine the effect of Bitcoin/Ether hashrate on the energy consumption by cointegration estimations. The structural break in this cointegration occurring mostly in 2019M10 (October 2019) actually corresponds to a spectacular rise of the Bitcoin and Ether price during of the Covid Pandemics.

Variable	Definition	Calculation	Sources	Observations	Mean	SD	Minimum	Maximum
PriEn	Primary energy consumption	Log of seasonal adjusted primary energy consumption	US Energy Information Administration	65	15.91	0.04	15.78	15.97
Eprod	Total electricity production	Log of seasonal adjusted total electricity production	International Energy Agency	65	13.69	0.02	13.62	13.72
Esup	Total electricity supply	Log of seasonal adjusted total electricity supply	International Energy Agency	65	13.69	0.02	13.62	13.72
Econ	Total electricity consumption	Log of seasonal adjusted total electricity consumption	International Energy Agency	65	13.62	0.02	13.55	13.65
BTChr	Bitcoin hashrate	Log of seasonal adjusted Bitcoin hashrate	https://www.blockchain.com/charts/hash-rate	65	16.90	1.70	13.67	18.94
ETHhr	Ethereum hashrate	Log of Ethereum hashrate	https://etherscan.io/chart/hashrate	65	11.22	1.79	6.47	13.31

Note: data is in monthly form ranging from 2016M1 to 2021M5

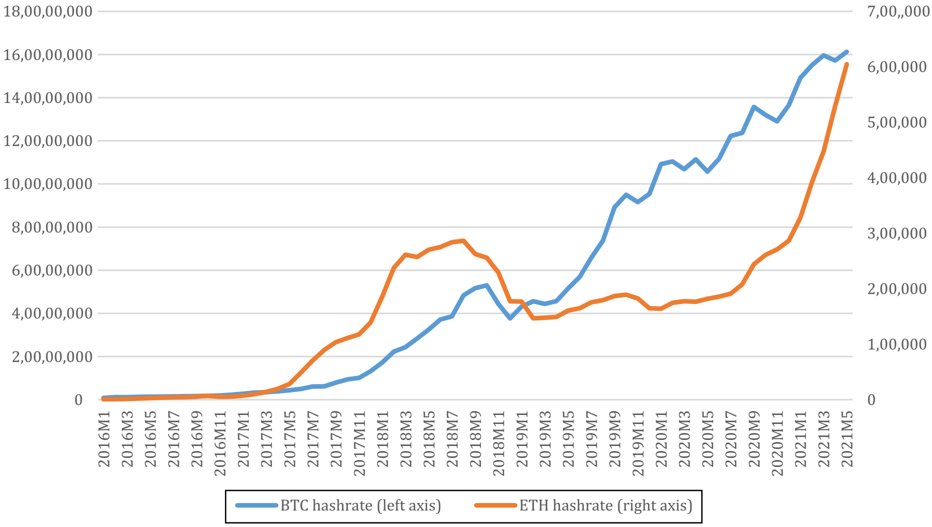
Table 1. Variables, definitions, calculations, source and data description



Note: Data ranges from 2016 Jan 01 to 2021 Sep 22

Figure 3.
(a) Bitcoin price and market capitalization and (b) Ether' price and market capitalization

This sudden increase in the price of cryptocurrencies generated debates – some authors (Clements, 2018; Campbell-Verduyn and Hütten, 2019) saying that it is simply because of the growing interest of society in cryptocurrencies combined with more and more media coverage and an increasing enthusiasm for initial coin offerings. Whatever the reason for



Note: Data ranges from 2016M1 to 2021M5

Figure 4. Bitcoin and Ethereum hashrate

which the Bitcoin and Ether prices (and activities) increased, it is essential to study its impact on the consumed energy, as these cryptocurrencies are known to consume a high level of electricity. This is the purpose of the following section.

4. Empirical results

This section presents and discusses the results of our empirical estimations for the two regimes (periods) identified in the previous section. Table 4 shows a positive significant influence of the Bitcoin hashrate on the electricity production, the electricity supply and the electricity consumption.

This triple positive influence is stronger in the short term – this short-run dependence can be explained by two facts:

(1) our sample covers a short window of only three years; and

	Dickey–Fuller test for unit root for level		Unconditional correlation matrix					
Variable	*Z(t)*	*MacKinnon approximate p-value*	PriEn	Eprod	Esup	Econ	BTChr	ETHhr
PriEn	−3.428***	0.0100	1.00					
Eprod	−4.437***	0.0003	0.84***	1.00				
Esup	−4.318***	0.0004	0.84***	1.00***	1.00			
Econ	−3.848***	0.0025	0.83***	0.98***	0.99***	1.00		
BTChr	−3.376***	0.0118	−0.10	0.01	0.02	0.02	1.00	
ETHhr	−5.511***	0.0000	0.09	0.19	0.19	0.20	0.92***	1.00

Notes: *** and ** are significant levels at 1% and 5%, respectively; data ranges from 2016M1 to 2021M5

Table 2. Stationary tests and unconditional correlation matrix

Table 3. Parameter stability tests, structural break tests, ARCH tests, Granger causality and cointegration tests

Part A: Structural break tests and LM tests

Variables	Cumulative sum test for parameter stability				Test for a structural break: Unknown break date			LM test for autoregressive conditional heteroskedasticity	
	Test statistic	1% critical value	5% critical value	10% critical value	Wald statistic	p-value	Estimated break date	χ^2	Prob > χ^2
PriEn	0.840	1.1430	0.9479	0.850	46.29***	0.0000	2020m3	19.40***	0.000
Eprod	0.841	1.1430	0.9479	0.850	11.28**	0.0145	2019m12	17.68***	0.000
Esup	0.803	1.1430	0.9479	0.850	10.23**	0.0237	2019m12	17.66***	0.000
Econ	0.857	1.1430	0.9479	0.850	11.82**	0.0112	2019m12	18.74***	0.000
BTChr	5.627***	1.1430	0.9479	0.850	330.8***	0.0000	2018m1	63.11***	0.000
ETHhr	6.587***	1.1430	0.9479	0.850	387.6***	0.0000	2017m6	62.92***	0.000

Part B: Granger non-causality tests

X	BTChr does not Granger-cause X		X does not Granger-cause BTChr		ETHhr does not Granger-cause X		X does not Granger-cause ETHhr	
	Z-bar	p-value	Z-bar	p-value	Z-bar	p-value	Z-bar	p-value
PriEn	0.307	0.579	0.340	0.559	0.055	0.814	1.248	0.264
Eprod	0.067	0.796	1.476	0.224	0.331	0.565	0.207	0.649
Esup	0.048	0.826	1.398	0.237	0.331	0.565	0.116	0.733
Econ	0.081	0.775	1.621	0.203	0.201	0.654	0.229	0.632

Part C: Cointegration tests

Variable: X	Maximum rank	Johansen cointegration test of X with BTChr				Johansen cointegration test of X with BTChr			
		Trace statistics	5% critical value	Maximum statistic	5% critical value	Trace statistics	5% critical value	Maximum statistic	5% critical value
PriEn	0	23.28**	15.41	14.48**	14.07	37.60**	15.41	26.75**	14.07
	1	8.796**	3.76	8.796**	3.76	10.85**	3.76	10.85**	3.76
Eprod	0	33.30**	15.41	24.69**	14.07	44.62**	15.41	27.45**	14.07
	1	8.613**	3.76	8.613**	3.76	17.51**	3.76	17.16**	3.76
Esup	0	32.28**	15.41	23.82**	14.07	43.58**	15.41	26.98**	14.07
	1	8.465**	3.76	8.465**	3.76	16.59**	3.76	16.59**	3.76
Econ	0	29.10**	15.41	21.23**	14.07	40.33**	15.41	26.69**	14.07
	1	7.873**	3.76	7.873**	3.76	13.64**	3.76	13.64**	3.76

Variable: X	Test statistics	Gregory–Hansen Test for cointegration with regime shifts of X with BTChr					Gregory–Hansen test for cointegration with regime shifts of X with ETHhr				
		Test statistic	Breakpoint	Date	5% critical value	1% critical value	Test statistic	Breakpoint	Date	5% critical value	1% critical value
PriEn	Zt	−6.22	49	2020m1	−4.61	−5.13	−6.42	49	2020m1	−4.61	−5.13
Eprod	Zt	−5.64	46	2019m10	−4.61	−5.13	−5.81	46	2019m10	−4.61	−5.13
Esup	Zt	−5.38	46	2019m10	−4.61	−5.13	−5.52	46	2019m10	−4.61	−5.13
Econ	Zt	−4.88	44	2019m8	−4.61	−5.13	−5.00	49	2020m1	−4.61	−5.13

Notes: *, ** and *** are significant levels at 10%, 5% and 1%, respectively; data ranges from 2016M1 to 2021M5.

Model: VECM	(1)	(2)	(3)	(4)
Dependent variable:	D_PriEn	D_Eprod	D_Esup	D_Econ
L._ce1	−0.197**	−0.391***	−0.368***	−0.275***
	[0.077]	[0.102]	[0.100]	[0.089]
Constant	0.029**	0.026***	0.025***	0.019***
	[0.012]	[0.007]	[0.007]	[0.006]
Dependent variable:	D_BTChr	D_BTChr	D_BTChr	D_BTChr
L._ce1	0.489**	1.131**	1.101**	1.171***
	[0.203]	[0.488]	[0.467]	[0.440]
Constant	0.012	0.009	0.008	0.004
	[0.031]	[0.033]	[0.033]	[0.031]
Cointegrating equations	χ^2	χ^2	χ^2	χ^2
_ce1	4.258**	4.822**	5.186**	6.138**
Johansen normalization restriction imposed				
_ce1				
PriEn	1			
Eprod		1		
Esup			1	
Econ				1
BTChr	−0.014**	−0.014**	−0.0048**	−0.0065**
_cons	−15.51	−15.51	−13.54	−13.44
Observations	64	64	64	64

Notes: *, ** and *** are significant levels at 10%, 5% and 1%, respectively; data is from 2016M1 to 2021M5; ce1: correction error term from VECM estimate; D_: the first difference; and L.: the one period lag

Table 4.
Bitcoin hashrate and energy consumption

(2) the Bitcoin hashrate really started to increase significantly after 2018 when one can observe a real interest from the market/society in this cryptocurrency.

The three relationships evoked above are quite straightforward: a higher hashrate requires a higher need for electricity that can be observed in the higher level of consumption and leading electricity providers to produce and supply more. More interestingly, our data suggest that the implementation of the "SegWit" mechanism did not really influence the Bitcoin's electricity consumption. To remind, the SegWit consists in increasing the number of transactions per block leading to a reduction of the amount of electricity required to validate one single transaction – our data indicate that, despite the adoption of the SegWit, the Bitcoin's electricity consumption still increases. Table 4 exhibits the influence of the Bitcoin's hashrate in the long and short run, while Table 5 presents the results of our analysis for two sub-periods.

The results in Table 4 indicate that the long-run analysis is really relevant – this is quite understandable given the more and more cryptocurrency mining activities. Table 5 shows the numbers for the two-sub periods.

The analysis of the two sub-periods is interesting. Between January 2016 and October 2019, the positive cointegration [7] of the Bitcoin hashrate on the production, supply and consumption of electricity appeared to be significant. This can be explained by the fact, at that time, the limit of 2016 blocks was enough to handle all transactions operated within 10 min implying that the network was able to re-adjust/reduce the computational difficulty every 10 min. In this context, the difficulty of solving the cryptographic problem related to the validation of a transaction can stay at a reasonable level with a constant hashrate and,

Table 5.
Bitcoin hashrate and energy consumption: two sub-periods

Model: VECM	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Period	2016M1–2019M10				2019M11–2021M5			
Dependent variable:	D_PriEn	D_Eprod	D_Esup	D_Econ	D_PriEn	D_Eprod	D_Esup	D_Econ
L._ce1	−0.967***	−0.761***	−0.704***	−0.590***	−0.457***	−0.711***	−0.691***	−0.651***
	[0.153]	[0.152]	[0.149]	[0.142]	[0.149]	[0.222]	[0.220]	[0.215]
Constant	−0.050***	−0.043***	−0.044***	−0.044***	0.012	0.015**	0.015**	0.016**
	[0.009]	[0.009]	[0.010]	[0.011]	[0.008]	[0.007]	[0.007]	[0.007]
Dependent variable:	D_BTChr	D_BTChr	D_BTChr	D_BTChr	D_BTChr	D_BTChr	D_BTChr	D_BTChr
L._ce1	−1.202**	−0.400	−0.400	−0.326	0.214	0.601*	0.598*	0.581
	[0.605]	[1.156]	[1.100]	[1.127]	[0.170]	[0.346]	[0.336]	[0.355]
Constant	0.040	0.081	0.078	0.079	0.024***	0.018*	0.018*	0.017
	[0.034]	[0.066]	[0.071]	[0.085]	[0.009]	[0.011]	[0.011]	[0.011]
Cointegrating equations	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2
_ce1	23.93***	13.27***	10.81***	9.496***	2.682	3.408*	3.694*	4.509**
Johansen normalization restriction imposed								
_ce1								
PriEn	1				1			
Eprod		1				1		
Esup			1				1	
Econ				1				1
BTChr	**−0.0102*****	**−0.0050*****	**−0.0051*****	**−0.0053*****	**−0.1584**	**−0.0756***	**−0.0821***	**−0.0897****
_cons	−15.81	−13.67	−13.67	−13.61	−12.89	−12.25	−12.12	−11.91
Observations	45	45	45	45	18	18	18	18

Notes: *, ** and *** are significant levels at 10%, 5% and 1%, respectively; ce1: correction error term from VECM estimate; D_: the first difference; and L.: the one period lag therefore, a relatively constant and low need of electricity. This first observation is important because it confirms that the Bitcoin's electricity consumption does not depend on the number of Bitcoin-based transactions made but rather on the blocks that are mined in 10 min. This article is one of the first empirical studies on this matter.

After October 2019, things changed but the long-run positive linkages between Bitcoin hashrate and energy variables still existed. As evoked earlier, a combination of technological ("SegWit"), societal (more media coverage) and possibly fraudulent (price manipulation through Tether) created a context in which the activities and the price of Bitcoin increased significantly. This increase in the price results from a higher demand for Bitcoin and it might have a real impact on the level of electricity required by the network to operate the Bitcoin-based transactions. In this context, the SegWit mechanism has been launched to allow blocks to hold more transactions and therefore deal with a higher number of transactions to be validated. However, despite the SegWit process allowing blocks to hold more transactions, the demand for Bitcoin transactions was, starting from October 2019, higher than the ability of the network to validate and record these transactions – in other words, the SegWit update was not enough to allow the network to handle all transactions in less than 10 min so that, within this short period of time, several sequences of 2016 blocks have been initiated to handle the high volume of transactions. This situation cancels the decrease of the algorithmic difficulty automatically programmed every 2016 blocks in blockchain technology – this explains that the Bitcoin's hashrate increased significantly. Statistically, this phenomenon made the Bitcoin activities big enough to become a highly energy-consuming market, and it marked the beginning of Bitcoin as a contributing factor to the world energy consumption (Mora *et al.*, 2018; Schinckus, 2020).

Regarding the influence of the Ether's hashrate, Tables 6 and 7 present the VECM results for our full period of study and for the two sub-periods (2016M1–2019M10 and 2019M11–2021M5). These tables show that the related dynamics between the Ether's hashrate and the energy consumption.

These two tables can actually be analyzed together. First, there is a long-run positive cointegration between the Ether's hashrate and the energy except for the electricity supply for the ETHhr in the cointegration equation (_ce1) for the period 2016M1–2019M10. This may indicate that there is probably no long-run relationship between the Ether's hashrate and the energy use in this period. However, the results show mostly insignificant cointegration between Ether hashrate and all energy proxies (Eprod, Esup and Econ) for the period 2019M11–2021M11, implying that there are no real long-run relationships between Ether hashrate and energy use in this period. Specifically, the Ether hashrate's coefficients (ETHhr) are significantly negative in our cointegration equation (_ce1 = Energy use [Eprod, Esup and Econ] + ETHhr), indicating that there is long-run positive relation between Ether hashrate and energy use proxies. This long-term dependence can actually be easily understood: Ether is the cryptocurrency used for all smart contracts based-transactions developed on Ethereum. This platform is actually becoming more and more used in a large range of business activities (including energy) explaining how Ether (i.e. cryptocurrency used in Ethereum platform) exhibits long-term influence on the energy indicators. In other words, the increasing importance of Ether in society increases its hashrate inducing a higher need in electricity. The Ether developers are aware about this point, as they announced in 2018 that Ether plans to switch from a POW-based platform to a Proof-of-Stake-based algorithm (Amanie Advisors and Ether Foundation, 2019) offering a lower energy-consuming process of validation.

Model: VECM	(1)	(2)	(3)	(4)
Dependent variable:	D_PriEn	D_Eprod	D_Esup	D_Econ
L._ce1	−0.014	−0.070	−0.048	−0.022
	[0.020]	[0.051]	[0.042]	[0.031]
Constant	−0.003	0.004	0.003	0.002
	[0.006]	[0.004]	[0.004]	[0.003]
Dependent variable:	D_ETHhr	D_ETHhr	D_ETHhr	D_ETHhr
L._ce1	−0.469***	1.897***	1.581***	1.296***
	[0.083]	[0.373]	[0.305]	[0.241]
Constant	0.000	0.000	0.000	0.000
	[0.025]	[0.027]	[0.026]	[0.026]
Cointegrating equations	χ^2	χ^2	χ^2	χ^2
_ce1	29.82***	32.70***	32.76***	33.11***
Johansen normalization restriction imposed				
_ce1				
PriEn	1			
Eprod		1		
Esup			1	
Econ				1
ETHhr	0.104***	−0.0246***	−0.0303***	−0.0385***
_cons	−17.30	−13.35	−13.28	−13.10
Observations	64	64	64	64

Notes: *, ** and *** are significant levels at 10%, 5% and 1%, respectively; data is from 2016M1 to 2021M5; ce1: correction error term from VECM estimate; D_: the first difference; and L.: the one period lag

Table 6.
Ether's hashrate and energy consumption

5. Conclusion

The existing literature acknowledges that an increasing number of transactions (trading volume) dealing with Bitcoin and Ether have an environmental impact through the high consumption of electricity required to validate these transactions. This perspective has been questioned by some technical works (Dittmar and Praktiknjo, 2019; Masanet *et al.*, 2019; Schinckus, 2020, 2021, Schinckus *et al.*, 2020, 2021) claiming that the validation (mining) is not operated on the transactions themselves but instead at the computational block level (each block compiling several transactions). Given the fact that the number of transactions can be increased in a block, a more sophisticated analysis is required. The vast majority of the existing studies on this topic consider that the number of transactions involving cryptocurrencies is an appropriate indicator to estimate their influence on electricity consumption. The major contribution of this article is to investigate a more relevant indicator, namely, hashrate (computational difficulty to solve cryptographic enigma associated with cryptocurrencies-related transaction). Our approach can be justified by the fact that there exists a technical solution ("SegWit" or Segregated Witness) consisting in increasing the number of transactions per blocks so that less electricity might be required to validate a transaction. With this purpose, our article investigates the relationship between the dynamics of hashrate of two major cryptocurrencies (Bitcoin and Ether) and their electricity consumption.

This article is the first empirical study investigating the relation between cryptocurrencies' hashrate and the electricity consumption. Our results confirm the positive link between Bitcoin/Ether's hashrate and their need in electricity – however, our analysis emphasizes that this positive link is not because of the trading volume as usually claimed in

Table 7. Ether's hashrate and energy consumption: two sub-periods

Model: VECM	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Period		2016M1–2019M10				2019M11–2021M5		
Dependent variable:	D_PriEn	D_Eprod	D_Esup	D_Econ	D_PriEn	D_Eprod	D_Esup	D_Econ
L._ce1	−0.788***	−0.667***	−0.225**	0.001	−0.518***	−0.510**	−0.487**	−0.456**
	[0.147]	[0.148]	[0.092]	[0.014]	[0.174]	[0.217]	[0.215]	[0.214]
Constant	−0.028***	0.024***	−0.006*	0.000	−0.028**	0.020**	0.020*	0.019*
	[0.006]	[0.006]	[0.003]	[0.003]	[0.011]	[0.010]	[0.010]	[0.010]
Dependent variable:	D_ETHhr	D_ETHhr	D_ETHhr	D_ETHhr	D_ETHhr	D_ETHhr	D_ETHhr	D_ETHhr
L._ce1	−3.219***	3.394	−4.278***	0.771***	−0.292	1.453**	1.439**	1.474**
	[1.056]	[2.184]	[1.021]	[0.155]	[0.466]	[0.671]	[0.647]	[0.696]
Constant	0.007	0.005	0.000	−0.000	0.049	0.007	0.007	0.006
	[0.046]	[0.081]	[0.037]	[0.033]	[0.030]	[0.031]	[0.031]	[0.033]
Cointegrating equations	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2
_ce1	4.172**	34.19***	6.079**	28.10***	2.768*	0.321	0.248	0.0416
Johansen normalization restriction imposed								
_ce1								
PriEn	1				1			
Eprod		1				1		
Esup			1				1	
Econ				1				1
ETHhr	**−0.0036****	**−0.0067****	**0.0057****	**−0.0768*****	**−0.0606***	**0.0083**	**0.0075**	**0.0030**
_cons	−15.92	−13.58	−13.78	−12.64	−15.17	−13.74	−13.73	−13.60
Observations	45	45	45	45	18	18	18	18

Notes: *, ** and *** are significant levels at 10%, 5% and 1%, respectively; ce1: correction error term from VECM estimate; D_: the first difference; and L.: the one period lag the literature – this positive relationship is actually because of an algorithmic treatment of blocks: the increasing number of transactions led to the launch of several sequences of 2016 blocks to validate. This situation generated very complex enigma to ensure the integrity of the data related to these transactions. Our focus on the two major cryptocurrencies can eventually be seen as a limitation of our analysis but, given its high replicability (i.e. our methodology uses public data and can be easily replicated for other cryptocurrencies), our paper also paves the way for further research on the topic.

Because our research questions the sustainability of Bitcoin and Ether, there are social and managerial implications to our paper. The former mainly refers to the confirmation of the energy-consuming validation of POW-based cryptocurrencies although it is possible to increase the number of transaction per block mined. Such conclusion suggests that society, as a whole, needs an alternative protocol to validate cryptocurrencies. From a managerial viewpoint, our study suggests that the use of POW cryptocurrencies might not be aligned with the increasingly important environmental, social and governance aspects of management. Managers considering the use of cryptocurrencies have to check their underlying protocol used for their validation so that the use of technology can totally be aligned with a broader corporate social responsibility.

To conclude this article with some recommendations, we would call for further research on three aspects:

(1) investigate the technical do-ability of improving the SegWit mechanism to increase the number of transactions per 2016 blocks so that, within 10 min, this limit of 2016 blocks could handle the high volume of transactions – this solution would allow the mining activities to keep a relatively low and stable algorithmic difficulty (as it was the case before October 2019);

(2) study the possibility to use an alternative algorithm to validate the blockchain-based transactions – proof-of-stake being one of them; and

(3) finally, investigate the potential use of alternative source of energy to support the need of energy of the technology.

While the first two points suggest practitioners and policymakers to focus/support either on an improvement of the current POW algorithm or on the replacement of this POW by an alternative consensus, the last suggestion could be an interesting path to investigate if the current POW cannot be changed or replaced – however, this solution might appear paradoxical, as it suggests a new way of producing more energy to ensure a higher energy consumption in the future – rather than changing the way the Bitcoin consumes energy. Debates are still raging on this very new matter.

Notes

1. Mora *et al.* (2018) generated plenty of discussions. Even though other studies (Dittmar and Praktiknjo, 2019) questioned the Mora *et al.* (2018) methodology, they all confirm the increasing trend in the Bitcoin's electricity consumption.
2. We thank the anonymous reviewer for her\his comment on this topic.
3. The data is total electricity production, consumption of 47 OECD countries.
4. For further details on this aspect, see https://www.census.gov/ts/papers/jbes98.pdf
5. By security, we mean immutability and traceability of data (i.e. very low probability of malicious actions such as hacking or modifying data).

6. At the very first step of our research, we thought to use a model based on AR terms, but after careful consideration, we decided not to proceed because this methodology is not totally appropriate for our scope. Precisely, in this study, we focus on the links between the hashrate of BTC, the one of ETH and the energy consumption. This implies cointegration between the variables (as confirmed by our statistical tests). In this context, we applied the VECM model rather than AR terms because through its error correction term (ec), the VECM provides a flexible tool to deal with the aforementioned issue.
7. It is worthy to notice that the coefficient of BTChr in Johansen normalization restriction imposed of ec1 imply that BTChr and energy consumption/electricity consumption are positive linked.

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Appendix

Variables	Source	Seasonal effect	N	Mean	Maximum	Minimum	SD
Total primary energy consumption (bil BTU)	US Energy Information Administration	Yes	65	8,146,870	605,396	6,511,472	9,659,732
Total electricity production (GWU)	International Energy Agency	Yes	65	883,348	54,905	750,894	993,182
Total electricity supply (GWU)	International Energy Agency	Yes	65	884,258	54,985	750,445	994,266
Total electricity consumption (GWU)	International Energy Agency	Yes	65	823,956	51,182	700,320	931,174
Bitcoin hashrate	https://www.blockchain.com/charts/hash-rate	Yes	65	54,528,947	52,774,995	854,633	161,000,000
Ethereum hashrate	https://etherscan.io/chart/hashrate	Yes	65	163,599	130,554	585	604,692

Notes: The hashrates of Bitcoin and Ethereum are monthly average. The seasonal effects are tested by X-12 monthly seasonal adjustment Method of US Department of Commerce and US Census Bureau. The seasonal effects are checked by X-12 of the US Department of Commerce and the US Census Bureau

Table A1. Variables, sources, seasonal effect and data description for raw data

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