Journal of Environmental Management 326 (2023) 116530

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

The environmental impact of cryptocurrencies using proof of work and proof of stake consensus algorithms: A systematic review

Moritz Wendl [a], My Hanh Doan [a], Remmer Sassen [b,*]

[a] TU Dresden, Faculty of Business and Economics, Chair of Business Administration, esp. Sustainability Management and Environmental Accounting, Markt 23, 02763, Zittau, Germany

[b] TU Dresden, IHI Zittau, Chair of Business Administration, esp. Environmental Management, Markt 23, 02763, Zittau, Germany

ARTICLE INFO

Keywords:
Systematic review
Cryptocurrency
Proof of work
Proof of stake
Environmental impact
Cryptocurrency algorithms

ABSTRACT

A systematic literature review is conducted to investigate the environmental impact of Proof of Work (PoW) and Proof of Stake (PoS) cryptocurrencies. Due to the focus of recent research on Bitcoin, an inductive approach has been applied to analyze and cluster the findings of PoW cryptocurrencies into seven aspects that effect the environmental impact of cryptocurrencies: resources, energy consumption, carbon footprint, environmental-related social and economic aspects, policy regulation and subsidization, and electronic waste. Subsequently, interconnections and rebound effects are presented and discussed by synthesizing results from each of the seven aspects into one scenario analysis inspired by the crackdown on cryptocurrency miners in China, 2021. Furthermore, it was observed that proposed policy regulation in literature is strongly focusing on miners. As the profitability of miners globally depends on the price of the PoW cryptocurrency, researchers and policymakers are advised to focus more on investors and third-party services such as regulated exchanges. Thus, identifying and implementing policies that demotivate investment in PoW cryptocurrencies could reduce their prices and the incentive to mine. Ultimately, it was assessed that PoW cryptocurrencies, especially Bitcoin, are historically associated with an ever-increasing environmental impact. In contrary, researchers address PoS as a sustainable alternative that poses a solution to the environmental issues related to PoW.

1. Introduction

In recent years, cryptocurrencies have gained a significant amount of popularity and attention. While El Savador adopted Bitcoin as an official currency, others praise cryptocurrencies as lucrative investment assets that offer a hedge against inflation risks. As researchers have tried to answer the question of whether Bitcoin is rather an asset or a currency, the actual added value of this technology remains questioned (Huynh et al., 2022). Whereas the idea of a digital currency has not been new, the novel underlying blockchain technology that Bitcoin uses has been revolutionary. Referred to as Proof of Work (PoW), Bitcoin's underlying algorithm relies on a decentralized computer network that validates transactions through a search puzzle of hash functions and rewards the successful validator (cryptocurrency miner) with rewards. Due to the increase in popularity and hence price of different PoW cryptocurrencies, these mining rewards became a lucrative, but increasingly competitive business. As more and more computational power was added to the system to participate in the mining process, the energy consumption and carbon emissions associated by this technology are causing widespread concern (Erdogan et al., 2022; Ren and Lucey, 2022; Wang et al., 2022). As of June 2022, Bitcoin's energy consumption is estimated to be on par with Sweden or Ukraine (Digiconomist, 2022) and its emissions alone are discussed as a threat to mitigating greenhouse gas emissions to meet the Paris Agreement (Truby et al., 2022). On top, effective mitigation is creating significant challenges, as traditional governmental and banking regulatory mechanisms are circumvented (Goodkind et al., 2020). However, other consensus algorithms to validate transactions have emerged. The most widespread alternative is Proof of Stake (PoS). Here, the probability to receive a reward for validating transactions is not linked to computing power provided, but to own capital staked within the system, which is also scarce and visible within the network and thus verifiable (Sedlmeir et al., 2020a).

As environmental degradation and climate change have strong implications for society, research on the environmental impact of cryptocurrencies based on widespread consensus algorithms is of importance. In this regard, a systematic review can thus help to find relevant sources

* Corresponding author.
E-mail address: remmer.sassen@tu-dresden.de (R. Sassen).

https://doi.org/10.1016/j.jenvman.2022.116530
Received 30 August 2022; Received in revised form 10 October 2022; Accepted 12 October 2022
Available online 10 November 2022

on a topic under investigation (Brocke et al., 2009) and determine what needs to be done to solve research problems (Hart, 1998). Hence, a systematic review based on the methodology of Fink (2005) is performed. The focus of this research paper is on sustainability of PoS and PoW in the context of environmental-related aspects. This leads to the following research question:

What is the environmental impact of cryptocurrencies using proof of work or proof of stake technology?

This literature review aims to contribute to current research by clustering findings in relevant literature into inductively identified environmental-related aspects and highlight interconnections and rebound effects between them. The novel proposed dimensions and their connection shall help to educate policy makers about the environmental impact of cryptocurrencies and show cause and effect of externalities associated.

2. Research background

2.1. Cryptocurrencies using proof of work consensus algorithms

The first decentralized distributed currency, Bitcoin, was proposed by an author, or group of authors by the pseudonym Satoshi Nakamoto in 2008 (Nakamoto and Bitcoin, 2008). In this system, financial institutions are not needed as an intermediary. In addition, the underlying blockchain technology provides a high level of consistency, security and reliability. This blockchain is referred to as a decentralized public ledger (Goodkind et al., 2020). A ledger is a record-keeping system and maintains relevant data of participants such as cryptocurrency balances and records of all genuine transactions within a network anonymously. Computers, who run specific blockchain software to validate transactions and store transaction histories are called nodes. These nodes submit transactions to the digital ledger, which are clustered in form of blocks. The blocks are linked via specific hash values and form a chain – the so called blockchain. Within a decentralized network, peers continuously agree on the order of newly added blocks to secure the data via a consensus mechanism, which is why this algorithmic process is called a consensus algorithm. Nowadays, there are various consensus algorithms (Köhler and Pizzol, 2019).

The consensus algorithm earliest adopted in blockchain is PoW (Hu et al., 2021). In a PoW algorithm, the process of validating transactions via nodes is called mining and is accomplished using brute-force computing power. In the case of bitcoin, a fixed mining rate of 10 min exists (Atkins et al., 2021a) and seven transactions per second can be processed by the entire network (Rebello et al., 2021). Only the first one to solve a complex computing task provides the hash identifier for a new block. The miner that succeeds awaits a reward that is distributed in form of the specific cryptocurrency mined (Goodkind et al., 2020; Leslie, 2020). For most PoW blockchains, the reward is typically halved every few years (Sedlmeir et al., 2020b). Bitcoin halvings take place every 210, 000 blocks until 2140, when all 21 million bitcoins have been mined.

To secure the functionality of PoW blockchain networks, the time span in which a new block is added to the blockchain must be kept constant. Therefore, the difficulty of the cryptographic puzzle to generate the validating hash adapts to the hash-rate to maintain a predefined mining rate. If more mining power is made available, e.g., due to increasing competition in mining, both the hash rate and the difficulty of the cryptographic puzzle increase. At the same time, new transactions keep record of all past validated transactions, what generates larger blocks that further increase the difficulty to solve these cryptographic problems. This leads to a further increase in energy consumption at a given energy efficiency of mining equipment (Sedlmeir et al., 2020a). Thus, the process of PoW generates financial value, but is requiring considerable amounts of energy with increasing competition (Bouraga, 2021; de Vries, 2019).

2.2. Cryptocurrencies using proof of stake consensus algorithms

The PoS algorithm was introduced in 2012 to solve the issue of the high resource consumption of PoW (King and Nadal, 2012). Within this network, nodes are called validators instead of miners. The validators deposit refundable amounts of coins (stakes) of a cryptocurrency that they own. The idea behind this design is that validators shall proof that they own and trust the cryptocurrency by staking refundable parts of their own cryptocurrency holdings. At the same time, malicious attacks would risk these contributed stakes, which in return should provide security and provide a consensus.

There are two main approaches. In the probabilistic approach, all participants have to compute a hash, similar to mining in PoW. Yet, the difficulty of the hash is dependent on the stake contributed. Hence, participants with high stakes solve a less complex cryptographic puzzle. In addition, there is only a limited time window available for these calculations, and the average difficulty of the calculations is significantly lower than for Bitcoin (Rebello et al., 2021).

In the deterministic approach, a set of validators confirm blocks by voting with weights proportional to each validators stakes (ibid.). Hence, in both approaches, there is no brute-force-based competition between nodes (Roeck and Drennen, 2022).

3. Research methodology

This work aims to complement the existing research status by summarizing and evaluating the environmental impact of cryptocurrencies using PoW and PoS algorithms described in literature. To identify all studies relevant to this topic, a systematic review is carried out. This approach was chosen, as it helps to identify relevant sources in a research field (Brocke et al., 2009) and can determine implications to solve research problems (Hart, 1998).

The following databases were used for the search: ScienceDirect and Link Springer (Articles). Based on the research question, the applied search string strives to regard three aspects: cryptocurrencies, the environmental impact as well as PoW and PoS algorithms. The final search string is as follows: (Cryptocurrency) AND (Sustainab* OR Environment* OR Energy) AND ("Proof of Work" OR "Proof of Stake")

Since the oldest cryptocurrency, Bitcoin, was first mentioned in a white paper in 2008, only papers from 2008 to 2022 (June 05, 2022) were considered. Through search engines, title and abstract were scanned and only English and German papers were considered in the literature search.

Since the focus of this research paper is on cryptocurrencies, papers addressing other use cases of blockchain have been excluded. Furthermore, papers which were not dealing with either PoW or PoS algorithms were not regarded. Also, papers that were not addressing environmental aspects were not considered. Additionally, the search results were exported from the databases and imported into Zotero to further exclude duplicates. However, no duplicates were found. Additionally, a forward- and backward search was conducted.

A total of 1237 items were gathered. The articles were first filtered by screening title and abstract. In a second step, the remaining articles were screened by scanning their full text. Each article was read until it was clear that it was relevant to this study and that the exclusion criteria did not hold.

Additional information about the 50 relevant papers can be retrieved in Table A.in the Appendix. To analyze and synthesize the literature, an inductive approach based on Thomas (2006) was followed to condense extensive and varied raw text data into a brief, summary format. In brief, inductive coding is used for researchers to identify text segments that are meaningful for a specific topic, and label them into suitable categories. In a first instance, all environmental aspects addressed in relevant papers were coded into two categories (information related to PoW and PoS) using MAXQDA. Due to the vast amount of information about the environmental impact of PoW cryptocurrencies, the respective information was further categorized. Via the inductive approach, seven categories could be identified: resources, electronic waste, energy consumption, carbon footprint, environmental-related social aspects, environmental-related social and economic aspects, general policy regulation and subsidization.

Even though these categories are interconnected and should be considered as a whole in reality, the individual analysis of these aspects shall provide a better and deeper understanding of the environmental impact of PoW cryptocurrencies.

4. Results

4.1. Environmental impact of proof of work cryptocurrencies

4.1.1. Resource aspects

Today's cryptocurrency mining is using large amounts of resources (Apatova et al., 2020; Atkins et al., 2021a; Sriman et al., 2021; Treiblmaier, 2021). In order to mine, miners have experimented with various hardware in order to increase computation power. Initially, Central processing units were used, before graphics processing units replaced them for a short period of time. Next, Field-programmable gate arrays were customized to support mining before the application-specific integrated circuits (ASICs) became state of the art within the mining business since 2013. ASICs are designed especially for mining and cannot be refunctioned (Malone and O'Dwyer, 2014).

Miners gain a competitive advantage by upgrading their equipment and thus increasing the energy efficiency of their mining equipment (less energy consumed per unit of computational power), which resulted in a race to develop and manufacture more efficient mining machines (de Vries, 2021a). In January 2011, an up-to-date graphics processing units with a processing power of 2 Gigahertz could expect to find more than two blocks per day. In November 2018, the same miner could only expect to find a new block every 472,339 years due to the increased competition in mining, which lead to an increase in hash-rate and an increasingly complex cryptographic puzzle to be solved. Thus, there is an incentive for miners to purchase up to date hardware. Also, it is a profitable business for manufacturers to produce faster mining machines (Stoll et al., 2019a). Nowadays, millions of machines using ASICs operate across the globe for mining (Atkins et al., 2021b), usually deployed in banks of thousands of machines called mining rigs (Leslie, 2020). Even though it is not possible to determine exactly how many machines are active in the network, de Vries and Stoll (2021) estimated that there were around 2.9 million active cryptocurrency mining machines in May 2021. To manufacture one million units of the most efficient mining device as of 2021, the Antimer S19 Pro, 149,476 silicon wafers are required, claiming huge capacities of semiconductor manufacturers and massive amounts of precious metals (ibid.). Due to the large amount of waste heat, also additional refrigeration equipment, fans and air conditioners are necessary, requiring further resources (Apatova et al., 2020).

4.1.2. Electronic waste

Electronic waste describes discarded electronic or electrical devices. As todays cryptocurrency mining occurs on highly specialized hardware concentrated in large-scale mining farms or pools (Atkins et al., 2021a; Goodkind et al., 2020; Schinckus, 2020), these machines do not serve a purpose other than the singular task they were produced for and become electronic waste after their usage for mining (de Vries, 2019,2021; Huynh et al., 2022). Electronic waste is a threat to the environment as it can result in toxic chemicals and heavy metals leaching. If recycled improperly, this can pollute soil, air and water (Apatova et al., 2020; de Vries and Stoll, 2021).

A methodology to estimate the electronic waste resulting from cryptocurrency mining is to estimate the quantity of mining machines within the network and the rate at which this equipment becomes disposed (de Vries, 2019). However, it is not possible to determine the exact amount of mining devices within a decentralized PoW network. However, lower bound estimates can be derived by multiplying the computational power within the network with the lowest amount of equipment weight per unit of computational power. In order to estimate the amount of annualized electronic waste, the total product stock of mining equipment is estimated and divided by the average product lifespan of the respective mining equipment (de Vries and Stoll, 2021). For 2018, the annualized lower bound estimate equaled 10,948 metric tons, or 134,5 g of waste per transaction. This is significantly less sustainable than the financial institution VISA, which had an estimated 0.0045 g of waste produced per transaction in 2018 (de Vries, 2019). In 2021, de Vries and Stoll (2021) estimated annualized 30,700 metric tons of e-waste or 272 g of waste per transaction, roughly tripling the previous estimate due to increased popularity in mining and highlighting the dynamic trend if PoW cryptocurrencies such as Bitcoin rise further.

De Vries (2019) expects that only cost-efficient mining equipment will be used, and older machines shut down as soon as they are not economically profitable. Atkins et al. (2021b) states that computational power in ASICs double every 6 months. This is a significantly higher rate than for customer hardware, which has been assessed to double in computational power roughly every 18 months according to Koomey's law (Koomey et al., 2011). As manufacturers increase the efficiency of mining equipment, new equipment has been estimated to becoming obsolete in approximately 1,5 years in 2018 (de Vries, 2019), and 1,29 years in 2021 (de Vries and Stoll, 2021). Also, manufacturers often do not have any recycling programs. Thus, the electronic waste generated especially in countries without electronic waste regulation such as Iran, Kazakhstan, and Malaysia, is handled in the informal sector. This is often causing severe damage to the environment and health (de Vries and Stoll, 2021). On top, additional refrigerator systems and fans used for regulating the heat of mining equipment create further electronic waste (Schinckus, 2020).

4.1.3. Energy consumption

Various authors attribute the high energy consumption of PoW cryptocurrencies to their fundamental algorithm design (e.g. Bouraga, 2021; Erdogan et al., 2022; Goodkind et al., 2020; Leslie, 2020; Malfuzi et al., 2020; Truby, 2018) as most of the energy consumed is wasted, because only the first one to complete a certain hash receives a reward (Morris, 2019; Rebello et al., 2021). By using vector error correction models to examine data from Bitcoin and Ether energy consumption from 2016 to 2021, the correlation between hash rate and energy consumption was reconfirmed by Schinckus et al. (2022).

It would be necessary to know the total network hash-rate as well as the exact mining hardware used to evaluate the exact energy consumption of PoW cryptocurrencies. Since it is not possible to determine the corresponding hardware for each individual participant in an open and non-access restricted PoW blockchain, the determination of power consumption is very difficult (Nair et al., 2020; Sutherland, 2019). There is no register with exact information about the running mining hardware and their energy consumption within a network (de Vries, 2019). However, the total hash-rate of PoW networks can be derived and used as a starting point for estimates.

In recent years, different methodologies have been introduced to approximate to a value of energy consumption at given timeframes. These methods were classified into four categories by Lei et al. (2021). Their terminology will be used in the following section. Due to the lack of empirical foundations, the estimates produced vary significantly among studies (Küfeoğlu and Özkuran, 2019; Stoll et al., 2019b), but have constantly trended upwards (Huynh et al., 2022; Schinckus, 2020), as high-demand and higher prices in Bitcoin prices have strongly increased Bitcoin's hash rate since 2017 (Roeck and Drennen, 2022).

Dating back to early 2014, a top-down approach was used by Malone and O'Dwyer (2014) to estimate the energy consumption of the Bitcoin network. This method is applied by multiplying the assumed average energy efficiency of the mining equipment used globally (Joule

Table 1
Estimates of energy consumption of PoW cryptocurrencies (own representation).

Author	Publishing Date	Focus	Methodology	2014	2015	2016	2017	2018	2019	2020	2021	2022
Digiconomist	Daily calculation since 2017; Data for 2022 retrieved on June 19, 2022	Bitcoin Bitcoin Cash	Top-down & Economic				**LB 7,37 UB 69,01**	**LB 40,42 UB 122,91**	**LB 43,97 UB 93,72**	**LB 49,13 UB 95,98**	**LB 45,69 UB 332,91**	**LB 65,32 BE 130,24**
CBECI	Daily calculation since 2011; Data retrieved from 2014 until June 19, 2022	Bitcoin	Hybrid top-down	**BE 3,76**	**BE 2,46**	**BE 8,24**	**BE 16,92**	**BE 45,43**	**BE 57,1**	**BE 68,51**	**BE 104,89**	**BE 107,55**
Küfeoglu and Özkuran (2019)	June 2018	Bitcoin	Hybrid top-down					**LB 15.47 UB 50,24**				
De Vries (2018)	May 2018	Bitcoin	Top-down &Economic				**LB 22 UB 67**					
De Vries (2019)	April 2019	Bitcoin	Top-down & Economic					**LB 40 UB 62,3**				
De Vries (2020)	December 2020	Bitcoin	Economic						**BE 87,1**			
Stoll et al., 2019a	July 2019	Bitcoin	Top Down & Economic					**BE 48,20**				
Li et al., 2019	February 2019	Monero	Extrapolation					**BE 0,65**				
Krause and Tolaymat (2018)	November 2018	Bitcoin, Ethereum, Litecoin, Monero	Top-down			**BE 2,85**	**BE 20,28**	**BE 44,01**				
Köhler and Pizzol (2019)	November 2019	Bitcoin	Top-down					**BE 31,29**				
Seidlmeier et al., 2020a	February 2020	Bitcoin, Ethereum	Top-down &Economic							**LB 60 UB 125**		
O'Dwyer and Malone, 2014	January 2014	Bitcoin	Top-down	**LB 0,88 UB 87,6 BE 26,28**								
McCook, 2018	July 2018	Bitcoin	Top Down					**BE 105,82**				

Estimates in TWh - LB = Lower-bound estimate - UB = Upper-bound estimate - BE = Best estimate.

consumed per computation) with the hash-rate of the Bitcoin network. Malone and O'Dwyer (2014) presented a range of 100 MW - 10 GW per day due to consideration of different mining equipment and presented a best estimate of 3 GW. However, the authors did not clarify the underlaying assumptions for their best guess. Also, they did not consider the profitability of mining devices, which led to an unrealistically high upper-bound estimate of energy consumption at the time due to consideration of outdated machines for this scenario (Vranken, 2017). In general, estimating the average energy efficiency of mining equipment comes with huge uncertainty. Within the top-down approach, profitability of mining and additional energy factors such as cooling systems for mining equipment are not considered (Apatova et al., 2020). Therefore, this approach is rather used for calculating lower bound results for the power consumption of PoW cryptocurrencies by using the most efficient mining device available as a base (de Vries, 2018, 2019, 2020; Digiconomist, 2022; Köhler and Pizzol, 2019; Krause and Tolaymat, 2018; Küfeoğlu and Özkuran, 2019; Li et al., 2019; McCook, 2018; Sedlmeir et al., 2020b; Stoll et al., 2019a).

Another methodology to assess the energy usage is the economic approach, which builds upon the top-down approach and further assumes that only mining hardware is used, which is profitable at the given electricity and cryptocurrency prices. Hence, market participants behave economically rational (Stoll et al., 2019a). Furthermore, it is assumed that profitable mining machines operate constantly throughout the year (de Vries, 2019; Di Febo et al., 2021; Stoll et al., 2019b). These assumptions may not be true for all participants, but the majority of computing power for relevant PoW cryptocurrencies is provided by companies or pools specializing in mining, for which this assumption seems reasonable (Sedlmeir et al., 2020a). Furthermore, it is assumed that miners spend 60% of their revenues on electricity. The average costs of operation in countries with significant participation in mining is often put at $0,05 per kWh (de Vries, 2019; McCook, 2018; Stoll et al., 2019a). This approach is suitable to calculate upper-bound estimates by assuming that all miners use the least energy efficient, but still profitable mining hardware, and derive the estimated energy consumption according to the current hash-rate (e.g. de Vries, 2018, 2019, 2020; Digiconomist, 2022; Sedlmeir et al., 2020b). Various authors (e.g. Li et al., 2019; Roeck and Drennen, 2022; Snytnikov and Potemkin, 2022; Sriman et al., 2021; Vaz and Brown, 2020) refer to the energy consumption of the Digiconomist (2022), a website developed by the Dutch researcher de Vries, which updates the energy consumption of Bitcoin on a daily bases and presents lower and upper bound estimates based upon this approach. However, this approach is criticized for being very sensitive to individual choices, such as assuming to what percentage of mining revenue is spent on energy consumption (Sedlmeir et al., 2020b).

Küfeoğlu and Özkuran (2019) applied a hybrid top-down approach to further reduce uncertainty by considering the relation of mining machine efficiency and profitability based on current cryptocurrency prices (Lei et al., 2021). This method, introduced by Bevand (2017), is intended to further reduce uncertainty when considering different hardware efficiencies. Yet, the specific composition of the mining equipment used to mine PoW cryptocurrencies remains uncertain. A website named "Cambridge Bitcoin Electricity Consumption Index" (CBECI) provides daily estimates based on the hybrid top-down methodology and is referred to in different studies regarded in this review (Erdogan et al., 2022; Lei et al., 2021; Milunovich, 2022).

A further method to estimate power consumption in a blockchain network is extrapolation based on direct measurement. Here, the aim is to measure the power consumption within a small network and derive a representative estimation for the whole network by multiplying the network hash rate or network nodes with the energy intensity (Lei et al., 2021).

Table 1 below shows quantified estimates by researchers of the energy consumption of PoW cryptocurrencies. To put the numbers presented into perspective, Bitcoins energy consumption of 87,1 Twh in 2019 would be almost half as high as the energy demand of all data centers globally (de Vries, 2020). Additionally, understudied cryptocurrencies could use up to 50% on top of Bitcoins energy consumption (Gallersdörfer et al., 2020). Compared to traditional banking systems, Bitcoins energy consumption in relation to the amount of transactions performed is enormous (de Vries, 2021b; Sedlmeir et al., 2020b). According to Vaz and Brown (2020), Bitcoin uses approximately 58 times more energy per transaction than Visa credit card transactions. Even bigger discrepancies are shown by de Vries (2019), who calculated an average electricity footprint per transaction of 491,4 kWh to 765,4 kWh for Bitcoin, whereas the global banking industry indicated a footprint of only 0,4 kWh at most. As of June 20th, 2022, the Digiconomist (2022) assesses that per single Bitcoin transaction, 951.246 VISA transactions could be powered.

Mining activities, which are typically clustered in certain areas, are criticized to increase the baseload of local grids. This can potentially cause imbalances, which might even lead to blackouts (Ullrich et al., 2018; Wang et al., 2022). On a more positive note, Apatova et al. (2020) mentions the possibility to facilitate energy used for bitcoin mining for short term balancing of energy in power grids.

In the long-term, Goodkind et al. (2020) expects a further rise in energy consumption. This is explained with the continues reduction of Bitcoins mining rewards, which would imply the necessity for competing miners to increase efforts to mine. In contrary, Küfeoğlu and Özkuran (2019) highlights that the discussion about Bitcoins energy consumption will likely persist until the year 2028, as 98,44% of the total supply of all Bitcoins will be mined.

4.1.4. Carbon footprint

While the energy efficiency of blockchain technology has tended to improve over the years, the energy consumption and resulting emissions of PoW cryptocurrencies have increased significantly and have come under criticism (Truby et al., 2022; Wang et al., 2022). These emissions are tightly correlated with the energy consumption from non-renewable energy sources.

Evaluating these emissions are associated with a lot of uncertainty (Gallersdörfer et al., 2020) and accurate estimations are hardly possible, because the carbon-intensity of mining differs by location and country due to the prevailing energy sources. Also, reliable data on network devices and locations are lacking (Apatova et al., 2020; Erdogan et al., 2022; Köhler and Pizzol, 2019; Schinckus, 2020).

A popular approach to calculate the carbon footprint of PoW cryptocurrencies is based on the average regional carbon intensity of power generation (Stoll et al., 2019b). For this, the Internet Protocol from big mining pools clustered in certain regions with cheap and plentiful energy are used to identify mining hotspots and their energy sources (de Vries et al., 2022). Krause and Tolaymat (2018) proposed a range of 3–15 $MtCO_2$ considering four of the biggest PoW cryptocurrencies in the timeframe of 2016 until June of 2018, namely Bitcoin, Ether, Litecoin and Monero. These estimates vary by a factor of over 4 due to the consideration of different emission factors in countries, whereas mining in Canada was the lower bound estimate and mining in India the higher bound scenario.

However, especially the energy consumption of Bitcoin is associated with significant carbon emissions (Apatova et al., 2020; Erdogan et al., 2022). These emissions alone are posing a threat to mitigating greenhouse gas emissions to meet the Paris Agreement (Truby, 2018; Truby et al., 2022). Köhler and Pizzol (2019) state that an increase or decrease of 10% in energy consumption leads to an increase or decrease of 9,9% in carbon emissions.

In 2018, the emissions resulting from Bitcoin mining activities were estimated to be 3–13 megatons of CO_2 ($MtCO_2$) (Krause and Tolaymat, 2018), 17.29 $MtCO_2$ (Köhler and Pizzol, 2019), 23,6–28,8 $MtCO_2$ (Stoll et al., 2019a), 19–29,6 $MtCO_2$ (de Vries, 2019) and up to 69 $MtCO_2$ (McCook, 2018). Although the estimates vary, they have steadily trended upwards. De Vries (2021a) estimated carbon emissions of 90.2 $MtCO_2$ in 2020, while Sarkodie et al. (2022) presents an estimated average of 108.92 $MtCO_2$ per year in 2021. Di Febo et al. (2021) forecasted annual emissions of 130.50 $MtCO_2$ in 2024 without policy interventions. According to Qin et al. (2020), these emissions could sum up to 2 gigatons until the year 2100 in a business-as-usual scenario. In contrary, Sedlmeir et al. (2020a) concludes that PoW cryptocurrencies do not represent a serious threat to the climate, as the carbon emissions would decrease along with the energy consumption after bitcoin halvings will further reduce the profitability of mining in the future.

To reduce this impact, energy efficient mining, as well an expansion of renewable energy shares are required in the cryptocurrency mining industry (Das and Dutta, 2020; Gallersdörfer et al., 2020; Snytnikov and Potemkin, 2022). Some miners have already committed to renewable energy to reduce carbon impacts, however these are just individual cases (Truby et al., 2022). On top, the consumption of renewable energy for PoW cryptocurrencies can lead to shortages in surrounding areas that do not have an excess of zero-carbon power capacity. These shortages are usually covered by fossil fuels, thus shifting the environmental impact to other parties (de Vries et al., 2022; Stoll et al., 2019b). Morris (2019) and Wang et al. (2022) similarly state that Bitcoin uses renewable electricity that could otherwise replace fossil energy sources for more useful work.

Qin et al. (2020) assumed that Bitcoin's carbon footprint has peaked already around 2020, if Bitcoin should reach carbon neutrality until 2050. This scenario is not only challenged by the previously stated carbon emission estimates by authors, but also by recent studies addressing the carbon intensity in Bitcoin mining. Stoll et al. 2019a) assessed an average implied global carbon intensity of Bitcoin mining of 480–500 g of CO_2 per kWh of energy consumed in 2018. After the crackdown in China in 2021, and the following relocation of miners in different countries, de Vries et al. (2022) re-evaluated the average carbon-intensity of mining to have increased to 557.76 gCO_2 per kWh in late 2021 due to carbon leakage. Hence, in 2020 the amount of renewable energy has been estimated to account for 39% (Truby et al., 2022) and 41,6% (de Vries et al., 2022), and has decreased to 25,1% in 2021 after the intervention in China (ibid.).

4.1.5. Environmental-related social aspects

Environmental-related aspects could affect or be affected by social aspects such as human health, security of energy supply and access to products and services.

Based on the assumption that 4434 metric tons of CO_2 could kill a person unnecessarily, Truby et al. (2022) states that the environmental impact of Bitcoin in 2021 attributed to 19,000 future deaths due to the annual emissions produced. On Ethereum, the second biggest PoW blockchain, 51,877 transactions would be sufficient to cause one further death, equaling a total of 7585 estimated deaths in 2021.

Goodkind et al. (2020) estimate that in 2018 for each dollar of Bitcoin value created, health and climate damages of 0.49$ (US) or $0.37 (China) occurred. The differences in the estimates are explained by the different values for statistical life expectancy in the USA and China.

Due to the large amount of semiconductor manufacturing capacities needed for producing mining equipment, PoW cryptocurrency equipment production is worsening the global ship shortages. This can delay the access to clean mobility for a number of customers who seek to purchase electric vehicles, which play a role in meeting the goals of the Paris agreement (de Vries and Stoll, 2021).

Kristoufek (2020) underlines cryptocurrencies feature to be able to be turned on and off simply, cheaply and efficiently to balance energy in times of overproduction and stabilize electricity grids and ensure energy provision in communities.

4.1.6. Environmental-related economic aspects

Environmental-related economic aspects describe how economic factors such as cryptocurrency price and trading volume are related to the environmental impact. The profitability of cryptocurrency mining increases along with a raise in price of a PoW cryptocurrency, as the mining rewards can be sold for a larger amount of money (Das and Dutta, 2020; Erdogan et al., 2022). This attracts more miners and ultimately increases energy consumption, carbon footprint and causes further externalities on the environment (Treiblmaier, 2021; Truby, 2018). The single largest cost for mining is electricity, followed by hardware costs (Atkins et al., 2021b). Even less energy efficient mining hardware becomes profitable again at higher PoW cryptocurrency prices, which can amplify the total energy consumption of PoW cryptocurrencies further (de Vries, 2020).

Similarly, if the market declines rapidly, the network's energy consumption does as well. This was observed in 2018, in which the Bitcoin price dropped by more than 80% after it reached almost $20,000 for the first time in 2017. According to (de Vries, 2021a), a Bitcoin price of $8000 could only sustain an energy consumption of at most 60 TWh per year, because miners can only bear the costs for a given level of energy consumption if they achieve a certain amount of income from mining. Malfuzi et al. (2020) assess that in countries with large resources of natural gas (e.g. USA, or Canada), and bio gas (e.g. Japan), combined with high electricity prices mining based on these resources is only profitable at Bitcoin prices higher than $20,000. Das and Dutta (2020) therefore title the energy price as the Achilles heel to miner's revenue in face of volatile and low income from mining rewards due to a low price of a respective currency. Assuming an average price of $0,05 per kWh, the share of electricity costs in the total costs was estimated to be at around 60% (de Vries, 2021b) and 80% (Truby et al., 2022). In June 2018, Delgado-Mohatar et al. (2019) estimate bitcoin mining to not be profitable with electricity prices above $0.14 per kWh. However, it was assessed that the hash-rate does not instantly rise and fall with the profitability. Thus, there is a delayed effect (Delgado-Mohatar et al., 2019), which is explained by the fact that some miners might continue mining at loss when expecting near rising Bitcoin prices. Treiblmaier (2021) concludes that the energy invested therefore could rather resemble the expectation of miners on how much the future gains from mining will be, rather than their current rewards.

Recent studies also researched the effect of trading volume on the environmental impact of cryptocurrencies. Sedlmeir et al. (2020b) assists that the energy consumption does not increase substantially when processing more transactions. Also, Schinckus et al. (2022) confirmed that the link between Bitcoin and Ether's hashrate and the electricity consumption is not dependend of trading volume. This contradicts other recent studies, which assess that a strong driver for energy consumption and carbon emissions is the trade volume. Just 1% increase in trade volume spurs both carbon and energy footprint by ~24% in the long-term (Sarkodie et al., 2022). By using variance decompositions combined with realized semi-variances for daily data from 2017 to 2019, a bidirectional influence between Bitcoin volumes, returns and energy consumption has been confirmed by Huynh et al. (2022).

By using the approaches of cross-sectional standard and absolute deviation of returns, Ren and Lucey (2022) observed that investors in energy-efficient cryptocurrencies follow the actions that major PoW cryptocurrencies perform in up markets.

As the PoW algorithm is designed to half the rewards for cryptocurrency mining every 210,000 blocks, which happens roughly every 4 years, the profitability, and ultimately the environmental impact should decrease long-term assuming constant Bitcoin and energy prices. Hence, the energy consumption could half along with the rewards, until the rewards are equaling the transaction fees (Sedlmeir et al., 2020b).

4.1.7. Policy regulation and subsidization

Even though Bitcoin has been adopted as official currency by El Savador, the impact of cryptocurrencies on the environment have not been widely included in policy debates yet. As the free market has failed to correct the treat of PoW cryptocurrencies to energy supplies and climate change, intervention is justified and necessary (Huynh et al., 2022; Truby et al., 2022). However, policy interventions to regulate the environmental impact of PoW cryptocurrencies are difficult to enforce as this transformative technology prevents traditional governmental and banking regulatory mechanisms (Goodkind et al., 2020). Therefore, it is crucial for policy makers to understand the carbon footprint of cryptocurrencies in order to take the right measures to keep global warming below 2 °C (Stoll et al., 2019a).

As a first starting point, policy makers could raise awareness towards investors, miners and manufacturers (de Vries and Stoll, 2021). This could pressure unsustainable cryptocurrencies to transition towards more sustainable alternatives, such as PoS (Truby et al., 2022).

Furthermore, so called pollution taxes are one instrument frequently discussed to internalize unaccounted and unpriced negative externalities (Apatova et al., 2020; Erdogan et al., 2022; Goodkind et al., 2020; Qin et al., 2020; Truby, 2018; Truby et al., 2022). Goodkind et al. (2020) state that these taxes could be levied on the sale of mining hardware or the sale of energy in known mining locations. Also, an efficiency dependent tax for mining equipment and a surcharge on profits from PoW cryptocurrencies is proposed (Erdogan et al., 2022; Truby, 2018; Truby et al., 2022). In addition, Erdogan et al. (2022) and Truby et al. (2022) propose a taxation at the point of transaction, which could be based on the emission levels or energy consumption of the type of platform. Any gains tax or income tax could be charged at a premium rated if PoW verification is used. Furthermore, Truby (2018) suggest to involve mining into emission schemes.

Truby (2018) describes PoW cryptocurrencies as threatening the planet and underlines the necessity to prevent similar models from emerging. Also, it is argued that bitcoin mining can become a threat to power grids (Atkins et al., 2021a; Ullrich et al., 2018). This widespread negative reputation has resulted in restrictive measures. The most restrictive measure proposed is strictly banning PoW cryptocurrencies (Qin et al., 2020).

In 2018, the energy board of Québec passed a monatorium on unapproved cryptocurrency mining after local grid destabilizations (Atkins et al., 2021b). In January of 2021, mining equipment has been seized, as outages were blamed on cryptocurrency mining activities (Arab News, 2021; as cited in de Vries, 2021b). Another recent example is the passed bill by New York State Senate on halting PoW miners until an environmental impact assessment is conducted (Truby et al., 2022). Also, the Swedish Financial Supervisory Authority and Environmental Protection Agency demanded a ban on mining, arguing that even the use of renewable electricity could delay the energy transition of essential services (de Vries et al., 2022).

However, the most prominent example of regulation of cryptocurrencies due to claimed environmental concerns was the proposed ban on cryptocurrency mining in China in 2019 (Leslie, 2020), which was executed between May and June of 2021 with controverse results (de Vries et al., 2022; de Vries and Stoll, 2021). Up until 2021, China was estimated to host most mining activities with up to 70% of computing power contributed to the Bitcoin network (Atkins et al., 2021a). Post ban a time-limited collapse of the Bitcoin hash-rate occurred (Truby et al., 2022). However, the possibility to re-locate cryptocurrency-mining almost anywhere with anonymity is a significant challenge for effective regulation (Atkins et al., 2021b; Goodkind et al., 2020). The crackdown on cryptocurrency mining has been effective within China, however the hash-rate has recovered as many miners relocated their mining devices into countries such as Canada, USA and Kazakhstan. Apatova et al. (2020) argues that these prohibitive measures will not lead to positive results. This is supported by the study of de Vries et al. (2022), concluding that the carbon intensity after the crackdown on PoW mining activities has increased by 17% in August of 2021 compared to August of 2020 due to relocation of miners in regions with less renewable energy production. In late 2021, the USA hosted over 30% of the global hash-rate and has now become the biggest destination for mining (Truby et al., 2022). Hence, miners seek locations with low regulation in combination with low energy prices (Atkins et al., 2021a; Köhler and Pizzol, 2019; Roeck and Drennen, 2022; Truby et al., 2022). In consequence, international regulation is required for decarbonization and for preventing carbon leakage (de Vries, 2021a; Di Febo et al., 2021; Goodkind et al., 2020; Roeck and Drennen, 2022; Truby, 2018). An instrument to combat this issue could be border tax adjustments (Truby et al., 2022).

Another point of discussion is the limitation of access to chip production for the few manufacturers of bitcoin mining devices. This could decrease cryptocurrency mining (de Vries and Stoll, 2021; Truby, 2018). A focus could also be set on regulated exchanges for cryptocurrencies as they interact with national banks and financial institutions. The following negative influence on the value of PoW cryptocurrencies would lower the economic attractivity for miners (de Vries, 2021b).

Wang et al. (2022) state that the problem is not the specific cryptocurrency, but the energy sources. As beforementioned, it was estimated that in 2020, only 39% (Truby et al., 2022) or 41,6% of cryptocurrency mining was done using renewable energy sources, before that percentage dropped to just 25% due to carbon leakage in 2021 (de Vries et al., 2022). Some US-based miners have even purchased disused coal power plants to ensure their power supply (Truby et al., 2022). Thus, policy makers need to enforce green renewable energy such as wind, solar (Beall, 2017; de Vries et al., 2022; Huynh et al., 2022; Roeck and Drennen, 2022; Sarkodie et al., 2022; Wang et al., 2022), and solid oxide fuel cell energy systems (Wang et al., 2022) for mining and transaction processes to decrease the carbon footprint. This is already the case in at least one location, Missoula County, Montana (USA) (Leslie, 2020).

To expand the share of renewable energy used for mining, different suggestions exist. Köhler and Pizzol (2019) as well as Truby et al. (2022) propose to incentivize blockchains using predominantly renewable energy sources through a more favorable taxation rate. Snytnikov and Potemkin (2022) propose to build new power plants generating renewable sources for miners. However, Schinckus (2020) states that building these dedicated renewable energy plants is associated with a high environmental impact and would thus not make PoW cryptocurrencies green. Furthermore, Schinckus (2020) argues that this approach would be paradoxical, since a solution for the energy hunger of PoW cryptocurrencies should be rather centered about reducing the energy consumption than on ways to produce more energy. On top, de Vries et al. (2022) stress that green energy sources would not solve all relevant issues such as electronic waste generation.

To mitigate the environmental impact of PoW cryptocurrencies, incentivizing measures and subsidizations play a role in discussion in current literature. Investments into R&D are not exclusive with taxing to internalize cryptocurrency damages and could be used along each other (Goodkind et al., 2020; Qin et al., 2020). To reduce the environmental impact of e-waste, de Vries and Stoll (2021) propose enforcing and improving recycling practices on a local level and seek global collaboration to limit waste volumes going into landfills. Furthermore, Di Febo et al. (2021) emphasize the importance to educate the environmental impacts of mining algorithms. This comforts the appeal of Köhler and Pizzol (2019), that discussions regarding regulation should be founded on a technical understanding.

Qin et al. (2020) argue that policies which raise electricity prices for miners will directly reduce the quantity of energy consumed for mining Bitcoin, and encouraging development of more energy efficient hardware (Qin et al., 2020). On the same note, suggestions to incentivize the development of more energy-efficient integrated circuits (Qin et al., 2020) and thus mining hardware (Truby et al., 2022) exist. In contrary, Sedlmeir et al. (2020b) argues that more efficient mining hardware would not reduce the energy consumption of a PoW Blockchain in the long term. This is supported by Sutherland (2019), who states that mining algorithm complexity, and not advances in hardware efficiency, are deciding factors for the energy consumption and sustainability of a cryptocurrency. In consequence, R&D could be subsidized to design more energy efficient cryptocurrency algorithms that still allow a secure validation process of anonymous transactions (Apatova et al., 2020; Goodkind et al., 2020; Sutherland, 2019; Truby et al., 2022; Ullrich et al., 2018).

A further recommendation is to incentivize the transition “towards green alternatives, typically proof-of-stake (Erdogan et al., 2022:8).” It is argued that the transition away from PoW must happen in order for a cryptocurrency to be sustainable (Sutherland, 2019).

4.2. *Environmental impact of proof of stake cryptocurrencies*

The most common alternative cryptocurrency consensus algorithm to PoW is PoS (Sedlmeir et al., 2020b; Sutherland, 2019). However, there is a lack of reliable quantifiable estimates on its energy consumption and their precise energy-saving potential compared to PoW (Sedlmeir et al., 2020b). The following chapter summarizes how PoS cryptocurrencies are addressed in literature in terms of their environmental impact.

PoS cryptocurrencies do not require the use of dedicated hardware to participate in the validation process. Therefore, manufacturers do not need to use resources to build dedicated equipment (de Vries, 2019). In fact, any devices with an internet connection (e.g. smartphones, tablets, computers) can participate (de Vries and Stoll, 2021). As no dedicated hardware is used, no additional electronic waste resulting from PoS cryptocurrencies is expected (de Vries and Stoll, 2021).

PoS is described as less energy intensive in comparison to PoW (Bouraga, 2021; Köhler and Pizzol, 2019, 2019; Leslie, 2020; Sriman et al., 2021; Stoll et al., 2019b; Truby et al., 2022) and very energy-efficient (Sedlmeir et al., 2020b). This is explained by the fact that there is no competition between miners. A low level of electricity consumption is assured in PoS, because only the selected validating miner computes a hash (Schinckus, 2020; Schulz et al., 2020). Hence, the carbon emissions of PoS are estimated to be a thousand-fold lower than emission caused by PoW (Truby et al., 2022). Furthermore, PoS can easily scale up to handle large transaction volumes without significantly affecting the environmental impact (Milunovich, 2022). However, mainly due to the redundant calculations characteristic of blockchain technology, the power consumption per transaction of PoS is roughly proportional to the number of participating nodes and thus still higher than that of traditional centralized systems (Sedlmeir et al., 2020a). Whereas no environmental-related social aspects such as human deaths could be identified, other social issues not related to the environmental impact such as biases towards validators with more funds for staking are mentioned (Beall, 2017).

According to de Vries and Stoll (2021) as well as Schinckus (2020), PoS appears to solve the energy challenges that PoW is associated with.

On a further note, the announced switch from PoS to PoW of Ethereum is seen as an important precedent that might motivate other blockchain platforms to transition towards more sustainable consensus algorithms (Milunovich, 2022; Sedlmeir et al., 2020b; Truby et al., 2022). However, if the transition fails, Truby et al. (2022) fear that the industry will rely all the more on PoW in the future.

5. Discussion

This systematic review examined how the environmental impact of PoS and PoW cryptocurrencies is evaluated by researchers. The timeliness of the literature reviewed shows that the environmental impact of PoW cryptocurrencies is increasingly a topic of debate. Research consistently assesses that the process of mining is associated with extensive energy consumption, carbon emissions, resources and electronic waste. Furthermore, several authors highlighted environmental-social externalities and the dependence of economic factors such as bitcoin price and trade volume on the environmental impact. Different methodologies to quantify these impacts cannot prevent a degree of uncertainty due to factors such as the unknown composition of used mining hardware and electricity prices. Yet, the results can confirm a steady upward trend in energy and carbon emission estimates. With regard to the literature reviewed, this work supports the assessments of Erdogan et al. (2022) and Gallersdörfer et al. (2020), that existing literature appears to focus on bitcoin rather than on alternative cryptocurrencies. Within the scope of this systematic review, no study has been identified that explicitly addresses the environmental impact of PoS currencies (see Table A in the Appendix). There is also no indication of possible environmental-related externalities related to PoS. Most research papers reviewed address PoS, emphasizing its relevance in recent debate. In this context, cryptocurrencies using PoS are consistently referred to as an alternative to PoW that seems to solve PoW's sustainability problems. The results presented and concluded shall serve as an answer to the initial research question. In addition, the seven inductively identified environmental-related aspects serve as an alternative proposition to the assessment of Vranken (2017), which concluded that Bitcoin's sustainability depends on a mix of environmental, economic, financial, and ethical aspects.

In the following, selected findings and contradictions in literature are highlighted and discussed. Ways to mitigate the negative effects of cryptocurrency mining have been proposed by various researchers. Yet, some mitigation approaches are controverse. For example, Erdogan et al. (2022) and Qin et al. (2020) suggested the incentivization of more energy efficient mining hardware. If a constant hash-rate was assumed, more energy efficient hardware would indeed lower the energy consumption. However, the hash-rate has steadily increased (Blockchain.com, 2022), as can be seen in Fig. 1 below.

It is important to highlight that the sudden drop in hash-rate in 2021 can be explained due to the crackdown on miners in China in 2021 and shows that the short decrease in hash-rate has been only temporary until miners relocated, as elaborated by e.g. de Vries et al. (2022). The overall steady uptrend can be explained by the fact that more miners switch to more energy-efficient hardware as long as it is profitable, which leads to higher hash-rates. However, only the amount of energy consumed per hash has been decreasing, but not the total amount of energy consumed within the network. There is also no indication that this would change by further increasing the energy efficiency of hardware. Thus, the view of Sedlmeir et al. (2020b) and Sutherland (2019) that more energy-efficient machines do not pose a solution for the environmental issues of Bitcoin is supported.

In contrary to the hash-rate, the historical price development of Bitcoin shown in Fig. 2 displays strong volatility compared to the hash-rate and a recent price-drop of Bitcoin to around $20,000 (CoinMarketCap, 2022).

Yet, the hash rate has not dropped significantly along with the profitability as a result of this sudden price drop. Following the argumentation of Delgado-Mohatar et al. (2019), this could be due to miners who continue mining at a temporary loss in expectation of further price rising. However, it should be emphasized that this could also mean that even at these lower prices, most of the mining equipment has not been removed from the network, because it is still running profitably.

In this regard, de Vries (2021a) concludes that Bitcoin could only sustain a lower-bound of 60 TW-hours (TWh) per year at a Bitcoin price of roughly $8000. While de Vries (2021b) assumed an average electricity price of $0,05 per kWh, another study estimated a global average of $0.046 per kWh (Blandin et al., 2020). Since electricity prices have been identified to be the main cost driver of cryptocurrency mining (Atkins et al., 2021a), adapting the lower price would drastically increase possible upper bound estimates in the scenario described by de Vries (2021b). Hence, this recent price drops would not make a significant amount of currently running mining machines unprofitable at these low energy-costs. As most mining hardware would remain running, this would provide a further possible explanation why the hash-rate does not show a significant effect. At which bitcoin price significant effects of reduced mining activity are evident should thus be further observed and researched as the situation is dynamic and the conclusions drawn within this work are hypothetical.

Furthermore, insights from the upcoming bitcoin halvings in 2024 and 2028 might be particularly important for researchers in this regard. Because these will reduce the current block rewards for successfully mining a PoW cryptocurrency (currently 6,25 Bitcoin) by 50% in each case and would significantly reduce the income of the miners, unless the price rises by the same factor in which rewards are decreased. This could naturally lead to a decreasing environmental impact of the Bitcoin network in the coming years, as pointed out by Küfeoğlu and Özkuran (2019) and Sedlmeir et al. (2020a). While this would inevitably be the case under the assumption of constant prices, it should be emphasized that the halving increases scarcity, as well as lower rewards reduce the sell-off of cryptocurrency miners, which could also incentivize investors to invest and keep bitcoin mining profitable.

In the following, the conclusions drawn from the separate analysis of the seven relevant aspects are synthesized and discussed. Fig. 3 below shows an exemplary scenario that connects possible effects of rising bitcoin prices with subsequent regional regulatory intervention, similarly to the crackdown on cryptocurrency miners in China in 2021. It aims to synthesize selected findings discussed within this systematic review and to show how different research can contribute to the overall

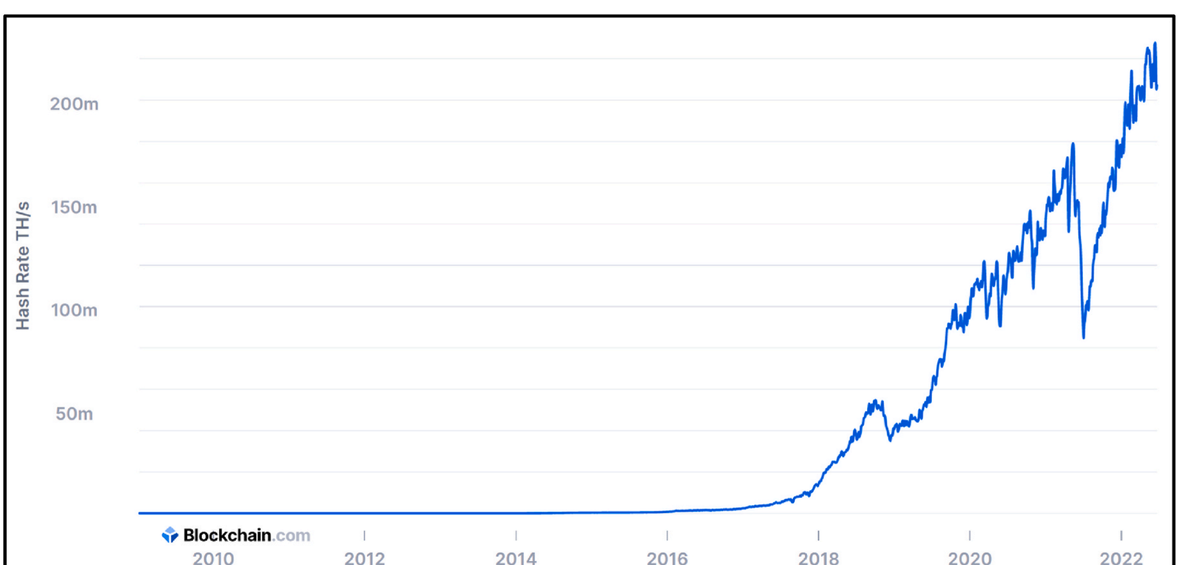

Fig. 1. Historical hash-rate – terahashes per second (TH/s),7 day moving average (Blockchain.com).

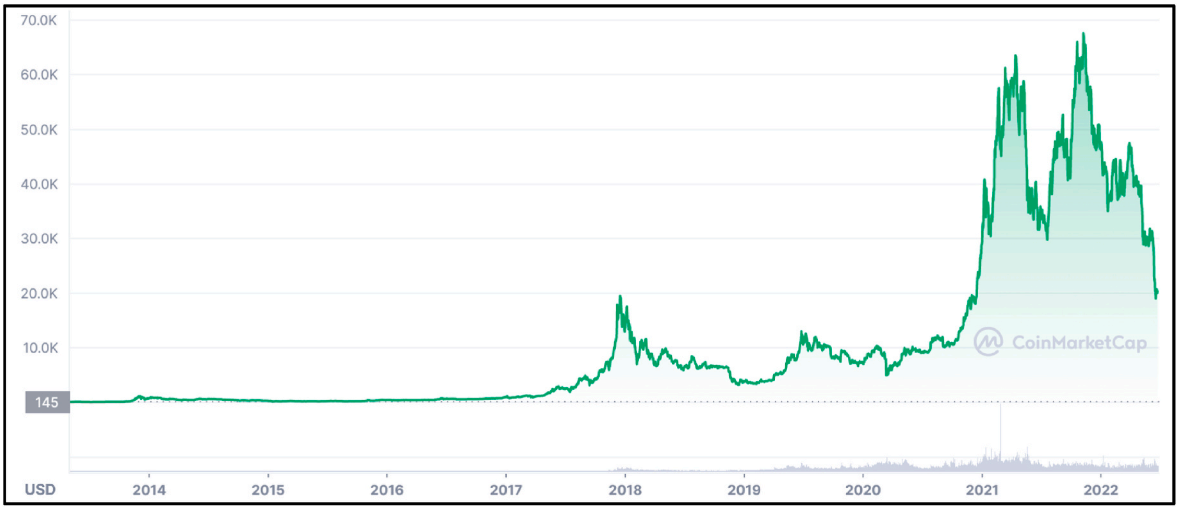

Fig. 2. Historical bitcoin prices (CoinMarketCap).

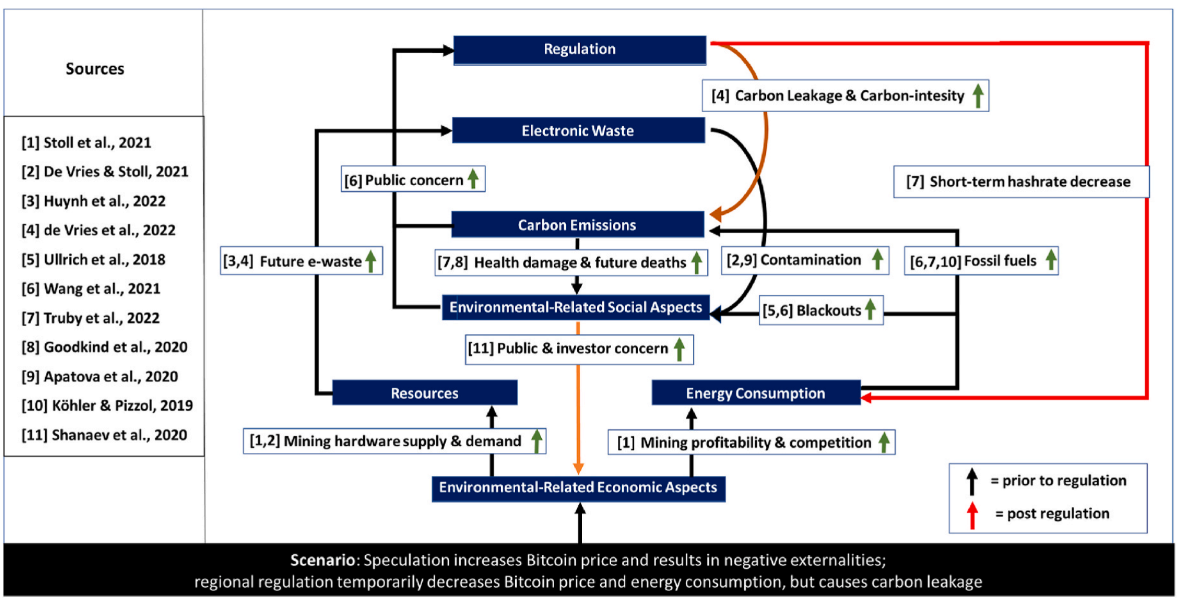

Fig. 3. Scenario - environmental externalities and rebound effects between seven environmental-related aspects of PoW cryptocurrencies (own representation).

picture of a very hypothetical research area due to various uncertain factors.

In this systematic review, in contrast to previous works, an attempt was made to identify and show connections between the findings of different authors. Explicitly considering all seven environmental-related aspects identified in this research paper and their interrelationship could serve to inform policy makers about possible rebound effects and help to choose appropriate mitigation instruments. Furthermore, this design and the chosen scenario illustrate that an important cause of the increase in electricity consumption, carbon emissions, and other negative externalities is ultimately related to the profitability of mining. As regulatory events have been assessed to be able to influence the price of bitcoin (Shanaev et al., 2020), policymakers should incorporate the economic aspects to a greater extent in policy making to reduce the profitability of mining. This should not only be achieved by aiming to increase e.g. electricity costs for miners or simply banning mining altogether, as this could lead to carbon leakage. Hence, policy intervention could aim to enforce different measures that negatively impact the bitcoin price in order to reduce miners' profitability and some measures found especially promising shall now be highlighted.

As described by de Vries (2021a), one way could be to focus on centralized exchanges, which are crucial for the exchange of fiat money and cryptocurrencies. For example, investors could be informed about the associated environmental impacts before buying PoW cryptocurrencies, which could raise awareness and concern among investors. A large-scale public education campaign could also reduce speculative profit expectations of investors. In this regard, Wang et al. (2022) concluded that overall attention to the environmental impact of cryptocurrencies would increase price fluctuations. The importance of general education on the environmental impacts associated with cryptocurrency mining, as highlighted by Di Febo et al. (2021), can therefore be supported. More restrictive measures, such as taxing and ultimately banning PoW cryptocurrencies from centralized exchanges might lead to purposeful results if softer methods fail to mitigate environmental externalities.

All in all, regulation implications proposed by authors reviewed show a focus on miners. The investors, which widely substituted the promise of a decentralized and secure payment system as a speculative asset (Bouraga, 2021; Truby, 2018), could be brought more into the center of attention. After all, investments from investors increase the price of Bitcoin and are therefore an important factor on which the profitability of mining is dependent upon. A recent mixed-method study by Mattke et al. (2021) highlighted seven bitcoin-specific investment motivations. It is suggested that further research should investigate possible demotivating factors such as the effect of negative reputation of PoW cryptocurrencies due to their environmental impact (Mattke et al., 2021). Similarly, Sarkodie et al. (2022) emphasized that environmentally conscious investors may fail to adopt Bitcoin as an investment option due to its energy and carbon-intensive PoW algorithm. In view of the results and the conclusions of this work, this research gap can be confirmed and further investigation is recommended.

6. Conclusion

The objective of this research paper was to investigate the environmental impact of PoW and PoS cryptocurrencies by conducting a systematic review. The results showed that the sustainability attributed differs substantially depending on the underlying consensus algorithm. In connection with PoW, seven aspects that impact or are impacted by the environment have been inductively identified and elaborated: resources, electronic waste, energy consumption, carbon footprint, environmental-related social and economic aspects, and policy regulation and subsidization. Despite different estimation methods and assumptions, researchers agree that the environmental impact has been increasing over time and regulation is necessary. However, methods proposed by authors to mitigate this impact focus heavily on miners.

Due to the competition and the resulting arms race in cryptocurrency mining equipment, it is argued that increasingly efficient mining hardware does not lead to raw energy reduction in the long term. By additionally considering the recent price decrease of Bitcoin and the inelastic response of the hash-rate, the possibility of over-estimation in electricity prices used in common estimation approaches has been pointed out. In face of carbon leakage due to regional intervention of cryptocurrency mining, the importance to include investors in policy regulation discussions is highlighted. In this regard, mandatory investor briefings about the environmental footprint of PoW at centralized exchanges, or large-scale public education campaigns are proposed. Stricter methods such as taxing and banning PoW cryptocurrencies from centralized exchanges are recommended if softer methods fail to mitigate environmental externalities. Measures that could potentially lead to decreasing Bitcoin prices are thus concluded to be of key importance to reduce the incentive for cryptocurrency mining globally. If decreasing or even stable bitcoin prices were achieved, the algorithmic predestined bitcoin halvings (see section 2.1) could naturally amplify demotivation for mining. However, higher scarcity and reduced sell-off from miners could drive prices up and hence act as counterforces.

Within the scope of this systematic review, researchers have not indicated any potential environmental-related issues of PoS cryptocurrencies. As the validation process of the consensus algorithm does not incentivize competition among computational resources, PoS is uniformly proposed to be a significantly more sustainable alternative to PoW.

This work complements current research by synthesizing findings of various authors. An exemplary scenario with rising Bitcoin prices and subsequent regulation highlights interconnections and rebound effects within the seven beforementioned environmental-related aspects. It also portrays how several researchers contribute to the overall picture of a very hypothetical research area due to various uncertain factors. Also, this layout could help policy makers to choose proper mitigation instruments and estimate possible consequences prior intervention.

In the following, the limitations of this study are outlined and an outlook for future research is given. First, only cryptocurrencies are considered. The environmental impact caused by other use cases of Blockchain technology were not addressed. Furthermore, this research only reviewed literature addressing the environmental impact of PoW and PoS cryptocurrencies, however many more consensus algorithms exist. Within its scope, this study does not evaluate the different underlying methodologies used by researchers within this research field in terms of best practice. Future studies, therefore, should investigate the estimation of the environmental impacts on a methodological level, such as the similarities and differences compared to life cycle assessment for other products/industries. Also, other databases and search strings could lead to different relevant literature. Due to the uncertainty of factors such as electricity prices, amount and kind of mining equipment and energy sources, conclusions drawn related to the environmental impact of PoW cryptocurrencies are hypothetical.

Future research could further investigate at which bitcoin price significant effects of reduced mining activity are evident. This could be observed and researched by considering historical and upcoming price and hash-rate movements. Of special interest are thus Bitcoin halving events. Furthermore, research to identify aspects that demotivate investments into PoW cryptocurrencies are recommended. This could help identify and implement effective tools to lower the price of PoW cryptocurrencies, thereby influencing mining profits, the incentive to mine, and ultimately the environmental impact. Finally, blockchain technology offers further use cases besides cryptocurrencies that could be explored and compared in terms of sustainability to the status quo.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

Table A
Collection of reviewed literature and focus (own representation)

Found via	Author	Publication	Year	Title	Main Focus Consensus Algorithm	Cryptocurrency	PoSmentioned
Link Springer (Articles)	Erdogan et al.	Journal article	2022	Analyzing asymmetric efects of cryptocurrency demand on environmental sustainability	PoW	Bitcoin, Ether, XRP	**x**
	Morris	Journal article	2019	Burning down the house: bitcoin, carbon-capitalism, and the problem of trustless systems	PoW	Bitcoin	**x**
	Rebello et al.	Journal article	2021	A security and performance analysis of proof-based consensus protocols	PoW, PoS, and more	Bitcoin, and various others	**x**
	Roeck & Drennen	Journal article	2022	Life cycle assessment of behind-the-meter Bitcoin mining at US power plant	PoW	Bitcoin	**x**

(continued on next page)

Table A (*continued*)

	Sedlmeier et al.	Journal article	2020b	The Energy Consumption of Blockchain Technology: Beyond Myth	PoW	Bitcoin	x
	Treiblmaier	Journal article	2021	Do cryptocurrencies really have (no) intrinsic value?	PoW	Bitcoin	x
	Vaz & Brown	Journal article Journal article	2020	Sustainable development and cryptocurrencies as private money	PoW	Bitcoin	x
Science Direct	Atkins et al.	Journal article	2021	Uneven development, crypto-regionalism, and the (un-)tethering of nature in Quebec	PoW	Bitcoin	
	Beall	Journal article	2017	Bitcoin energy bill matches Ecuador's	PoW	Bitcoin	x
	Bouraga	Journal article	2021	A taxonomy of blockchain consensus protocols: A survey and classification framework	PoW, PoS	No specific currency in focus	x
	Das & Dutta	Journal article	2020	Bitcoin's energy consumption: Is it the Achilles heel to miner's revenue?	PoW	Bitcoin	
	Delgado-Mohatar et al.	Journal article	2019	The Bitcoin mining breakdown: Is mining still profitable?	PoW	Bitcoin	
	Goodking et al.	Journal article	2020	Cryptodamages: Monetary value estimates of the air pollution and human health impacts of cryptocurrency mining	PoW	Bitcoin	x
	de Vries	Journal article	2018	Bitcoin's Growing Energy Problem	PoW	Bitcoin	
	de Vries	Journal article	2019	Renewable Energy Will Not Solve Bitcoin's Sustainability Problem	PoW	Bitcoin	x
	de Vries	Journal article	2020	Bitcoin's energy consumption is underestimated: A market dynamics approach	PoW	Bitcoin	
	de Vries	Journal article	2021	Bitcoin boom: What rising prices mean for the network's energy consumption	PoW	Bitcoin	
	de Vries	Journal article	2022	Revisiting Bitcoin's carbon footprint	PoW	Bitcoin	x
	de Vries & Stoll	Journal article	2021	Bitcoin's growing e-waste problem	PoW	Bitcoin	x
	Di Febo et al.	Journal article	2021	From Bitcoin to carbon allowances: An asymmetric extreme risk spillover	PoW	Bitcoin	
	Gallersdörfer et al.	Journal article	2020	Energy Consumption of Cryptocurrencies Beyond Bitcoin	PoW	Top 20 PoW cryptocurrencies	
	Kristoufek	Journal article	2019	Bitcoin and its mining on the equilibrium path	PoW	Bitcoin	
	Küfeoğlu & Özkuran	Journal article	2019	Bitcoin mining: A global review of energy and power demand	PoW	Bitcoin	
	Leslie	Journal article	2020	Will Cryptocurrencies Break the Energy Bank?	PoW	Bitcoin	x
	Li et al.	Journal article	2019	Energy consumption of cryptocurrency mining: A study of electricity consumption in mining cryptocurrencies	PoW	Monero	
	Malfuzi et al.	Journal article	2020	Economic viability of bitcoin mining using a renewable-based SOFC power system to supply the electrical power demand	PoW	Bitcoin	x
	Milunovich	Journal article	2022	Assessing the Connectedness between Proof of Work and Proof of Stake/Other Digital Coins	PoW, PoS, and more	14 different cryptocurrencies	x
	Nair et al.	Journal article	2020	An Approach to Minimize the Energy Consumption during Blockchain Transaction	PoW	Bitcoin, Ether	x
	Qin et al.	Journal article	2020	Bitcoin's future carbon footprint	PoW	Bitcoin	
	Ren & Lucey	Journal article	2022	Do clean and dirty cryptocurrency markets herd differently?	PoW, PoS, and more	6 PoW, 12 "clean" cryptocurrencies	x
	Schinckus	Journal article	2020	The good, the bad and the ugly: An overview of the sustainability of blockchain technology (Schinckus, 2020, S. 1)	PoW	Bitcoin	x
	Sarkodie et al.	Journal article	2022	Trade volume affects bitcoin energy consumption and carbon footprint	PoW	Bitcoin	
	Stoll et al., 2019a	Journal article	2019	The Carbon Footprint of Bitcoin	PoW	Bitcoin	x
	Snytnikov & Potemkin	Journal article	2022	Flare gas monetization and greener hydrogen production via combination with cryptocurrency mining and carbon dioxide capture	PoW	Bitcoin	
	Sutherland	Journal article	2019	Blockchain's First Consensus Implementation Is Unsustainable	PoW	Bitcoin	x
	Truby	Journal article	2018	Decarbonizing Bitcoin: Law and policy choices for reducing the energy consumption of Blockchain technologies and digital currencies	PoW	Bitcoin	x
	Truby	Journal article	2022	Blockchain, climate damage, and death: Policy interventions to reduce the carbon emissions, mortality, and net-zero implications of non-fungible tokens and Bitcoin	PoW	Bitcoin, Ether	x

(*continued on next page*)

Table A (*continued*)

	Wang et al.	Journal article	2022	An Index of Cryptocurrency Environmental Attention (ICEA)	PoW	Bitcoin	
Forward & Backward Search	Apatova et al.	Book Chapter	2020	Stability and Sustainability of Cryptotokens in the Digital Economy	PoW	Bitcoin	x
	Huynh et al.	Journal article	2022	Energy Consumption and Bitcoin Market	PoW	Bitcoin	
	Köhler & Pizzol	Journal article	2019	Life Cycle Assessment of Bitcoin Mining	PoW	Bitcoin	x
	Krause & Tolaymat	Journal article	2018	Quantification of energy and carbon costs for mining cryptocurrencies	PoW	Bitcoin, Ether, Litecoin, Monero	x
	Lei et al., 2021	Journal article	2021	Best practices for analyzing the direct energy use of blockchain technology systems: Review and policy recommendations	PoW	No specific currency in focus	x
	Mc Cook	Report	2018	The Cost & Sustainability of Bitcoin	PoW	Bitcoin	
	Malone and O'Dwyer, 2014	Book Chapter	2014	Bitcoin Mining and ist Energy Footprint	PoW	Bitcoin	
	Schinckus et al. (2022)	Journal article	2022	Cryptocurrencies' hashrate and electricity consumption: evidence from mining activities	PoW	Bitcoin, Ether	x
	Sedlmeier et al.	Journal article	2020a	Ein Blick auf aktuelle Entwicklungen bei Blockchains und deren Auswirkungen auf den Energieverbrauch	PoW	Bitcoin	x
	Sriman et al.	Journal article	2021	Blockchain Technology: Consensus Protocol Proof of Work and Proof of Stake	PoW, PoS	Bitcoin	x
	Ullrich et al.	Conference Paper	2018	Proof-of-Blackouts? How Proof-of-Work Cryptocurrencies Could Affect Power Grids	PoW	Bitcoin	
	Vranken	Journal article	2017	Sustainability of bitcoin and blockchains	PoW	Bitcoin	x

References

Apatova, N.V., Boychenko, O.V., Korolyov, O.L., Gavrikov, I.V., Uzakov, T.K., 2020. Stability and sustainability of cryptotokens in the digital economy. In: Vishnevskiy, V.M., Samouylov, K.E., Kozyrev, D.V. (Eds.), Distributed Computer and Communication Networks: Control, Computation, Communications. Springer International Publishing, pp. 484–496. https://doi.org/10.1007/978-3-030-66242-4_38, 1337.

Atkins, E., Follis, L., Neimark, B.D., Thomas, V., 2021a. Uneven development, crypto-regionalism, and the (un-)tethering of nature in Quebec. Geoforum 122, 63–73. https://doi.org/10.1016/j.geoforum.2020.12.019.

Atkins, E., Follis, L., Neimark, B.D., Thomas, V., 2021b. Uneven development, crypto-regionalism, and the (un-)tethering of nature in Quebec. Geoforum 122, 63–73. https://doi.org/10.1016/j.geoforum.2020.12.019.

Beall, A., 2017. Bitcoin energy bill matches Ecuador's. New Scientist, 236(3150) 8. https://doi.org/10.1016/S0262-4079(17)32143-7.

Bevand, M., 2017. Bitcoin miners consume a reasonable amount of energy—and it's all worth it. Bitcoin Magazine. *https://bitcoinmagazine.com/articles/op-ed-bitcoin-miners-consume-reasonable-amount-energy-and-its-all-worth-it*.

Blandin, A., Pieters, G., Wu, Y., Eisermann, T., Dek, A., Taylor, S., Njoki, D., 2020. 3rd global cryptoasset benchmarking study—CCAF publications. https://www.jbs.cam.ac.uk/faculty-research/centres/alternative-finance/publications/3rd-global-cryptoasset-benchmarking-study/.

Blockchaincom, 2022. Historical hash-rate. Blockchain.Com. https://www.blockchain.com/charts/hash-rate.

Bouraga, S., 2021. A taxonomy of blockchain consensus protocols: a survey and classification framework. Expert Syst. Appl. 168, 114384 https://doi.org/10.1016/j.eswa.2020.114384.

Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A., 2009. Reconstructing the giant: on the importance of rigour in documenting the literature search process. ECIS.

CoinMarketCap, 2022. *https://coinmarketcap.com/currencies/bitcoin/*. *Bitcoin price today, BTC to USD live, marketcap and chart. CoinMarketCap.*.

Das, D., Dutta, A., 2020. Bitcoin's energy consumption: is it the Achilles heel to miner's revenue? Econ. Lett. 186, 108530 https://doi.org/10.1016/j.econlet.2019.108530.

de Vries, A., 2018. Bitcoin's Growing Energy Problem 2, 801–805. https://doi.org/10.1016/j.joule.2018.04.016.

de Vries, A., 2019. Renewable energy will not solve Bitcoin's sustainability problem. Joule 3 (4), 893–898. https://doi.org/10.1016/j.joule.2019.02.007.

de Vries, A., 2020. Bitcoin's energy consumption is underestimated: a market dynamics approach. Energy Res. Social Sci. 70, 101721 https://doi.org/10.1016/j.erss.2020.101721.

de Vries, A., 2021a. Bitcoin boom: what rising prices mean for the network's energy consumption. Joule 5 (3), 509–513. https://doi.org/10.1016/j.joule.2021.02.006.

de Vries, A., 2021b. Bitcoin boom: what rising prices mean for the network's energy consumption. Joule 5 (3), 509–513. https://doi.org/10.1016/j.joule.2021.02.006.

de Vries, A., Gallersdörfer, U., Klaaßen, L., Stoll, C., 2022. Revisiting Bitcoin's carbon footprint. Joule 6 (3), 498–502. https://doi.org/10.1016/j.joule.2022.02.005.

de Vries, A., Stoll, C., 2021. Bitcoin's growing e-waste problem. Resour. Conserv. Recycl. 175, 105901 https://doi.org/10.1016/j.resconrec.2021.105901.

Delgado-Mohatar, O., Felis-Rota, M., Fernández-Herraiz, C., 2019. The Bitcoin mining breakdown: is mining still profitable? Econ. Lett. 184, 108492 https://doi.org/10.1016/j.econlet.2019.05.044.

Di Febo, E., Ortolano, A., Foglia, M., Leone, M., Angelini, E., 2021. From Bitcoin to carbon allowances: an asymmetric extreme risk spillover. J. Environ. Manag. 298, 113384 https://doi.org/10.1016/j.jenvman.2021.113384.

Digiconomist, 2022. Bitcoin historic sustainability performance—digiconomist. https://digiconomist.net/bitcoin-historic-sustainability-performance/.

Erdogan, S., Ahmed, M.Y., Sarkodie, S.A., 2022. Analyzing asymmetric effects of cryptocurrency demand on environmental sustainability. Environ. Sci. Pollut. Control Ser. 29 (21), 31723–31733. https://doi.org/10.1007/s11356-021-17998-y.

Fink, A., 2005. Conducting research literature reviews: from the internet to paper. SAGE.

Gallersdörfer, U., Klaaßen, L., Stoll, C., 2020. Energy consumption of cryptocurrencies beyond bitcoin. Joule 4 (9), 1843–1846. https://doi.org/10.1016/j.joule.2020.07.013.

Goodkind, A.L., Jones, B.A., Berrens, R.P., 2020. Cryptodamages: monetary value estimates of the air pollution and human health impacts of cryptocurrency mining. Energy Res. Social Sci. 59, 101281 https://doi.org/10.1016/j.erss.2019.101281.

Hart, C., 1998. Doing a literature review: releasing the social science research imagination. SAGE Publications Inc.

Hu, Q., Yan, B., Han, Y., Yu, J., 2021. An improved delegated proof of stake consensus algorithm. Procedia Comput. Sci. 187, 341–346. https://doi.org/10.1016/j.procs.2021.04.109.

Huynh, A.N.Q., Duong, D., Burggraf, T., Luong, H.T.T., Bui, N.H., 2022. Energy consumption and bitcoin market. Asia Pac. Financ. Mark. 29 (1), 79–93. https://doi.org/10.1007/s10690-021-09338-4.

King, S., Nadal, S., 2012. PPCoin: peer-to-peer crypto-currency with proof-of-stake. Undefined. https://www.semanticscholar.org/paper/PPCoin%3A-Peer-to-Peer-Crypto-Currency-with-King-Nadal/0db38d32069f3341d34c35085dc009a85ba13c13.

Köhler, S., Pizzol, M., 2019. Life cycle assessment of bitcoin mining. Environ. Sci. Technol. 53 https://doi.org/10.1021/acs.est.9b05687.

Koomey, J., Berard, S., Sanchez, M., Wong, H., 2011. Implications of historical trends in the electrical efficiency of computing. IEEE Ann. Hist. Comput. 33 (3), 46–54. https://doi.org/10.1109/MAHC.2010.28.

Krause, M.J., Tolaymat, T., 2018. Quantification of energy and carbon costs for mining cryptocurrencies. Nat. Sustain. 1 (11), 711–718.

Kristoufek, L., 2020. Bitcoin and its mining on the equilibrium path. Energy Econ. 85, 104588 https://doi.org/10.1016/j.eneco.2019.104588.

Küfeoğlu, S., Özkuran, M., 2019. Bitcoin mining: a global review of energy and power demand. Energy Res. Social Sci. 58, 101273 https://doi.org/10.1016/j.erss.2019.101273.

Lei, N., Masanet, E., Koomey, J., 2021. Best practices for analyzing the direct energy use of blockchain technology systems: review and policy recommendations. Energy Pol. 156, 112422 https://doi.org/10.1016/j.enpol.2021.112422.

Leslie, M., 2020. Will cryptocurrencies break the energy bank? Engineering 6 (5), 489–490. https://doi.org/10.1016/j.eng.2020.03.011.

Li, J., Li, N., Peng, J., Cui, H., Wu, Z., 2019. Energy consumption of cryptocurrency mining: a study of electricity consumption in mining cryptocurrencies. Energy 168, 160–168. https://doi.org/10.1016/j.energy.2018.11.046.

Malfuzi, A., Mehr, A.S., Rosen, M.A., Alharthi, M., Kurilova, A.A., 2020. Economic viability of bitcoin mining using a renewable-based SOFC power system to supply the electrical power demand. Energy 203, 117843. https://doi.org/10.1016/j.energy.2020.117843.

Malone, D., O'Dwyer, K.J., 2014. Bitcoin mining and its energy footprint (p. 285. https://doi.org/10.1049/cp.2014.0699.

Mattke, J., Maier, C., Reis, L., Weitzel, T., 2021. Bitcoin investment: a mixed methods study of investment motivations. Eur. J. Inf. Syst. 30 (3), 261–285. https://doi.org/10.1080/0960085X.2020.1787109.

McCook, 2018. The cost & sustainability of bitcoin (August 2018) | hass McCook—academia.edu. https://www.academia.edu/37178295/The_Cost_and_Sustainability_of_Bitcoin_August_2018_.

Milunovich, G., 2022. Assessing the connectedness between proof of work and proof of stake/other digital coins. Econ. Lett. 211, 110243 https://doi.org/10.1016/j.econlet.2021.110243.

Morris, D., 2019. Burning down the house: bitcoin, carbon-capitalism, and the problem of trustless systems. AI Soc. 34 (1), 161–162. https://doi.org/10.1007/s00146-018-0870-4.

Nair, R., Gupta, S., Soni, M., Kumar Shukla, P., Dhiman, G., 2020. An approach to minimize the energy consumption during blockchain transaction. Mater. Today Proc. https://doi.org/10.1016/j.matpr.2020.10.361.

Nakamoto, S., Bitcoin, A., 2008. A peer-to-peer electronic cash system. Bitcoin 4, 2. https://Bitcoin.Org/Bitcoin.

Qin, S., Klaaßen, L., Gallersdörfer, U., Stoll, C., Zhang, D., 2020. Bitcoin's future carbon footprint. ArXiv Preprint ArXiv:2011.02612.

Rebello, G.A.F., Camilo, G.F., Guimarães, L.C.B., de Souza, L.A.C., Thomaz, G.A., Duarte, O.C.M.B., 2021. A security and performance analysis of proof-based consensus protocols. Anal.Telecommun. https://doi.org/10.1007/s12243-021-00896-2.

Ren, B., Lucey, B., 2022. Do clean and dirty cryptocurrency markets herd differently? Finance Res. Lett. 47, 102795 https://doi.org/10.1016/j.frl.2022.102795.

Roeck, M., Drennen, T., 2022. Life cycle assessment of behind-the-meter Bitcoin mining at US power plant. Int. J. Life Cycle Assess. 27 (3), 355–365. https://doi.org/10.1007/s11367-022-02025-0.

Sarkodie, S.A., Ahmed, M.Y., Leirvik, T., 2022. Trade volume affects bitcoin energy consumption and carbon footprint. Finance Res. Lett. 48, 102977 https://doi.org/10.1016/j.frl.2022.102977.

Schinckus, C., 2020. The good, the bad and the ugly: an overview of the sustainability of blockchain technology. Energy Res. Social Sci. 69, 101614 https://doi.org/10.1016/j.erss.2020.101614.

Schinckus, C., Nguyen, C.P., Chong, F.H.L., 2022. Cryptocurrencies' hashrate and electricity consumption: evidence from mining activities. Stud. Econ. Finance 39 (3), 524–546. https://doi.org/10.1108/SEF-08-2021-0342.

Schulz, K.A., Gstrein, O.J., Zwitter, A.J., 2020. Exploring the governance and implementation of sustainable development initiatives through blockchain technology. Futures 122, 102611. https://doi.org/10.1016/j.futures.2020.102611.

Sedlmeir, J., Buhl, H.U., Fridgen, G., Keller, R., 2020a. Ein Blick auf aktuelle Entwicklungen bei Blockchains und deren Auswirkungen auf den Energieverbrauch. Informatik-Spektrum 43 (6), 391–404. https://doi.org/10.1007/s00287-020-01321-z.

Sedlmeir, J., Buhl, H.U., Fridgen, G., Keller, R., 2020b. The energy consumption of blockchain technology: beyond myth. Bus.Inf. Syst. Eng.g 62 (6), 599–608. https://doi.org/10.1007/s12599-020-00656-x.

Shanaev, S., Sharma, S., Ghimire, B., Shuraeva, A., 2020. Taming the blockchain beast? Regulatory implications for the cryptocurrency Market. Res. Int. Bus. Finance 51, 101080. https://doi.org/10.1016/j.ribaf.2019.101080.

Snytnikov, P., Potemkin, D., 2022. Flare gas monetization and greener hydrogen production via combination with cryptocurrency mining and carbon dioxide capture. IScience 25 (2), 103769. https://doi.org/10.1016/j.isci.2022.103769.

Sriman, B., Ganesh Kumar, S., Shamili, P., 2021. Blockchain technology: consensus Protocol proof of work and proof of stake. In: Dash, S.S., Das, S., Panigrahi, B.K. (Eds.), Intelligent Computing and Applications. Springer, pp. 395–406. https://doi.org/10.1007/978-981-15-5566-4_34.

Stoll, C., KlaaBen, L., Gallersdörfer, U., 2019a. The carbon footprint of bitcoin. SSRN Electron. J. https://doi.org/10.2139/ssrn.3335781.

Stoll, C., KlaaBen, L., Gallersdörfer, U., 2019b. The carbon footprint of bitcoin. SSRN Electron. J. https://doi.org/10.2139/ssrn.3335781.

Sutherland, B.R., 2019. Blockchain's first consensus implementation is unsustainable. Joule 3 (4), 917–919. https://doi.org/10.1016/j.joule.2019.04.001.

Thomas, D., 2006. A general inductive approach for analyzing qualitative evaluation data. Am. J. Eval. 27, 237–246. https://doi.org/10.1177/1098214005283748.

Treiblmaier, H., 2021. Do cryptocurrencies really have (no) intrinsic value? Electron. Mark. https://doi.org/10.1007/s12525-021-00491-2.

Truby, J., 2018. Decarbonizing Bitcoin: law and policy choices for reducing the energy consumption of Blockchain technologies and digital currencies. Energy Res. Social Sci. 44, 399–410. https://doi.org/10.1016/j.erss.2018.06.009.

Truby, J., Brown, R.D., Dahdal, A., Ibrahim, I., 2022. Blockchain, climate damage, and death: policy interventions to reduce the carbon emissions, mortality, and net-zero implications of non-fungible tokens and Bitcoin. Energy Res. Social Sci. 88, 102499 https://doi.org/10.1016/j.erss.2022.102499.

Ullrich, J., Stifter, N., Judmayer, A., Dabrowski, A., Weippl, E., 2018. Proof-of-Blackouts? How proof-of-work cryptocurrencies could affect power grids. In: Bailey, M., Holz, T., Stamatogiannakis, M., Ioannidis, S. (Eds.), Research in Attacks, Intrusions, and Defenses. Springer International Publishing, pp. 184–203. https://doi.org/10.1007/978-3-030-00470-5_9.

Vaz, J., Brown, K., 2020. Sustainable development and cryptocurrencies as private money. J. Ind. Bus. Econ. 47 (1), 163–184. https://doi.org/10.1007/s40812-019-00139-5.

Vranken, H., 2017. Sustainability of bitcoin and blockchains. Curr. Opin. Environ. Sustain. 28, 1–9. https://doi.org/10.1016/j.cosust.2017.04.011.

Wang, Y., Lucey, B.M., Vigne, S., Yarovaya, L., 2022. An Index of cryptocurrency environmental attention (ICEA). China Finance Rev. Int. 12 (3), 378–414. https://doi.org/10.1108/CFRI-09-2021-0191.