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Review

Sustainable energy and digital currencies: challenges and future prospect

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ABSTRACT

Due to the impressive growth in digital coins trading, most cryptocurrencies' market cap has increased drastically. Therefore, more people are engaged in the mining process, causing a significant increase in electrical power consumption. To make cryptocurrency technology sustainable, using renewables such as photovoltaic solar power, wind energy, tidal power, geothermal power, hydroelectric power, fuel cell, and biomass has been implemented. Moreover, to decrease electrical power consumption in the cooling process of mining systems and computers, using phase change material (PCM) has been recommended. Since the cryptocurrency mining process is very competitive, only those miners will survive who employ the most competitive mining systems and benefit from the lowest electrical power costs. While the profitability of renewable electricity-based mining is lower than grid-based mining, the latter method compensates for better sustainability in cryptocurrency and lower environmental costs. This paper reviews the possible ways to make the cryptocurrency mining process clean and environmentally friendly.

1. Introduction

In 2009, the world's first Blockchain was created by Satoshi Nakamoto by introducing Bitcoin (BTC) with the hope of developing an independent and decentralized monetary system. Blockchain is an exposed, distributed ledger that records transactions between parties in a verifiable and permanent manner [1]. Due to impressive growth in BTC trading, the BTC market cap is currently more than $ 630 billion, and many discussions have been made on BTC and its pros and cons [2]. Transparency and anonymity, as well as no central authority, are the essential advantages [3], while security, scalability [4], double spending [5], sustainability of the market structure, and energy consumption are the most disadvantages of the cryptocurrency [6]. Since cryptocurrency does not exist in a physical form, it is a peer-to-peer payment system. Consumers have an extraordinary ability to pull cash out of cryptocurrency ATMs, buy goods and services with cryptocurrency at online retailers, and use cryptocurrency at some brick-and-mortar stores. The currency is tradeable on various exchanges, and initial coin offerings (ICOs) draw interest across the investment spectrum. There is no central exclusive manager of the ledger in cryptocurrency technology, with significant responsibility for updates, storage, and verification of transactions. In contrast, all participants of the cryptocurrency network hold a copy of the ledger, and all transactions are transparent and visible to all users. Cryptocurrencies have passed a long journey from their obscure origins. While cryptocurrencies were disdained as a gadget for speculators and criminals by the mainstream financial world, significant progress has been made in the industry, and cryptocurrency has proven itself a legitimate and world-changing financial tool [7]. The BTC [8], Ethereum (ETH) [9], Binance (BNB) [10] have experienced massive growth in users and price; however, there are still doubts about the outcomes of wide cryptocurrency adoption. Particularly, huge concerns about electrical power consumption in the cryptocurrency mining process have raised skeptics among environmentalists due to realizing carbon emissions in the power generation process. It is claimed that just BTC mining is responsible for 0.5 percent of global electricity consumption [11]. Marcel Thum [12] believes that cryptocurrency mining is a waste of resources. It is claimed the BTC itself might consume as

much energy as all global data centers [13]. Calculations indicate that one dollar's worth of BTC requires seventeen megajoules of energy, which is more than double the amount of the required energy to extract one dollar's worth of copper, gold, and platinum [14]. Mora et al. [15] pointed out that the cryptocurrency mining process actively contributes to global warming, where BTC mining itself could push global warming above 2°C. Tomlinson et al. [16] stipulated that current Blockchain projects do not contribute to a sustainable future due to technical issues and a conceptual framing that favors the status quo rather than transformative alter. Carbon emission modeling of the BTC mining process in China demonstrated that the energy consumption of this process is expected to peak in 2024 at 296.59 Twh and emit 130.50 million metric tons of carbon emission [17].

Because of the environmental effects of fossil fuels used in the BTC mining process, the Tesla company suspended vehicle purchases using BTC [18]. In contrast, cryptocurrency advocates have claimed that BTC and other cryptocurrencies are the crucial part of deploying a carbon-neutral grid. They believe that cryptocurrency miners are flexible and unique energy buyers with a fixed location requiring only an internet connection and easily interruptible load [19]. Recently, using Blockchain in the development of smart cities has been considered by the researchers [20]. It is believed that cryptocurrency has considerable advantages over centralized currencies because it does not rely on any trusted intermediary or single point of failure [21]. Double spending is crucial in cryptocurrency because the tokens can be easily copied and double-spent without an appropriate security mechanism. This issue could devaluate cryptocurrency and threat customers' trust in the currency [5]. However, this problem has been solved using only upspent outputs of the previous transaction as an input of a subsequent transaction. Meanwhile, the order of transactions is specifying by their sequential order in the Blockchain [3]. This process effectively timestamps transactions by hashing them into an ongoing hash-based Proof of Work (POW) chain. Therefore, the POW not only discourages spam but also is considered an easy way to check the proof of computational effort [22]. However, this solution comes at high computational and energic costs and has become one of the crucial criticisms of cryptocurrency in recent years [23].

2. Cryptocurrency mining process

Same as gold, Bitcoin, the most widely-known crypto network, cannot simply be created arbitrarily, and it requires energy to extract [24]. Bitcoin is created through a computational process known as mining, and it has not been issued, endorsed, or regulated by any central bank. Since cryptocurrency has no bank to regulate it, the mining systems are employed to verify transactions by solving cryptographic problems, similar to complex math problems [25]. While cryptocurrency appears to be a well-established trading method, there are still so many energy and environmental issues. While gold is extracted from the earth, crypto must be mined via a computer-generated process. Cryptocurrency mining has become an attractive business since it offers a robust financial incentive. For mining each block, the miner receives a block reward and the transaction fees of the transactions in the block. However, cryptocurrency mining is a costly and challenging activity. Initially, general computers were employed to mine cryptocurrency, but they switched to advanced hardware, offering higher performance and lower energy costs. Large-scale mining companies must pay to build mining farms capable of vast amounts of processing power, and then the mining process itself requires large quantities of electricity. With mining operations for Bitcoin and other cryptocurrencies taking up the same share of electricity as many countries, miners must be careful not to spend more than they make.

Several factors should be considered to choose the most appropriate mining hardware and software. The first criteria is the mining equipment price (measured per GHs), which is influenced by the hash rate and the lead time. The energy cost is another factor that is considered by cryptocurrency miners. Efficient equipment with the lowest electrical power consumption and minimum heat emission is preferred. The difficulty (an arbitrary dimensionless value that measures how difficult finding a hash below a given target is) is the third factor [26]. Over the past few years, the required electricity for the energy-hungry cryptocurrency mining process has become a controversial topic [27]. The electrical energy required for a single Bitcoin transaction is 1775 kWh, equivalent to the power consumption of an average U.S. household over 60.84 days. The related carbon footprint is about 843.12 kgCO_2, equal to the carbon footprint of 1,868,656 VISA transactions or 140,521 hours of watching YouTube. In July 2021, the energy consumption of the Bitcoin mining process was reported 135.12 TWh, comparable to the power consumption of Sweden, and the released CO_2 emission was estimated 64.18 Mt, comparable to the carbon footprint of Serbia & Montenegro [28]. Figure 1 illustrates Bitcoin's energy consumption since Jan 2017 [29].

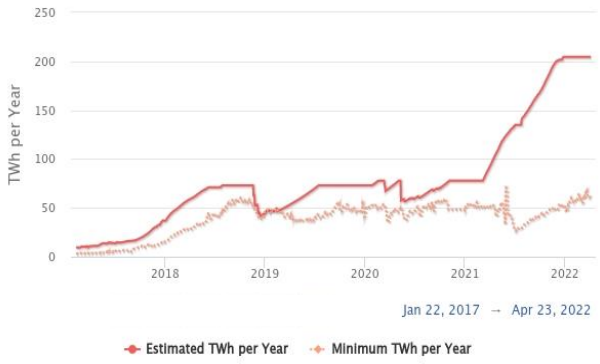

Figure 1. Bitcoin energy consumption [29]

It should be noted that Bitcoin energy consumption is just related to the mining process, and the energy consumption of cooling systems, third parties (wallets, exchanges, and payment solution providers), and Bitcoin ATMs were not considered. As a reference of comparison, the annual energy required for the entire banking sector is estimated 650 TWh, including data centers that process transactions, branches, and ATMs. Nevertheless, Alex de Vries [30] believes that the digital currency energy consumption is underestimated and proposed a market dynamic approach to evaluate the exact amounts of the required energy for BTC mining. Corber et al. [31] investigated the influences of BTC price volatility as well as the dynamics of cryptocurrency

mining characteristics on the utility companies and underlying energy markets. It is stipulated that BTC prices have a significant impact on the mining process and consequently its energy consumption [32]. While the BTC price rises, more people are engaged in the mining process, causing a significant increase in energy consumption [33].

It should be noted that BTC is accounted for 2/3 of the total cryptocurrency energy consumption, and the mining of the other digital coins should be considered in energy and environmental studies [34]. To get rid of generated heat in the cryptocurrency mining process, a cooling system should be employed that burdens additional electrical power expenditure. Using phase change material (PCM) in cryptocurrency mining devices and computers, as well as mining warehouses, could be helpful to minimize the electrical power required for cooling systems in the mining process. The idea of using PCMs in electronic devices [35], refrigeration systems [36], solar power generation systems [37], and residential buildings [38] was developed by several researchers, and the benefits of the PCMs in terms of energy-saving were highlighted; however, it has not been investigated in cryptocurrency mining process yet.

3. Digital currencies mining and renewables

It is claimed that the annual Bitcoin network energy uses as much as the country of Argentina, and the Ethereum network demand is as much electrical power as the entire nation of Qatar [39]. Approximately 65% of bitcoin mining systems are located in China, where most of the country's energy demand is generated from coal [40]. About 48% of the worldwide mining capacity is situated in the Sichuan province in China, where electricity is cheap [41]. Coal and other non-renewable energy sources are currently the major electrical power sources throughout the world, both for cryptocurrency mining operations and other industries. However, burning fossil fuels is a significant contributor to global warming due to the carbon dioxide (CO_2) emission. The Bitcoin mining process accounts for approximately 35.95 million tons of annual CO_2 emissions, the same amount as New Zealand [42].

To make the mining process greener, implementing a carbon tax on the BTC miners was suggested. However, a carbon tax would make BTC mining less attractive and decrease the price of BTC [43]. Because of the environmental issues, large-scale miners have started to employ renewables in the rigs to mitigate mining costs and make the most significant profit possible. Based on Adjeleian et al. [44], the application of Blockchain could be helpful for the development of renewable energy and has the capability to reshape the sustainable energy market. Application of decentralized energy systems such as wind turbines, photovoltaic solar power generation, tidal power for clean power generation for mining systems has been developed in the research [45]. In solar-powered mining systems, once the solar panel itself is paid, the miners get rid of a hefty electricity bill, and the cost of mining becomes free, and consequently, the mining process becomes more profitable. Although utilization of solar energy has been noticed by the Governments in recent years, solar still accounts for 2.3% of the total energy demand in the United States. Considering wind power, hydropower and biomass, approximately 19.8% of the total U.S energy demand is generated by renewables [46]. The promising news is that according to the International Energy Agency (IEA), the cost per megawatt to build solar plants is recently dropped below fossil fuels worldwide for the first time [47]. Crypto Climate Accord [48] aims to achieve net-zero emissions from electrical power consumption associated with all of their respective crypto-related operations by 2030. In June 2021, Blockstream mining company announced its collaboration with American-based Square.Inc company for solar-powered BTC mining [49]. In this cooperation, five million dollars is invested in the facilities by Square.Inc and the 100% renewable energy-based mining infrastructure is going to be completed by Blockstream. The wind-based electricity generation in the U.S. increased threefold in 2020 compared to 2011, reached to 118.3 gigawatts.

The contribution of wind and hydropower to the U.S. electrical supply is 7.1% and 7%, respectively, where the most wind power is generated in Texas and the Midwest. Further development of wind and hydroelectric power could pave the road to deliver more transparent energy usage and sustainability metrics in the cryptocurrency. In June 2021, China Government increased its regulatory squeeze on cryptocurrencies to shut down up to 90% of the BTC mining capacity in the country [50]. The China central bank stipulated cryptocurrencies have disrupted the regular order of the economy and increased the risks of illegal cross-border transfers of assets and illegal activities such as money laundering. This decision made BTC's price and the whole cryptocurrency market fallen by 20% and 12%, respectively, due to uncertainty about the cryptocurrency future. Nevertheless, cryptocurrency mining won't cease due to this crackdown, and the operators will relocate their mining systems elsewhere. Texas, USA, is one of the best candidates for large-scale mining systems that could benefit from the new restrictions in China due to its low-cost electrical power and the unique regulatory environment [51]. Due to electricity price volatility in Brazil, Bastian-Pinto et al. [52] suggested hedging electricity price risk by investing in the digital coin mining facility to generate new mined cryptocurrency. Recently, El Salvador Government announced this country is going to adopt BTC as legal tender and develop the geothermal electric companies to come up with a plan for volcano-powered BTC mining [53]. In southwest China, where the local electrical power demand is relatively low, a large amount of hydroelectrical power is generated [54]. However, the power export capacity of this region is limited due to the lack of high-quality grid infrastructure. Therefore, Yunnan and Sichuan provinces are suitable regions for industries with high-demand electrical power, and mining cryptocurrency in these provinces could be a clean and environmentally friendly process. The only issue here is seasonal variability in hydroelectric power due to the variation in water availability through droughts/floods/rain. For instance, in Sichuan province, the average electrical power generation in the wet seasons is three times that of the dry season. To balance these hydroelectrical power fluctuations, other types of electricity generation should be employed, and coal-based power generation is the most available candidate. Consequently, the cryptocurrency mining process in this region is not technically 100% green. On the other hand, the digiconomist's results prove that the development of cryptocurrency could

lead to huge environmental issues. De Vries [55] believes that these environmental dilemmas will not be solved by renewable and sustainable energy and suggested changing the POW algorithm with "Proof of Stake" (POS) as the best solution. The POS protocol was proposed by ETH, the world's second-largest digital coin behind BTC. This protocol was developed to address environmental concerns about the POW system by omitting competition between miners. Without the competition, there is no computing power arms race for miners to participate in [56]. The next generation of cryptocurrency needs to focus more on the problems related to scalability, interoperability, and sustainability on crypto platforms [57]. Imran [58] pointed out that it is not correct to compare Blockchain mining energy consumption with VISA's energy utilization per transaction because, while VISA consumes this energy specifically for the transaction, Bitcoin's electricity consumption is dedicated to protecting all transactions dating back to 2010. He concluded that in the long-term mining process, renewable energy would become profitable. It is believed that the marginal cost of renewable electricity generation continues to decrease relative to the marginal costs of fossil fuel-based electricity generation, which can enhance the miners' incentive to shift towards sustainable energy [59]. Turby [23] investigated the possibility of sustainable development of cryptocurrency without damaging this sector. The author discussed several regulatory and fiscal approaches to restrict the digital currency's energy utilization and its ecological implications. It was indicated that since cryptocurrency's success is due to miners and incentivizing investors to earn profits, using these incentives to change the energy consumption pattern by fiscal means can help the digital currency to obtain environmental targets. The price of cryptocurrency is not only decided by the traders, but the price is also related to the electrical power price. The cryptocurrency mining competition has led to the deployment of more energy-efficient hardware to be financially viable [60]. The energy demand of the digital coins mining process is typically supplied by the electrical power from the grid. This method is best suited for use in countries with low electrical power prices, such as China, Russia, and Iran. However, the necessity of exploiting power generating systems with better performance than fossil fuel-based power generation systems is felt.

For instance, investigation about using electrical power generated by solid oxide fuel cell (SOFC) in the digital coins mining process has been investigated and claimed that SOFC has higher electrical efficiency [61]. The SOFC electrical power generation is in the early stage of commercialization; therefore, the initial cost of the SOFC-based mining process would likely be high. Nevertheless, using biogas instead of natural gas in the SOFC process would be cheaper and more affordable [62]. It is claimed that using biogas in SOFC is more economical than its exploitation in micro-gas turbines and internal combustion engines (ICE) [63]. Figure 2 demonstrates the concept diagram of the cryptocurrency mining process using a biogas-based SOFC system for electrical power generation [61]. Electrical power generation by natural gas and biogas in the SOFC systems for the cryptocurrency mining process is affordable when the BTC price is higher than $20,000. The natural gas-based cryptocurrency mining process is better suited for the countries such as U.S. or Canada, where the electrical power price is high, but natural gas is cheap. The biogas-based cryptocurrency mining process is better suited for European countries and Japan, where the prices of natural gas and electrical power are high. Moreover, in Southeast Asian countries such as Indonesia, Malaysia, and Thailand, where a huge amount of biogas is available due to palm oil mill effluent (POME), this mining strategy could be affordable [64]. Indonesia and Malaysia have over 1,000 palm oil mills that produce almost 90% of the global palm oil supply that generates around 126 million tonnes of POME yearly [65]. Aside from POME, organic waste and animal manure can also act as feedstock for biogas production. The annual electricity potential of biogas from cattle, pig, and poultry waste in Indonesia and Malaysia is about 80 TWh and 10 TWh, respectively, which is more than sufficient to replace diesel fuel in the power sector [66]. The operating cost and the capital cost are two crucial factors considered by the miners. The deciding factor for the miners is operating costs in the countries where natural gas and electricity are expensive, while capital cost is the deciding factor in the countries with low natural gas and electricity prices.

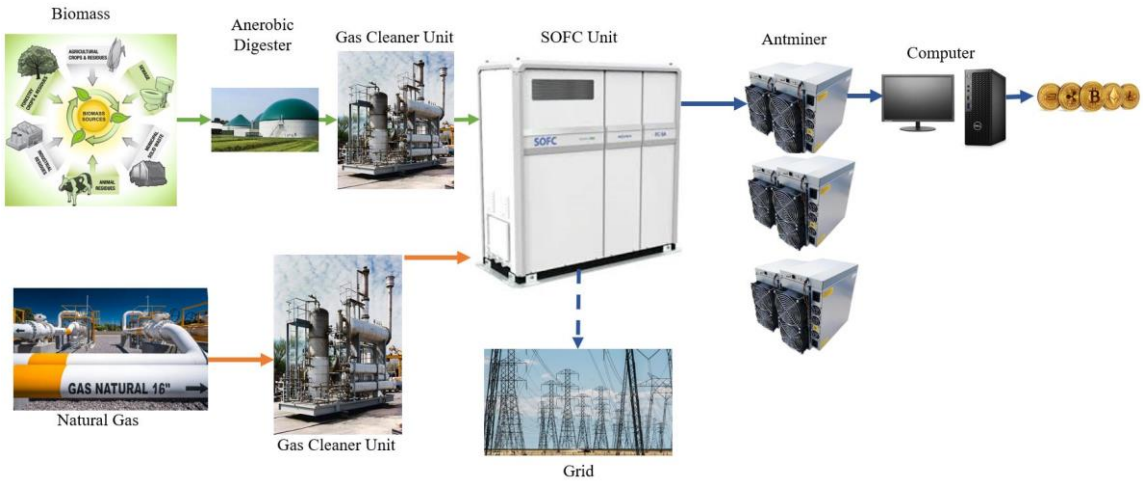

Figure 2. Using SOFC to generate electrical power for cryptocurrency mining

Cryptocurrency technology is still in its infancy, and its future lies within speculation and hyperbole. Since the digital mining process is an energy-hungry technology, using energy consumption reduction methods such as phase change material in mining warehouses, mining systems, and computers is recommended to make it sustainable. Depending on the region, the required electrical power for the cryptocurrency mining process could be supplied by the grid (generated from fossil fuels) or renewables. Compared to fossil fuel-based electricity, electrical power generation by renewables have lower profitability at lower cryptocurrency prices due to the higher capital expenditure. However, considering operation expenditure, environmental costs, and sustainability issues for fossil fuel-based electricity, it can be concluded that renewables are beneficial options for the cryptocurrency mining process. The cryptocurrency mining process by renewables is affordable for miners when the cryptocurrency price is high. Ultimately, there is a need for digital coins to control the outrageous electrical power consumption to become green and sustainable.

Ethical issue

Authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. Authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

Authors' contribution

All authors of this study have a complete contribution to manuscript writing.

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Abbreviations

BNB: Binance
BTC: Bitcoin
ETH: Ethereum
ICE: Internal combustion engines
ICOs: Initial coin offerings
IEA: International Energy Agency
PCM: Phase change material
POME: Palm oil mill effluent
POS: Proof of Stake
POW: Proof of Work
SOFC: Solid oxide fuel cell