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THE IMPACT OF BLOCKCHAIN TECHNOLOGY ON THE ENVIRONMENT

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Abstract. *This paper focuses on the environmental impact of blockchain technology, particularly on electricity consumption for equipment operation and cooling. During its operation, the device energy is converted into heat, which must be efficiently dispersed. Additionally, the paper examines the rate of mining equipment replacement and the subsequent e-waste concerns. The impact of blockchain technology on the environment is a complex and debated topic. Only the following two aspects are discussed in this paper:*
1) Energy Consumption: (a) Positive Impact: Blockchain technology, especially in the context of cryptocurrencies like Bitcoin, has been criticized for its high energy consumption due to the consensus mechanism called Proof of Work (PoW). However, some blockchain networks use alternative consensus mechanisms like Proof of Stake (PoS), which is more energy-efficient, and b) Negative Impact: PoW-based blockchains, such as Bitcoin, require significant computational power, leading to high energy consumption. The environmental impact is a concern, especially if the electricity used comes from non-renewable sources.
2) Mining and E-Waste: (a) Positive Impact: Blockchain technology can help in tracking the supply chain and provenance of minerals, which could reduce the use of conflict minerals and promote ethical mining practices. (b)Negative Impact: The mining of cryptocurrencies involves specialized hardware that becomes obsolete quickly, contributing to electronic waste (e-waste). This can have negative environmental consequences if not properly managed and recycled.
The central topic of this paper is electric energy consumption and as a consequence CO_2 emission footprint. Because of the fast growth of data centers and mining centers, consumption of electric energy has grown exponentially in the past decade. Together with the consumption of electric energy, CO_2 emission grows dramatically.

Key words: *Blockchain, crypto-assets, e-waste, waste energy*

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1. INTRODUCTION

Over the last decade and a half, blockchain technology has emerged as a revolutionary digital tool adopted across various business domains. This technology operates as a decentralized and distributed ledger, recording every transaction and securely storing encrypted data of the entire transaction history. Initially, blockchain technology could be operated through an ordinary computer, but specialized graphics cards (GPU) became necessary as it grew. Today, using highly specialized devices is mandatory for working with blockchain technology.

However, the widespread adoption of blockchain technology has raised several concerns, including a considerable increase in electricity consumption and e-waste generation. As the usage of blockchain technology continues to surge, these issues are becoming more severe.

In 2008, Nakamoto's publication of "A Peer-to-Peer Electronic Cash System" [1] had a profound impact on public interest in a new form of currency. This system allowed for the direct transfer of funds between users without the involvement of intermediaries or central banks in issuing the currency. The media extensively covered Bitcoin's initial transactions and creation, which greatly contributed to its rapid adoption by users. The primary focus was on the fact that it was the first decentralized, peer-to-peer online currency with inherent value that did not rely on a central issuer. Its value was solely determined by market demand and supply. [2] [3]

Litecoin emerged as a cryptocurrency in 2010, shortly after Bitcoin. It gained unexpected popularity as a payment system over time, coinciding with the public's growing interest in Bitcoin's value and market volatility. This surge in attention sparked significant media coverage and curiosity about the underlying technology. With blockchain software being open source, anyone with knowledge and interest could download and install it to build their payment systems. The CoinMarketCap website regularly updates the number of new payment systems created each month (Figure 1a).

The pursuit of a better quality of life has resulted in humans exploiting natural resources with little consideration for the consequences. As a result, several issues have emerged that now jeopardize our well-being [4]. Initially, mining cryptocurrency on standard computers consumed less electricity. However, introducing specialized devices called Application-Specific Integrated Circuits (ASIC) made mining more profitable and popular. Each new generation of mining equipment needs more electricity and processing power for profitability [5].

It's interesting to note the discrepancies in the number of registered cryptocurrency systems depending on the source of data. For instance, while CoinMarketCap.com lists 10,300 cryptocurrencies, Statista.com lists only 8,685. This suggests that locating smaller cryptocurrency systems can be challenging and that the registration process may not always be dependable. However, based on rough estimations, it's reasonable to assume that approximately 9,500 cryptocurrency systems warrant analysis. To provide a comparison, the United Nations only recognizes 152 official fiat currencies. [8].

Certainly, let's explicitly outline the three main aspects: energy consumption, carbon footprint, and e-waste, in the context of the impact of blockchain technology on the environment.

Let's start with energy consumption. PoW-based blockchains, such as Bitcoin, require significant computational power, leading to high energy consumption. The environmental impact is a concern, especially if the electricity used comes from non-renewable sources.

Second, carbon Footprint. The carbon footprint is a concern, especially in PoW-based blockchains, as the energy-intensive mining process can result in a substantial carbon footprint, particularly when powered by non-renewable energy sources.

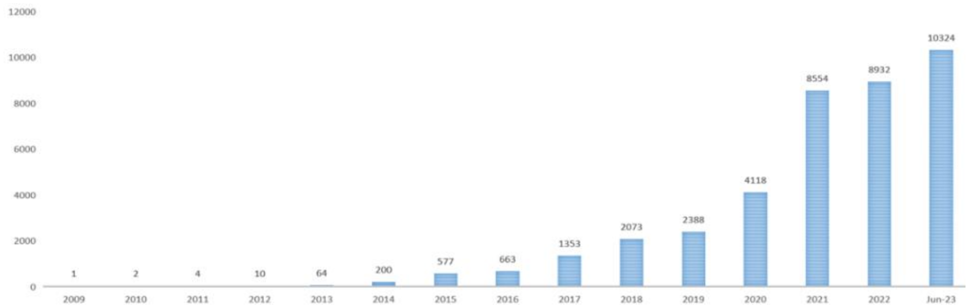

Fig. 1a Growth in the number of cryptocurrencies [6]

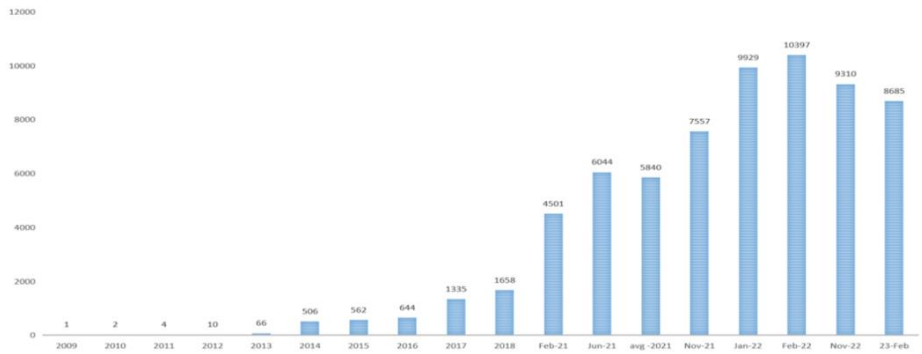

Fig. 1b Growth in the number of cryptocurrencies [7]

Third is E-Waste. The mining of cryptocurrencies involves specialized hardware that becomes obsolete quickly, contributing to electronic waste (e-waste). This can have negative environmental consequences if not properly managed and recycled.

By considering these three aspects—energy consumption, carbon footprint, and e-waste—it becomes clearer how blockchain technology's environmental impact is multifaceted, with both positive and negative dimensions. It underscores the importance of adopting eco-friendly practices and sustainable solutions within the blockchain industry to mitigate potential negative environmental consequences.

2. LITERATURE OVERVIEW

In 2008, Satoshi Nakamoto [1] published the first paper on blockchain technology. The paper proposes a new technology solution that utilizes cryptography, digital signatures, and peer-to-peer networking to secure a distributed ledger. This ledger contains all records that are linked chronologically in blocks.

Three papers are essential in defining a methodology that accelerates block registration and reduces electricity consumption:

1. In their paper [9], provide an overview of the block chain technology architecture and assess its future developments.

2. The paper ‘The Carbon Footprint of Bitcoin’, [10] analyses the consumption of electricity necessary for cryptocurrency mining equipment

3. In 2019, several papers analyzing Bitcoin electricity consumption. By then, the number of ASIC devices and transactions had increased significantly, so the problem became visible [11].

4. Many authors [12], [13] , in their papers, analyze the problem of electronic waste in detail.

5. Large number of websites have started to deal with the topic of cryptocurrencies. Sucha are CoinMarketCap in 2013 [14], and www.digiconomist.net , started onMarch 2014).

Educational and scientific institutions are actively researching the use of cryptocurrencies. The University of Cambridge's Cambridge Centre for Alternative Finance (CCAF) is a prominent player in this field, closely monitoring advancements and presenting findings on blockchain technology.

Measuring the environmental impact of blockchain technology is a challenging task due to several inherent complexities and uncertainties. Here are some of the problems associated with measuring this impact, along with considerations for how it can be measured:

a) Diversity of Blockchains

Problem: There is a wide variety of blockchain networks, each with its consensus mechanisms, scalability solutions, and energy requirements. Measuring the environmental impact requires accounting for this diversity

Measurement Approach: Conducting specific assessments for each blockchain network based on its unique characteristics and consensus mechanism can provide a more accurate measurement. Standardized metrics may need to be developed to compare different blockchains.

b) Energy Source Variability

Problem: The environmental impact depends on the energy source used for mining or validating transactions. Blockchains can operate on energy from renewable or non-renewable sources, leading to different carbon footprints.

Measurement Approach: Assessing the energy mix of the specific blockchain network and considering the carbon intensity of the energy sources can provide insights into its environmental impact. Transparent reporting of energy sources by blockchain projects is crucial.

c) Dynamic Nature of Technology

Problem: Blockchain technology is evolving rapidly, with changes in consensus algorithms, energy efficiency improvements, and the development of more sustainable practices. This makes it challenging to measure a moving target.

Measurement Approach: Regularly updating assessments and keeping track of technological advancements is essential. Periodic reviews and revisions of measurement methodologies will be necessary to account for changes in the technology.

d) Incomplete Data and Transparency

Problem: Some blockchain projects may not disclose key information, such as their energy consumption, making it difficult to accurately measure their environmental impact.

Measurement Approach: Encouraging transparency and standardized reporting within the blockchain industry is crucial. Independent audits and verifications can help ensure the accuracy and completeness of the data provided.

e) Economic Incentives and Behavior

Problem: Economic incentives within blockchain networks can influence miners' behavior, affecting their energy consumption and environmental impact. Changes in token values and mining rewards can impact miners' decisions.

Measurement Approach: Understanding the economic incentives and aligning them with environmental sustainability goals can be crucial. Analyzing the behavior of participants in response to economic changes can help predict and measure environmental impacts.

f) Lack of Consensus on Metrics

Problem: There is no universal agreement on standardized metrics for measuring the environmental impact of blockchain technology.

Measurement Approach: Establishing industry-wide standards for measuring environmental impact, including metrics for energy consumption, carbon footprint, and e-waste generation, can provide a common framework for assessment.

In summary, measuring the environmental impact of blockchain technology is a complex task that requires addressing the diversity of blockchains, considering energy source variability, adapting to the dynamic nature of technology, ensuring transparency, accounting for economic incentives, and establishing consensus on measurement metrics. Developing standardized methodologies and encouraging industry-wide collaboration will be essential for accurate and meaningful assessments.

3. Characteristics of Blockchain Technology

Bitcoin mining began in 2009 when the first Bitcoin block was created. It involves verifying transactions and adding new blocks to the blockchain network. The blockchain system works by connecting blocks together in a continuous chain [15]. Did you know that every time a new transaction is made in the blockchain network, it needs to be processed by a mining node? These nodes work tirelessly to combine these transactions and find the elusive 'Proof of Work' (PoW) for the block. It's like a digital treasure hunt, and the miners who solve the puzzle first get to add the block to the chain and earn some cryptocurrency as a reward. Cool, right? [1]. In the process of mining Bitcoin, the initial miner successfully solves a challenging mathematical problem, referred to as Proof of Work (PoW), and distributes the block to all the nodes on the network. The nodes then validate and incorporate the new block into their list, and the cycle repeats for the subsequent block. As a token of appreciation for their hard work, the miner who effectively completes a block is awarded Bitcoin, which can be traded on cryptocurrency exchanges for a profit. Since network participants invest time and energy, the process is similar to that of a miner, which is why the term "mining" has been adopted for this activity [1].

Within the Bitcoin network, miners engage in a competition to generate a new block, add it to the chain, and earn a Bitcoin as a reward. This competition involves a computational guessing game that is deliberately designed to be challenging. Only a valid proof of work (PoW) can result in a new block being added to the blockchain. The miner who successfully guesses the PoW completes the block and is rewarded for their efforts. All miners in the network participate in this competition, expending a significant amount of electricity to perform PoW calculations. The more powerful a miner's device, the greater their likelihood of successfully creating a new block and earning a profit. The profitability of the system relies on the efficiency of a device and its electricity consumption per calculation. Essentially, a machine is more cost-effective if it can perform more calculations per unit of consumed electricity. This is the fundamental operating principle of the Bitcoin mining system.

Proof of Stake (PoS) is a blockchain formation system that differs from the traditional Proof of Work (PoW) system. In PoS, the participants do not compete with each other.

Instead, the system selects the computers that can create the next block in the blockchain based on the amount of currency invested as collateral. This means that the more currency a participant invests, the more likely they are to be chosen to create the next block [16]. In the Ethereum system, participants are required to invest funds. The blockchain production process is determined through a random selection software. The principle is that the more funds invested, the higher the chances of producing the next blockchain. Miners still need to have adequate equipment capacity. However, in this case, the power of the device is not the decisive factor. In his paper [17] states that in September 2022, Ethereum switched from PoW, to PoS, reducing the electricity consumption by 99.84%.

Apart from the two commonly used methods, several other methods such as Proof of Burn (PoB), Proof of Authority (PoA), Practical Byzantine Fault Tolerance (pBFT) and Proof of Capacity (PoC) have been used less frequently in previous works [9].

PoS blockchain requires less electricity for operation than other models. There are multiple ways in which Blockchain can be organized.

A public blockchain provides unfettered access to its network for anyone with a computer or mobile device, without necessitating any permission. The consensus mechanism, whether Proof of Work (PoW) or Proof of Stake (PoS), is utilized to incorporate novel entries in the network information. Every node can partake in the consensus procedure in a public blockchain. With an effortless process for adding a new member, expanding this form of blockchain organization is a breeze. Due to the increasing number of members and information exchange, transaction confirmation slows down data processing [18].

On a public blockchain network, transactions can be viewed by anyone due to their transparent nature. The decentralized storage of records across numerous participants' computers ensures that transactions cannot be tampered with. The effectiveness of the system is directly proportional to the number of participants and transactions managed by the protocol. Nevertheless, privacy concerns arise with public blockchain technology as the data being shared needs to be safeguarded.

A private blockchain is a type of blockchain network that is closed and managed by a central authority. The central authority controls the access of participants to the network, and grants access rights based on specific authorizations. Access to the private blockchain is limited, ensuring secure and controlled access for authorized participants only.

A private blockchain is governed by a sole organization that holds full control and makes the ultimate decision on consensus. The central authority in charge of the business manages the visibility of information for users. Nevertheless, private blockchains pose a challenge in terms of transaction immutability, since records can be modified due to the restricted number of participants. Despite this, the overall efficiency and speed of private blockchain systems tend to surpass those of public ones, given the lower number of users and transactions. Private blockchains have limited expansion due to reliance on centralized network management. All participants must be recognized and may face restrictions on system usage [9].

A hybrid blockchain is a combination of both private and public blockchains, where a new member needs approval from all other participants to join. Hybrid blockchains are gaining popularity among experts, who predict a promising future for this type of blockchain. A hybrid blockchain is a type of blockchain that involves multiple institutions and is partially decentralized. This means that only a select few nodes are able to establish a consensus. The growth and inclusion of new members is dependent on a central organizer, but individual users have free and open access to publicly available data. [9]

4. Application Area for Blockchain

Blockchain technology was first created to support cryptocurrencies, but its potential for business applications was quickly realized. The technology is built on three fundamental components: 1) Private Key Cryptography, 2) Peer-to-Peer Networks, and 3) the Blockchains protocol [19]. As a distributed computing technology, blockchain is decentralized, transparent, immutable, and anonymous. Due to its several advantages, it has been rapidly adopted by the business environment. Although the first research on its application was focused on the financial industry, the interest in this technology quickly spread to other areas of business. In literature, you will find research papers that demonstrate the application of blockchain technology in various areas [20]:

- Financial applications, (payments, loans)
- Cryptocurrencies
- State administration (data on citizens, voting, data on ownership)
- Internet of Things (IoT)
- Health services
- Business applications
- Supply chain management
- Energy industry
- Data management
- Education (online education, student data, exams, grades, diplomas, and certificates).

Blockchain applications, except for cryptocurrencies, usually need a hybrid or private organizational form.

5. Electricity Consumption for the Operation of Blockchain Technology

Governments around the world are increasingly pressuring cryptocurrencies, particularly Bitcoin, to reduce their energy consumption. [21] The Cambridge Bitcoin Electricity Consumption Index reports that the Bitcoin system uses 138.8TWh of electricity per year. To provide context, a single Bitcoin transaction requires 703.25 kWh of electricity, while VISA only uses 148.63 kWh for 100,000 transactions[1].

To estimate the number of active devices in the Bitcoin system, we can rely on the statistics published by 'pools'. These pools are made up of miners who combine their computing power to increase their chances of earning profits. Although there are only a few of these pools, it is possible to calculate the total number of devices used in the Bitcoin network based on their results. On the website [22] , the hash rate distribution results, indicating the success of block formation, are given with percentages of the share of the largest pools. All the major pools are displayed on an interactive diagram, including the 'Braiins Pool,' which has a participation rate of 0.941% in the total sum of all the pools achieving results. This data is monitored interactively on the Blockchain.com website, and it changes over time. On the Braiins Pool website, the current number of active miners is displayed interactively, and this number changes over time. For instance, on June 29, 2023, at 7 p.m., there were 76,972 active devices (miners). Based on this data, it can be estimated that the total number of miners is approximately eight million. If we assume that the

[1] Bitcoin average energy consumption per transaction compared to that of VISA as of May 1, 2023 [30]

average ASIC device has a power of 3.4 kWh, the calculation shows that it consumes about 24GWh. This data roughly matches the data presented on the Cambridge Bitcoin Electricity Consumption Index website and can be considered relevant because the number of miners active on the network is continually changing. According to the estimated data, the total consumption of the Bitcoin payment system is 138.8 TWh/Year. This high level of electricity consumption, with an upward trend, could not go unnoticed, so regulators in certain countries had to enact legislation for the operation of these systems.

When comparing the Bitcoin and Ethereum systems, it is evident from the diagram that there is a significant difference in their electricity consumption. Prior to September 2022, Ethereum utilized the PoW system, which consumed considerably more energy compared to the PoS system that they switched to. The change in the system led to a 99% reduction in electricity consumption, making it an environmentally sustainable option [23].

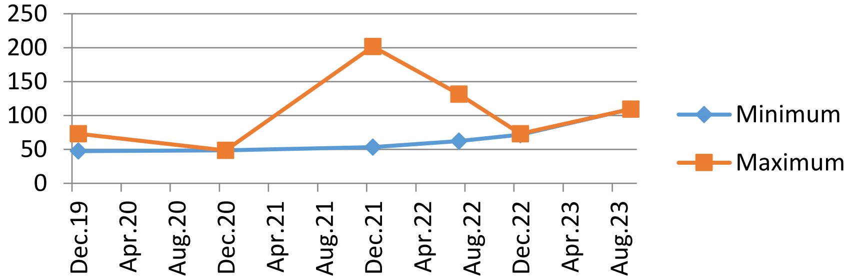

Fig. 2a Bitcoin energy consumption (Twh/Year - Estimated) worldwide 2017-2023 [23]

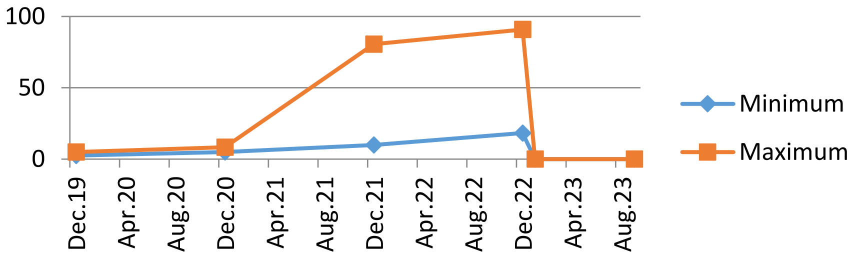

Fig. 2b Ethereum energy consumption (Twh/Year - Estimated) worldwide 2017-2023 [23]

In the analysis of electricity consumption literature, a narrow focus on conventional payment systems is prevalent, neglecting other payment options. According to Figure 1, the precise count of diverse cryptocurrency systems remains elusive, with varying outcomes from different data sources. It is important to acknowledge that the initial twenty payment systems constitute 90% of the entire cryptocurrency production. Despite their lesser size, they possess a network of miners, whose electricity usage should be considered. Given approximately 9,000 cryptocurrency systems as per Figure 1, their energy consumption cannot be overlooked. According to [6] Bitcoin currently dominates the cryptocurrency market with a 68% share, while Ethereum is a distant second with a 13% share. If we were to equate this market share to electricity consumption, we would need to add 32% of the energy consumed by other cryptocurrencies to the current electricity consumption of Bitcoin. This would result in a total energy consumption of 183.2 TWh/year.

5.1. The problem of secondary consumption of electricity

A significant limitation to the existing body of research, data, and literature related to electricity usage in blockchain technology is that it solely accounts for the energy consumed by the equipment. Yet, to maintain optimal performance, proper temperature regulation and cooling are also essential components. The application-specific integrated circuit (ASIC) chip of the device operates within a temperature range of 70°C to 80°C. The device should be installed in an air-conditioned room where the ambient temperature ranges from 10°C to 35°C, to ensure optimal operation. The temperature of the device's plate must be maintained below 90°C. The electricity consumption of the device varies based on the type and manufacturer, and for better quality, it ranges from 3,300W to 3,500W [24].

The process of cryptocurrency mining generates a significant amount of heat, requiring intensive cooling to ensure the proper functioning of the mining devices. Typically, these devices are installed in large-scale operations known as "farms," where the sheer number of devices and energy consumption necessitate the dissipation of a substantial amount of thermal energy to maintain optimal temperatures.

The conventional method for cooling mining equipment involves situating it in cooler areas where the temperature is naturally lower, thus reducing the need for excessive electricity to maintain safe temperatures. However, there are times of the year when simply introducing fresh cold air is insufficient, and more extensive cooling measures must be taken. The energy required for such cooling is often disregarded in literature, as it necessitates a thorough analysis of the installation site, including the duration and frequency of cooling needs. Unfortunately, acquiring this information can be difficult since the total number of devices connected to the network is constantly fluctuating due to equipment replacements and repairs. Furthermore, connectivity problems can hinder the accuracy of these assessments.

5.2. Carbon Footprint as a consequence of cryptocurrency mining

Blockchain technology has a significant carbon footprint due to its energy-intensive process of verifying transactions and creating new blocks on the blockchain. The energy consumption of blockchain technology results in significant greenhouse gas emissions, which contribute to climate change.

The answer to the question of how much renewable energy is used for cryptocurrency mining depends on who you ask. Cryptocurrency miners and related businesses claim that 74% of the energy they consume comes from renewable sources. However, a more objective analysis shows that coal and gas remain significant energy sources for electricity production in many countries. It is also worth noting that most mining equipment is located in regions where the cost of electricity is low.

Despite this, there is cause for concern as 75% of Bitcoin mining in 2020 occurred in China, where estimates suggest that up to 40% of the energy consumed was generated from coal [10]. It is difficult to pinpoint the location of individual miners, so all other data presented are estimates. It is important to note that cryptocurrency mining has been banned in the Republic of China since July 2021 [25].

Based on the paper [26] following three formulas calculating required power, energy required, and energy consumption:

$$\text{Power Required (MW)} = \text{Network Hashrate}\left(\frac{\text{T Hash}}{\text{second}}\right) \cdot \text{Rig Power Efficiency}\left(\frac{\text{Joules}}{\text{M Hash}}\right) \quad (1)$$

$$\text{Energy Required }(\text{MWh}) = \text{Power Required }(\text{MW}) \cdot \text{Block Time }(\text{hour}) \quad (2)$$

$$\text{Energy Consumption }(\text{MWh}) = \frac{\text{Households' No.TX} \cdot \text{Energy Required }(\text{MWh})}{\text{Total blokchain network No. TX}} \quad (3)$$

Total blockchain cost is:

$$\text{Cost }(\text{USD}) = \text{Ether price }(\text{USD}) \cdot \text{Gas amount} \cdot \text{Gas price in ether}\left(\frac{wei}{10^{18}}\right) \quad (4)$$

$$\text{Total blockchain cost} = \sum_{i=1}^{n} \text{No. TX} \cdot \text{Cost}_i \quad (5)$$

where *i* represents the number of days (i. e. *n* days).

The data presented by Digiconomist [23] states that the Carbon Footprint is 56.96 Mt CO_2, which corresponds to the Carbon Footprint of Portugal. Data on the carbon footprint of a single Bitcoin transaction, which is 379.14 kg CO_2, is available on the same website.

When comparing the carbon footprint data of Bitcoin and the Ethereum system, interesting results are obtained. In September 2022, the Ethereum system changed the mechanism of block formation and switched to PoS. On an annual level, the amount of carbon dioxide has not yet been recalculated, but it is already known that Ethereum produces 0.01 kg of CO_2 per transaction. This means that Ethereum has a 3,900 times smaller carbon footprint than Bitcoin. This information is of particular interest to the world community, which is trying to reduce the impact of carbon dioxide in the atmosphere [27].

5.3. The problem of electronic waste

Cryptocurrency mining, specifically Bitcoin as the largest system, causes significant issues with used equipment that needs to be disposed of. E-waste is a major environmental hazard as it contains toxic chemicals and heavy metals that are released into the soil when the equipment is discarded. This leads to air and water pollution caused by improper recycling. [10] The short life cycle of cryptocurrency mining equipment requires quick replacement to maintain business profitability.[2] To gain a deeper understanding of this matter, it is necessary to delve into the mechanics of the system by taking a look at Bitcoin as an example. On this system, each mining machine vies to produce a new block, with the probability of success being directly correlated to its share of computing power. The production of hashes, which are utilized in the block recalculation algorithm, requires electricity. The efficacy of hardware is contingent upon the amount of energy it consumes,

[2] The latest model, Graphic Processing UNIT (GPU) used for mining, is the A100. This is a graphics processor from the tensor category- [31]

with devices capable of performing more calculations per unit of energy being more economically advantageous.

The reason for the rapid renewal of mining equipment is found in Koomey's Law [28] Moore's Law and Koomey's Law both predict exponential growth in computing power and energy efficiency, respectively in the same period of 18 months. The fast-paced progress of technology has resulted in a frequent replacement of equipment, often within a mere 18 months of its initial use. This is due to the continual introduction of newer models with enhanced processing capabilities, rendering older equipment less profitable. As time passes, cryptocurrency mining becomes less efficient with aging equipment. Once 18 months have passed, the outdated devices are unable to compete with the newer models and must be disposed of. Regrettably, repurposing mining devices for other tasks is not possible, leaving the discarded equipment as electronic waste.

When analyzing the geographical location of mining farms, it's evident that they are mostly situated in northern regions due to the low average temperature which helps in reducing the cooling costs It's a known fact that e-waste processing factories are usually located far away from the places where e-waste is generated. This is why the percentage of e-waste recycling is low. Globally, only 20% of all e-waste is recycled, while the rest ends up in landfills that pose a risk to the environment. [12]

The current information available on e-waste associated with mining equipment pertains solely to Bitcoin, disregarding the other 9000 cryptocurrency systems depicted in Figure 3. Considering that Bitcoin constitutes approximately 68% of all cryptocurrencies generated, it is necessary to augment the number of installed devices by 32% to encompass the total number of ASIC devices. Taking this estimation into account, it can be concluded that there exist roughly 8 million Bitcoin mining devices. Nevertheless, taking into account the 32% increase, the total number of installed devices surges to 10.5 million.

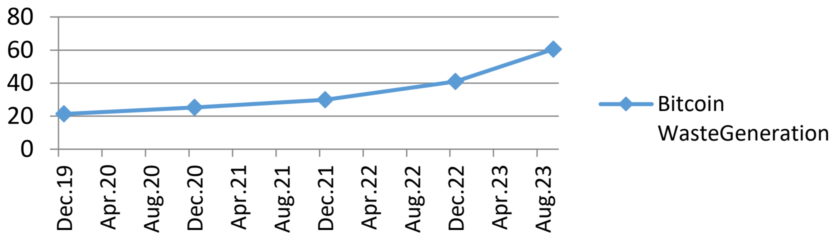

Fig. 3 The amount of e-waste generated (kilotonnes per Year - Estimated) by Bitcoin [23]

All devices that are 18 months or older are disposed of and replaced with new ones. According to Statista – Annual Total Electronic Waste, the amount of such waste is over 50 kT.

6. Discussion

With the rise of cryptocurrency mining equipment comes a concerning increase in environmental pollution. However, it's worth noting that the issue is specific to cryptocurrency mining and not blockchain technology as a whole. There are solutions available, such as private or hybrid blockchain models, that can reduce the environmental impact.

Private blockchain, for instance, is designed for closed systems with limited access. All nodes work together on a shared task, eliminating the need for devices to compete for rewards. This results in lower electricity consumption and longer device lifespans, reducing electronic waste. By considering alternative blockchain models, we can prioritize sustainability and reduce our impact on the environment.

The hybrid model for organizing blockchain shares similarities with the private approach, but is designed to handle a much larger volume of transactions. In contrast to the private blockchain, there is less competition between individual devices and no requirement for any device to perform at the highest speed.

In the realm of public blockchains, there is typically a significant volume of users. When these users are concentrated within domains such as state administration, healthcare, pension funds, and other similar public affairs, the workload is notably less demanding than that of cryptocurrencies. The tasks involved in these areas do not necessitate the use of the fastest devices or solving intricate algorithms within a short timeframe. As a result, the implementation of blockchain technology in these sectors does not present significant environmental protection challenges.

Public cryptocurrencies with a high number of mining devices present a significant challenge. The Proof-of-Work (PoW) consensus methods used by these currencies can vary greatly in terms of energy consumption, with Bitcoin requiring a substantial amount of electricity. This has led to regulatory proposals aimed at limiting the operation of these systems in many countries. However, Ethereum's mining mechanism has made impressive strides by reducing electricity consumption by 99.84%. Replacing PoW mining with an efficient system can ease the strain on power systems, especially with regard to climate change.

When examining the energy usage of cryptocurrency mining, it is crucial to take into account the overall energy expended in this process. This encompasses not just the energy consumed during mining, but also the energy used to regulate the temperature of the rooms containing the mining equipment. In the case of sizable mining operations, it may be feasible to boost energy efficiency by harnessing the excess thermal energy produced by the equipment to heat another area. Such a measure would drastically enhance the energy utilization coefficient.

Cryptocurrencies are having a growing impact on the electricity market, causing prices to rise. The mining farms, regardless of their location and electricity sources, have a significant effect on consumption.

Implications of the research are:

- Transparent and Sustainable Supply Chains
- Renewable Energy Tracking
- Environmental Credits and Incentives
- Efficiency Gains in Processes
- Decentralized Energy Grids

Further research can be focused on recommendations and Mitigation Strategies

- Transition to Sustainable Consensus Mechanisms
- Renewable Energy Adoption
- E-Waste Management
- Industry Collaboration and Standards
- Education and Awareness

The blockchain trilemma requires a balance between scalability, security, and decentralization. On-chain solutions are secure and decentralized but slow and expensive.

Second-layer solutions offer scalability but less decentralization. P2P energy trading is limited by regulations and professional regulators. Overcoming these limitations can result in a secure, scalable, and cost-efficient system. Ethereum is computationally intensive and can result in slow and expensive transactions.

The use of green energy certificates is a mechanism employed in various industries, including blockchain, to support and promote the use of renewable energy sources. These certificates, also known as Renewable Energy Certificates (RECs) or Guarantees of Origin (GOs), are tradable instruments that represent the environmental attributes of electricity generated from renewable sources.

Here's how the process generally works:

- **Renewable Energy Generation:** Renewable energy producers, such as solar or wind farms, generate electricity using clean and sustainable sources.
- **Certificates Green Energy Certificates:** For each unit of renewable energy produced, a corresponding green energy certificate is issued. This certificate verifies the environmental attributes of the energy, indicating that it comes from a renewable source.
- **Trade and Purchase:** These certificates can be bought and sold on the market independently of the physical electricity. Entities, including blockchain projects, can purchase these certificates to demonstrate their commitment to using renewable energy.
- **Environmental Claims**: By holding and retiring these certificates, organizations make environmental claims that they have supported the generation of renewable energy equivalent to their energy consumption. This helps them meet sustainability goals and showcase a commitment to reducing their carbon footprint.
- **Verification and Transparency**: The use of green energy certificates provides a level of transparency and verification in the energy market. Buyers can ensure that the energy they are using or claiming to use has a renewable origin.

It is important to note that while green energy certificates offer a way for organizations to support renewable energy and make environmental claims, they are not without criticism. Some argue that relying solely on certificates may not directly contribute to the reduction of greenhouse gas emissions if the energy mix at the physical location is not predominantly renewable. Therefore, organizations are encouraged to adopt a comprehensive approach to sustainability, including on-site renewable energy generation and energy efficiency measures, in addition to purchasing green energy certificates.

7. CONCLUSION

The potential of blockchain technology is promising for the future, and its usage is expected to increase over time. However, it's essential to note that the energy requirements of different block formation mechanisms vary and must be considered in the planning phase. To ensure the sustainable operation of blockchain systems, this issue must be taken into account.

Topics, such are: (a) Smart Contracts and Efficiency, (b) Environmental Solutions: and (c) Public Awareness and Education are out of the scope of this paper, but the authors took into consideration during they made research.

The world of cryptocurrencies is expanding quickly, though it remains a relatively small part of the financial landscape. Financial institutions around the globe are keeping a close eye on the developments in this field, with some even exploring and adopting blockchain technology for their operations. By integrating this technology, banks can move away from PoW systems, taking a step towards reducing both electricity consumption and e-waste.

When evaluating the environmental impact of our financial systems, it's important to consider the feasibility of widespread cryptocurrency adoption within the PoW block formation model. Bitcoin, for instance, is primarily utilized for speculative investment purposes and, while it can be used for payments and ATM withdrawals, several limitations make these use cases uncommon. One of the most significant constraints is the speed of transactions, with only 3 to 4 transactions per second possible on the Bitcoin network. In contrast, VISA can handle up to 56,000 transactions per second, making it a more practical option for high-volume transactions in real-world settings.

Generating cryptocurrencies can be a lucrative business model for states, as it enables them to sell electricity at a higher value. Nonetheless, it's important to note that the state's control over the flow of these funds is a major concern. Bitcoin gained from mining cannot be registered by the state because it is converted on a crypto exchange that can be located anywhere globally. The actual money earned from this transaction can be sent to any destination. Investing in mining facilities and renting them out can offer a steady source of income to both individuals and states, which can be taxed. However, from a global standpoint, this type of non-renewable resource consumption and significant air pollution pose a problem for future generations.

Finally, green energy certificates in blockchain, while promoting renewable energy, relate to the environmental impact:

- **Positive Environmental Impact**:
  - **Chain Footprint Reduction**: Blockchain projects can offset their carbon footprint by purchasing green energy certificates, supporting renewable energy, and reducing greenhouse gas emissions.
  - **Promotion of Renewable Energy**: Green energy certificates boost demand for renewable energy, leading to increased investment in sustainable energy infrastructure and accelerating the shift towards a cleaner and more sustainable energy grid.
  - **Encouraging Sustainable Practices**: Green energy certificates show blockchain's commitment to the environment, improving its reputation and encouraging other sectors to do the same.
- **Considerations and Criticisms:**
  - **Physical Energy Mix**: Green energy certificates may have limited impact if the energy mix in the host region is still non-renewable, reducing the actual carbon emission reduction at the source.
  - **Need for Holistic Approaches**: Green energy certificates alone are not enough. On-site renewable energy generation, energy efficiency improvements, and responsible waste management should be combined for an effective sustainable approach in blockchain projects.
  - **Ensuring Additionality:** Green energy certificates should ensure the additionality of renewable energy projects, creating new capacity instead of just redistributing existing renewable energy.
- **Transparency and Reporting:**
  - **Transparent Reporting**: Green energy certificates promote transparency in environmental reporting. Blockchain projects can demonstrate their commitment to renewable energy through transparent documentation of certificate purchases.
  - **Stakeholder Communication**: Clear communication of green energy certificates can boost environmental credibility and foster trust.

In summary, the use of green energy certificates in blockchain has a positive environmental impact by supporting renewable energy and reducing carbon footprints. However, it is essential for blockchain projects to adopt a comprehensive and transparent approach, considering the physical energy mix, ensuring additionality, and communicating their sustainability efforts effectively.

REFERENCES

[1] S. Nakamoto, "Bitcoin: A Peer-to-Peer Electronic Cash System", 2008. [Online]. Available: www.bitcoin.org.

[2] M. Peck, "Blockchains: How They Work and Why They'll Change the World," *IEEE Spectrum*, vol. 54, no. 10, pp. 26–35, 2017.

[3] M. Peck and S. Moore, "The Blossoming of the Blockchain", *IEEE Spectrum*, vol. 54, no. 10, pp. 24–25, 2017.

[4] S. Vujičić, M. Cogoljević and Z. Nikitović, "The Development of Ecological Awareness in the Republic of Serbia", *Int. Rev.*, vol. 2022, no. 1-2, pp. 51–59, 2022.

[5] K. O'Dwyer and J. Malone, "Bitcoin Mining and its Energy Footprint", In Proceedings of the 25th IET conference 2014, Limerick, 2014, pp. 36–27.

[6] "Cryptocurrency Prices, Charts and Market Capitalizations", June 2023. [Online]. Available: www.coinmarketcap.com.

[7] "Number of cryptocurrencies 2013-2023", June 2023. [Online].

[8] B. Siddika, M. Amaya and T. Marstonl, "The water and carbon footprint of cryptocurrencies and conventional currencies", *J. Clean. Prod.*, p. 137268, vol. 411, July 2023.

[9] Z. Zheng, S. Xie, H. Dai, X. Chen and H. Wang, "An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends", In Proceedings of the 6th IEEE International Congress on Big Data, June 2017, pp. 557–564.

[10] C. Stoll, L. Klaaßen and U. Gallersdo, "The Carbon Footprint of Bitcoin", *Joule*, vol. 3, no. 7, pp. 1647–1661, June 2023.

[11] S. Küfeoğlu and M. Özkuran, "Bitcoin mining: A global review of energy and power demand", *Energy Res. Soc. Sci.*, vol. 58, p. 101273, Dec. 2019.

[12] A. De Vries and C. Stoll, "Bitcoin's growing e-waste problem", *Resour. Conserv. Recycl.*, vol. 175, p. 105901, Dec. 2021.

[13] L. Meihui, M. Khokhar, I. Patra, "Ecological Supply Chain: Tools For Evaluating E-Waste – World Perspective", *Prob. Sustain. Dev.*, vol. 18, no. 2, pp. 167–182, 2023.

[14] B. Chez, "Today's Cryptocurrency Prices by Market Cap", July 2023. [Online]. Available: https://coinmarketcap.com/

[15] D. F. Kudriakov and M. V. Chernyaev, "The role of blockchain technology in improving the efficiency of fuel & energy companies", *Int. Rev.*, vol. 1–2, pp. 87–95, 2022.

[16] V. Buterin, "Next Generation Smart Contract & Decentralized Application Platform (White Paper)," 2014. [Online]. Available: http://www.theblockchain.com/docs/Ethereum_white_papera_next_generation_smart_contract_and_decentralized_application_platformvitalik-buterin.pdf.

[17] A. De Vries, "Cryptocurrencies on the road to sustainability: Ethereum paving the way for Bitcoin, Patterns 4," Jan. 2023. [Online]. Available: https://www.cell.com/patterns/fulltext/S2666-3899(22)00265-3 (22.06.2023). [Accessed 22 June 2023].

[18] Z. Zheng and X. Shaoan, "Blockchain challenges and opportunities: a survey", *Int. J. Web and Grid Services*, vol. 14, no. 4, p. 352, 2018.

[19] M. Niranjanamurthy, B. Nithya and S. Jagannatha, "Analysis of Blockchain technology: pros, cons and SWOT", *Cluster Comput.*, vol. 22, pp. 14743–14757, 2019.

[20] M. Fernández-Caramést and P. Fraga-Lamas, "Review on the Use of Blockchain for the IoT", *IEEE Access*, vol. 6, pp. 32979-33001, 2018.

[21] "Cambridge Bitcoin Electricity Consumption Index," University of Cambridge, 1923. [Online]. Available: https://ccaf.io/cbnsi/cbeci. [Accessed 18 July 2023].

[22] [Online]. Available: www.blockchain.com/explorer/charts/pools.

[23] Digiconomist, "Bitcoin Electronic Waste Monitor", June 2023. [Online]. Available: https://digiconomist.net/bitcoin-electronic-waste-monitor/.

[24] Software Testing Help, "10 Best ASIC Miners For Mining Cryptocurrency in 2023," June 2023. [Online]. Available: www.softwaretestinghelp.com.

[25] T. J., "Bitcoin Mining Hashrate by Country", May 2023. [Online].

[26] K. Coutinho, P. Wongthongtham, B. Abu-Salih, M. A. Abu Saleh, N. K. Khairwal, "Carbon emission and cost of blockchain mining in a case of peer-to-peer energy trading," *Frontiers in Built Environment*, vol. 8, pp. 1-13, Sept. 2022.

[27] "Global E-Waste - Statistics & Facts," July 2023. [Online]. Available: https://www.statista.com/topics/3409/electronic-waste-worldwide/.

[28] F. A., "What is Koomey's Law and why could it replace Moore's Law in importance among chip makers?", June 2023 [Online].

[29] [Online]. Available: https://www.statista.com/statistics/881541/bitcoin-energy-consumption-transaction-comparison-visa/.

[30] "A100", 2023. [Online]. Available: https://www.nvidia.com/en-us/data-center/a100/.