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Green blockchain – A move towards sustainability

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ABSTRACT

In recent years, blockchain technology has seen significant growth and widespread adoption in various industries. However, one major drawback of blockchain investments is their substantial energy consumption, which has negative impacts on both the economy and the environment. The main cause of concern is the generation of atmospheric carbon emissions resulting from excessive energy usage. This research study aims to identify blockchain networks and systems that assert themselves as environmentally friendly and determine which of them produces the least amount of carbon emissions, such as Cardano, Tezos, and Bitgreen. This has been accomplished by following a comprehensive hybrid literature review. Our study has identified 23 blockchain networks that consume significantly less power and release fewer carbon dioxide emissions compared to the Bitcoin network. Some of these environmentally friendly networks include Algorand, Fantom, MobileCoin, and Electroneum. Additionally, we have found various projects and organizations that support greener blockchain initiatives, such as the Renewable Energy Certificate Mechanism, Green Digital Finance Alliance, GreenTrust, and the Energy Web Foundation. While several projects in this area have been recognized and examined, comprehensive research and analysis are still needed to provide empirical evidence regarding the power consumption and carbon dioxide emissions of these claimed environmentally friendly blockchains. This is due to the relatively early stage of development in this field.

1. Introduction

Blockchain (BC) is a revolutionary technology that has brought about significant disruptions across various industries, including banking, finance, automotive, healthcare, and more. Its impact is far-reaching, with estimates suggesting substantial growth from $11.54 billion in 2022 to a projected $162.84 billion by 2027 (Statista, 2022). BC technology has the potential to revolutionize global trade and transactions. However, the process of cryptocurrency mining, which involves verifying transactions on a BC network, requires substantial computational power and electricity consumption (Escobar et al., 2022). Unfortunately, a significant portion of the world's electricity is derived from non-renewable sources such as natural gas and coal, leading to a considerable carbon footprint associated with BC's energy consumption (BCI, 2023).

Between 2018 and 2022, the annual electricity consumption attributed to global cryptocurrency mining experienced substantial growth, with estimates indicating a doubling to a quadrupling of usage. As of August 2022, published estimates place the total global electricity consumption for cryptocurrencies between 120 and 240 billion kilowatt-hours per year (WhiteHouse, 2022). This range surpasses the annual electricity consumption of several individual countries like Argentina or Australia. It constitutes approximately 0.4%–0.9% of the world's yearly power usage, which is comparable to the combined electricity consumption of all conventional data centers worldwide (WhiteHouse, 2022).

The combined global electricity generation attributed to cryptocurrency mining with the highest market capitalizations leads to an approximate annual emission of 140 $\pm$ 30 million metric tons of CO2. This accounts for approximately 0.3% of the world's annual CO2 emissions. In the USA, cryptocurrency mining is estimated to result in emissions ranging from 25 to 50 Megatons of CO2 per year, equivalent to 0.4%–0.8% of the country's total CO2 emissions. These emission levels are similar to those produced by diesel fuel consumption in U.S. railroads (WhiteHouse, 2022).

The notion of green BC has garnered significant attention in recent years, driven by apprehensions about the environmental consequences associated with cryptocurrency mining and BC-based systems. Green BC

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entails the utilization of BC technology in an environmentally sustainable manner, prioritizing the reduction of carbon emissions and energy consumption (Oudani et al., 2023). In recent times, there has been a surge in the establishment of green BC initiatives. These initiatives operate within the broader BC ecosystem, which encompasses a comprehensive network of technologies, companies, organizations, and individuals engaged in the development, deployment, and utilization of BC-based solutions. The BC ecosystem represents a collaborative environment where various stakeholders work together to advance the adoption and application of BC technology in diverse sectors (Qian et al., 2022). Green BC initiative's goal is to advocate for the adoption of sustainable energy alternatives and to minimize the adverse effects associated with cryptocurrency mining and BC operations (Varavallo et al., 2022).

According to the previous studies, there are not enough categorizations in the literature, to address the question of how BC might promote sustainability (e.g. (Massaro et al., 2020; Calandra et al., 2023),). In (Massaro et al., 2020), the study's findings strongly emphasize sustainable production, efficient energy management, and climate change. The primary use of BC concerning sustainability is to lower supply chain costs (Calandra et al., 2023). Similarly, (Parmentola et al., 2022) conducted a systematic literature review to look into how BC technology is thought to be able to influence sustainability. Their findings showed that BC technology may promote environmental sustainability by enhancing energy efficiency, encouraging the development of safe and dependable smart cities, and aiding the realization of a sustainable supply chain (Parmentola et al., 2022). Accordingly, this study aims to conduct an analysis and provide a summary of these initiatives, examining their efforts to promote the use of renewable energy sources and mitigate the environmental impact associated with BC technology. This study answers the following research questions.

RQ1. Which cryptocurrencies with green BC technology have emerged?

RQ2. What are the initiatives that have been established to promote green BC technology?

This paper envision a valuable contribution by offering an analysis and summary of the major endeavors undertaken to establish sustainability in the BC industry. It refers to these initiatives as solutions or techniques aimed at achieving green BC. While various areas within the BC ecosystem, such as decentralized finance, non-fungible tokens (NFTs), and supply chain management, have proposed measures to achieve a sustainable BC environment, this paper specifically focuses on green BC initiatives. It serves as an early effort to provide insights into these initiatives. The rest of the paper is organized as follows. Section 2 and Section 3 discuss the research background and the reasons for the urgent need for green BC, respectively. Section 4 presents the research method applied in this study. Section 5 provides an analysis proposed initiative. Section 6 discusses the findings of the paper and Section 7 provides future research directions and concludes the paper.

2. Background

Many cryptographic networks utilize BC technology to facilitate various transactions (Alzoubi et al., 2022a). Although the number of cryptographic networks is rapidly expanding, we will narrow our focus to the two prominent networks, Bitcoin and Ethereum, in this particular section in order to effectively introduce the research problem at hand.

2.1. BC concept

Transactions within a BC network are cryptographic instructions signed by network participants, which aim to modify the state of the network. In the case of Bitcoin, a basic transaction involves transferring cryptographic value, commonly referred to as coins, from one account to another. A BC can be defined as a sequential series of blocks. Each block consists of different data, including the creation date and other essential information required for the creation and execution of transactions. These blocks are interconnected, forming a chain-like structure, commonly known as the BC (White-Case, 2022). Bitcoin, as a digital asset lacking intrinsic value and operating without a central authority or issuer, is considered revolutionary in the evolution of fiat currencies. It served as the foundation for BC technology and paved the way for the emergence of other cryptocurrencies. Consequently, when discussing implementations beyond Bitcoin, many individuals opt to use the broader term "distributed ledger technologies" to encompass various BC applications and platforms (UNCTAD, 2021).

BC implementations exhibit variations, notably in terms of network management and permissions, resulting in two fundamental categories: public BCs and private BCs. A public BC, also known as a permissionless BC, allows anyone to access and view all transactions taking place on the network. Additionally, anyone can participate in the network and contribute to maintaining the ledger. Bitcoin serves as an example of a public BC. In contrast, a private BC also referred to as a permissioned BC, imposes restrictions on both information access and network maintenance, limiting them to a selected group of known participants. Private ledger technology finds application in enterprise use cases where immutable transactions are required and can be verified by only a few designated nodes (UNCTAD, 2021). In second-generation BCs (BC 2.0), the ledger is capable of recording computer code. This means that, in addition to registering payment transactions, BCs can also store and execute "smart contracts" automatically when certain pre-defined conditions are fulfilled. Smart contracts are code-based self-executing contracts that allow for the facilitation, verification, or enforcement of a contract's provisions. They eliminate the need for intermediaries and enable the trustless and decentralized execution of agreements. BC 2.0 platforms allow for the inclusion and execution of smart contracts, enhancing the capabilities and functionality of BC technology (Alzoubi et al., 2022b).

In terms of market value, Ethereum is the second-largest cryptocurrency platform, ranking just behind Bitcoin. Ether (ETH) is the cryptocurrency token that is generated as a reward for miners who perform computations to secure the Ethereum BC. The issuance of Ether as a reward for mining activities incentivizes miners to contribute their computational power and resources to secure the Ethereum network (UNCTAD, 2021). Our discussion primarily revolves around two prominent BC networks, namely Bitcoin and Ethereum, as they are the most widely recognized and utilized. It is worth noting that Bitcoin and Ethereum together account for over 60% of the total market capitalization of cryptocurrencies, highlighting their significance and impact within the cryptocurrency industry (WhiteHouse, 2022). Despite the widespread popularity of Bitcoin and Ethereum, these networks have encountered certain technical limitations that hinder their widespread application within Industry 4.0. One of the key challenges is the issue of high-power consumption as well as high transaction fees, and scalability. In this paper, we will focus only on the power consumption that results in high CO2 emission.

2.2. Cryptocurrency minning

In a BC network, miners are users who add new blocks to the chain. To link a new block to the BC, miners must solve a mathematical puzzle (Alzoubi et al., 2021). This process, known as mining, requires powerful computing and consumes a lot of energy. Miners compete to solve the puzzle, and the first one to find a solution can add the next block. Validation in BC is based on consensus, where everyone in the network has the same information and accepts it as accurate (Gail, 2022). Due to the high computational requirements, cryptocurrency mining consumes significant energy and emits a big amount of CO2 (Iberdrola, 2023). Consensus mechanisms play a critical role in powering the mining and validation of cryptocurrencies in distributed ledger technology systems. One of the most well-known consensus mechanisms used in BC networks is Proof of Work (PoW), which is employed by Bitcoin and the initial version of Ethereum (Alzoubi et al., 2022c) to conduct the mining process (Alzoubi and Aljaafreh, 2023).

As of August 2022, it was estimated that Bitcoin consumes a significant portion of the total global electricity usage related to cryptocurrencies, ranging from 60% to 77%. Ethereum was estimated to account for approximately 20%–39% of the total electricity usage related to cryptocurrencies (WhiteHouse, 2022). In October 2022, Ethereum switched to the Proof of Stake (PoS) consensus method because of excessive power consumption of PoW. Fig. 1 depicts the energy costs and CO2 emissions of Bitcoin and Ethereum when they were both utilizing PoW, as well as the energy consumption and CO2 emissions of Bitcoin and Ethereum, before and after switching to PoS. This comparison shows the significant decrease in power consumption after Ethereum switched to PoS and it also shows the huge amount of power required to min using the PoW-based Bitcoin network.

Fig. 1 illustrates the annual energy consumption of Bitcoin alone, which according to studies uses more than 140 TWh. This is equivalent to Switzerland using twice as much power annually. In particular, an enormous rise in energy usage has been seen in Ethereum (UNCTAD, 2021). Increasing the number of miners could speed up block addition and improve mining productivity. However, PoW has faced criticism, particularly regarding global warming, leading to calls for change and alternative consensus mechanisms (TheTimes).

In the PoS consensus mechanism, validators take on the responsibility of adding blocks to the BC instead of miners. This approach introduces a different method for block addition. PoS utilizes an algorithm to select the validator who will be responsible for adding the next block to the BC. To participate as a validator in a PoS network, individuals must stake a specific number of coins on the network. These staked tokens serve as a deposit and determine the validator's eligibility. The PoS algorithm then randomly chooses the next validator from the pool of deposited tokens. This means that every token staked on the network represents a potential candidate for selection. Consequently, as the number of stakes increases, the probability of being chosen for block validation also increases (PcW-Australia, 2022). The PoS mechanism offers benefits such as reduced computer processing power requirements, resulting in lower power consumptions and CO2 emissions, compared to the PoW process (White-Case, 2022).

2.3. The need for green BC

In response to concerns about the environmental impact of traditional digital currencies, efforts have been made to create alternative models that prioritize low environmental effects. These alternative cryptocurrencies are often referred to as "green cryptocurrencies." Green cryptocurrencies aim to reduce the carbon footprint associated with the mining and validation processes of digital currencies (White--Case, 2022). These techniques should optimize performance, reduce energy consumption, and address environmental concerns. The future of the BC industry is increasingly influenced by sustainability considerations. The ongoing research and innovation in the industry aim to create more sustainable and efficient cryptographic solutions, which will contribute to the growth and adoption of BC-based cryptocurrencies while aligning with environmental goals (Casper, 2023).

The growing energy consumption of cryptocurrencies has attracted significant media attention, particularly following Tesla CEO Elon Musk's announcement in May 2021. Musk announced that Tesla will stop accepting Bitcoin as payment owing to issues with the environment related to its energy use. This decision brought further awareness to the issue and sparked discussions about the sustainability of cryptocurrencies (Iberdrola, 2023). Additionally, research conducted by institutions such as the Judge Business School at Cambridge University has also confirmed the increasing energy consumption of cryptocurrencies. These studies have provided empirical evidence and data to support the concerns raised regarding the environmental impact of cryptocurrencies, further contributing to the ongoing dialogue surrounding their sustainability.

Because many computing or mining facilities conceal their locations and won't record their electricity usage, it is impossible to directly track the overall power consumption of today's cryptocurrency networks. However, analytical estimations of electricity use are possible (BCI, 2023). Cryptocurrency mining operations have high load factors as they consume electricity continuously, stressing the electricity system during peak hours. This can lead to equipment lifespan reduction, blackouts for other customers, and an increased fire risk (Bitgreen, 2023). The increased demand for electricity caused by cryptocurrency mining can lead to higher power rates for local customers. Additionally, if mining activities migrate to other locations due to changing conditions or regulations, the local consumers may still end up bearing the costs. This could include the expense of unpaid infrastructure upgrades required to support mining operations in the area (WhiteHouse, 2022). The path to a more sustainable and environmentally friendly future for the BC sector and the planet as a whole requires understanding and backing green BC projects. It is crucial to be aware of green BC initiatives and efforts for the following reasons (PcW-Australia, 2022; Bada et al., 2021; Liu et al., 2021):

- Traditional BC networks, particularly those built on the PoW algorithm, have come under fire for their excessive energy usage and CO2 emissions. Alternatives that are in line with the increasing concern for environmental sustainability are provided by green BC initiatives.
- Adopting green BC solutions may show a commitment to corporate social responsibility and sustainability as environmental awareness grows in importance for both customers and enterprises.
- Governments and regulatory bodies may impose stricter environmental regulations on BC networks. By being aware of and supporting green BC initiatives, businesses and individuals can stay ahead of potential regulatory changes.

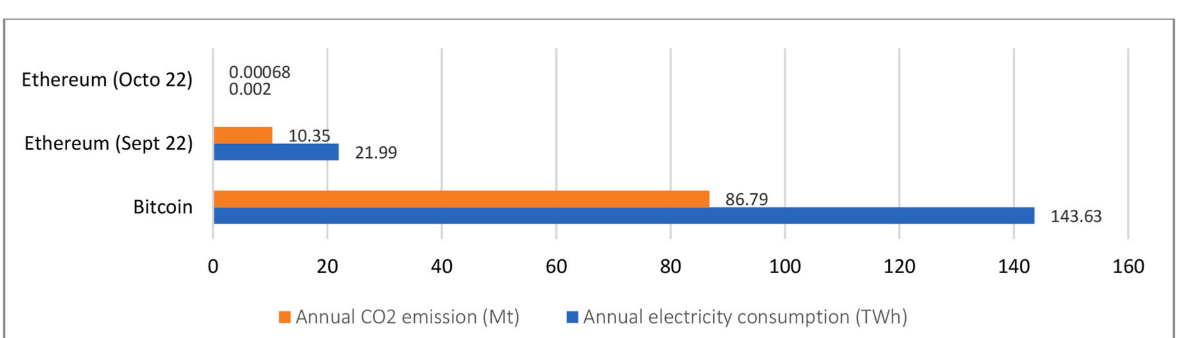

Fig. 1. Annual electricity and CO_2 emission for Ethereum and Bitcoin (based on (CCRI, 2023)).

- Eco-friendly BC solutions and research into energy-efficient consensus algorithms are driven by green BC efforts. The BC industry as a whole may experience more acceptance and improved productivity as a result of these advancements.
- Supporting green initiatives can enhance a company's reputation and attract environmentally-conscious customers, investors, and partners.

Green BC technology has the potential to be more useful in a variety of contexts (Nygaard and Silkoset, 2023). Green BC is in line with eco-friendly methods, making it extremely applicable in industries where sustainability and lowering carbon footprints are crucial (Varavallo et al., 2022). This includes the use of renewable energy, agriculture, and forestry, all of which need tracking and confirming environmentally acceptable operations (Bao et al., 2023). Moreover, green BC can be extremely helpful in the energy industry due to its energy-efficient design. It may facilitate sustainable energy projects, manage networks more effectively, and improve energy distribution (Bao et al., 2023). Furthermore, green BC improves traceability and transparency, which makes it a good option for supply chain management (Mohamed et al., 2023). This is especially important in sectors like food and medicines where it's important to confirm the legitimacy and caliber of the items. Additionally, in the financial industry, green BC may simplify transactions, eliminate middlemen, and consume less energy, resulting in cost savings and environmental sustainability (Qin et al., 2023). Another area that may benefit from green BC is climate change mitigation by facilitating carbon credit trading, tracking emissions, and incentivizing eco-friendly practices (Polas et al., 2022). Finally, green BC can provide efficient and secure data exchange across several systems, from energy management to transportation (Bao et al., 2023).

3. Research method

According to (Massaro et al., 2017), a structured literature review needs to follow a logical framework. Since they have a focus and insights on what writers write, literature evaluations help clarify how knowledge debate develops (Secinaro et al., 2022). Structured review can offer particular sets of questions about the organization of knowledge and the historical evolution of the subject that may aid researchers in formulating creative approaches. Accordingly, this study follows the outlines provided by (Massaro et al., 2017) to obtain answers to RQ1 and RQ2. We searched across leading publishers' databases such as Elsevier, IEEE, Emerald, Springer, Taylor, Google Scholar, and MDPI to identify research on the topic of green BC. Our search strategy employed a combination of "AND" and "OR" logical operators to identify articles related to green BC. Specifically, we used the query "(green BC OR green blockchain) AND (sustainability OR power OR energy OR eco-friendly)" to perform our search, as described in (Alzoubi et al., 2016).

However, we found these databases limited existing research in this area. To supplement the literature review, we also explored industrial websites, practitioner blogs, and professional reports to gather information. As the paper's focus is on current and future initiatives and projects related to green BC, which are still being investigated by governments and agencies, the majority of the findings are based on information obtained from industrial and professional websites. According to (Paul and Criado, 2020), our approach can be characterized as a hybrid review method, which incorporates a minimum of two distinct approaches.

4. Findings

This section discusses green BC cryptocurrencies, as well as other projects and initiatives that support the concept of green BC. It is worth noting that the discussion in the following sections primarily revolves around power consumption and CO2 emissions, as these are the specific areas of focus in the paper. The 23 green BCs, identified in this paper, are included in Table 1 along with a comparison of their annual power usage, annual CO2 emissions, and power needed for each transaction.

4.1. Green BC cryptocurrencies

This section provides a response to RQ1. Various green BC cryptocurrencies have been proposed as alternatives to PoW-based systems. These cryptocurrencies are designed to reduce the environmental impact associated with traditional PoW systems. They strive to be more sustainable and inflict less damage on the planet. Notably, these green BC cryptocurrencies appear to be highly efficient when it comes to their energy requirements, making them more environmentally friendly compared to PoW-based cryptocurrencies. This section discusses these solutions. The 23 green BC are included in Table 2 along with a comparison of each BC's possible advantages and disadvantages.

4.1.1. Cardano

Cardano, founded by Charles Hoskinson, a co-founder of Ethereum, has its primary purpose to serve as a digital coin or cryptocurrency. Hoskinson claims that Cardano consumes 1.6 million times less energy than Bitcoin. This achievement is attributed to Cardano's use of the PoS consensus mechanism, which eliminates the energy-intensive mining process associated with Bitcoin. Cardano aims at net-zero CO2 emissions while still providing investors with profitable opportunities. To make Cardano as environmentally friendly as possible, the company maintains a designated "Group Head of Sustainability" who collaborates with experts in the field. Cardano can reach 1000 Transaction Per Second (TPS), uses 0.05159 kilo-Watt-hour (kWh) of energy per transaction, and the entire network only uses 0.6 Giga-watt-hour (GWh) of energy per year, emitting around 290 tons of CO2 (CCRI, 2023). Cardano and Ethereum have several similarities, however, the former lacks a lot of the latter's token's bloat. This enables Cardano to grow up without sacrificing speed or efficiency in order to fulfill the rising demand for the coin (Matthews et al., 2023).

4.1.2. Tezos (Tez)

One of the first PoS-based smart contract-based BCs that is self-upgradable and scalable is Tezos. It is a noteworthy piece of cryptocurrency technology that has a reputation for openness and creativity. The ticker symbol for the Tezos BC is XTZ, and it uses the cryptocurrency "Tez" for operations (Matthews et al., 2023). With the help of Tezos' on-chain governance system, the network may continue to advance without having to undergo a hard fork. As a result, network users may effectively suggest, vote on, accept, and implement enhancements. The French financial institution "Societe Generale" and several businesses, including Red Bull, Honda, and McLaren Racing, are all adopting Tezos (Matthews et al., 2023). Tezos works with smart contracts, much similar to Ethereum. However, it distinguishes itself by being as decentralized as possible, enabling owners of XTZ to submit recommendations and decide whether to implement updates (Brooke, 2022). An estimated 128 MWh of energy is utilized yearly by Tezos validators, resulting in emissions of 53.79 tons of CO2 (CCRI, 2023). Tezos can process 52 TPS. It achieves this transaction throughput while consuming approximately 41 Wh of energy (Tezos, 2023).

4.1.3. Chia (XCH)

Chia (XCH) is a cryptocurrency that can be mined utilizing Amazon Web Services cloud infrastructure. Setting up chia "farming" is quick and easy, and it is less complex compared to mining other currencies. Chia serves as a platform for BC and smart transactions, allowing participants to utilize their unused hard drive space for a distributed network. Chia Network employs the Proof-of-Space-Time (PoST) consensus mechanism. Developed in 2017, Chia aims to address the issue of high energy consumption in cryptocurrency mining (Matthews et al., 2023). According to TRG Datacenters, Chia is a sustainable

Table 1
Summary of green BC characteristics.

Cryptocurrency	Power consumption/Year (MWh)	CO2 emission/Year (t)	Power (Wh/Tx)	Consensus	Website
Cardano	631.91	290.04	51.59	PoS	https://cardano.org/
Tezos	128.94	53.79	41.45	PoS	https://tezos.com/
Chia	190,000	_	23	PoST	https://www.chia.net/
Polkadot	70.25	32.24	17.42	PoS	https://polkadot.network/
Ripple	474	400	7.9	XRP	https://ripple.com/
Ethereum	2045.68	684.12	6.294	PoS	https://ethereum.org/en/
Flow	715	_	6.03	PoS	https://flow.com/
Avalanche	718.15	268.11	4.76	PoS	www.avax.network/
Bitgreen	86,178	_	1.21	zk-SNARK	https://bitgreen.org/
Hedera	_	_	0.17	Hashgraph	https://hedera.com/
Solana	3012.97	1382.96	0.51	PoH, PoS	https://solana.com/
IOTA	6000	_	0.111	Tangle	www.iota.org/
Nano	_	_	0.111	Lattice	https://nano.org/
Polygon	107.18	49.2	0.103	PoS	https://polygon.technology/
Tron	162,867.85	69.47	0.07	DPoS	https://tron.network/
Stellar	481	173	0.22	FBA	https://stellar.org/
Algorand	4160.83	1909.82	0.008	PoS	https://algorand.com/
Fantom	8.2	_	0.000028	Lachesis	https://fantom.foundation/
MobileCoin	_	_	≈0	FBA	https://mobilecoin.com/
Electroneum	_	_	≈0	PoR	https://electroneum.com/
Near Protocol	_	174	_	PoS	https://near.org/
XDC	7.4446	_	_	XDPoS	https://xdc.org/
Mina	_	_	_	PoS	https://minaprotocol.com/

cryptocurrency token that has been built to be less energy-intensive. Chia Network asserts that it consumes 0.12% (or 0.172 TWh) of the yearly energy required by the Bitcoin system. Nevertheless, as of 2022, it is estimated that Chia Network has consumed 0.19 TWh (Brooke, 2022). Moreover, some detractors continue to assert that Chia isn't as environmentally benign as it promises since it has contributed to a sharp increase in demand for computer equipment and rising quantities of e-waste.

4.1.4. Polkadot (DOT)

A framework for connecting BCs that enables expansion and interconnection across chains by joining many BCs into only one network (Polkadot, 2023). In Polkadot's selected PoS-based mechanism, validators have the ability to stake tokens on behalf of other users. With Polkadot, individuals holding the DOT token can entrust it to validators, effectively "locking up" their currency. By doing so, they can earn rewards or interest in the BC network. This staking process allows users to potentially gain additional tokens or obtain voting privileges within the ecosystem. Compared to Bitcoin, Polkadot promises to use less energy throughout each transaction. According to CCRI investigation, the Polkadot system utilized around 70.25 MWh in 2022 and released 32.24 CO2 into the atmosphere (CCRI, 2023).

4.1.5. Ripple (XRP)

Ripple incorporates certain design features of Bitcoin, enabling users to transfer and receive cryptocurrency using public and private key encryption, similar to Bitcoin. However, unlike Bitcoin, Ripple does not require mining or specialized equipment to secure its ledger and validate transactions. Instead, servers transmit transactions to the network for review. Consensus on the authenticity of transactions is achieved through verification by "unique nodes," which are permissioned servers maintaining a "unique node list." If at least 80% of users accept a transaction based on software rules (Investopedia, 2023). Ripple coin consumes approximately 474 MWh of electricity and emits around 400 tons of CO2, with each transaction utilizing 7.9 Wh (Investopedia, 2023).

4.1.6. Ethereum (ETH)

Ethereum serves as a globally distributed platform based on BC technology. Its primary association lies with Ether (ETH), a cryptocurrency native to the platform. Ethereum offers individuals the opportunity to create secure digital technologies of their choosing (Ethereum, 2023). While a token is available to compensate contributors for their work on the BC, it can also be utilized, upon approval, to purchase tangible goods and services. Smart contracts, an integral aspect of decentralized applications, are inherently supported within Ethereum. Before the transition to a PoS consensus mechanism in 2022, the Ethereum network operated on a PoW system, which demanded substantial energy consumption to ensure security and decentralization. During this period, Ethereum's annual energy consumption ranged from 21.99 TWh to 0.002 TWh, resulting in a reduction in CO2 emissions from 10.35 Megatons to 0.00068 Megatons. However, following the Merge to PoS, Ethereum aims to achieve a more energy-efficient and environmentally friendly approach to maintaining network security and consensus (CCRI, 2023). Also reduced from 2.51 GWh to merely 0.23 MWh was the amount of energy needed for each ETH transaction (CCRI, 2023).

4.1.7. Flow (FLOW)

Flow is a PoS BC designed specifically for developing internet-scale protocols and applications that demand high throughput and low latency. In the Flow network, the tasks of mining and data verification are divided into four distinct processes. This division enhances accessibility and efficiency as anyone with a stable internet connection can participate in the Flow validator program (Matthews et al., 2023). Flow enables individuals with minimal or no computational power to participate in the less energy-intensive aspects of a transaction, promoting inclusivity. Flow claims to be over 200,000 times more efficient than Bitcoin, with an annual consumption of 715 MWh. It is anticipated that Flow will utilize only around 6.03 Wh per transaction or approximately 180 MWh per year for the entire network (Matthews et al., 2023).

4.1.8. Avalanche (AVAX)

Avax serves as the native cryptocurrency of the Avalanche smart contract platform, which operates on a PoS algorithm. One of the key features of Avalanche is its ability to deploy customized private or public BCs known as subnets. These subnets can support up to 4500 TPS. Transactions undergo verification by multiple small, randomly selected subsets of network users. Only when these subsets collectively validate the transactions are they considered final (Matthews et al., 2023). In the Avalanche network, validators for new blocks are more likely to be selected from the most invested AVAX holders. Holding AVAX tokens is also a requirement for voting on Avalanche governance proposals. Avalanche has been recognized as one of the BC networks with excellent

Table 2
Summary of green BC advantages and limitations.

Cryptocurrency	Advantage	Limitations
Cardano	• Focused on sustainability. • High scalability.	• Slower development progress compared to some competitors.
Tezos	• Self-amendment feature. • Strong governance model. • Smart contract capabilities.	• Limited adoption compared to more established platforms.
Chia	• Energy-efficient consensus. • Eco-friendly.	• Still in the early stages of development.
Polkadot	• Interoperability. • Strong team and community.	• Complex ecosystem. • Potential centralization concerns.
Ripple	• Strong financial industry partnerships.	• Legal and regulatory challenges. • Centralized control
Ethereum	• Smart contract pioneer. • Large developer community. • Decentralized applications (DApps).	• scalability issues.
Flow	• User-friendly. • Developer-focused.	• Relatively new and less well-known.
Avalanche	• Highly scalable. • Robust security.	• Still gaining traction. • Competition from established networks.
Bitgreen	• Environmentally friendly. • Focuses on sustainability solutions.	• Limited adoption and less widely known.
Hedera	• Fast and low-cost transactions. • Strong governance.	• Less decentralized than some other BCs.
Solana	• High throughput. • Low fees.	• Recent network stability issues. • Centralization concerns.
IOTA	• Feeless transactions. • Focus on IoT applications.	• Security concerns.
Nano	• Instant transactions. • Feeless and scalability.	• Limited adoption.
Polygon	• Scalability solution for Ethereum. • Strong DeFi presence.	• Still closely tied to Ethereum's success and limitations.
Tron	• High throughput. • Large user base.	• Centralization concerns. • Past controversies.
Stellar	• Fast and low-cost cross-border transactions.	• Competition with other cross-border payment solutions.
Algorand	• High scalability and energy-efficient. • Strong developer support.	• Growing competition in the smart contract platform space.
Fantom	• High throughput and low fees. • Support DeFi ecosystem.	• Still relatively new and evolving.
MobileCoin	• Focus on privacy and security. • User-friendly.	• Limited adoption and use cases.
Electroneum	• Mobile-focused. • User-friendly.	• Limited adoption and recognition.
Near Protocol	• Developer-friendly. • Focus on user adoption.	• Competition in the smart contract platform space.
XDC	• Fast and secure transactions. • Focus on enterprise solutions.	• Limited mainstream recognition.
Mina	• Lightweight and scalability. • Privacy features.	• Still in the early stages of development and adoption.

energy efficiency in 2022. According to a CCRI investigation, the Avalanche network consumed approximately 718.15 MWh of energy annually. This amount represents a mere fraction, approximately 0.0005%, of the energy consumed by the Bitcoin network (CCRI, 2023).

4.1.9. Bitgreen (BITG)

BitGreen is a BC project that utilizes the zk-SNARK (Zero-Knowledge Succinct Non-Interactive Argument of Knowledge) consensus technique. This technique enables the proof of ownership of specific information, such as a secret key, without revealing the actual information or necessitating communication between the prover and verifier. BitGreen also leverages the Substrate Software Development Kit (SDK), which empowers developers to create customized BCs tailored to specific applications. This flexibility allows for the creation of BC solutions designed for specific use cases (Bitgreen, 2023). One of BitGreen's main objectives is to encourage environmentally friendly behavior. It achieves this by incentivizing users through rewards for engaging in sustainable actions such as consuming ethically sourced coffee, utilizing public transportation, and participating in volunteering activities. In terms of energy consumption, BitGreen aims to be a greener alternative to Bitcoin, utilizing only 0.06% of Bitcoin's current yearly usage, which amounts to 86,178 MWh. Additionally, each transaction on the BitGreen network consumes a minimal amount of energy, approximately 1.21 Wh per BITG transaction (Bitgreen, 2023).

4.1.10. Hedera (HBAR)

The infrastructure of Hedera Hashgraph is highly energy-efficient compared to the Bitcoin BC, with a remarkable efficiency ratio of 250,000 times. The native cryptocurrency of the Hedera platform utilizes a low energy consumption of just 0.001 kWh per transaction. This efficiency is achieved through the implementation of a PoS consensus algorithm (Mae, 2023). Hedera processes transactions concurrently rather than sequentially, resulting in faster transaction speeds. The Hedera Governing Council includes notable entities like Google, Boeing, Deutsche Telekom, LG, and others. To reduce its CO2 emissions, Hedera has formed a partnership with the Climate Neutral Group. Furthermore, Hedera Hashgraph has joined forces with Power Transition, a cloud-based software and hardware platform. This partnership enables the development of sustainable initiatives, including the provision of more efficient energy to households in the United Kingdom. Power Transition's platform facilitates peer-to-peer energy trading and microgrid management, promoting the adoption of renewable energy sources and optimizing energy usage (Mae, 2023).

4.1.11. Solana (SOL)

The architecture of Solana enables high scalability, as it has a theoretical maximum throughput of 28.4 million TPS on a 40-gigabit network, far surpassing the maximum throughput of 710,000 TPS on a regular gigabit network (Investopedia, 2023). Within the Solana ecosystem, on-chain transactions are resolved using SOL, the platform's native cryptocurrency (Gail, 2022). Both Proof-of-History (PoH) and PoS consensus mechanisms are used by Solana's BC. PoS enables validators to verify a transaction based on the number of coins or tokens they own, whereas PoH enables very rapid timestamped transaction verification. This enables the network to concentrate on verifying current transactions without having to consult nodes' prior temporal assertions. Nodes are required to follow predetermined transaction ordering, which promotes consistency (Gail, 2022). In terms of Solana's energy usage, each transaction requires around 0.51 Wh, while the total network's annual energy use is about 3012.97, resulting in roughly 1382.96 tons of CO2 emissions (Gail, 2022).

4.1.12. IOTA (MIOTA)

IOTA is a cryptocurrency that utilizes distributed ledger technology and introduces a unique consensus mechanism known as the Tangle. The Tangle is a patented technology and operates as a Directed Acyclic Graph (DAG) algorithm. The Tangle does not rely on blocks, validators, miners, or transaction fees. In the Tangle consensus method, users are required to validate two previous transactions before they can finalize their own IOTA transactions. This structure promotes a self-regulating network where transaction validation occurs through the cumulative efforts of all participants (Matthews et al., 2023). Because it eliminates the hassle of large transaction fees, which would call for human supervision and intervention—exactly what the IoT was intended to avoid—IOTA's structure is intriguing for application in the IoT ecosystem. IOTA's network can support up to 1000 TPS. IOTA network is said to utilize only 0.111 Wh per transaction and 6000 MWh of energy yearly (Gail, 2022).

4.1.13. Nano (XNO)

Nano is a cryptocurrency that stands out for its key attributes of being feeless, fast, and energy-efficient. It has been in existence since late 2015 and continues to maintain a small carbon footprint. Nano does not rely on mining, which contributes to its scalability and lightweight nature (Kriptomat, 2023). Nano employs a technology called block-lattice, which extends beyond the concept of a traditional BC. It utilizes an account chain for each user on the network. While Nano's block lattice technology is energy-efficient, it still relies on a PoW process for transaction verification (Kriptomat, 2023). Under the Open Representative Voting (ORV) process utilized by the Nano platform, account holders vote for their favorite representatives, who then attempt to securely validate blocks of transactions (Kriptomat, 2023). Nano can process up to 125 TPS using only the sender and receiver account chains. A single Nano transaction has been shown to use as little energy as 0.111Wh. Nano may be a good option for micropayments since users' elected representatives don't get paid for their involvement, enabling free transactions (Kriptomat, 2023).

4.1.14. Polygon (MATIC)

Polygon emerged as one of the top altcoins in 2021 due to its scalability solutions. Acting as a "Layer-2 BC," Polygon works in collaboration with Ethereum to enhance transaction speed and lower network expenses. By leveraging the PoS consensus mechanism, decentralized applications operating on Ethereum's BC can carry out their transactions on the Polygon network. The ability of Polygon to handle over 65,000 TPS gained significant popularity, especially during the rapid growth of NFTs (Brooke, 2022). For a single transaction within the Polygon, the estimated electricity usage is approximately 0.103 Wh. The yearly power consumption of the network is estimated to be around 107.18 MWh, which leads to approximately 49.2 tons of CO2 emissions (CCRI, 2023). Polygon's team has committed to providing $20 million in financing for various programs that utilize technology to address climate change. Additionally, they have pledged to allocate $400,000 toward the purchase of carbon credits. The objective is to gradually retire these credits, effectively "removing" CO2 from the environment. These initiatives demonstrate Polygon's commitment to supporting sustainable solutions and actively contributing to the fight against climate change (Brooke, 2022).

4.1.15. Tron (TRX)

Tron utilizes an account-based approach, allowing control over TRX and TRX token balances through cryptographic keys and protocol issues. The platform implements Delegated Proof of Stake (DPoS) as a consensus mechanism, in which a rotating group of 27 "super representatives" validate transactions and maintain the system's transaction history. Every 6 h, a new set of super representatives is chosen, granting them access to the newly generated TRX by the protocol. Additionally, every 3 s, blocks are appended to the BC, and participants who successfully create valid blocks receive a reward of 32 TRX (Gail, 2022). The entire TRON network consumes approximately 0.07028 Wh of energy per transaction, equivalent to approximately 162,867.85 KWh annually, resulting in an estimated emission of about 69.47 tons of CO2. On an individual node level, the power requirement is only 0.0001915 Wh for each transaction (CCRI, 2023).

4.1.16. Stellar lumens (XLM)

The Stellar network emerged as a separate entity from Ripple to bridge the divide between traditional financial institutions and digital currencies. Stellar is considered a genuine contender to PayPal because it allows both institutions and individuals to access the network without incurring any charges (Matthews et al., 2023). Notably, prominent entities such as IBM, Deloitte, and various banking institutions from India, France, Nigeria, and the Philippines have shown considerable interest in participating in the network (Iberdrola, 2023). The Stellar network stands out with its consensus mechanism, which is an open-source system relying on a limited number of trustworthy nodes instead of the entire network for transaction validation. This unique approach enables a shorter and faster authentication cycle, resulting in reduced costs and energy consumption. This consensus mechanism is known as Federated Byzantine Agreement (FBA) (Iberdrola, 2023). A single transaction using XLM is estimated to consume approximately 0.22 Wh of energy. On an annual basis, the Stellar network itself is estimated to consume around 481 MWh, resulting in an emission of approximately 173 tons of CO2 (Iberdrola, 2023).

4.1.17. Algorand (ALGO)

As a relatively new public BC, Algorand has not undergone extensive testing in real-market conditions as of 2023 (Algorand, 2023). However, it introduces an interesting concept where coin holders who stake their tokens are rewarded with governorships and voting rights within the BC network. Algorand was designed to be energy-efficient from its inception and does not rely on mining (Matthews et al., 2023). According to the information provided by the Algorand website, each transaction on their network consumes approximately 0.008 Wh of energy. The yearly electricity usage of the Algorand network is estimated to be around 4160 MWh, which leads to approximately 1909 tons of CO2 emissions (Algorand, 2023).

In 2021, Algorand formed a partnership with ClimateTrade, a company leveraging BC technology to assist businesses in reducing their carbon footprint. This collaboration highlights Algorand's commitment to environmental sustainability and leveraging BC technology for a positive impact in combating climate change (Gail, 2022). Through this collaboration, Algorand has implemented a mechanism to allocate a portion of its transaction fees for the acquisition of carbon credits. These carbon credits are used to offset and reduce the carbon impact of the Algorand network (Algorand, 2023).

4.1.18. Fantom (FTM)

Fantom is a cryptocurrency designed for decentralized applications as well as enterprise applications. It aims to provide a scalable, fast, and secure platform for building and deploying various types of applications. Fantom utilizes a DAG consensus mechanism called the "Lachesis protocol" to achieve high throughput and low latency (Najumi, 2022). The Fantom BC consumes an estimated 0.024–0.028 Wh of energy per transaction. Considering the entire Fantom network, the annual energy consumption is estimated to be around 8.2 MWh. It is interesting to note that this is less than the average annual total power consumption of a single US home, which is approximately 10.7 MWh. This suggests that the energy usage of the Fantom network is relatively efficient and compares favorably to the energy consumption of traditional household activities (Najumi, 2022).

4.1.19. MobileCoin (MOB)

This simple payment system utilizes the existing cellular network and a cryptocurrency that consumes minimal energy. It provides instant digital currency transactions that are environmentally friendly, easy to use, and maintain user privacy. Supporters of MobileCoin (MOB) have contributed renewable energy resources to offset the network's emissions, aiming to achieve carbon-negative status for the foreseeable future. The founder of Signal application served as MOB's initial technical advisor, and the project has gained significant investment interest, including from Coinbase Ventures. (Matthews et al., 2023). By directly integrating with desktop or mobile chat applications, the network reduces barriers to cryptocurrency usage. It leverages the FBA algorithm, enabling MOB to achieve both speed and energy efficiency while maintaining a decentralized nature.

4.1.20. Electroneum (ETN)

Like MOB, Electroneum (ETN) is a mobile-centric cryptocurrency payment network established in 2017. While originating in the UK, its primary objective is to provide a secure, fast, and reliable payment solution to the approximately one billion people worldwide who lack access to traditional banking services. In March 2018, the platform introduced one of the earliest Android mobile mining applications, potentially pioneering the concept (Matthews et al., 2023). Electroneum switched to a Proof-of-Responsibility (PoR) BC in 2019. PoR enables the project to select its miners. There are 12 validators in this permissioned network, and they are all non-governmental organizations. These organizations receive awards for their validation, and they put the money they receive to good use. Universities will eventually be able to serve as network validators as well. PoR significantly lowers the amount of power needed to mine ETN, which is comparable to illuminating one light bulb every day instead of 2.4 million (the pace of hashing was multiplied by millions, dropping from over four Giga hashes to under one-half of a kilo hash) (Matthews et al., 2023).

4.1.21. Near protocol (NEAR)

Introduced in 2020, the NEAR Protocol represents a third-generation BC. It operates on a sharded, PoS model as a layer one smart contract platform, enabling it to handle 1000 TPS. NEAR Protocol is certified as a carbon-neutral BC and offers a wide range of applications, including NFTs, games, and other content. The NEAR Protocol development platform also serves as a foundation and collective that allocates funds to expand the NEAR ecosystem, utilizing the NEAR token (NEAR, 2023). The network is energy-efficient and cost-effective, with users and developers sharing 30% of transaction costs. Additionally, by utilizing the network, users inadvertently contribute to offsetting CO2 emissions (Matthews et al., 2023). The NEAR Protocol currently generates approximately 174 tons of CO2 per year (NEAR, 2023).

4.1.22. XDC network (XDC)

The XDC Network is a hybrid BC that utilizes the DPoS consensus mechanism. This enables the network to establish hybrid relay bridges, achieve spontaneous block finality, and facilitate interoperability for its users. The primary objective of the XDC Network is to enhance transaction security and promote transparency among various stakeholders, particularly for cross-border trading, through interoperability (XDC, 2023). DCB Bank has made the strategic decision to migrate its insurance system to the XDC Network BC. They view this hybrid BC as the optimal solution to address the challenges they encounter with centralized systems. The DPoS consensus mechanism employed by the XDC Network ensures that the energy consumption associated with producing XDC coins and maintaining a stable decentralized network is equivalent to that of a simple word processor. XDC demonstrates exceptional energy efficiency, utilizing only 7446 KWh of power. Moreover, transactions can be completed within seconds, achieving impressive speeds of up to 2000 TPS. Compared to PoW mining, the DPoS consensus mechanism reduces energy usage by a factor of ten (XDC, 2023).

4.1.23. Mina Protocol (MINA)

Boasting a mere 22 kb in size, Mina is promoted as the most lightweight BC ever created. Its participants contribute to the network by rapidly synchronizing and validating it. This sets it apart from numerous other BCs that rely on intermediaries with substantial processing power to operate nodes, making Mina fairer and environmentally sustainable. Despite being established in 2017, the development and testing of the Mina Protocol took four years before its official launch in March 2021 (Matthews et al., 2023). Because Mina is decentralized and lightweight, any user may participate fully in the PoS consensus. Unlike most other BCs, transactions are validated on-chain after being calculated off-chain using a significantly smaller proof. For MINA, data for both energy usage and CO2 emissions are unavailable.

4.2. Green BC support initiatives

This section provides a response to RQ2. Although many green BC initiatives are still in their early stages, they have already yielded notable outcomes and progress. However, the impact of these projects has been relatively limited thus far, given their nascent development status. Nonetheless, the following highlights some significant achievements and advancements resulting from these endeavors. These supports can be categorized into three major themes; renewable energy, carbon neutrality, and energy efficient use, as shown in Fig. 2.

4.2.1. Renewable energy

We could identify several efforts whose main focus was on using and supporting renewable energy resources, as explained in the following points.

- Solarcoin: It is a global and independent cryptocurrency that operates on the principle of sustainability by utilizing the PoA consensus mechanism to verify the transactions, which uses less energy, compared to PoW-based solutions. It incentivizes solar energy producers by rewarding them with SolarCoins, aiming to promote and incentivize the generation of solar energy (SolarCoin, 2023). By generating solar energy through solar panels, individuals can earn one SolarCoin for every 1 MWh produced (SolarCoin, 2023).
- The Renewable Energy Certificate Mechanism: It is a mechanism that enables Bitcoin miners to buy certificates for green power, which serve as evidence that a specific amount of green power was produced and supplied into the electrical system (EPA, 2023).
- The BC for Climate Foundation (BFCF): It aims to address climate change by leveraging BC technology for carbon accounting, supply chain management, and green energy solutions. The foundation promotes the adoption of BC-based solutions to facilitate transparent and efficient tracking of carbon emissions, ensuring accurate carbon accounting practices (BFCF, 2023). Several BC-based technologies have been created by BFCF, including the climate TRACE effort, which monitors carbon emissions from substantial sources using satellite images and artificial intelligence (BFCF, 2023).
- The Green Digital Finance Alliance: It is a global charitable foundation that focuses on supporting initiatives that align with environmental sustainability, such as encouraging the development and adoption of eco-friendly BC technologies (GDFA, 2023). To hasten the implementation of green finance ideas, they collaborate with governments, technological companies, and financial organizations.
- The Crypto Climate Accord: A program was started in 2021 to lower the carbon footprint of the Bitcoin business by 50% by 2025 and to operate it entirely with renewable energy by 2030 (CCA, 2023). Several prominent cryptocurrency companies, including Ripple, CoinShares, and Bitso, along with others, have pledged their support for the Crypto Climate Accord.
- Clean Energy Buyers Association: It is a group of global corporations, creators of green power, and suppliers who cooperate to improve the affordability and availability of green energy (CEBA, 2023). Although not entirely focused on BC, CEBA's activities are in line with programs for integrating renewable energy sources that utilize BC technology.
- ReGal 38183: It is a provider of financial compliance solutions and green financial services. They offer customers the opportunity to invest in projects that prioritize sustainability through a startup called Green BC (StartUs, 2023). This platform allows individuals to align their financial choices with their values and contribute to environmental and social considerations.

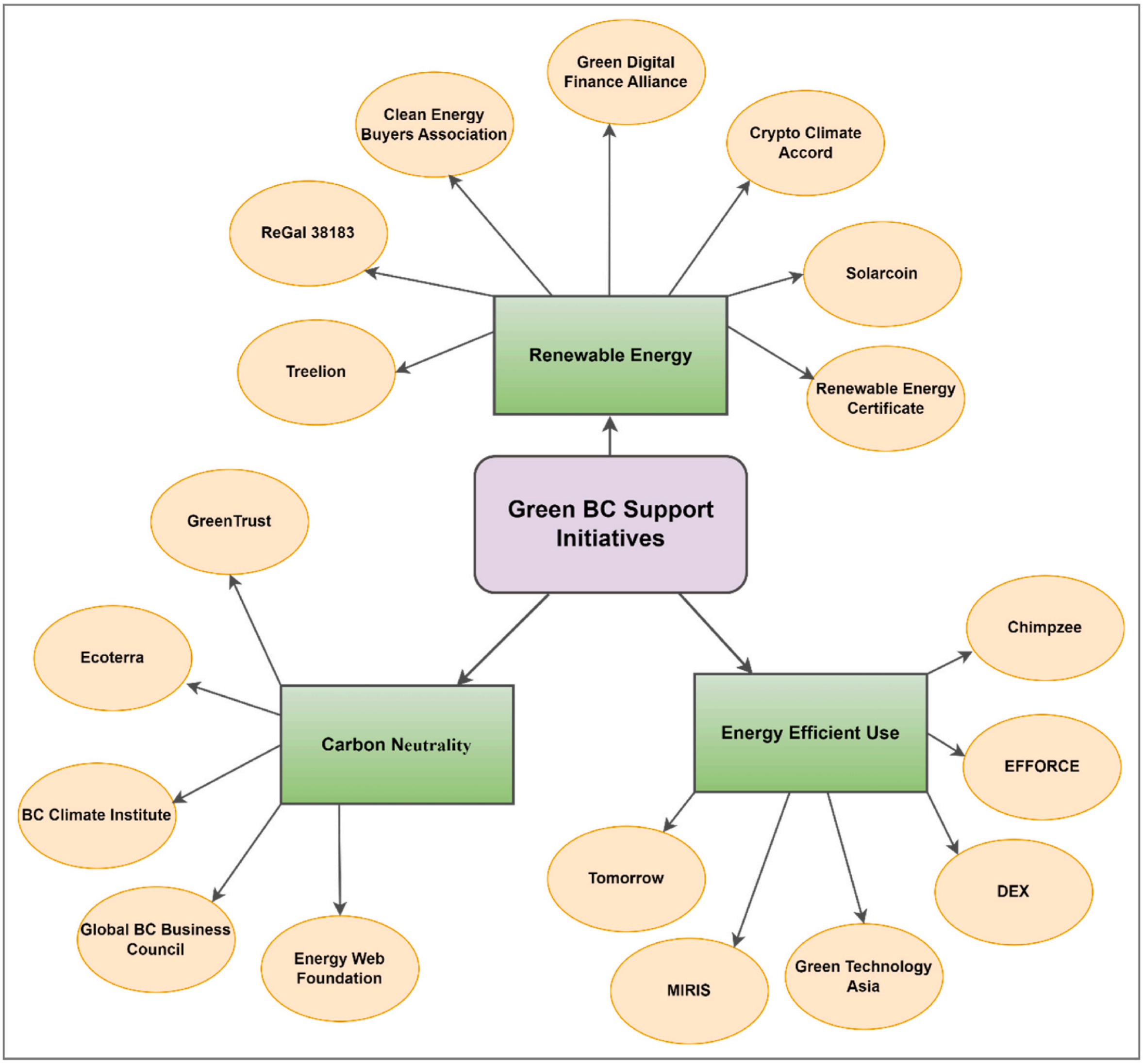

Fig. 2. Green BC support initiatives.

- Treelion: It is a Chinese firm that specializes in developing a financial digital network specifically for ecological enterprises within the BC industry. Their focus is on establishing a decentralized system for issuing and managing green digital assets through the utilization of green digital financial infrastructure (TreeLion, 2023). This infrastructure enables the seamless integration of BC technology across multiple industries to support and facilitate the transition toward environmentally sustainable practices.

4.2.2. Energy efficient use

We also identified several efforts whose main focus was on using energy in efficient way, as explained in the following points.

- EFFORCE: The entire goal of this innovative BC is to assist cryptocurrency investors in making money while supporting programs for energy efficiency that are beneficial to the environment (Matthews et al., 2023). Smart contracts are used by the EFFORCE algorithm to transfer the subsequent savings to owners of tokens.
- Chimpzee: The Chimpzee initiative is a recently introduced Web 3 project that offers a unique mechanism that allows investors to generate passive income while also contributing to environmental conservation and the protection of endangered animals. At the core of the Chimpzee ecosystem is the CHMPZ token, which operates on the Ethereum BC.
- The Decentralized Energy Exchange (DEX): DEX is a platform built on BC technology that facilitates the trading of green energy certifications and other energy-focused commodities (DEX, 2023). By leveraging BC's transparency and traceability, DEX aims to provide a trusted and secure platform for participants to buy and sell renewable energy certificates and related products.
- Green Technology Asia: It is an Asian-based entity that promotes the adoption of environmentally friendly and sustainable technologies, including BC (GTA, 2023). Their focus lies in conducting research, providing education, and fostering a community dedicated to advancing sustainable practices within the technology sector.
- MIRIS: It is a systematic platform designed to facilitate the selection, monitoring, and reporting of fund transfers in financial initiatives (StartUs, 2023). The framework is based on an open architecture and draws upon the principles outlined by the International Capital Market Association's Green Bond Principles. MIRIS aims to provide a transparent and standardized approach to green finance, ensuring that funds are allocated towards environmentally sustainable projects and initiatives.
- Tomorrow: Tomorrow is a German startup that offers transparent and sustainable mobile banking facilities. Their premium account,

called Tomorrow Zero, enables users to fund precise environment change projects, such as biogas facilities in Vietnam, clean drinking water initiatives in Uganda, and smallholder development in Peru (StartUs, 2023). The company also aligns with the Sustainable Development Goals (SDGs) and invests in green bonds issued by Germany's Förderbank Nordrhein-Westfalen.

4.2.3. Carbon neutrality

We also identified several efforts whose main focus was on decreasing the CO2 emission, as explained in the following points.

- GreenTrust: To aid global efforts to achieve carbon neutrality by 2050, GreenTrust is a decentralized BC platform that operates on a carbon-neutral system. Through the use of carbon offset certificates, individuals can trade them for GNT tokens. As part of its sustainability initiatives, GreenTrust plants a tree for every 350 transactions conducted on the network (Matthews et al., 2023).
- Ecoterra: It is a BC-based platform that aims to drive environmental change by fostering a comprehensive ecosystem. This ecosystem encourages individuals to engage in environmentally friendly actions. Through the Ecoterra app, users can accumulate Ecoterra tokens, with each recyclable item assigned a specific value in Ecoterra (Brooke, 2022). The platform recognizes every ton of carbon offset as a milestone, which contributes to the individual or business' impact profile. Additionally, when specific goals are achieved, such as planting 100 trees or cleaning 20 beaches, they are transformed into NFTs (Brooke, 2022).
- The BC Climate Institute: It is an advocacy group that investigates how global warming and BC technology interact (BCI, 2023). They do research, examine the possibilities of BC solutions for solving climate concerns, and encourage environmentally friendly behavior in the BC industry.
- The Global BC Business Council Sustainability Working Group: The group's goal is to investigate how BC technology might advance sustainability and mitigate global warming (GBBC, 2023). For BC-based solutions in fields like green power, managing supply chains, and carbon offsets, the group concentrates on creating guidelines, standards, and use cases.
- The Energy Web Foundation: It is a non-profit organization focused on developing and promoting free and open-source BC technologies for the energy sector. The foundation aims to accelerate the decarbonization and adoption of green energy (EWP, 2023). Through collaborations with leading energy companies, such as Siemens Energy and Shell, the foundation explores and implements BC solutions to drive sustainable energy practices and reduce carbon emissions.

5. Discussion

Despite the above-reported efforts, there is still more work to be done in making BC technology more environmentally friendly and reducing its carbon footprint. This study provides a comprehensive overview of various initiatives and advancements in the field of sustainable BC. In this section, we discuss the implications of green BC efforts and highlight the limitations of this study.

5.1. Implications

The projected annual global power consumption of BC networks supporting cryptocurrencies in 2022 is estimated to be between 120 and 240 billion kWh (WhiteHouse, 2022). However, it is important to note that the power usage of cryptocurrencies can vary rapidly as miners adjust their operations in response to market fluctuations and adopt new technologies. These factors can significantly impact the overall power consumption of BC networks. The projected annual global power consumption of BC networks supporting cryptocurrencies in 2022 is estimated to be between 120 and 240 billion kWh. However, it is important to note that the power usage of cryptocurrencies can vary rapidly as miners adjust their operations in response to market fluctuations and adopt new technologies. These factors can significantly impact the overall power consumption of BC networks. (News-BTC, 2023).

Moreover, the number of cryptocurrencies that will emerge, their level of popularity, and the consensus mechanisms they will utilize are highly uncertain variables. These variables will have an impact on the power demand. It is important to note that compared to the risks associated with the expansion of PoW networks, the risks associated with PoS or other energy mechanisms are significantly lower. This suggests that transitioning to more energy-efficient consensus mechanisms could help mitigate the environmental concerns related to cryptocurrency power consumption (WhiteHouse, 2022). The potential for rapid growth in cryptocurrencies power demand further underscores the importance of improving data collection and analysis methods to better understand and monitor the electricity usage associated with cryptocurrencies (WhiteHouse, 2022).

According to Table 1, numerous cryptocurrencies have the potential to become environmentally friendly in the future. Examples include Fantom, MobileCoin, and Electroneum, which consume minimal energy per transaction, resulting in negligible CO2 emissions. On the other hand, cryptocurrencies such as Tezos, Polkadot, Ripple, and Ethereum, among others, still require a relatively high amount of power per transaction, although they are significantly lower compared to Bitcoin transactions. This leads to the following remark: while the term "green" is often associated with renewable energy sources, its usage in the context of cryptocurrencies may not accurately reflect the energy-saving nature of these BC systems. Referring to them as "environmentally friendly" cryptocurrencies would indeed be more representative of their energy-efficient characteristics compared to Bitcoin and other energy-intensive cryptocurrencies.

Legislation and regulations contribute a crucial role in addressing sustainability concerns related to cryptocurrency activities. The implementation of effective regulations can help mitigate the environmental impact of cryptocurrencies and promote more sustainable practices (Mishra et al., 2022). For instance, the Markets in Cryptocurrencies legislation being considered by the European Commission highlights the need for environmental and climate impact data and the establishment of minimum sustainability requirements for consensus processes. These measures aim to ensure that cryptocurrencies operate in an environmentally responsible manner. The Chinese government's decision to ban cryptocurrency transactions in 2021 was also influenced by environmental considerations.

5.2. Challenges and recommendations for green blockchain adoption

The following recommendations are suggested for thought in order to secure the responsible growth of cryptocurrencies (WhiteHouse, 2022; Oudani et al., 2023; Varavallo et al., 2022; Parmentola et al., 2022; Iberdrola, 2023; Bao et al., 2023; Mohamed et al., 2023; Qin et al., 2023; Polas et al., 2022; Mishra et al., 2022; AlAhmad et al., 2021; Teng et al., 2021):

- **Sustainable cryptocurrencies:** By implementing green BC, it would be possible to mitigate the environmental impact of Bitcoin mining, such as CO2 emissions. It is essential to adopt a consensus mechanism that minimizes the risk of approving fraudulent transactions, eliminates the resource-intensive competition inherent in PoW, allows each machine to focus on unique tasks, and optimizes energy consumption. This transition from PoW to PoS or a similar energy-efficient alternative is crucial.
- **Renewable energies:** Implementing green BC can effectively address the issue of CO2 emissions generated by the Bitcoin sector. To bridge this gap, numerous startups have emerged with diverse solutions. One approach involves cryptocurrency mining firms utilizing carbon credits to incentivize the transition to cleaner energy

sources. They can either generate their credits by adopting greener practices or purchase carbon credits from other companies to offset their emissions. Additionally, providing rewards such as tax exemptions or grants to businesses and individuals who adopt environmentally friendly cryptocurrency methods can further encourage the use of green energy sources, energy-efficient mining equipment, and other sustainable practices.

- **Current cryptocurrency situation:** Authorities should conduct a thorough assessment of the energy grid's capacity and reliability to support current and future Bitcoin mining operations. This evaluation will help determine the need for creating, revising, or enforcing standards to ensure the dependable supply of power to the system. In order to make informed decisions about the energy and environmental impacts of cryptocurrencies, authorities should consider collecting and analyzing data from power utilities and Bitcoin miners. This data should cover aspects such as the environmental impact of mining, energy demand, and energy consumption. It is crucial to encourage mining companies and equipment manufacturers to be transparent and openly disclose this information. Furthermore, authorities should allocate funds for research and development projects focused on improving the energy efficiency of BC technologies and exploring innovative approaches to sustainable mining practices. This may involve exploring alternative consensus mechanisms, promoting the use of eco-friendly mining equipment, and creating incentives to encourage sustainability in the industry.
- **Standards and regulations:** Since green BC is still in its early stages, regulations have not been developed or finalized yet, there is a need to implement specific environmental regulations tailored to the cryptocurrency sector, which include requirements for energy-efficient mining practices, the utilization of renewable energy sources, and participation in carbon offset programs. Mandate transparency within the Bitcoin industry by requiring businesses to disclose their energy consumption, environmental impact, and sustainability initiatives. This will enable stakeholders and investors to hold companies accountable and make well-informed decisions. Establish standards for extremely low energy intensities, limitations, or elimination of energy-intensive consensus processes, and gradually increase standards to ensure that the generation of carbon-free electricity matches or surpasses the growing electricity demand of these operations.
- **Collaborate with Stakeholders and international organizations:** Promote collaboration among governmental bodies, industry leaders, environmental organizations, and academic institutions to collectively address sustainability challenges associated with digital assets. Through this collaboration, industry-wide standards and best practices can be developed. This collaboration may involve knowledge sharing, collaboration on cross-border initiatives, and sharing of best practices to create a collective impact.
- **Awareness:** Raise awareness among cryptocurrency users about the negative environmental consequences of their activities and guide how to minimize their carbon footprint. This can be achieved by promoting ethical investing practices, advocating for the adoption of energy-efficient mining techniques, and supporting sustainable initiatives within the BC industry. By educating users and empowering them to make environmentally conscious choices, we can collectively work towards reducing the environmental impact of cryptocurrencies.

5.3. Limitations and future research directions

The findings of this study rely primarily on information obtained from green BC websites, as well as professional websites, blogs, and agencies in the field. However, it is important to note that research in this area is limited due to the early phase of expansion of the green BC initiatives. Furthermore, it is important to note that the list of 23 identified cryptocurrencies is not exhaustive. While there are several more cryptocurrencies available online that are described as green BC, the selection provided in this paper is based on the availability of data related to these specific cryptocurrencies. Further research is needed to enhance our understanding and foster innovation in this domain. It is recommended that authorities might encourage and fund research and development initiatives that enhance the sustainability of cryptocurrency mining.

Energy system estimations play a crucial role in predicting future energy consumption, considering factors such as service demands, available power alternatives, costs, and technology efficiency (WhiteHouse, 2022). However, the current estimations often fail to accurately reflect the energy consumption of digital technologies such as BC networks. This flaw leads to inaccurate energy forecasts specifically for digital systems. To improve energy forecasting for digital systems, it is necessary to address this modeling flaw and develop estimation techniques that properly account for the energy consumption of BC networks. By incorporating these factors into the modeling process, more accurate energy projections can be obtained, enabling better planning and management of energy resources in the context of BC mining.

Moreover, it is essential to analyze how the currency's blocks are created and maintained. Understanding the process of block creation and maintenance provides insights into the energy consumption associated with the cryptocurrency (Iberdrola, 2023). Future research may also focus on scaling issues in green BCs to help them handle a bigger volume of transactions while still being energy-efficient including layer 2 solutions and sharding methods. Additionally, the interoperability between multiple green BC networks and conventional systems may be investigated for improvement. Especially in the supply chain and energy industries, this will make it easier to share and integrate data seamlessly (Mohamed et al., 2023). Finally, governments and regulatory agencies need to set up frameworks to control green BC technologies, assuring compliance with environmental requirements, as the popularity of green blockchain increases.

6. Conclusions

BCs offer numerous advantages, including openness and anonymity, but they also require significant financial resources to operate effectively. In recent years, the BC industry has witnessed various technological advancements and initiatives aimed at improving energy efficiency. This study aimed to identify and analyze these initiatives, examining their impact on electricity consumption and CO2 emissions. The study identified and discussed 23 BC platforms that make environmental or green claims. These platforms were evaluated in terms of their potential to reduce CO2 emissions and enhance energy efficiency. Additionally, the study identified several initiatives that incentivize and reward the reduction of CO2 emissions within the BC industry. These initiatives include Solarcoin, the Renewable Energy Certificate Mechanism, BFCF, the Green Digital Finance Alliance, the Crypto Climate Accord, Clean Energy Buyers Association, ReGal 38183, Treelion, EFFORCE, Chimpzee, DEX, Green Technology Asia, MIRIS, Tomorrow, GreenTrust, Ecoterra, the BC Climate Institute, the Global BC Business Council Sustainability Working Group, and the Energy Web Foundation.

The increasing popularity of green coins and projects in the BC industry is driven by their potential for scalability and reduced CO2 costs. These initiatives prioritize environmental sustainability and attract a significant user base. Their advantages are likely to inspire the development of new BC solutions that prioritize ecological concerns and drive improvements in existing ones. The study's findings offer valuable insights into the ongoing efforts to promote environmentally friendly operations in the BC industry. The research identifies potential BC platforms and compares their power consumption and CO2 emissions, providing a helpful starting point for companies planning to adopt eco-friendly BC solutions. Additionally, the paper presents a list of organizations that incentivize firms to reduce their CO2 emissions, encouraging the adoption of greener BC platforms by these entities. It serves as a valuable resource for understanding the current landscape of green BC initiatives and advocates for further research and innovation in this field.

CRediT authorship contribution statement

Yehia Ibrahim Alzoubi: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Alok Mishra:** Methodology, Formal analysis, Validation, Writing – review & editing, All authors have read and agreed to the published version of the manuscript, Both authors have significantly contributed to this paper.

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.

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