IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 28 November 2024, accepted 15 December 2024, date of publication 27 December 2024, date of current version 9 January 2025.

*Digital Object Identifier 10.1109/ACCESS.2024.3523672*

SURVEY

# Application of Blockchain Technology in Carbon Trading Market: A Systematic Review

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This work was supported in part by the University of Johannesburg and in part by the National Research Foundation, South Africa.

**ABSTRACT** The carbon trading system is a mechanism that employs carbon caps (limits) and taxation to regulate the rate of carbon dioxide emissions produced by human activities. To further strengthen the effectiveness of this mechanism, the United Nations (UN) initiated the Kyoto Protocol in 1997, enabling the trading of carbon emission rights in exchange for financial compensation. As a result, the market value rose to \$10.9 billion in 2005, with an annual growth rate of approximately 8%, reaching \$95 billion in 2023. Despite this expansion, the system's management has remained centralised since its inception, leading to issues such as a lack of transparency and openness in the trading process, inefficiencies in the trading mechanisms, and inaccurate or dishonest centralised data recording. The rapid expansion of the market and the accompanying challenges underscore the need for blockchain technology (BCT), which offers a decentralised, secure, and tamper-proof system. Although several research publications have demonstrated the potential enhancements that BCT could contribute to the carbon market, no systematic review has yet examined the optimal implementation of BCT within the context of carbon trading and taxation. This study, therefore, undertakes a systematic review of peer-reviewed research articles published between 2015 and 2023 using the PRISMA methodological framework. Our analysis establishes the feasibility and viability of a blockchain-powered solution for carbon trading, alongside the development of a comprehensive framework for its effective implementation, designed to stand the test of time in the fast-evolving technological landscape. Furthermore, this comprehensive review identifies research gaps, offering future researchers direction in exploring blockchain applications within the Emissions Trading System (ETS) domain. Overall, this review fosters a digitalised and incentivised shift towards renewable energy sources.

**INDEX TERMS** Blockchain technology, carbon emission, carbon footprint, carbon trading, distributed ledger technology, emission trading system, greenhouse gas, PRISMA, systematic review.

## LIST OF ABBREVIATIONS

| | |
|---|---|
| 4IR | Fourth Industrial Revolution. |
| API | Application Programming Interface. |
| BCT | Blockchain Technology. |
| $CO_2$ | carbon dioxide. |
| $CO_2e$ | carbon dioxide equivalent. |
| CTS | Carbon Trading System. |
| ETS | Emission Trading System. |
| EU | European Union. |
| EU ETS | European Union Emission Trading System. |
| GHG | Greenhouse Gas. |
| IoT | Internet of Things. |
| KP | Kyoto Protocol. |
| MRV | Monitoring, Reporting, and Verification. |
| P2P | Peer-to-peer. |
| PoW | Proof of work. |
| PoS | Proof of stake. |
| RQ | research questions. |
| UN | United Nations. |

The associate editor coordinating the review of this manuscript and approving it for publication was Mueen Uddin.

## I. INTRODUCTION

The rise in global temperature is attributed to the corresponding increase in emissions of carbon dioxide ($CO_2$) and other Greenhouse Gas (GHG) into the atmosphere as a result of daily human activities, which may currently be unavoidable [1]. In a bid to mitigate the negative effects that the emission of these gases has on the Earth's temperature, including the destruction of the atmosphere and oceanic eco-systems, the United Nations (UN) convened in 1997 to initiate a Carbon Trading System (CTS) through the Kyoto Protocol (KP). The KP initiative is based on $CO_2$ emission rights, which can be allocated to individuals or firms. These rights are considered commodities that may be traded for financial compensation [2]. Carbon trading is thus defined as the exchange of GHG emission rights for monetary rewards within a market framework aimed at reducing GHG and $CO_2$ emissions due to their adverse effects on the atmosphere [3].

Several milestones mark the historical development of Emission Trading System (ETS), between the meeting of UN members to create the KP and the development of the pioneering ETS. These milestones encompass key international agreements that led to early initiatives of this scheme, as seen in Figure 1. In 1991, the European Union (EU) introduced carbon taxation mechanism, paving the way for the KP, which was initiated by the UN in 1997 [4]. Subsequently, in 2001, the United States withdrew from the KP and moved to establish the United Kingdom (UK) ETS in 2002 [5]. A significant milestone occurred in November 2004 when Russia ratified the KP, granting the treaty full legal backing [6]. This ratification then led to the establishment of the largest ETS globally (European Union Emission Trading System (EU ETS)) in February 2005 [4]. Following this, several developments ensued, including the formation of the Regional Greenhouse Gas Initiative (RGGI) in 2009, which capped emissions in the electricity sector of approximately 10 northeastern US states [7]. In the years that followed, several national and regional CTSs were introduced as countries developed their own ETSs to control emissions. Some of these countries include New Zealand ETS in 2008 [8], Japan's ETS in 2010 [9], and China's regional carbon trading pilots in 2013, which resulted in the establishment of a national ETS in 2021 [10]. South Korea also launched its ETS in 2012 [11].

The positive effects of implementing the KP became evident in 2005, as highlighted in a report by the World Bank on the carbon trading market. The report indicated that the KP contributed to the carbon market reaching a value of \$10.9 billion in 2005 [12]. A recent World Bank carbon pricing report further noted that revenues from carbon taxes and ETS amounted to approximately \$95 billion in 2023 [13]. This figure is projected to increase to \$100 billion by 2030 and \$250 billion by 2050 [14].

The EU ETS is the first international CTS and is currently in its fourth phase of development (2021–2030), having been established in 2005 [15]. This system operates by allocating carbon credits to each emitting entity, with emission rates monitored against these credits. Entities that effectively reduce their emissions through the use of renewable energy sources end up having surplus carbon credits at the end of the month. These surplus credits can then be traded for

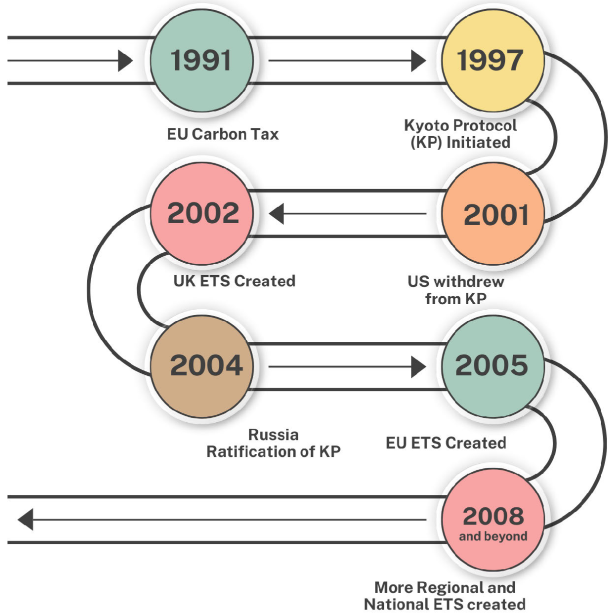


**FIGURE 1. Historical milestones of carbon market.**

financial incentives to entities requiring additional credits to meet their emission needs [16]. Additionally, entities that exceed their allocated credits are required to pay a carbon tax to the government. The government, in turn, reinvests these tax revenues into the community by funding eco-friendly initiatives aimed at reducing the effects of the location's GHG emissions.

Managed by EU member states and other European nations, the EU ETS is presently a centralised system encompassing over 10,000 power plants and industries across the 27 EU member states, as well as Iceland, Liechtenstein, and Norway [17]. In addition to this pioneering ETS, 28 other national and regional ETS schemes are operational, with eight nations actively developing similar systems and 12 considering implementation [18]. Currently, no African country has successfully implemented and deployed the ETS, though Nigeria is exploring its implementation [18]. South Africa, as a leading African nation in this regard, introduced a carbon tax mechanism in June 2019 [19].

The existing CTS faces several challenges, including a lack of transparency and openness in the trading process, inefficiencies in trading mechanisms, and issues with the record-keeping process [20]. Additionally, the system is subject to the risks of centralised data manipulation and a lack of trust and integrity among the parties involved in the system's operability [21]. Benlekey [22] has advocated for an end-to-end digitalisation and the decentralisation of post-2020 records to enhance the ETS's effectiveness and resolve the challenges of the system.

The rapid expansion of the market's value, coupled with the challenges of the current centralised CTS, underscores the need for a system that is stable, secure, decentralised, transparent, and tamper-proof. These requirements have brought Blockchain Technology (BCT) to the forefront, as it inherently possesses these characteristics and more [23]. BCT operates as a decentralised network of users and validators [24], with its decentralised nature being crucial for mitigating single points of failure and ensuring the trustworthiness and transparency of transactions conducted within the system.

Several studies have highlighted the role of BCT in addressing challenges associated with traditional CTS [25], [26]. In an effort to make the carbon trading market more transparent, secure, and efficient, [27], [28] proposed a blockchain and Internet of Things (IoT)-enabled Peer-to-peer (P2P) carbon quota trading platform, which addresses issues such as double counting and falsified emissions reductions. This approach advances the global goal of achieving net-zero carbon emissions while reducing the effects of climate change. Furthermore, an innovative emissions trading system tailored for Africa, [29] proposed a blockchain-based incentivised means of reducing emissions through the carbon market mechanism. A case study analysis conducted by [30] confirms that incorporating blockchain technology into the carbon trading market indeed provides these benefits. However, it also introduces certain challenges, such as high transaction costs, a steep learning curve, high gas fees for transaction processing, and various other challenges.

Despite the increase in studies based on BCT, there remains a limited number of studies focused on conducting a systematic and comprehensive review of BCT and its applications within the carbon trading domain. The existing literature review [31] based on carbon trading is not a systematic review, while the available systematic review [32] examines the topic predominantly from an economic perspective rather than from a technological or implementation standpoint.

This research is motivated by the need to achieve the global net-zero carbon emissions target and to mitigate climate change alongside its associated negative effects. Additionally, the necessity of encouraging a transition to renewable energy has prompted this systematic literature review, which seeks to propose a robust methodology for implementing a sustainable ETS. Thus, this study aims to conduct a systematic review of the literature to address the existing gap regarding the application of BCT within the carbon market domain. The study is further guided by the research questions (RQ) outline as follows:

**RQ 1**: What is the current state-of-the-art application of blockchain technology in the carbon footprinting, taxation, and trading domains?

**RQ 2**: What is the most appropriate methodology to develop a blockchain-powered carbon footprinting and trading application?

**RQ 3**: What are the current research gaps and limitations in the existing literature, and potential future study direction for enhancing future BCT-powered carbon trading systems?

The necessity and urgency of this review stem from the growing global climate crisis, which causes several detrimental effects on the ecosystem, such as the rise in global temperature beyond a sustainable level caused by GHG emissions [33]. This situation calls for timely and innovative solutions to achieve net-zero carbon emissions and mitigate GHG emissions through a transition to renewable energy sources. This research, therefore, provides insights into the application of blockchain to carbon emission management based on the analysis of 32 research publications. Furthermore, it identifies gaps to guide future research directions.

## II. EXISTING CARBON TRADING SYSTEMS

Subsequent to the establishment of the pioneering ETS (the EU ETS) comprising EU member states, Iceland, Norway and Liechtenstein, other national and regional ETSs have emerged. Some of these countries include China [34], Mexico, France, Sweden, and others. Surprisingly, there is currently no ETS in Africa [18], [19].

As shown in Figure 2, 28 other national and regional ETS have been deployed and are in full operation; eight nations are currently developing the system, while 12 are considering implementing the system [35]. Apart from Nigeria, which is now considering the implementation of a national ETS, no other country in Africa is close to implementing and deploying the system in Africa.

One-third of the global population is governed by the EU ETS; however, this system accounts for only 17% of total worldwide GHG emissions [35]. The working principle of the current carbon market relies on the Monitoring, Reporting, and Verification (MRV) of emission value. The proposed enhancement to this MRV mechanism involves integrating digitalisation into the system to improve its effectiveness. In the post-2020 context, the system is expected to function through end-to-end digitalisation, meaning digital devices would be used throughout the entire system cycle, right from the initial monitoring (sensing) of carbon to its storage in the database (reporting) and subsequently to its trading within the system [22]. This process is illustrated in Figure 3.

To further improve the system, Benlenky [22] proposes the use of BCT in place of a centralised database to solidify the digitalisation of the system. This approach is intended to ensure the immutability and auditability of the records.

The current centralised EU ETS has demonstrated a 20% reduction in emissions during the 2020s compared to levels recorded in the 1990s [15]. However, a primary challenge facing the existing centralised EU ETS, as well as national and regional ETS schemes, is a deficiency in trust and transparency, which casts doubt on the validity of reserved carbon credits [36]. This lack of transparency increases the risk of manipulation and fraud within the system [37]. Additionally, there is the issue of carbon leakage [38], indicating that not all carbon values are accurately accounted for. The system also exhibits a complex trading pattern and incurs high transaction costs. These challenges collectively result in low participation

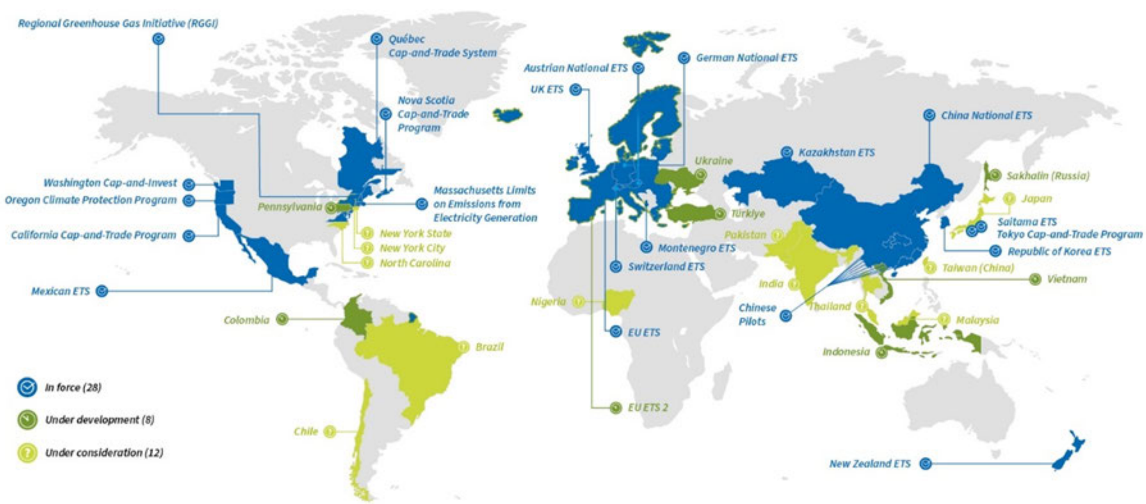


**FIGURE 2.** Infographics of the existing national emission trading system [18].

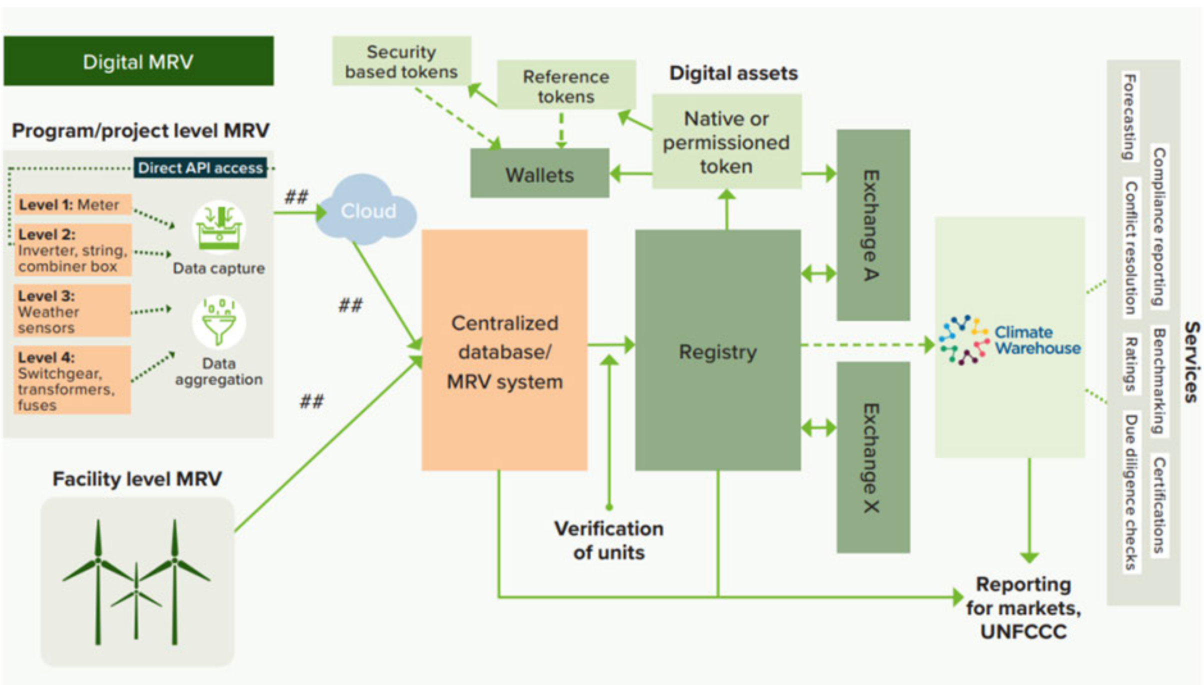


**FIGURE 3.** End-to-end digitalisation of carbon market infrastructure [22].

in the incentivised trading system, subsequently leading to reduced market liquidity and inappropriate price fixing [13].

### *A. DISADVANTAGES OR DRAWBACKS OF THE EXISTING SYSTEM*

While the existing carbon trading markets have made significant progress in reducing carbon emissions and mitigating their associated effects, certain drawbacks within the system persist and call for attention. Addressing these issues is essential to enhancing the system's effectiveness, thereby advancing its objective of achieving net-zero carbon emissions and ultimately fostering a carbon-neutral ecosystem. Some of these drawbacks include:

- *Lack of Standardised Legal Framework*: An adage goes thus - "where there is no law, there is no sin", a notion closely aligned with the challenges facing the current ETS. The absence of a centralised regulatory framework guiding market operations [39] allows for conflicts of interest among stakeholders on various decisions, leading to opaque and potentially non-transparent processes. Such deficiencies can result in issues like over-crediting or double-counting, thereby undermining the integrity of the markets. These issues raise serious concerns regarding the market's mechanism design, supply regulation, and adherence to its ultimate objective—reducing emissions [40].

- *Exclusion of Smaller Players*: The design of the current carbon market does not give room to smaller emitting entities (''small players''), as it is predominantly occupied by large-emitting entities (''big players'') due to a lack of inclusivity [41]. This exclusivity creates operational ambiguity, as participation is limited to large emitting entities only, thereby limiting competition and innovation among local initiatives.
- *Lack of Automated Monitoring, Reporting & Verification Process*: The current carbon market relies on a manual method of emissions reporting, which is susceptible to human error, potentially resulting in either underreporting or overreporting the emission record [42]. Furthermore, the absence of automated systems hinders effective data tracking, preventing real-time assessment of the goal of achieving net-zero carbon goals. This lack of automation also gives room for manipulation and corruption, as data control remains in control of humans, allowing for potential tampering that compromises the credibility of the data [43].
- *Increased Production Cost & Product Price*: Imposing taxes on emitting entities for their emissions and/or requiring them to purchase additional carbon quotas in the market when needed raises production costs, as manufacturers must now account for these added expenses alongside their existing costs. To accommodate this additional financial burden, manufacturers are likely to increase product prices, thereby indirectly passing on carbon taxation costs to end consumers through inflated prices [44].
- *Skills Gap for Full Digitisation of the System*: The current expansion of the carbon market underscores the necessity for digitalisation and automation of the system to improve its effectiveness. However, this digitalisation process requires highly skilled professionals in digital technologies, a resource that is presently scarce [45]. Consequently, the shortage of qualified professionals capable of facilitating the transition from manual to fully digitalised carbon markets hinders the system's potential to function on a global scale.
- *Low Transaction Volume and Liquidity*: Using China, the largest carbon-emitting country [46], as a case study for the adoption of blockchain or other emerging technologies in the carbon trading space. A study conducted by [47] proves that the integration of emerging technologies can initially result in low transaction volume and liquidity in the market. Pointing out that the design of the existing CTS lacks sufficient scalability and adaptability to incorporate emerging technologies. This outcome arises because individuals often require time to develop trust and loyalty for new technologies, underscoring the need for substantial awareness initiatives targeted at communicating the benefits of the technologies. Such efforts would prepare the existing CTS for the adoption of emerging technologies, ensuring it is able to stand the test of time.
- *Fraud and Unfair Distributional Effects*: A study [48] conducted on the EU ETS, which is a typical example of the existing CTS, has pointed out the issues of fraud and unfair distributional effects in the system. The study highlights an unfair distribution of costs, whereby companies pass on the expense of purchasing carbon allowances to consumers through increased product prices rather than adding the costs to their operating expenditure. This burdens consumers with the financial implications of carbon allowances. Additionally, significant instances of fraud have been identified within the system. These include the recycling of certified emission reductions (CERs) and the issuance of non-additional offset credits after transactions have been successfully performed, making credits that have been officially assigned unable to provide any additional emission reduction, rendering them redundant.

## III. OVERVIEW OF BLOCKCHAIN TECHNOLOGY

Blockchain technology has gained prominence as the underlying mechanism behind the well-known cryptocurrency, Bitcoin [49]. It has achieved widespread market acceptance, with leading multibillion-dollar corporations such as Amazon, Microsoft, Rakuten, and Coca-Cola, among others, recognising it as a payment medium [50]. Blockchain's primary advantage lies in its capacity to enhance security, immutability, and integrity within systems alongside other performance-driven characteristics. Furthermore, it shifts trust and confidence away from central authorities—such as institutions, governments, and corporations—towards system users and stakeholders [51].

### A. CHARACTERISTICS OF BLOCKCHAIN TECHNOLOGY

BCT has attracted significant academic interest due to its distinctive features and technological solutions, which address limitations in traditional systems across various domains, including the carbon market. Notable features include:

- *Decentralisation*: No central authority, thereby preventing single point of failure [51].
- *Transparency & Privacy*: All participating nodes can view information regarding transactions accessible to them without compromising the privacy of the contractual terms [52].
- *Data Security*: BCT provides encrypted security, ensuring transaction protection for both parties involved in the system. Thus, ensuring the integrity of the process [53].

- *System Autonomy*: Smart contracts enable the system to operate autonomously, eliminating the need for third-party escrow [54]. They trigger specific actions based on predefined conditions once the terms of the agreement are fulfilled [51].
- *Safe & Reliable*: The operational principle of the distributed ledger (DL) ensures that each transaction among network participants is accurately recorded in a shared ledger. Since a consensus network is established, any issues within a transaction link can be directly located and traced [55].
- *Efficient and Convenient*: The blockchain system is efficient as all entities within the network adhere to the same protocol, ensuring compliance with a shared consensus algorithm. The system's convenience is based on BCT's capacity to automatically validate transactions and consistently update the optimal trading route and schedule based on historical trading data [55]. The removal of intermediary parties further enhances ease and efficiency for all participants within the network [53].
- *Open & Inclusive*: Small and Medium Enterprises (SMEs) can easily participate in the system, as BCT does not impose size restrictions for market entry [55]. This inclusivity is essential, particularly given that, in 2010, SMEs in China alone were responsible for 53% of the country's carbon emissions [53]. Collectively, SMEs thus hold a more significant impact than the 'big players'.
- *Distribution*: All participating nodes possess a real-time copy of all updated records. This distributed architecture eliminates any single point of failure or vulnerability to attacks [51].
- *Data Correctness & Immutability*: Once a record is added to the chain, it cannot be modified, rendering it tamper-proof. This feature prevents fraudulent activities and eliminates the possibility of double spending and/or double counting [51], [56].
- *Traceability and Auditability*: Right from its genesis block, BCT maintains a historical record of all transactions and actions executed on all the subsequent blocks [51].
- *Trustworthiness*: The strict operational framework of the technology makes it a reliable entity for powering trading activities [51], thereby ensuring that the entire process remains transparent to all network participants [57].
- *Cost-Effectiveness*: Blockchain-based systems enhance operational efficiency by reducing both the number of human agents required and the execution time. This eliminates the need for third parties, thereby lowering enterprise transaction costs and simplifying oversight and management for governmental and inspection agencies [56].

### B. CONSENSUS MECHANISM

Recent studies have identified various consensus mechanisms, each offering distinct characteristics, advantages, and limitations. Given that the blockchain system operates without centralised management, all participating nodes must reach a consensus before a new block is added to the chain. The method used to achieve this consensus is determined by performance metrics, such as operational speed, data security, scalability, and resource requirements (e.g. electricity) [24]. Consensus mechanisms, alongside cryptography, jointly function to secure the distributed network [58].

The following list consists of an overview of the consensus mechanism used by [12], [53], [59], [60], [61], and [62], and others that were included in [24]. It should be noted that the list is not in any particular order; the selection of an appropriate mechanism will depend on the available resources and the specific objectives intended for the application.

#### 1) PROOF OF WORK (PoW)

pow is a typical consensus protocol used for validating nodes within a distributed ledger. It uses the Secure Hash Algorithm 256 (SHA-256) to secure all blocks in the network [59]. To add a block to the chain, an entity must identify the correct hash below the system's predetermined difficulty level using various complex mathematical models [63]. The primary limitation discouraging its adoption is the large amount of resource consumption, particularly electricity. Nonetheless, Proof of work (PoW) remains an excellent option for achieving enhanced security and decentralisation [64]. Bitcoin uses this protocol [24], and it was previously used by Ethereum before its recent transition to Proof of stake (PoS) [65].

#### 2) PROOF OF STAKE (PoS)

The possibility of creating or adding a block to the network is determined by the entity's input (stake) in the system, specifically in terms of coin ownership. A noteworthy vulnerability of this protocol is the potential for the instantaneous creation of multiple blocks on the chains, as it is not expensive [24].

#### 3) DELEGATED PROOF OF STAKE (DPoS)

This consensus mechanism allows token holders to elect a delegate identified as a trustworthy entity who will carry out their voting rights on their behalf. It was said to be more effective than PoW and PoS because it drastically reduced the energy needed to validate transactions [12].

#### 4) BYZANTINE FAULT TOLERANCE (BFT)

The concept behind the name is the resolution of the Byzantine General's decision puzzle, where there is always a communication challenge between generals when they need to determine if they should attack or retreat. It uses hashes, digital signatures, and metadata in its consensus algorithm. Hyperledger Fabric uses it [63]. Manderoux et al. [60] mentioned that it results in less system overhead and improves the execution speed of execution. It also makes hacking difficult because it requires a lot of computing power, which makes it quite expensive to operate.

#### 5) DELEGATED PROOF OF REPUTATION (DPoR)

DPoR enhances DPoS by improving system security, which is particularly relevant in the context of the carbon market. In this approach, voting power is calculated based on the carbon reduction contributions of emitting enterprises, with higher reputation values granting greater influence. Reputations are derived from voting outcomes and recent interactions, with a preference for positive interactions. Block packing and propagation are then efficiently conducted by the miner with the highest reputation, and verified blocks are securely appended to the chain. This consensus mechanism reduces incentives for malicious voters to collude, rendering attacks both economically burdensome and time-intensive [61].

#### 6) FEDERATED BYZANTINE AGREEMENT (FBA)

The FBA consensus mechanism enables network entities to validate transactions that have been formally approved by their trusted validators. Consequently, this approach relies on a minimal number of validators deemed trustworthy by network entities. Ripple and Stellar use FBA in varying capacities [24].

#### 7) PROOF OF AUTHORITY (PoAu)

PoAu, a consensus mechanism named by Gavin Wood, co-founder of Ethereum [66], requires the authorisation of one or more predefined members (authorities) to update information in the distributed ledger. This mechanism adopts a more centralised approach to facilitate chain management and governance. An example of its application is found in the Energy Web Blockchain, which has demonstrated its effectiveness by achieving confirmation times of three to four seconds and processing thousands of transactions per second [24].

#### 8) PROOF OF ELAPSED TIME (PoET)

Validators assign a waiting time to each entity across the network. During this period, entities enter a hibernation mode and are subsequently reactivated by the validators in ascending order of their assigned waiting times [63]. This algorithm is used by Hyperledger Sawtooth. A limitation of this approach is its reliance on an Intel-powered environment, which indirectly suggests the presence of a centralised authority [24].

#### 9) PROOF OF ACTIVITY (PoA)

The PoA mechanism integrates the functionalities, benefits, and limitations of both PoW and PoS mechanisms. For a block to be added to the chain, it must first undergo the PoW mechanism, followed by the PoS mechanism [24]. Network validators continue to fulfil their role by vetting transactions [63].

#### 10) PROOF OF BURN (PoB)

To add a block to the chain, entities are required to transfer a certain amount of coins to an escrow wallet. The greater the number of coins held, the higher the probability of successfully adding the block to the chain. The funds placed in these escrow accounts are committed by the validators and are no longer accessible to the entities [24], [63]. This mechanism is used by Slimcoin.

#### 11) PROOF OF CAPACITY (PoC)

PoC enables a block in the chain to leverage the available storage capacity of a disk. It encourages entities to compile a list of all possible block hashes in advance, so they subsequently only need to upload the file size details. This approach significantly reduces computational time. Examples of its application include blockchain networks such as Chia and BurstCoin, among others [67].

#### 12) PROOF OF IMPORTANCE (PoI)

The PoI mechanism appends a block to the blockchain by evaluating the importance of the block. This assessment is based on the quality of the transaction in conjunction with the track record or reputation of the entity within the network. The New Economy Movement (NEM) uses this mechanism [68].

## IV. RESEARCH METHODOLOGY

To answer the aforementioned research questions of this study, we use a systematic review method to identify, analyse, and interpret all applicable research publications. This section of the article presents the research methodology used for the review process.

### A. SELECTION OF RESEARCH KEYWORDS, DATABASE AND PRACTICAL SCREENING CRITERIA

Using the search method suggested by [69], the review used purpose and snowballing sampling techniques and snowball to identify suitable articles for the study. At the initial stage, articles were obtained from a combination of peer-reviewed journals indexed in the Scopus database without any restriction on the year of publication. The outcome of the search still has the year of publication to be between 2015 and 2023 because the study is still in its infancy. Several reasons can validate the preference for the Scopus database over the Web of Science database. Firstly, the Scopus database has been said to have 60% more content than the Web of Science [70]. The content ranges across several topics from different disciplines and areas of study, such as science, social science, art, and many more. Second, Scopus is at the forefront with the most cited databases of peer-reviewed journals worldwide. At the time of writing this, Scopus currently has close to 26,000 active peer-reviewed titles that range across 330 disciplines [71]. It gives access to more details on global publications, authors, and institutions. In the preliminary stage, an organised keyword query was conducted using the combination of specific keywords in the title, abstract, and keywords to obtain studies specifically based on BCT. Exact keywords used include 'Blockchain', 'Smart Contract', 'Distributed Ledger', 'Cryptocurrency', and 'Ethereum'. Taking this step further, to obtain studies that applied BCT to the carbon trading domain, the following specific keywords were used in the query to obtain the relevant literature for the study: 'Carbon Taxation', 'Carbon Trading', 'Carbon Financing', and 'Carbon Footprint'. This combination of keywords limited the search result to only works of literature related to the application of BCT to the carbon trading domain.

Combining keywords 'Blockchain' and 'Carbon Market domain' resulted in 190 documents from the advanced query functionality. To ensure that the study is only based on studies that have gone through the review process, the search result was narrowed down to only peer-reviewed journals, resulting in the removal of conference proceedings, book chapters, and technical reports from the materials to be studied because these types of publications have a scientifically minimal well-vetted approach.

The application of emerging BCT to the carbon market domain is still in its infancy. This was evident in the fact that the resulting documents were published between 2015 and 2023, even though no restriction was put on the years the papers were published. The query was also limited to articles only in the final publishing stage. No restriction was added to the field of study from which the study was published as long as English is the primary language.

In the intermediate stage, to ensure that no relevant study is left out. A snowball sample was conducted using a literature review tool known as litmap (litmap.com). This was done to identify relevant studies that were not included in the resulting documents obtained from the Scopus database query. Only the forward snowball technique was used as the result only contained the studies referenced by the resulting publications from the Scopus database search. The screening process was conducted by reading the abstract of these references to rationalise their relevance to the study. The process included an additional 15 articles to the final list of articles from the Scopus database search.

The full text was further reviewed to validate its relevance to the study. Examining the full text of the samples results in the elimination of 1 study as it is a review article. Reducing the final list to fourteen articles. In the final evaluation stage, a manual examination of the abstract of the 71 publications is performed based on the consensus reached by the authors that the study must be strictly based on the combination of BCT and carbon markets to create a solution.

After thorough vetting to confirm the study's quality based on the study's theme and removing duplicates, the list was combined to make up 32 documents studied. The explanation of this process can be seen in Figure 4.

The final query used to obtain the resulting files can be found in Appendix A.

### B. METHODOLOGICAL EVALUATION AND THEMATIC ANALYSIS

To ensure that researchers and experts prioritise areas of future research that remain unexplored. Rigorous methodological screening criteria were established.

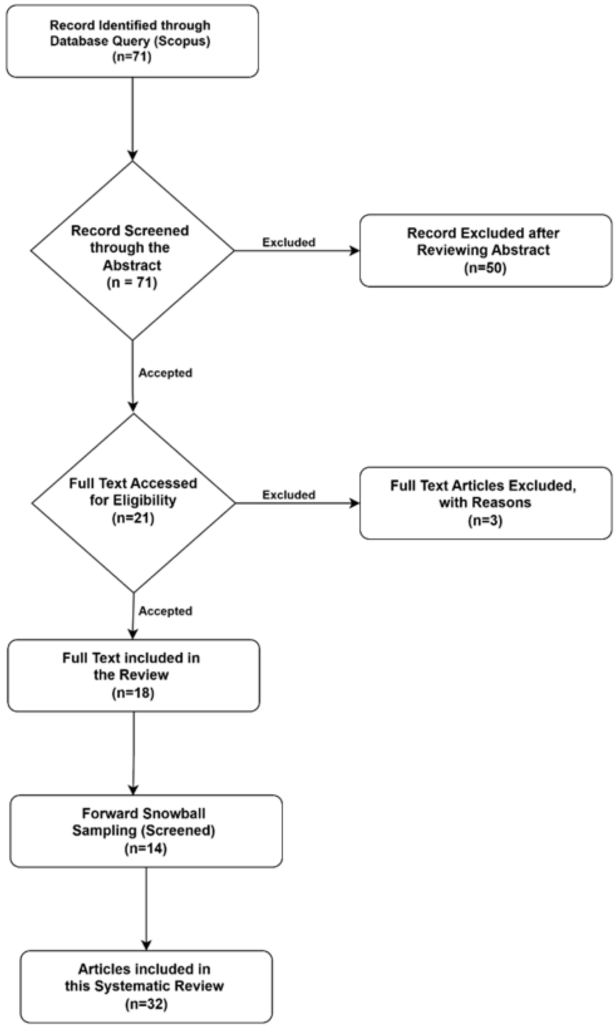


**FIGURE 4.** Literature search procedure.

The categorisation method resulted in the revelation of themes and significant discoveries of the applications of BCT in the carbon markets inspired by Singh et al.'s [72] article. A review protocol was adopted for the methodological examination and content analysis of the 32 published articles chosen. The categorisation used in reviewing these publications has been said to be adopted from previous theoretical articles. The analysis pillar got information on each study's bibliographic data, motivation, and aim. This includes the journal, publication year, geographical area (country where the study was conducted), citations, and the discovery made by each publication author.

### C. OVERVIEW OF THE FINDINGS AND GENERAL CHARACTERISTICS

A combination of 32 enlisted articles was thoroughly examined to categorise them according to their significant characteristics. This section of the study reports the identified characteristics of the analysed studies, including their categorisation by year of publication, methodological features, geographical location, and the number of citations received.

The categorisation of the studies based on the year the study was conducted or published was of great significance. The application of BCT to the carbon market first emerged in academia in 2015. Since then, the annual number of studies in this field has remained minimal, with the highest number of publications in this domain per year being only nine (9), recorded in 2020 and 2022. This underscores the fact that there are still significant opportunities to explore emerging trends through further exploratory studies. Figure 5 shows the total number of research publications per year covering the range of 2015 to 2023.

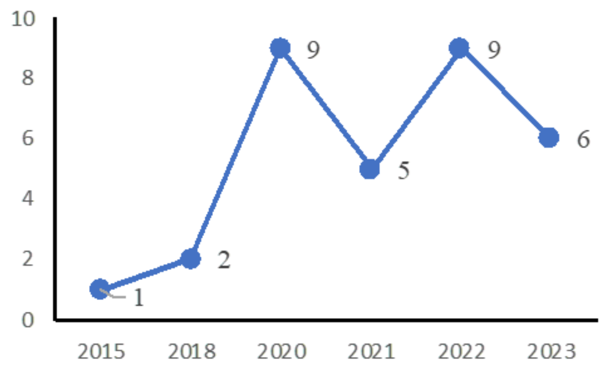


**FIGURE 5.** Total number of publications per year (total count: 32).

Considering the methodology used to conduct the studies that were reviewed. Of the 32 articles, Sustainability (Switzerland), Energies, Applied Science, and Journal of Cleaner Production published seven, four, three, and two studies, respectively. Unique publishers published the remaining sixteen studies. (See Figure 6).

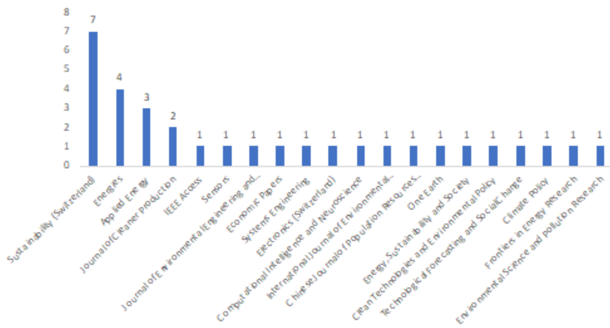


**FIGURE 6.** Total number of publications per Journal (total count: 32).

The methodology used mainly by the researchers is conceptual (9). It was closely followed by modelling (8) and mixed methods (6). Compared to the methods mentioned, fewer studies use simulation (3) and experimental (2) methods. Just one study used each of the following methods: Survey, Case Study, Review of the literature, and Evaluation of multiple criteria. With regard to the industry targeted by the solution or study, most of the studies, totalling 20, do not specify any particular sector. Beyond this, the transport and energy/power/electricity sectors each account for three studies. Other sectors, including the construction industry, payment channels, supply chain, coastal ecosystems, fashion apparel industry, and forestry, are represented by just one study each. See Figure 7 for more details.

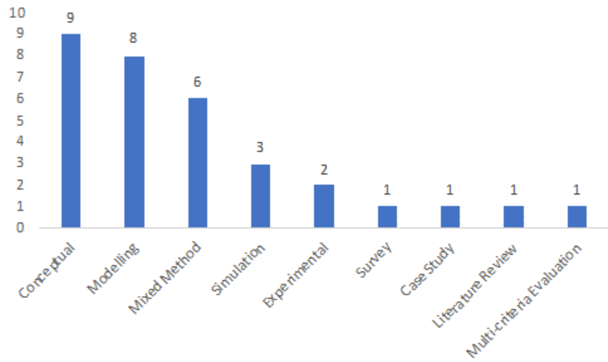


**FIGURE 7.** Total number of publications per research method used (total count: 32).

In terms of the impact of the publications, judging by the number of citations obtained by each of the publications under consideration, a total count of 853 citations was obtained in all the publications. The study by [25] received the highest number of citations, with 247. The details of the citation count of each of the other studies as of the time of writing this article are included in Appendix B.

The number of publications on the subject of consideration from each country shows that of the 195 countries in the world [73], only researchers from 11 countries (5.6%) are paying attention to the topic. China takes the half-share (16) of the total number of studies. Germany, the United Kingdom, and the United Arab Emirates followed closely with four, three, and two publications, respectively. Countries such as Singapore, Romania, South Korea, India, Australia, Japan and New Zealand also show that they are paying attention to the problem of climate change through carbon gas by publishing one study each on the subject matter. See details in Figure 8.

## V. RESULT AND DISCUSSION

### A. RQ 1: WHAT IS THE CURRENT STATE OF THE APPLICATION OF BLOCKCHAIN TECHNOLOGY IN CARBON FOOTPRINTING, TAXATION, AND TRADING?

Blockchain technology must undergo a comprehensive review to establish its applicability within a domain that has predominantly relied on conventional methods in its operations. This process aims to ascertain whether it will be a better replacement for the traditional system.

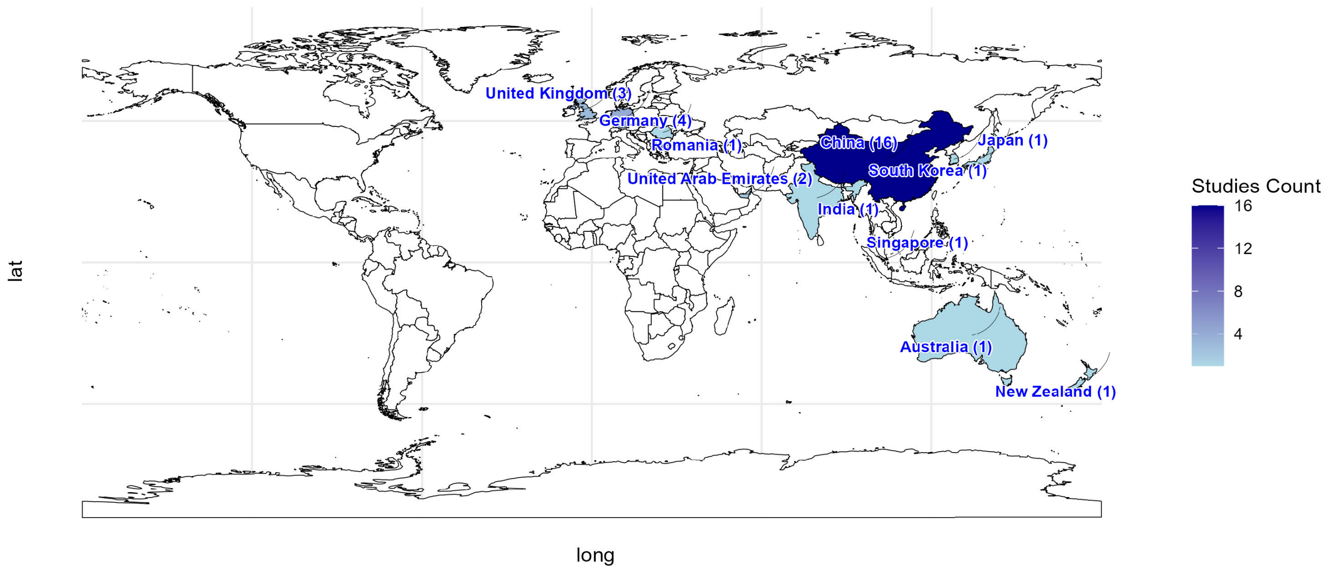


**FIGURE 8.** Distribution of study by geographical location (total count: 32).

### 1) CATEGORISATION OF BLOCKCHAIN PLATFORMS

Blockchain is a distributed network consisting of network users and validators. Categorising blockchain platforms into various divisions can be done using different parameters. These include the access rights of the platform; here, we have the public, private, and hybrid blockchain. Another parameter that can be used to categorise the Blockchain platform is the development purpose, which includes specific purpose/bespoke and general purpose. The last classification of the blockchain platform is its categorisation by the governance and protocols that see to the platform's operation; under this division, we can talk about the open-source and closed-source blockchain platforms [24].

Users can have full access rights or validated access rights or actions depending on how the system is configured. In a public blockchain system, all globally connected internet users can join and participate in the mining of block(s) to the chain. This contradicts the private blockchain system, where access is only limited to the users authorised by the system's validators. Other comparative points include the fact that any network member has the right to modify the contents of the public/permissionless blockchain, and the reward or encouragement system is based on some required resources like computational work, power or electricity, and many more. In a private or permissioned blockchain, only validators can modify the network's content. There is no anonymity with the permissionless network, as the user's identity is known to the validator nodes. Additionally, there is no need for a system-induced reward mechanism since the integrity of the validator nodes is tested and trusted. Due to the points above, private/permissioned networks tend to be faster and more efficient at the expense of being immutable and censorship-resistant. Moreover, some blockchain architectures allow the combination of the features of both private and public ledgers to operate hybridly. This type of hybrid operation is known as the consortium blockchain [24]. It is also known as a bespoke private blockchain network used for specific purposes in an industrial setting [74].

Categorising blockchain networks based on the purpose of development or the functionality that the system is meant to perform, there are blockchain platforms that are built to serve a specific purpose; for example, Bitcoin is strictly for monetary transactions, and those that are meant to serve a general purpose; for example, Ethereum was built to serve a wide range of applications [75], [76]. Based on the governance and protocols, we have the open source architecture in which the network can access community decisions, which is always done in a transparent and open-to-all mechanism. On the contrary, in closed-source blockchain, every modification of rules and systems of operation is done privately [24].

Notable is the fact that there is no 'one-solution-fits-all' tool for a proposed blockchain-powered solution. It all depends on the requirement with which the system programmer is working on and the end goal that is to be achieved.

### 2) REASON FOR DISCONTINUING THE CONVENTIONAL CARBON TRADING METHOD

The issues currently facing the conventional carbon trading scheme call for an urgent reformation. The problem of the traditional carbon trading scheme encompasses several critical issues. Firstly, there is the issue of lack of transparency and a high risk of corruption within the system. This trust issue is compounded by the complex allocation of carbon allowances, leading to an unjust distribution of allowances among participants. Furthermore, the fragmented nature of carbon markets and the lack of integration undermine the efficiency of the trading mechanism and limit the options available for carbon mitigation strategies. Furthermore, the calculations of the carbon budget are vulnerable to manipulation and abuse, exacerbating the challenges faced by this system. The carbon allowance allocation process is intricate and contributes to the complexity of the system. Moreover, carbon trading enables wealthy countries to purchase more carbon credits, allowing them to continue polluting the environment without sufficient restraint. The absence of standardised emission measurement tools further hinders progress, and the lack of a unified carbon trading market adds another layer of complexity to an already convoluted system. Furthermore, participating in carbon trading often incurs significant transaction costs, making it an expensive endeavour [51]. Moreover, since the energy sector is distributed, using a centralised mechanism to power its trading or taxation is no longer appropriate [76].

Mandaroux et al. [60] also highlighted the issues inherent in the traditional carbon trading scheme, identifying these as not only significant challenges but also persistent problems that necessitate the integration of emerging technologies, such as Blockchain, to enhance system efficacy. These issues include the sale of carbon credits that may not exist or, more concerningly, may belong to another party. Tax fraud is prevalent, with offenders exploiting systemic vulnerabilities. Additionally, the growth of internet crime and computer hacking presents a serious threat, enabling criminals to misappropriate valuable carbon credits. Due to lax regulations, financial crimes are facilitated within the carbon trading framework, underscoring the urgent need for a more secure and transparent method for managing and trading carbon credits.

### 3) MERITS OF THE INTEGRATION OF BLOCKCHAIN INTO CARBON TRADING SYSTEM

Integrating Blockchain into the carbon market offers several advantages, including the following:

- **Market Transparency**: Blockchain enhances the transparency and traceability of transactions and actions within the carbon market [1], [36], [51]. The integration of blockchain technology into carbon trading markets enhances the transparency of the market through its immutable and auditable ledger, which influences the behaviour of market participants and improves the accountability of records in a manner accessible to all market participants. Additionally, it addresses inefficiencies by enabling automation, enhancing liquidity, and providing reliable data. This transformation of the market ecosystem has the potential to foster global integration and promote cross-border innovation over the long term.
- **Trustworthiness**: The blockchain-powered emissions trading system also fosters greater trust among market participants, as they can be assured that the system is less susceptible to human manipulation and the transactions are not dependent on any centralised authority [1]. The automated and decentralised nature of the records, which are accessible to all, enhances transparency and further strengthens the trust participants have in the market [62].
- **Effective Integration with Other Technologies**: Blockchain enables reliable integration with other technological solutions. For instance, satellite imagery and other technologies can trust the system if it is blockchain-powered [36].
- **Liquidity of the Carbon Market**: Blockchain facilitates the liquidity of the carbon market, simplifying the processes of buying and selling carbon quotas, as well as converting quotas into cash [36]. This is possible as blockchain makes it possible for small and medium-scale emitting entities to be able to trade independently of larger emitting entities, resulting in a highly liquidified trading system that operates without the risk of manipulation by the "big players" through centralisation [51].
- **Supply Chain Credibility**: The carbon-credit supply chain, powered by blockchain, gains increased credibility, especially when combined with other Fourth Industrial Revolution (4IR) technologies such as IoT and Artificial Intelligence (AI). As it improves the efficiency, accessibility, and integrity of carbon credits within the supply chain [36].
- **Reduced Administrative Cost**: A significant advantage of integrating blockchain into carbon trading is the reduction in administrative costs, as the system is automated and operates through the use of smart contracts [1]. This ensures that the system is decentralised, distributed, and automated. Consequently, it requires minimal human intervention, effectively eliminating the need for manual reporting of carbon emissions [60], [62].
- **Enhanced Accountability**: Due to blockchain's immutable nature, it ensures robust accountability in the carbon trading market, preventing double counting of emissions quotas [60], [62]. The openness of the records allows for easier verification by network participants [36].
- **Elimination of Third Parties and Intermediaries**: The decentralised nature of blockchain promotes direct interactions between entities without the need for intermediaries, facilitating global interaction and reducing administrative costs [36], [51].
- **Greater Participation Level**: In a typical carbon market, there are various participants, each exhibiting different behavioural patterns, whether in the context of being a buyer or a seller; some are active participants, while others are more passive. However, when the carbon market is powered by BCT, it encourages even the most passive participants to engage with the market. This is because they are aware that it operates as a decentralised carbon quota marketplace, where no single entity holds control or has the ability to manipulate

it. This then promotes greater inclusiveness within the market, enabling participation regardless of individual behaviour or disposition, as participants will have full confidence in the integrity of the system [59].

- **Ehanced Security**: Powering carbon markets with blockchain enhances the security of the market, as the encryption mechanisms are based on advanced cryptographic techniques [51]. This ensures that the data remains highly secure and not vulnerable to unauthorised alterations. In addition, transacting in a blockchain-powered carbon trading market requires verification and authorisation through digital signatures [77], ensuring that only authorised parties can initiate and validate information. Concepts such as zero-knowledge proofs also enable the validation of transactions without disclosing sensitive information, thereby preserving confidentiality [78]. All these mechanisms ensure that the market remains secure and reliable [60].

#### 4) DEMERITS OF THE INTEGRATION OF BLOCKCHAIN INTO CARBON TRADING SYSTEM

While blockchain provides effective solutions when integrated into the carbon market, particularly in addressing issues of transparency and automation, it is not a panacea [36]. This means it does not resolve all the challenges faced by the market, and it comes with its own disadvantages, which are as follows:

- **Lack of Regulatory Framework**: The fact that BCT is still in its infancy is demonstrated by the absence of a standard legal framework governing its adoption in the carbon trading sector. It is important to recognise that existing regulations, such as the General Data Protection Regulation (GDPR) of the EU, address data privacy concerns. Given that blockchain records are stored permanently, there is currently no legal framework for navigating these regulations, which poses a significant issue that must be resolved before considering the full adoption and deployment of blockchain in the carbon trading market. Furthermore, different blockchains use different consensus mechanisms, which significantly influence their operation. In the context of using BCT to power a carbon trading market, there is no standardisation of rules or regulations, nor is there any consensus on which specific mechanism should be used. This lack of standardisation extends to the national, regional, continental, and global levels, making it a crucial issue for the structured development of blockchain-powered carbon markets [36]. To address the lack of a regulatory framework for blockchain adoption in carbon trading markets, both strategic action and targeted research are required. Proposed strategies include the development of a globally recognised regulatory framework governing the adoption of blockchain-powered carbon trading systems. This could be established by multilateral organisations such as the United Nations Framework Convention on Climate Change (UNFCCC) or the International Organisation for Standardisation (ISO) to standardise a unified framework that ensures consistent implementation across regions. Additionally, protocols should be implemented to ensure data encryption, anonymisation, and access control, specifically tailored for carbon market participants, in compliance with existing data protection laws. An awareness campaign should also be launched to educate stakeholders about the fundamentals of blockchain technology and its implications for carbon market implementation.
- **Environmental Impacts**: Some blockchain networks are still powered by the PoW consensus mechanism, such as Bitcoin [79] and SiaCoin [80], which generate a substantial amount of carbon emissions. Calling for the implementation of environmental regulations that govern the use of such blockchains, particularly when they are intended to power a market aimed at mitigating environmental pollution. To promote the use of energy-efficient blockchain networks in powering the carbon trading market, the system should adopt blockchain networks based on PoS consensus mechanisms and other energy-efficient protocols, such as Proof of Authority. Additionally, collaboration between renewable energy providers and blockchain network operators should be encouraged to ensure that renewable energy sources are used to power blockchain nodes. A reward mechanism should also be implemented to incentivise operators to transition to renewable energy sources. Furthermore, blockchain architectures should be designed using lightweight solutions, such as Directed Acyclic Graphs (DAG) or Sharded Blockchains, which require minimal computational power. Similarly, to reduce the computational load on the main network, layer 2 solutions, such as roll-ups or sidechains, could be employed.
- **Privacy Concern of Necessary Stakeholders**: One of the disadvantages of using blockchain in carbon trading markets is the privacy concerns of major stakeholders, such as governments, individuals, and business owners. Blockchain records are decentralised, immutable, and accessible to anyone, which may lead to reluctance among these stakeholders regarding the storage of their data in such an open system. Consequently, this lack of privacy could deter their participation in the market. To address the privacy concerns of stakeholders in a blockchain-powered carbon trading system, the adoption of a consortium blockchain network or a hybrid of private and public blockchain is recommended [62]. Additionally, privacy-enhancing technologies should be implemented, including the use of Zero-Knowledge Proofs (ZKPs), which enable transaction verification without exposing underlying data. Advanced encryption techniques, such as Homomorphic Encryption, should also be employed, allowing data to be analysed without

revealing raw data. Tiered access controls should be implemented to provide different levels of data accessibility based on stakeholder roles (e.g., buyers, sellers, regulators). Furthermore, to clear out misconceptions and foster trust in privacy-centric systems, regular workshops and training sessions should be conducted. These sessions should focus on managing privacy concerns in emerging technologies and include case studies demonstrating the successful implementation of privacy-preserving blockchain-powered carbon trading systems. It is also essential to encourage blockchain developers to prioritise privacy as a core feature of the system rather than treating it as an afterthought.

- **Lack of Scalability**: Another challenge associated with using blockchain in carbon trading markets is the limited scalability of blockchain networks at the moment. This poses a significant concern, particularly as emission data is expected to be transmitted directly and automatically from IoT sensor devices every second. The issue arises because existing blockchain networks face constraints related to scalability, latency, and throughput [62]. For instance, Hyperledger Fabric is currently capable of handling only 150 transactions per second under minimal latency, with a total transaction capacity of approximately 20,000 [81]. This metric would be insufficient if all large emitting entities were to migrate to this system. To address the scalability challenges of blockchain in managing large sets of real-time data from IoT systems, Layer-2 scaling solutions, such as rollups and sidechains, can be implemented. These solutions enable large transaction volumes to be processed off-chain, thereby reducing congestion on the main chain. Additionally, the blockchain network can be partitioned into smaller, parallel chains known as shards to distribute the workload effectively; this technique is referred to as sharding. For IoT systems, IoT-specific blockchain networks, such as IOTA, can be utilised. These networks are powered by Directed Acyclic Graphs (DAG), which enhance scalability. Moreover, prioritisation and batch-processing techniques can be applied. The prioritisation technique leverages edge computing to preprocess IoT data locally before sending it to the blockchain, reducing the load on the network. Similarly, batch processing groups similar transactions for collective verification, further minimising network congestion.

#### 5) CASE STUDIES ANALYSIS OF THE EFFECT OF BLOCKCHAIN ON CARBON TRADING MARKET

The carbon trading market has traditionally operated as a centralised marketplace, controlled by a central authority and reliant on manual reporting of emissions. However, the advent of blockchain has introduced immutability, decentralisation, and transparency across various sectors, including the carbon trading market. The integration of blockchain into this market has had a range of effects on real-world carbon trading, including positive impacts on transaction prices and data transparency. However, it also presents certain challenges, such as scalability limitations and the absence of a standardised legal framework. Some of the case studies that will be examined to assess the impact of blockchain integration in real-life carbon trading markets are as follows:

1) **Shanghai Environment and Energy Exchange**: A case study analysis was conducted on the Shanghai Environment and Energy Exchange to assess the impact of integrating BCT into the carbon trading market, specifically to determine whether this integration would influence the transaction prices within the market. The first transaction using this integration took place on 2nd April 2022. The findings indicate that blockchain has indeed contributed significantly to the carbon trading market. One of the key benefits is the improvement in the accuracy of emission data. The introduction of blockchain facilitated P2P transactions, fostering a greater level of trust and ensuring the authenticity of data. It also enabled cross-regional participation, unlike the conventional system, which limited participation to entities within the same region. The analysis further demonstrated that, prior to the introduction of blockchain, there was no significant effect on the market price of carbon quotas. However, following the integration of blockchain, the market price of carbon became bullish, reflecting increased stability and more predictable pricing. These positive outcomes contributed to the development of more refined policies as the market became more stable. Despite these advantages, the integration of blockchain into the carbon marketplace is not without its challenges. One of the primary challenges is the steep learning curve, as BCT requires substantial technical expertise, making it difficult for some participants to engage fully. Additionally, there is the issue of scalability, as an increase in transactions can result in delays due to the limited computing throughput available. There are also challenges related to the complexity of integrating blockchain with existing systems. Lastly, the lack of a regulatory framework governing the adoption of blockchain in the carbon trading market presents a significant challenge, as there are no established rules to support its widespread implementation [30].
2) **China's Carbon Market**: A case study analysis was conducted on the effects of implementing BCT in China's carbon markets, using Matlab simulation. This analysis conducted an explorative analysis of the topic from three perspectives: the macroscopic level, which considers policy incentives; the mesoscopic level, focusing on how BCT promotes advancements in China's carbon markets; and the microscopic level, which examines the effects on carbon trading

enterprises. This study revealed that China's pilot provincial and municipal carbon markets now cover more than 20 industries and approximately 3,000 companies. The findings show that the integration of BCT facilitates technological innovation, drives industrial transformation, and has notable impacts on market participants. For instance, participants experience increased trust in their relationships with other market entities, and entrepreneurs are increasingly motivated to explore innovative methods for reducing emissions. Additionally, the integration of blockchain into the carbon market has several benefits, such as real-time transaction capabilities, as well as the clearing and settlement of transactions being carried out on-chain, thus improving the accuracy of transaction reconciliation. Over time, these changes contribute to market stability as adoption grows. Furthermore, the case study noted that BCT has the potential to challenge and transform conventional, waterfall methods of transaction processing models. Because smart contract-powered processing, for instance, addresses trust issues while promoting automation and digitalisation within the markets. Nevertheless, some adverse effects were identified, some of which include the fact that market participation depends on market size. This reduces market participation as the market size is still low due to low sensitisation of the potential of blockchain on the carbon market. Highlighting the need for government intervention to introduce supportive policies that encourage the adoption of BCT in the carbon market [82].

3) **Pilot Programs in Shenzhen and Beijing**: An analysis examining the impacts and evolution of carbon trading through the application of BCT uses data from the most recent eight carbon trading pilot systems in China. The study noted that the duration required for companies to learn and effectively implement BCT depends on their willingness to adopt it. Among the positive effects identified, BCT was found to reduce the administrative costs associated with reporting carbon records, and it also enhances the privacy of participants within the carbon trading market. However, an identified challenge is the imbalance between the number of market participants and the potential capacity of the market, resulting from the slow rate of technology adoption [83].
4) **Microgrid Case of Urawa Misono, Japan**: A case study involving 10 consumers, 5 prosumers, and a shopping mall, all connected via an embedded distribution line to the primary utility grid, was conducted to explore the effects and challenges of BCT within the energy sector. This expository study focused primarily on the challenges associated with the current stage of technology adoption. Findings from the study indicated several notable challenges of BCT in its adoption and use in the carbon trading space, including issues related to scalability, limited throughput, low latency, and insufficient data storage. Furthermore, there is no legal framework in place to accommodate the peculiarity of the blockchain systems, and there is restricted interoperability, as systems powered by one blockchain network cannot seamlessly integrate with another. Although the blockchain network provides a certain level of inherent security, it remains vulnerable to cybersecurity threats if the code is improperly implemented. The study offered recommendations to address these challenges from various perspectives. From a societal perspective, broader public acceptance of the technology and skill development across society are essential. Environmental experts should resolve the uncertainties around the lack of a legal framework by establishing a robust legal structure to support the appropriate adoption of the technology. Finally, from an institutional perspective—primarily concerning entities responsible for emissions—it was recommended to set renewable energy targets [84].
5) **China's electric power sector**: The impact of BCT on the carbon trading market was evaluated through a case study analysis of China's carbon trading market, established to support the country's goal of achieving net-zero emissions by 2030 and attaining carbon neutrality by 2060. China's digitalised national ETS was launched on 16 July 2021. At the time of the case study analysis, it was noted that the volume of carbon traded had reached 179 million tons, with a turnover of approximately 7.68 billion yuan. Although the system currently functions in a manual manner, with carbon credit allocation, reporting, and verification carried out manually and in a centralised manner, the analysis result shows that the integration of BCT could enhance the system's transparency, security, and fairness, thereby improving market efficiency. However, some barriers continue to hinder the full adoption of blockchain in this domain, which include the lack of comprehensive legal support for the process [21].

Table 1 presents a comparative analysis of the case studies of real-world blockchain-based carbon trading systems that were examined. From the table, it is evident that blockchain technology offers significant benefits, including enhanced transparency and accuracy, which address the long-standing challenges in traditional carbon trading systems. These advantages are consistent across most of the case studies and include reduced transaction costs and processing times while fostering greater market participation and inclusivity.

However, several challenges are apparent across the case studies. These include limited scalability, inadequate data privacy measures, and the absence of a regulatory framework to guide the adoption of blockchain technology in the carbon trading domain. To address these limitations, it is recommended that collaboration and cooperation be established among governments, companies (or emitting

**TABLE 1.** Comparison of the analysis of the blockchain-powered carbon trading systems case studies.

| Case Study | Sample Size | Objective | Benefits | Challenges |
|---|---|---|---|---|
| Shanghai Environment and Energy Exchange | - | Cell Impact of integrating BCT into the carbon trading market. | • Improved accuracy.<br>• Trustworthy and authentic data.<br>• Cross-regional participation.<br>• Stable and predictable market price. | • Steep learning curve.<br>• Lack of scalability.<br>• Existing System Integration Complexity.<br>• Lack of regulatory framework. |
| China's Carbon Market | 20 industries and 3,000 companies | Effect on BCT implementation in China's carbon market from various perspectives. | • Enhanced trust among market participants.<br>• Real-time transactions clearing and settlement.<br>• Automation and digitalisation of within the markets. | • Market participation depends on market size.<br>• Reduced market participation. |
| Pilot Programs in Shenzen and Beijing. | 8 carbon trading pilot systems in China. | Impacts and evolution of carbon through the application of BCT. | • Reduce administrative costs.<br>• Enhances participants' privacy. | • Imbalance between the number of market participants and the potential capacity of the market.<br>• Slow rate of technology adoption. |
| Microgrid Case of Urawa Misono, Japan | 10 consumers, 5 prosumers, and a shopping mall. | Effects and challenges of BCT within the energy sector. | - | • Limited scalability and throughput.<br>• Low latency and insufficient data storage.<br>• No legal framework guiding technology adoption.<br>• Restricted system interoperability.<br>• Vulnerability to cybersecurity threats when code is improperly implemented. |
| China's electric power sector. | China carbon trading market. | Evaluation of the impact of BCT on the carbon trading market. | • Improve market efficiency through enhanced transparency, security and fairness. | • Lack of comprehensive legal support. |

entities), and technology providers. This joint effort would help develop a comprehensive regulatory framework to guide the adoption of blockchain technology while also tackling scalability and infrastructure barriers identified in the case studies.

Additionally, the case studies highlighted the effectiveness of implementing blockchain solutions in smaller, segmented regions, as demonstrated by the pilot programme in China. This approach helps identify system-specific challenges before scaling up, underscoring the need for more segmented real-world case studies and analyses across other regions of the world. Finally, to ensure awareness and proper orientation, stakeholders should receive training and resources for capacity building, enabling the smooth integration and adoption of blockchain technology within the carbon trading domain.

### B. RQ 2: WHAT IS THE MOST APPROPRIATE METHODOLOGY THAT CAN BE USED TO DEVELOP A BLOCKCHAIN-POWERED CARBON FOOTPRINT AND TRADING APPLICATION?

#### 1) ENTITIES INVOLVED IN THE MODEL

Since the operation or functionality of the system has to do with the interaction between two or more different parties, a number of studies highlighted the roles/entities involved in the system. Based on its practical usage and description, each of the roles listed highlighted by the articles under review can be explained as follows:

- *Authority*: supported by the government to make policies that regulate the system [26]. They reserve the right to issue permits and other assets needed to appropriately run the system [25]. They determine coverage, set the total amounts of carbon available, and allocate allowances [21]. As used by other authors, other terms used for the role that serves the same functionality of an Authority include Protocols, Government, Regulator and Supervisor, Organisers, Market Regulators (Policy Makers), Country-related gates [1], [21], [39], [51], [54], [62], [85], [86], [87].
- *Auditors*: are saddled with the responsibility of enforcing the laws established by the Authorities [26]. They act as an independent rating agent or evaluator [25]. Zhao and Chan [86] use the term validators to describe them as they verify transactions and provide services to carbon traders to ensure continuous maintenance of the system. Lu et al. [54] used a keyword more related to blockchain, as they describe this role as a decentralised enforcer because they consist of smart contracts such as the user registration contract (URC), the emission cap registration contract (ECRC), the emission permit purchase contract (EPPC) and emission violation contract (EVC), which respond to the core functionalities of the CTS. The fact that they also act as intermediaries between the system user and the government is one of the reasons why we can call them Validators [53]. Based on the system's architecture, there can also be consensus nodes that are high-reputation users that form a voting committee for validating transactions and adding transaction records to the blockchain [21].
- *Firms*: These are the businesses or end-users responsible for the emissions [26]. They act as the seller and the buyer in the carbon emissions markets [25]. Hartmann and Thomas [85] labelled them as Carbon Service Providers (CSP) and highlighted their role as project development, advising project clients through project registration and MRV processes, and aggregating carbon projects.
- *Individuals*: are the clients/customers that send or receive carbon allowances [1]. Terms used to describe similar roles by different authors include Project, Traders, Regulated Entities, Users, Manufacturers, Contractors, Buyers, Sellers and Element [21], [25], [53], [54], [62], [86], [88].
- *Technical Roles and Entities*: One of these is the Smart Meter, which provides data through its embedded sensor. These data will then be converted into carbon credits traded on the system [88]. As stated by Sadawi et al. [51], this is the standalone carbon emitting system. As there may be a need to resolve any problem or fault developed by the system, Shu et al. [53] consider the establishment of a technical department to be a good idea. This department is responsible for performing scheduled system maintenance, fixing bugs when they arise, and upgrading the system to meet the continuously improving demand placed on the CTS. We also have an administrator who works through an Application Programming Interface (API) [1].

All these roles must taken into account when designing or implementing a CTS powered by BCT to ensure a fully functioning and highly robust system.

**TABLE 2.** Average weighted total of proposed system.

| Article | Weighted total of the proposed system | | | Grade |
|---|---|---|---|---|
| | Minimum | Maximum | Average | |
| [26] | 7.43 | 7.92 | 7.68 | Very Good |
| [25] | 6.97 | 7.37 | 7.17 | Good |
| [62] | - | - | 7.64 | Very Good |
| [90] | - | - | 8.14 | Very Good |
| [53] | 7.2 | 7.8 | 7.5 | Very Good |
| **Average** | **7.20** | **7.70** | **7.62** | **Very Good** |

### 2) EVALUATION AND ANALYSIS OF THE BCT-POWERED CARBON TRADING APPLICATION

Konidari and Mavrakis [89] proposed a new multicriteria evaluation method that incorporates the combination of three standard multicriterion analysis (MCA) methods: the analytical hierarchy process (AHP), the Multi-Attribute Theory (MAUT), and the simple multi-attribute ranking technique (SMART). Channel toward evaluating climate change mitigation policy instruments and the need for a tool that helps climate policymakers conduct quantitative evaluations leveraging the criteria that reflect the policymakers' and stakeholders' preferences.

To confirm its viability, some of the authors evaluated the carbon trading application built with BCT using the new multicriteria analysis proposed by Konidari and Mavrakis [89]; the table 2 summarises the outcome of the evaluation.

This implies that comparing the proposed system to the existing conventional system, the proposed system has a better advantage in terms of environmental, political, and feasibility evaluation.

To further establish the feasibility of the system, Wang et al. [91] used a pilot study survey to support the assertion that BCT is worth it as it offers a two-way solution to improve the supply chain and reduce carbon emissions. Hu et al. [61], through a case study that illustrated that carbon trading using their proposed inner penalty mechanism powered by RoEE (Reputation of Emitting Enterprises), explained that BCT-ETS is more efficient in reducing carbon emissions than traditional or conventional methods. Xue et al. [92] also estimated the performance of the built CTS and deduced that the system meets the data processing efficiency and security demands. The accuracy rate of the model was over 92% and the data processing rate exceeded that of BCT alone. The duration of data processing was approximately 70 ms. The model was also evaluated in 100 experiments with different types of data, and the average

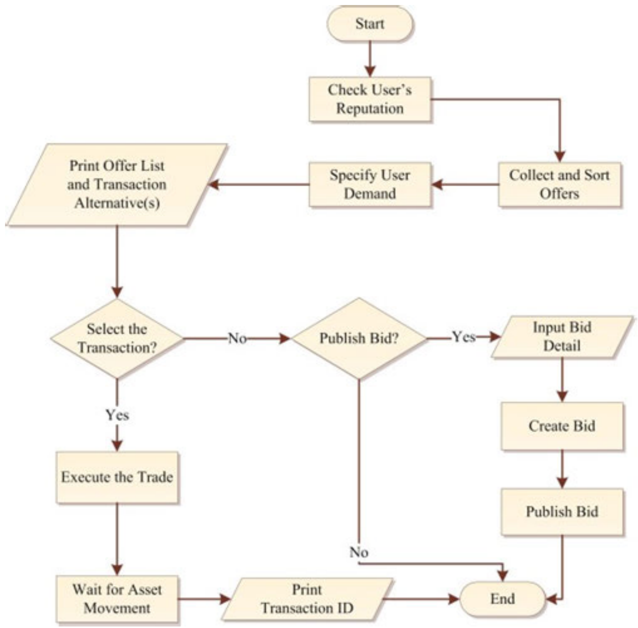


**FIGURE 9. Typical trading process of a blockchain-powered carbon trading system [25].**

accuracies were consistent between different types of data. For example, the accuracy rates for the economic, sports, and education data types were 91.4%, 92.1%, and 90.5%, respectively.

Based on the rationales given by the various studies conducted above, it can be confirmed that using BCT for the CTS is a viable and future-proof solution.

### 3) OPERATIONAL CONCEPT OF THE SYSTEM

Several previous studies have discussed how a digitalised carbon market flow should run from the beginning to the end.

In an effort to encourage continued and regular usage of the system, the algorithm Khaqqi et al. [25] used to power their system does not just reward the reduction of carbon emissions. But it also keeps track of the user's reputation; the user here is the Trader. As illustrated in the figure 9, the operational flow of the system is as follows. Buyers begin by collecting the offers from Sellers that they have access to, estimating this by their reputation or track record in their usage of the system thus far. The system then verifies the Buyer's reputation to grant access to the offers. Once authenticated, the offers are sorted according to their priority values (PVs). The top-ranked offers are selected first, and if they do not fulfil the buyer's needs, they can move on to the subsequent requests in the list until their requirements are met or until they reach the end of the list. When none of the offers are satisfactory, the buyer can wait or publish his bid. It is important to note that any published offer or bid becomes binding, and once the other party selects it, the initiator cannot withdraw it. Finally, the system operates with a protocol that includes market segmentation (price) and priority value order, which together determine the position of the bid on the final list of the other parties involved [25].

Hue et al. [59] also describe the process by which the system is meant to operate. The process begins with initialisation, where the seller kicks-starts the smart contract by specifying the offer conditions. Next, in the match bids and offers phase, an auction is conducted for the buyers, inviting them to submit their bids on the smart contract. After this, the bidding winner is selected, marking the end of the auction, with the buyer who bids the highest price emerging as the winner. At this point, the remaining buyers can withdraw their deposit from the smart contract. Subsequently, the credit is transferred from the seller to the winning buyer in the ownership exchange step. Finally, using access to the smart meter, once the smart contract has confirmed the transfer of the carbon credit from the seller to the buyer, the seller's wallet is credited with the highest buyer's deposit.

### 4) THE DESIGN OF THE SYSTEM

The system design should focus on meeting some major ETS requirements. These include authentication to ensure secure access, trustworthiness in all transactions, transparency in the process, and unbiased trading to maintain fairness. Additionally, the system aims to be incentive-compatible, encouraging active participation. It also incorporates dynamic bidding updates for flexibility and responsiveness and bidding strategy analysis to optimise outcomes. It should also include MRV mechanisms to provide data-driven insights and accountability [90]. When analysing the designed system, it is essential to meet the following design goals. The data must be correct based on the strength of IoT and blockchain. It should be auditable by the market regulator in a trustworthy way. The system should be able to automate carbon trading market activities without relying on third-party escrow since it is powered by a smart contract [54].

Based on the result, various tools can be used to implement the system. The core blockchain engine to build a CTS could be designed using multiple methods. One option is the multichain blockchain, derived from Bitcoin Core software; blockchain supports mining, financial transactions, and smart contracts. Another option is Ethereum, which facilitates smart contracts through its well-trusted currency, Ether [93]. Alternatively, a new dedicated blockchain engine could be created, specifically tailored to the carbon trading market, and a currency dedicated to trading allowances could be established. The authors then recommended considering Hyperledger, an open-source BCT, particularly Hyperledger Fabric and Hyperledger Composers, for their robust support of smart contracts. These tools have received contributions from industry leaders such as IBM, Intel, and SAP Ariba, making them a compelling choice for this blockchain engine design [51].

The front-end application can then be built with HyperText Markup Language (HTML) and JavaScript for easy and efficient user interaction. Moving forward, a suitable library can be used to connect the front-end application to the blockchain engine. For Ethereum, there are options of either Web3.Js (the heaviest size) or Ethers.js (smaller and more straightforward to ensure that the front-end application does not lag). These two libraries are JavaScript libraries, which have great support for Hypertext Transfer Protocol (HTTP) [51].

To develop a blockchain-powered carbon trading solution, Mitrea et al. [94] used Ethereum. Al Kawasmi [88] created one of the pioneering systems of this kind using Bitcoin. Khaqqi et al. [25] used Multichain, a private or permissioned blockchain network. Another permissioned blockchain network, Hyperledger Fabric, was adopted by Lu et al., Muzumdar et al., and Sadawi et al. [51], [54], [90]. In addition to implementing the system using Hyperledger Fabric, Lu et al. [54] also used Hyperledger Caliper to evaluate system performance. For MRV, which may involve sensitive information accessible only to stakeholders, Li et al. [62] specifically recommend a consortium or hybrid model of private and public blockchain platforms, such as Hyperledger Fabric. Abiodun et al. [29], in their pioneering ETS for Africa study, used both Hedera and Solana blockchain platforms. Sipthorpe et al. [36] conducted a study to assess 39 organisations developing blockchain-based solutions; among these, 18 are using Ethereum, with one employing Ethereum 2.0 and another using Energy Web Origin (a fork of Ethereum, meaning it was developed from Ethereum). Three organisations used Stellar, while five of the 39 used Hyperledger Fabric. Seven companies are using Native blockchain platforms, with one organisation each deploying Cosmos, Cardano, and Polygon. Six of the 39 organisations did not disclose which blockchain platform they used to build their carbon trading market. These platforms are highlighted to inform future researchers of the diverse range of blockchain platforms available for the development of upcoming blockchain solutions.

As previously mentioned, there is no strict rule governing the choice of the blockchain platform for developing a blockchain solution, whether it is to be a permissioned/public platform or a permissionless/private platform. Each stakeholder involved in the system's design should carefully assess the advantages and disadvantages associated with each of these systems to make an informed decision. This decision ultimately depends on the specific requirements of the system and the preferences of the developer. For a comprehensive overview of the advantages and disadvantages of private versus public blockchains, please refer to Appendix C, which includes the compilation by Franke et al. [37].

#### 5) THE IMPLEMENTATION OR METHODOLOGY OF THE SYSTEM

The system's expected outcomes should be structured to start from the user registration stage, where a public and private key are assigned to each system user. Following this, the organiser undertakes the initial allocation or auction of credits. Subsequently, certified emission reductions (CERs), which act as trading units, are registered within the system. Validators then process and record these transactions to ensure transparency and accuracy. Furthermore, the system integrates emission accounting via external devices, such as sensors and the IoT, to collect environmental data and seamlessly incorporate it into the blockchain. Finally, commitment enforcement takes place as user nodes transfer their credits to the organiser node to fulfil commitments. Validation nodes meticulously examine the volume of committed credits relative to the recorded cap and implement predefined penalties as needed to maintain the system's integrity and fairness [86].

To make the blockchain-powered CTS a robust, global, and reliable solution for the carbon trading market. The following system implementation methodology was proposed by [51]:

A three-level framework (Sender, Cross-Transfer Level / Protocol and Receiver) consisting of two types of blockchains (public and private, or consortium) was implemented. The framework was designed by connecting sensors to a blockchain. The framework design is based on connecting the low-level blockchain to carbon emission sensors and meters using the blockchain of things (BoT) concept. To enter data generated from IoT devices into the Hyperledger Fabric blockchain, a lightweight Remote Procedure Call (RPC) protocol called JSON-RPC should be used.

Simulations can be conducted using the Ethereum platform to confirm the usability of the cross-chain transaction mechanism framework. Testing of the smart contract deployment can also be carried out using the MetaMask and remix IDE [95].

Sensors wiring and connection could be done using node-red, an IoT network for programming IoT devices, so it is incorporated with Hyperledger Fabric to get data from IoT devices and feed and process information into a blockchain. Users' interaction with the Hyperledger blockchain can be done by building a user-friendly front-end application running a software development kit (SDK) with it. Depending on the language of choice, some available SDKs include Java SDK, Python SDK, Node.js SDK, and many more. After an agreement between the buyer and the seller, data transfer from the seller to the buyer will be done using any of the following protocols. Polkadot, Interledger, or Hyperledger Grid protocols [51].

#### 6) LAYERS INVOLVED IN THE IMPLEMENTATION OF THE SYSTEM

The implementation of an application follows a step-by-step process, with each step representing each phase of the system development process. By comparing the steps used by some of the studies under consideration, the layers have more similarities than the number of disparities they have.

Mandaroux et al. [60] implement a Distributed Ledger Technology (DLT) solution targeting the emission trading domain to reduce the probability of fraudulent attacks. The methodology used for the implementation was divided into six layers: Hardware, data, network, consensus, application, and novel identity layer. Hu et al. [61] also designed a blockchain-powered distributed ETS, which uses the following implementation layers. Data, network, consensus, incentive, contract, and application Layers. These architectural layers are similar to those used by [21], [53], [56], [93], and [96]. The only difference is that [21], [93], [96], introduced new terminologies at some layers of the architectures; these include terms like Contract, Basic Service, External Interface, P2P Network, Core technology, Interface, Adapter, User application and Smart Contract Layer. A brief overview of each of the architectural layers includes: These architectural layers are similar to those used by [21], [53], [56], [92], [97]. The only difference is that [21], [92], [97] introduced new terminologies at some layers of the architectures; these include terms like Contract, Basic Service, External Interface, P2P Network, Core technology, Interface, Adapter, User application and Smart Contract Layer. A brief overview of each of the architectural layers includes:

1) *Data layer*: This includes information on each of the participating entities in the network, various enterprise data such as Clean Energy Package (CEP) transactions, emissions data, asymmetric encryption, hash algorithms, and other technical elements [56], [61]. For traceability and verification of transactions, the data are stored with the time stamp of when they occurred [53]. The currently available blockchain platforms for these functionalities include the public/permissionless, private/permissioned, or hybrid/consortium blockchain platform [60]. It should be considered a significant layer of the system, and therefore, it must be tamper-proof and fully backed up [92].
2) *Network Layer*: It is the layer that controls communication and ensures the efficiency of data transmission [92]. A P2P communication model between nodes should be used to ensure the equal status of all emitting enterprises [60], [61]. This type of network architecture is needed to foster transparency, openness, security, and traceability of transactions [53]. The network should be a decentralised data structure and authentication of identity [97].
3) *Consensus layer*: Encapsulates the consensus mechanism algorithm for data authentication and identification [92]. The importance of this layer lies in the fact that it is necessary to maintain the integrity and security of the system as a whole. The layer ensures that all participants agree on the state of the blockchain by reaching a consensus on the validity of data before they are added to the blockchain [53], [56].
4) *Incentive layer*: This layer motivates participants to contribute to the blockchain system. It typically involves rewarding participants with tokens or cryptocurrencies for their participation in validating transactions or maintaining the network. This layer encourages active participation and helps secure the blockchain system. For example, once the proposers validate and package the information, they will receive a commission from other nodes to recognise their contribution to the system's data security [53], [61]. This goes further to ensure that the system encourages users to comply with the rules of the system functionalities [56].
5) *Contract layer*: This includes the smart contracts, scripts, codes, and algorithms [97] used to automate the execution of carbon trading actions [61]. Smart contracts are self-executing agreements with predefined rules and operational conditions, ensuring that contractual terms concerning the system's functionality are enforced without human intervention [53].
6) *Application layer*: The application layer consists of the user interface and end-user applications, offering different interfaces for regulatory bodies, trading partners, and traders, reflecting the unique roles and access levels of each [60]. This layer integrates all other layers and presents them to users in an accessible format [61]. The resulting system is commonly referred to as decentralised applications (DApps), as it uses and is constructed on blockchain infrastructures [53]. Prior to accessing this virtual carbon trading application, participants or traders are required to undergo authentication using tools such as Decentralised Identifiers (DID) and Verifiable Credentials (VC). The former functions as the identity anchor for each participant, while the latter operates as the emissions certificate [60].

Other layers not included in the list above but are of utmost importance include the hardware layer, which has to do with the interconnection of the nodes involved using a decentralised distribution [60]. The need for this layer can be demonstrated by using hardware infrastructure, such as sensors and IoT devices, to get data written into the distributed ledger.

Regular updates and routine system maintenance are needed to ensure that the software continually meets the industry's requirements. This validates the need for the technical layer. This layer will serve the function of providing system management services (Basic Service Layer) and offering invoking services for external applications (External Interface Layer) in case there is a need to integrate the application with another existing application through an API [97].

### C. RQ 3: WHAT ARE THE CURRENT RESEARCH GAPS AND LIMITATIONS IN THE EXISTING LITERATURE, AND POTENTIAL FUTURE STUDY DIRECTION FOR ENHANCING FUTURE BLOCKCHAIN TECHNOLOGY (BCT)-POWERED CARBON TRADING SYSTEMS?

#### 1) CHALLENGES OF BLOCKCHAIN TECHNOLOGY

Any technology offering significant advantages is expected to also present certain disadvantages. Given that BCT and its application across various domains remain relatively new, it is essential to watch for potential "bottlenecks" when replacing conventional systems. This vigilance is necessary to ensure that BCT does not introduce more challenges than the benefits it aims to deliver.

Yang et al. [96] identified that, as the technology is still new, there are unavoidable challenges at this stage. Some of the challenges identified by the author include scalability, interoperability, privacy leakage, and legal issues.

- *Scalability*: The storage capacity of each block is limited. During transaction processing, BCT requires that all entities within the network maintain a copy of the data. Consequently, as the rate or volume of transactions increases, there is a heightened risk of blockchain network failure due to the limited storage capacity of each block.
- *Interoperability*: Blockchain solutions presently operate in isolation, with no mechanisms in place for inter-communication or information sharing. For instance, a solution developed on the Bitcoin platform cannot communicate with a solution built on Ethereum.
- *Privacy leakage*: As BCT operates in a decentralised manner, it is essential to achieve consensus among the network entities to add information to the network. Transaction details are publicly accessible and transparently available to all entities, which could lead to potential privacy breaches. Additionally, network users may alter the consensus mechanism, potentially obstructing new transactions for questionable purposes. This vulnerability arises from the "51% attack," where control over computing resources is held by more than half of the entities on the network [98].
- *Legal Issues*: Currently, there is no established consensus on the legal framework supporting the use of BCT across various global domains. This absence of regulation could make BCT a potential tool for illicit activities, such as money laundering, financing terrorism, and other actions that could destabilise the financial market. Such risks arise because the supervision and monitoring of criminal activities within BCT are considerably more tedious.

#### 2) RESEARCH GAP FOR FUTURE RESEARCHERS TO EXPLORE

As Jiang et al. [83] observed, "Although some scholars have gradually directed attention towards research in the field of blockchain technology and carbon trading, they remain in the early stages of conceptual discussion regarding the integration of BCT and carbon trading, and do not provide direct empirical evidence or policy recommendations for BCT's application within the behaviours and activities of carbon trading enterprises." The greater the inclination of companies to adopt BCT, the shorter the time required for them to learn and master the technology, thereby accelerating the learning process. Consequently, increasing efforts are being devoted to advancing blockchain's practical applications in carbon trading research, leading to the development of more user-friendly applications that various industries can readily adopt.

Hua et al. [59] identified the limitation of their implementation as a lack of fault tolerance or data recovery mechanisms during smart meter data collection. The effect is that once the connection is broken, the issuance subsystem stops working without any attempts to reconnect.

A study by Sipthorpe et al. [36] to access 39 organisations interested in developing blockchain technological solutions found that most developed solutions are currently found in Europe, North America and Asia. This means that blockchain solutions are concentrated in more technologically developed countries, and five of the eight Asian organisations originate in Japan, Singapore, or China. Note that only one project was founded in South America and none of the organisations originated in Africa.

A study conducted by Sipthorpe et al. [36] examining 39 organisations involved in the development of blockchain technological solutions found that the majority of these solutions are currently concentrated in Europe, North America, and Asia. This indicates a predominance of blockchain solutions in more technologically advanced countries, with five of the eight Asian organisations based in Japan, Singapore, or China. Notably, only one project was established in South America, and none of the organisations originated in Africa.

#### 3) INNOVATIVE MODELS OF BLOCKCHAIN TECHNOLOGY IN THE CARBON TRADING MARKET FOR FUTURE RESEARCH

Some innovative models of how BCT can be included in the carbon trading market suitable for future researchers to explore are as follows:

1) **Tokenisation of Emission Rights**: An innovative model for future research on the application of blockchain in carbon trading markets is the tokenisation of emissions rights. Although the blockchain network is currently being used as a technology for powering CTS, carbon emission rights themselves could be tokenised, functioning similarly to a cryptocurrency. In this model, the right to emit carbon would be tied to an available balance, such that when an entity emits GHG, the balance of tokens would decrease accordingly, and vice versa. This approach would facilitate the use of emissions rights as a medium of exchange, similar to well-known cryptocurrencies such as Bitcoin, Solana, and others [99].
2) **Individualised Participation in the Market**: Most blockchain-based models for carbon trading are primarily implemented at the level of large emitting entities, often excluding individual participation and thus lacking inclusivity. A potential innovative model worth exploring in future research is a personalised carbon trading approach, which would foster a more inclusive CTS. This model would reward individuals for eco-friendly actions, allowing these rewards to be converted into tradable carbon credits. Such a framework would encourage individuals to monitor their behaviour and contribute to emission control within the carbon markets, thereby fostering green

practices among individuals in addition to large emitters that are part of the market already [100].

3) **Use of Smart Contract within the IoT device**: The existing model uses smart contracts to facilitate the trading process and automate actions once transaction agreements are fulfilled. To take this further, smart contracts can be integrated with the IoT system, allowing the process of using IoT-powered sensors to capture and report emissions data to be processed by smart contracts. This integration would enhance the inclusive functionality of smart contracts within the system.
4) **Layer 2 Technologies**: To address the scalability challenges that have hindered the full adoption of BCT, alongside high transaction fees and related issues, we propose the implementation of a layer-2 blockchain solution as an innovative model for future applications. This model involves off-chain transactions, as opposed to processing all transactions on the main chain, through solutions such as zkSync, which operates on Zero Knowledge Proof (ZKP) technology. This approach would enhance transaction processing speeds and alleviate congestion on the main chain, thereby significantly improving system scalability while simultaneously reducing transaction fees and the overall costs associated with using BCT in carbon trading markets [30].
5) **Involvement of all Supply Chain Participants**: Currently, certain supply chain participants are not engaged in the carbon trading market, resulting in manufacturers and other large emitting entities being the primary participants. This structure risks placing an excessive burden on manufacturers. It is recommended that supply chain participants, such as retailers and intermediaries, be incorporated into the market. This inclusion would facilitate a two-way cost-sharing contract, enabling intermediaries to support manufacturers in breaking even within the carbon market.
6) **Cooperative Investment Strategy**: It is recommended that a cooperative investment strategy should also be integrated into the blockchain-powered carbon trading market, as this market exemplifies a platform where value is exchanged. This involves the process of making provisions for emitting entities to acquire carbon credits through shared costs or without upfront payments in other to balance competition with cooperation. Given that BCT inherently enhances trust within the system, this approach would present no significant challenge. Such a model would facilitate greater adoption of BCT, as transactions could be performed regardless of an emitting entity's current financial status [101].
7) **Off-chain Payment System**: The predominant payment method for carbon quota transactions within the blockchain-powered carbon market is cryptocurrency. As an alternative or supplementary option, a payment system using the conventional Web 2.0 methods should also be available. This would accommodate participants who may not be part of the cryptocurrency world yet but wish to participate in the decentralised carbon trading market to manage their emissions. An off-chain payment system could be an effective solution, removing access barriers caused by crypto-payment and reducing transaction fees, thereby enhancing both the speed and scalability of the system. [23].
8) **Robust Legal Framework**: It has been rightly established that a significant hindrance to the adoption of blockchain in the carbon trading market is the absence of a supporting legal framework. Therefore, it is recommended that a robust legal framework be established to support the adoption of this technology within the carbon trading market. This initiative should be undertaken by the relevant governing authorities in collaboration with environmental experts.

## VI. CONCLUSION

### A. IMPLICATIONS OF THE STUDY

The study contributes to the available BCT-powered carbon trading literature in three unique ways.

Firstly, this research offers an essential overview of blockchain applications within the carbon trading market by reviewing 32 studies, thereby providing researchers with guidance on application areas as well as publication channels. Secondly, in response to the ongoing debate regarding the limited technologies available for constructing an effective CTS [72], this study considers the development of a CTS using BCT as a major contribution. Finally, the review aims to identify existing gaps that may pave the way for future research directions, alongside proposing specific questions for further investigation.

### B. CONCLUSION

The study conducted a systematic review of the literature based on carbon trading market systems that have been designed or implemented using BCT. This review examines the development of this blockchain application domain from 2015 to 2023. Data was gathered from 32 research publications, revealing that relatively few studies have focused exclusively on the application of BCT within the carbon trading market.

Although BCT has matured within the technology market, offering numerous benefits, its application within the carbon trading domain remains in its early stages and is accompanied by certain challenges.

While there is already a substantial understanding of the BCT concepts, scholars should endeavour to develop solutions using this technology to gain deeper insights into the practical applications of current ideas and the theoretical framework. Such efforts would move beyond merely discussing the benefits of BCT in theory, enabling real-world experiences through practical applications accessible to the entire population, regardless of the size or volume of their market participation.

This study is specifically limited to the use of BCT within the carbon market. However, research publications such as [95] have explored the combined operation of the carbon trading market alongside other trading mechanisms for energy sources, such as the distributed photovoltaic power generation market, using blockchain. To maintain a clear focus on addressing the research question, the authors have opted to leave such studies for future research or to recommend them as potential avenues for further investigation by other researchers.

Furthermore, while other methods exist for the indirect use of blockchain in reducing carbon emissions, this review is confined to published work on the direct application of blockchain to carbon footprinting, trading, and taxation. Although other studies extensively examine blockchain's role in emissions reduction, they often involve third-party innovations or technologies, such as electric vehicles, electronic waste management, and the circular economy. To maintain a focused examination of the carbon footprinting associated with daily human activities and industrial processes, the carbon footprint generated by BCT itself has been excluded from this study. These studies instead explore the feasibility of BCT for long-term use with reduced carbon emissions associated with the technology.

### C. FUTURE STUDY EXPLORATION

The study primarily analysed existing research on blockchain technology within the carbon trading market domain, with the aim of providing a comprehensive overview and establishing a foundation for future exploration in this emerging field. The mechanisms and implementation strategies of the proposed innovative model were not fully explored, reflecting the scope and limitations of the current study. This provides a potential avenue for future researchers to further investigate the advantages and challenges of blockchain technology in carbon trading markets. These aspects were only outlined broadly in the study to offer readers a general overview without delving into the underlying mechanisms. By doing so, the study aims to lay the groundwork for subsequent research to explore these mechanisms in depth and propose targeted solutions.

Additionally, the study offered limited elaboration on how the proposed innovative model could be implemented, including the associated challenges and potential solutions. While these aspects were highlighted, they were not comprehensively addressed, thus encouraging further scholarly investigation. This gap serves as an invitation for future research to examine these issues in greater detail, thereby contributing to the advancement of knowledge in this domain.

Furthermore, the article addresses significant aspects, such as achieving the global goal of net-zero carbon emissions and promoting the transition to renewable energy; it provides limited logical linkage between the identified issues in current carbon trading systems and the application of blockchain technology. This connection has the potential to be articulated more explicitly. Consequently, this presents an opportunity for future researchers to deepen the analysis by establishing a stronger logical bridge between the research background and the questions related to blockchain applicability. Such efforts could enhance the credibility and effectiveness of the carbon trading market, incentivise greater participation, and contribute to reduction in emissions.

**TABLE 3. Publications included in the review.**

| S/N | Reference | Title |
|---|---|---|
| 1 | [25] | 'Incorporating seller / buyer reputation-based system in blockchain-enabled emission trading application.' |
| 2 | [26] | 'Blockchain enhanced emission trading framework in fashion apparel manufacturing industry.' |
| 3 | [59] | 'A blockchain based peer-to-peer trading framework integrating energy and carbon markets' |
| 4 | [88] | 'Bitcoin-based decentralised carbon emissions trading infrastructure model' |
| 5 | [51] | 'A comprehensive hierarchical blockchain system for carbon emission trading utilising blockchain of things and smart contract' |
| 6 | [12] | 'Blockchain of carbon trading for UN sustainable development goals' |
| 7 | [91] | 'Blockchain technology and its role in enhancing supply chain integration capability and reducing carbon emission: A conceptual framework' |
| 8 | [37] | 'Designing a blockchain model for the Paris agreement's carbon market mechanism' |
| 9 | [85] | 'Applying Blockchain to Australian Carbon Market' |
| 10 | [60] | 'A European emissions trading system powered by distributed ledger technology: An evaluation framework' |
| 11 | [61] | 'Delegated Proof of Reputation Consensus Mechanism for Blockchain-Enabled Distributed Carbon Emission Trading System' |
| 12 | [62] | 'A blockchain-based emissions trading system for the road transport sector: policy design and evaluation' |
| 13 | [102] | 'Blockchain application for the Paris agreement carbon market mechanism-a decision framework and architecture' |
| 14 | [83] | 'The influencing factors of carbon trading companies applying blockchain technology: evidence from eight carbon trading pilots in China' |
| 15 | [36] | 'Blockchain solutions for carbon markets are nearing maturity.' |
| 16 | [86] | 'When is blockchain worth it? A case study of carbon trading.' |
| 17 | [54] | 'STRICTs: A Blockchain-enabled Smart Emission Cap Restrictive and Carbon Permit Trading System' |
| 18 | [90] | 'A permissioned blockchain enabled trustworthy and incentivised emission trading system.' |
| 19 | [103] | 'The Impact of Digital Economy of Resource-Based City on Carbon Emissions Trading by Blockchain Technology' |
| 20 | [53] | 'Blockchain-enhanced trading systems for construction industry to control carbon emissions' |
| 21 | [104] | 'Mechanism analysis of applying blockchain technology to forestry carbon sink projects based on the differential game model' |
| 22 | [97] | 'Emission trading innovation mechanism based on blockchain.' |
| 23 | [56] | 'Research on the Blue Carbon Trading Market System under Blockchain Technology' |
| 24 | [87] | 'Simulation Research On Carbon Emissions Trading Based On Blockchain' |
| 25 | [105] | 'Global carbon surcharge for the reduction of anthropogenic emission of carbon dioxide' |
| 26 | [1] | 'A Carbon Accounting and Trading Platform for the UK Construction Industry' |
| 27 | [106] | 'Research on Carbon-Trading Model of Urban Public Transport Based on Blockchain Technology' |
| 28 | [43] | 'A Novel Credible Carbon Footprint Traceability System for Low Carbon Economy Using Blockchain Technology' |
| 29 | [21] | 'Smart contract design and process optimisation of carbon trading based on blockchain: The case of China's electric power sector.' |
| 30 | [94] | 'Privacy-Preserving Computation for Peer-to-Peer Energy Trading on a Public Blockchain' |
| 31 | [23] | 'A Blockchain-Based Method for Optimizing the Routing of High-Frequency Carbon-Trading Payment Channels' |
| 32 | [92] | 'Power enterprises-oriented carbon footprint verification system using edge computing and blockchain' |

Another limitation of the study is its exclusive reliance on the Scopus database for article data collection. While Scopus is widely regarded as the largest and most reputable academic database, its sole use may introduce issues related to incomplete disciplinary coverage or regional bias in the study. These limitations could potentially affect the representativeness of the research findings.

## APPENDIX A
## SEARCH QUERY

*Search Query Used for the Advanced Scopus Database Search*

TITLE-ABS-KEY ((‘‘Blockchain*’’ OR ‘‘Blockchain’’ OR ‘‘Smart Contract*’’ OR ‘‘Distributed Ledger*’’ OR ‘‘crypto currenc*’’ OR ethereum) AND (‘‘Carbon tax*’’ OR ‘‘Carbon trad*’’ OR ‘‘Carbon footprint*’’ OR ‘‘Carbon finance *’’)) AND (LIMIT-TO (LANGUAGE, ‘‘English’’)) AND (LIMIT-TO (PUBSTAGE, ‘‘final’’)) AND (LIMIT-TO (DOCTYPE, ‘‘ar’’) OR LIMIT-TO (DOCTYPE, ‘‘cp’’) OR LIMIT-TO (DOCTYPE, ‘‘ch’’) OR LIMIT-TO (DOCTYPE, ‘‘re’’) OR LIMIT-TO (DOCTYPE, ‘‘cr’’))

## APPENDIX B
## PUBLICATIONS INCLUDED IN THE REVIEW

See Table 3.

## APPENDIX C
## COMPARISON OF PUBLIC AND PRIVATE BLOCKCHAIN

Typical Comparison between Public and Private Blockchain platforms [37].

| | Ethereum | Hyperledger Fabric |
|---|---|---|
| | *Permissionless and Public* | *Permissioned and Private* |
| **Advantages** | Total transparency for internal and external actors | Full control over who has access to the network and validates transactions |
| | Support from external actors, e.g., develop further applications for participation | Over APIs, it can be implemented as process layer connecting the existing infrastructure, or as new system |
| | Project-chain to increase privacy during the implementation of corresponding adjustments | Development of smart contracts in different programming languages possible |
| | Make use of synergies from existing energy and governmental projects | Existing high-end cases of usage in the energy field, e.g., TenneT |
| | Large community which provides full nodes to stabilize the blockchain | Can define tokens upon the blockchain and no other tokens necessary |
| | Independent creators of the architecture | No transaction fees |
| | Reduction of server costs by relying on public full nodes | Developed by the independent Linux Foundation |
| | Can be integrated as a process layer on the existing server infrastructure of the UNFCCC or as a new system | Low potential for forks |
| | Transaction size smaller (0.2 KB compared to 3 KB) | Channels for private transactions |
| **Disadvantages** | High transaction fees (~$131 per day for the Paris Agreement) | Limited access and transparence for external actors |
| | Cannot control who validates transactions | No support or synergies possible with external associations or foundations |
| | Data security and integrity is not ensured at other full nodes | Closed system is more vulnerable against node failures |
| | Depends on existence of Ethereum | Necessary to establish a network of full nodes |
| | A high number of forks with PoS | Storage will increase by approximately 1.17 GB per year. |
| | Have to store the Ethereum blockchain (current size: approximately 115 GB) | |

**FIGURE 10.** Typical comparison between public and private blockchain [37].

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