sustainability

Systematic Review

Blockchain's Scope and Purpose in Carbon Markets: A Systematic Literature Review

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Abstract: Carbon markets, particularly emission trading schemes (ETS) and carbon offset projects, are significant mechanisms in climate change mitigation. However, there are still a number of unresolved issues regarding their attractiveness and efficient functioning. Blockchain, as the core of "3D's concept" (including decentralization, decarbonization and digitalization), could be considered as a candidate solution for carbon markets' improvement. A systematic literature review was conducted to identify the role of blockchain in ETS and carbon offset projects, its key features, implementation challenges and proposed applications, by analyzing and discussing the content of relevant studies, and grouping the results into domains. This study's findings show that blockchain has great potential to be adopted in carbon markets. However, there is no data on blockchain use cases in energy efficiency, chemical processes and industrial manufacturing, waste disposal, and agriculture. Blockchain-based household and transportation carbon offset projects are linked to renewables through energy trading. Renewables and forestry are the most appropriate domains for blockchain adoption, considering various criteria of quality for carbon offset projects. Blockchain is currently immature in carbon markets because of its own drawbacks and challenges. This study also highlights research gaps and offers research directions to inspire researchers for conducting related investigations.

Keywords: blockchain; carbon markets; carbon credits; carbon offset projects; emissions trading scheme; systematic review

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1. Introduction

Carbon dioxide (CO_2) is considered to be the most important greenhouse gas (GHG) of anthropogenic origin-caused climate change. The emergence of carbon emissions consequences forced the international community to develop mechanisms for their regulation. A carbon tax became the first form of regulation, and it subsequently reduced carbon emissions. The cap-and-trade (CAT) system instituted under the 1990 Clean Air Act in the United States is credited with achieving significant reductions in acid-rain-causing sulfur-dioxide emissions by power plants [1]. The Kyoto Protocol, adopted in 1997 and launched into force in 2005, was the first attempt aimed at reducing and regulating GHGs internationally [2].

1.1. Emission Trading Schemes (ETS)

Based on the cap-and-trade system, emission trading has actually transformed carbon into a commodity. Most trading schemes use one-ton carbon-dioxide (tCO_2e) units for sale, or convert non-CO_2 gases into CO_2-equivalent units for the purposes of carbon credits trading. Thus, it gave an impetus for launching national compliance carbon markets (CCM), also known as emission trading schemes (ETS) worldwide (Figure 1). According to Jiang et al. [3], the ETS of the CCM global share in 2021 was approximately USD 270 billion, representing the equivalent of 15.8Gt CO_2-e traded on them. According to Refinitiv [4], the total compliance carbon market value in 2021 was EUR 762 billion, or approximately USD

850 billion, up 164% from 2020 on higher carbon prices. In 2022, the CCM value maintained the growth trend, reaching EUR 865 billion (nearly USD 924 billion) [4].

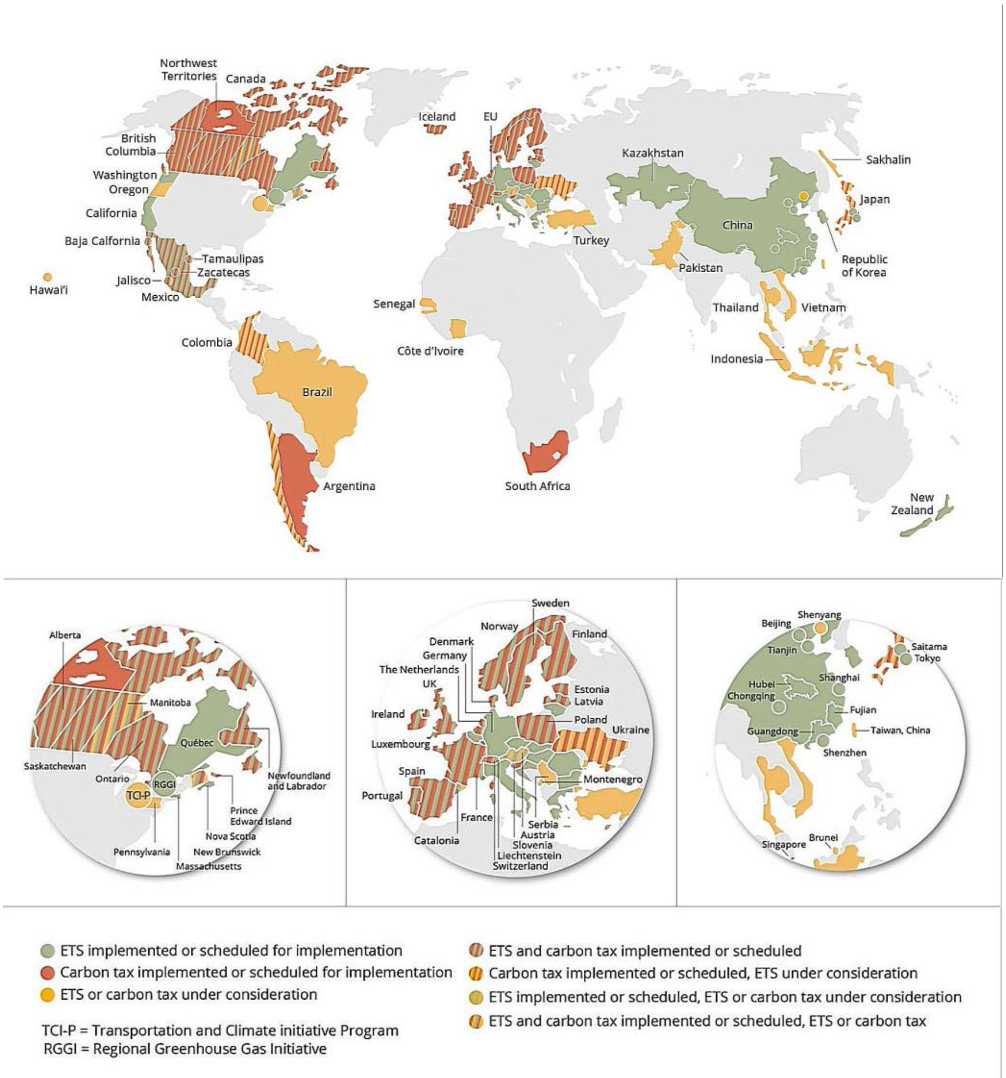

Figure 1. The world map of carbon taxes and emissions trading schemes (ETS), adapted from [5].

1.2. The Emergence of the Voluntary Carbon Markets (VCM)

In addition to emissions trading on national, regional or international markets, the Kyoto Protocol also provided so-called "flexibility mechanisms": the Clean Development Mechanism (CDM) and Joint implementation (JI) projects [6,7]. The resulting certified emission reductions (CERs) can then be used by the Annex I Party to help meet its emission reduction target. Thus, it became possible to expand carbon credits creation by the cultivation of avoidance/reduction projects (e.g., renewable energy, methane capture) or through removal/sequestration projects (e.g., direct carbon capture and storage, afforestation and reforestation projects) [8]. Therefore, it also created the basis for the emergence of voluntary carbon markets (VCM) worldwide. Most often in such markets, companies are guided by the principles of Environment, Social, Governance (ESG) and Corporate Social Responsibility (CSR) in order to decrease their carbon footprint [9]. In contrast to carbon credits generated in CCM through the ETS, verified emission reductions (VERs) or carbon credits of VCM flow horizontally. The issuing of carbon credits under VCM are determined by the cultivation of carbon offset projects in order to purchase carbon credits that, therefore, could be traded on carbon markets. In comparison to the compliance markets, voluntary carbon markets are developing rapidly. However, the recent Ecosystem

Marketplace report [10] reveals that the VCM value in 2021 was only USD 2 billion. About 500 million carbon credits were also traded in the same year, surpassing the previous year by 66%.

1.3. Carbon Offset Projects

The Ecosystem Marketplace report [10] generally identifies eight categories of carbon offset projects in VCM (Table 1). The related typology is shown in Figure A1 in Appendix A.

Table 1. Voluntary Carbon Market (VCM) transaction volumes, prices, and values by category in 2020–2021, adapted from [10].

Categories	2020			2021		
	Volume (Million $MtCO_2e$)	Price (USD)	Value (Million USD)	Volume (Million $MtCO_2e$)	Price (USD)	Value (Million USD)
Forestry and land use	57.8	5.40	315.4	227.7	5.80	1327.5
Renewable energy	93.8	1.08	101.5	211.4	2.26	479.1
Chemical processes/Industrial manufacturing	1.8	2.15	3.9	17.3	3.12	53.9
Waste disposal	8.5	2.69	22.8	11.4	3.62	41.2
Energy efficiency/Fuel switching	30.9	0.98	30.4	10.9	1.99	21.9
Household/Community devices	8.3	4.34	36.2	8.0	5.36	43.3
Transportation	1.1	0.64	0.7	5.4	1.16	6.3
Agriculture	0.5	10.38	4.7	1.0	8.81	8.7

1.4. Basic Challenges of Carbon Market Functioning

Along with the diversity and opportunities of carbon markets, there are still a number of unresolved issues regarding their attractiveness and harmonious, efficient functioning.

1.4.1. The Allocation of Carbon Emission Quotas

With the establishment of CCM, carbon prices have been far too low to motivate companies to make efforts to reduce their emissions. Companies have to invest more in the purchase of carbon credits rather than in emission reduction technologies or projects [11–15]. Thus, the mechanism of carbon emission quotas allocation is considered important from the point of view of the overall climate policy for cost-effective GHG reduction. Generally, permits are distributed among companies/industries on a national/regional scale either for free (grandfathering) or through auctions [16]. Grandfathering means that the government is able to allocate permits on the basis of past usage, on some measure of output, or to politically-favored groups [17]. When credits are grandfathered, this puts new or growing companies at a disadvantage relative to more established and well-known companies [18]. Thus, this could be perceived as a protectionist obstacle for new participants in their markets. Alternatively, the emission allowances can be distributed through auctioning by selling to the highest bidders, rather than allowing polluters to receive carbon credits for free [17].

1.4.2. Carbon Leakage

The JI projects and the CDM under the Kyoto Protocol created the opportunity for huge businesses or whole industries to transfer their production facilities to other countries which have low environmental regulation standards. The direct result of this patchwork of mechanisms is known as "carbon leakage".

1.4.3. The Growing Collapse of CDM Projects

According to the United Nations Framework Convention on Climate Change (UNFCCC) [19], as of 30 April 2023, 7844 CDM projects were registered. However, due to the prolonged downward trend in CER prices, potential projects were not commercially viable and the number registered by UNFCCC [19] gradually decreased (Figure 2). Thus, the CDM has failed to consistently deliver development and sustainability benefits [20,21].

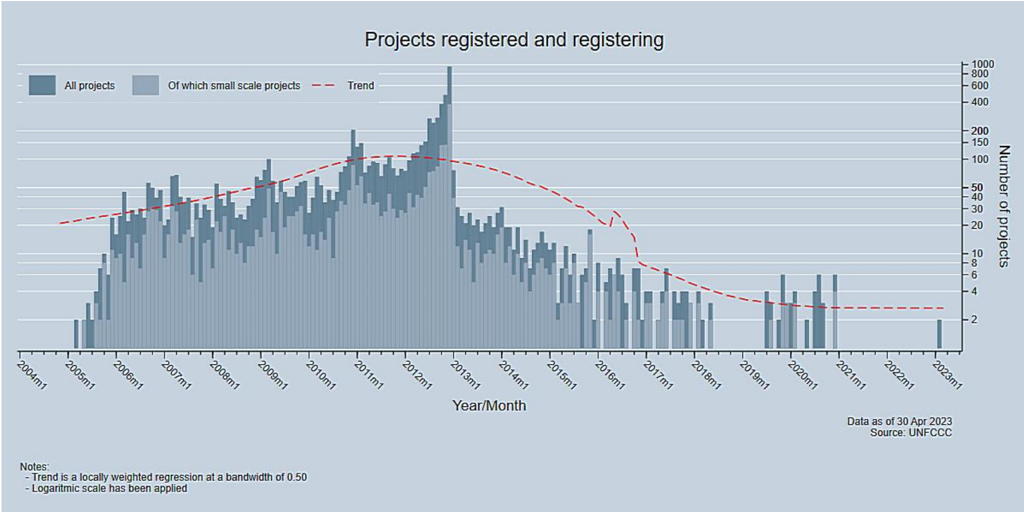

Figure 2. Monthly registered Clean Development Mechanism (CDM) projects in 2005–2023, adapted from [19].

1.4.4. Quality Criteria in Carbon Offset Projects

Notably, the size of the voluntary market for carbon offset projects is still quite low (USD 2 billion in 2021 compared to USD 851 billion for mandatory projects in the same year) [4,10]. Companies betting on the implementation of such projects with an often difficult-to-identify contribution to climate change mitigation are much more likely to engage in greenwashing. Studies of carbon offsets highlight a number of challenges facing the implementation of avoidance/reduction and removal/sequestration projects.

First of all, there needs to be a baseline and measurement criterion. The baseline setting is the amount of emissions that would occur in the absence of a proposed project. In order to estimate the amount of stored carbon, there should be an established methodology that does not exaggerate the potential for carbon sequestration [22].

Secondly, carbon offset projects should be verifiable and transparent. Projects need to have carbon storage verified by third-party experts and respective data should be open-access for stakeholders [23]. The fulfillment of this criterion could ensure the credibility of the project, which is the key to the inflow of investments and obtaining financing.

Additionality is also considered an equally important criterion. Carbon offset projects could be recognized as "additional" if emissions reduction and/or an increase of GHGs absorption was formed due to measures taken in addition to or in contrast to the business-as-usual practice in accordance with current legislation and accepted business norms [24]. For example, the installation of renewable energy sources can be carried out on the basis of financial feasibility for reasons of saving electricity costs or in accordance with the adopted normative legal acts.

Fourthly, the criterion of permanence is important. In the case of forest carbon offset projects, being an option of nature-based solutions (NBS), there is a risk of deforestation and forest degradation factors, i.e., pests and diseases outbreak, forest fires, and unsustainable logging [25]. Thus, it may reverse the gains in stored carbon. Registries for these offsets generally require that there be insurance, a buffer, or some other mechanism to make up for potential losses.

The next important criterion of quality is the double-counting issue. The fact is that carbon is essentially a somewhat intangible gas, the physical transmission of which cannot easily be fixed. Thus, when an emission reduction is sold to another country or company abroad, a bona fide selling country must make an adjustment to its emissions and delete it from its volume, i.e., record the transfer of reductions for use elsewhere. In practice, however, it turns out that the emissions reductions will be taken into account twice–both for the seller and the buyer [26].

Possible co-benefits of carbon offset projects are also considered to be an integral part of their quality. Co-benefits are any positive impacts, other than direct GHG emissions mitigation, resulting from carbon offset projects. This positive influence often lies in education improvement, environment conservation, and bringing other socio-economic benefits [27]. Most, if not all, co-benefits interact with one another, and therefore, are achieved simultaneously when reducing carbon emissions.

Finally, "carbon leakage" within carbon offset projects is also important. A classic example of leakage is when large reforestation plantations displace the subsistence agriculture of native communities and lead to new deforestation elsewhere to compensate for the lost cropping area [28].

1.5. Blockchain as a Solution to the Improvement of Carbon Market Functioning

The above overview of carbon markets highlights their complexity. The Paris Climate Agreement, adopted in 2015, is in fact the successor to the Kyoto Protocol, which expired in 2020, and has also taken into account the role of carbon markets (Article 6) [29]. The establishment of the CCM and VCM has created a number of difficulties related to the effectiveness, accountability, transparency and operability of these mechanisms. In particular, carbon credits and carbon offsets themselves, as well as the volumes of GHG released or reduced, are big data that must be kept in a special register. The system of their distribution and relative transactions between countries/industries/companies/projects is not always carried out according to open principles. In this connection, disputes arise, and protectionist measures such as carbon tax implementation are put into effect [30]. At the same time, the main issue about real carbon emissions reduction due to the measures taken remains open. Thus, it is a must for each party in this process to make a measurable impact. In order to mitigate climate change and global warming, regulate carbon credits transactions and their allocation, and improve carbon offset projects management, blockchain could be considered as a candidate solution.

Schletz et al. [31] emphasize the value of blockchain for global carbon markets in the scientific literature concerning two basic aspects. On the one hand, some studies [32–35] suggest that blockchain is able to promote the digitalization of the measuring, reporting, and verification (MRV) processes during climate mitigation activities. On the other hand, some studies [36,37] suggest that the possible implementation of blockchain in carbon markets could combine heterogeneous national emission accounting systems in one meta-registry (e.g., "The Climate Warehouse" proposed by the World Bank [38]).

In this article, authors performed a systematic literature review (SLR) to understand the role of blockchain in two forms of carbon markets (including ETS and carbon offset projects), and identify its key features, implementation challenges, and proposed applications, by reviewing existing case studies and filling the knowledge gaps. To the best of our knowledge, there is no study comprehensively investigating the potential of blockchain technology in carbon markets. The structure and research design of this article were inspired by reviewing the study of He and Turner [39]. The authors conducted an SLR for the assessment of blockchain's possible implementation in forestry, while highlighting its benefits, opportunities and challenges. Based on this method, some other scholars propose blockchain technology for implementation in green technologies, decarbonization management practices, and sustainable business models [40–42].

The research objectives of this study: (1) to investigate the operation features of blockchain in ETS; (2) to reveal the scope of blockchain in carbon offset projects; (3) to assess technology's potential to meet the criteria of quality in carbon offset projects; and (4) to identify the obstacles and challenges of its implementation in carbon markets. The contribution of this study is to provide guidance for decisions and policy-makers, startups, stakeholders and others involved or interested in the field of "3D's concept" (namely decentralization, decarbonization and digitalization) about blockchain's scope and purpose in

ETS and carbon offset projects. Furthermore, this study also provides a platform for further research directions, concepts and improvements regarding blockchain implementation in carbon markets.

This paper consists of six sections. Section 1 introduces the development and main challenges of carbon markets (including ETS and carbon offset projects). Section 2 introduces blockchain technology. Section 3 presents the systematic literature review methodology, the research questions, and the data collection procedure. Section 4 discusses the findings of this SRL. Section 5 highlights the theoretical implications and presents further research directions. Section 6 provides the conclusion and limitations.

2. Blockchain Overview

The concept of blockchain technology was proposed by Satoshi Nakamoto in 2008, and was first applied in practice when Bitcoin appeared in 2009 [43]. Currently, cryptocurrencies are among the most promising blockchain applications. Mainly due to decentralization (bypassing intermediaries, such as banks), their implementation for individual and organizational purposes created huge potential for business [44]. However, the scope of blockchain is noticeably wider. Blockchain is a system of records on the transfer of any value on the principle of "peer-to-peer".

According to Mougayar [45], there are "three different, but complementary definitions of the blockchain: a technical, business, and legal one". Technically, "the blockchain is a back-end database that maintains a distributed ledger (DLT), that can be inspected openly" [45]. Business-wise, "the blockchain is an exchange network for moving transactions, value, assets between peers, without the assistance of intermediaries" [45]. Legally, "the blockchain validates transactions, replacing previously trusted entities" [45].

As shown in Figure 3, the first block in the chain is called the "Genesis block". Each node in the network has an identical copy of the blockchain, where each block represents a set of timestamped transactions and a connection with the previous block. The chain of blocks is constantly growing while each new block is added [46]. Each block header contains a hash of the previous block, so there is no opportunity to imperceptibly change the transaction in the previous block [47]. The block body contains a list of verified transactions, their amounts, addresses of the parties and some other details [48]. Thus, having the last block, it is possible to get sequential access to all the previous blocks in the blockchain.

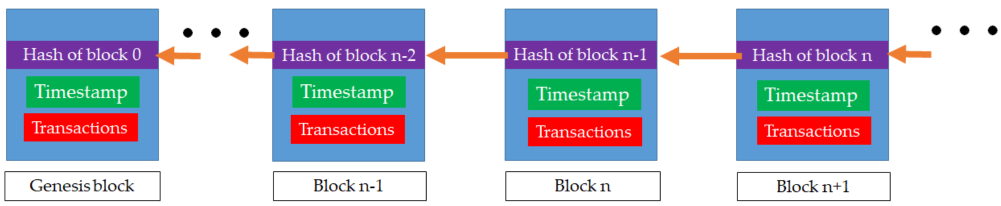

Figure 3. The operation principle of blockchain.

Basically, there are two main types of blockchain: public (permission-less) and private (permissioned) [49]. Public blockchains can be read by any user, each of whom has the right to form transactions [50]. Bitcoin and Ethereum are examples of permission-less blockchains [43,51]. Private blockchains are blockchains in which the creation of blocks is centralized and all rights to conduct such operations belong to one organization. The "general public" can only read information—only trusted nodes are able to audit, manage databases and other applications [50]. Some researchers [39,49] and Ethereum founder Vitalik Buterin [50] also highlight the consortium (hybrid) blockchain. Its peculiarity is that the approval process in it is controlled by a pre-selected set of nodes. However, the consortium blockchain is still not widely distributed.

2.1. Consensus Mechanism

In the blockchain, which is a decentralized system that does not have a single governing body, various algorithms have been developed to achieve consensus. The consensus algorithm in the blockchain is a set of certain mathematical rules and functions that allow it to reach an agreement between all participants (nodes) and ensure the operability of the network. Currently, there are several different methods of reaching consensus.

Bitcoin uses the Proof of Work (PoW) consensus mechanism to randomly select a node that can find and offer a new block to the network [43,45,51]. In the case of PoW, all computers on the network that are tasked with maintaining the security of the blockchain (in the case of Bitcoin, they are called miners) work on calculating a mathematical function called a hash. As soon as a new block is found and distributed to all nodes, it is checked whether this block is a valid block with all legitimate transactions. The nodes then add this block to their own copy of the blockchain. PoW is an expensive and energy-intensive method due to the required computing power [45,50].

Proof of Stake (PoS) is an alternative method that does not require special equipment [45,49]. In the case of PoW, the probability that a participant will add the next block of transactions to the chain is determined by the hash level. In the case of PoS, miners must deposit their "bet" of the digital currency in order to get a chance to be randomly selected as a validator. Thus, in a way, the process is similar to a lottery. PoS is considered as a more sustainable and environmentally friendly alternative to PoW, and iss more protected from a "51% attack" [50]. However, since the system gives preference to organizations with a large number of tokens, PoS has attracted criticism for the fact that it can lead to centralization. A well-known PoS platform is Ethereum (after the Merge update). The Practical Byzantine Fault Tolerance (pBFT) consensus algorithm requires a 2/3 majority of members to reach consensus [45,49].

In addition to the above consensus mechanisms, there are also Delegated Proof-of-Stake (DPoS), Proof-of-Action (PoA), Proof-of-Authority (PoA), Proof of Burn (PoB), Proof of Capacity (PoC), Proof-of-Elapsed Time (PoET), Proof-of-History (PoH), and Proof-of-Importance (PoI) consensus mechanisms [45,49]. Each of them has its own set of advantages and disadvantages. In all cases, the goal of the consensus approach is to ensure the security of the network, mainly through economic means: an attack on the network should be too expensive, and its protection should be more profitable.

2.2. Smart Contracts and Oracles

The "smart contract" is a certain business logic that works on the network, moving value in the semi-autonomous mode and ensuring the fulfillment of payment agreements between the parties [45,52]. The smart contracts make it possible to perform reliable and confidential transactions without the participation of external intermediaries, represented by banks or government agencies. In addition, such transactions are traceable, transparent and irreversible. This technology not only contains information about the obligations of the parties and sanctions for their violation, but also automatically ensures the fulfillment of all the terms of the contract (Figure 4). The example of a platform implementing smart contracts is Ethereum, which was proposed in 2013 [52].

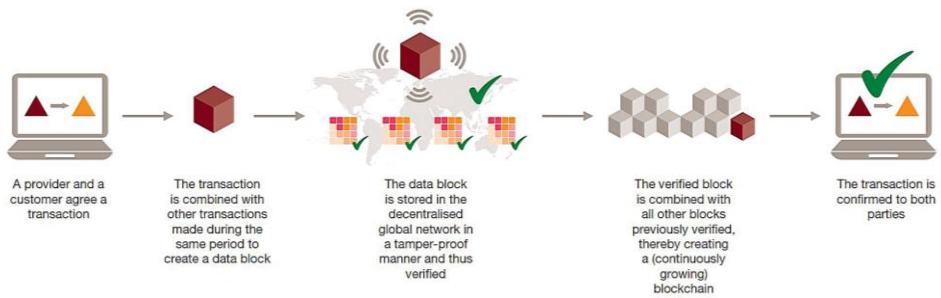

Figure 4. Smart contract process principle in blockchain, adapted from [53].

In addition, some special services are used to connect smart contracts with the outside world. The oracle is a tool for smart contracts to access data from the world outside the blockchain [45]. Being a type of "smart" contract itself, the "oracles" take data from the outside world and put it into the blockchain to fulfill conditions under other "smart" contracts. In other words, the oracle is a service that provides "trusted" data for the smart contract through the transactions [45]. Oracles make the data usable in the blockchain. They allow smart contracts to automatically perform calculations when their conditions are met.

2.3. Tokens and Cryptocurrency

Tokens include the intangible form of physical assets, e.g., securities, services, and goods [45,54]. Unlike cryptocurrencies, tokens can be issued and managed completely centrally. The token is inextricably linked with the initial coin offering (ICO) [54]. If companies enter the initial public offering (IPO) on the stock exchange in order to receive investments, then the ICO is used on the crypto exchange for this. With the advent of a large number of new blockchain startups and ICOs, tokens began to be divided into different categories, depending on the purpose, application, legal status, technical level and basic value. Nowadays, security, utility, debt, asset-backed and non-fungible tokens (NFT) are known [45,54–57].

There is a significant difference between tokens and cryptocurrency. According to Mougayar [45], while the issue and verification of token transactions can be centralized and decentralized, cryptocurrencies can only be decentralized; while the price of tokens can be influenced by a very wide list of factors in addition to supply and demand (issuance of additional tokens, binding to other assets), the price of cryptocurrencies is fully regulated by the market; and while tokens do not necessarily have to be launched on their own blockchain, cryptocurrencies always have their own blockchain [58].

In some ways, tokens are analogs of company shares [54]. If a person buys tokens, he makes a contribution to the development of a blockchain project. The creators of the project are focused on the rapid transformation of planned ideas into a popular system. The token holder is charged interest on the investments that were made by him for some time [54]. As for the cryptocurrency, it is a virtual tool that allows the quick and convenient transfer of value, and it is often used on the Internet [45].

3. Research Methodology

To address the research objectives within the topic, a systematic literature review was performed. This technique lies in an evidence-based literature review that helps collect and summarize relevant studies, and identify the state-of-art data of the research topic by conducting an analysis and synthesis of the current literature findings without bias [59]. We chose the SLR as the research method because the general goal of the study was to investigate the scope and purpose of blockchain technology in carbon markets. The SLR of this review article is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [60], combined with the SLR guide proposed by Okoli and Schabram [61]. The synergy of these two guidelines provides more thorough analysis of both quantitative and qualitative studies with subsequent data synthesis. Our systematic review was adopted and conducted in five steps: (1) research questions; (2) search strategy; (3) data selection; (4) data extraction; and (5) analysis, synthesis and reporting.

3.1. Research Questions

Based on the objectives of this research work, the following research questions (RQ) were formulated:

RQ1. What are the operation features of blockchain in ETS?
RQ2. What is the scope of blockchain in carbon offset projects?
RQ3. How does blockchain address the criteria of quality in carbon offset projects?
RQ4. What are the obstacles and challenges of blockchain implementation in carbon markets?

3.2. Search Strategy

In order to gather relevant papers, a search strategy was developed for this systematic literature review. According to the research topic and objectives, we set the searching string in two domains: 'blockchain' and 'carbon'. In the 'blockchain' domain, we included variations of keywords relevant to this section: "blockchain*" and "block chain". In the 'carbon' domain, the keyword "*carbon*" was added. The search string was formed by a combination of two domains by 'AND' as 'blockchain'-group keywords AND "*carbon*" keyword:

("blockchain*" OR "block chain") AND ("*carbon*")

In order to provide a comprehensive overview, we conducted multiple searches on different databases. These included the Scopus, Web of Science, ACM digital library and IEEE Xplore databases for collecting relevant articles. Scopus and Web of Science are commonly well-known databases containing high-quality peer-reviewed studies. Blockchain, being an integral part of information technologies (IT) and computer engineering, lies in the field of high-tech. Thus, we considered the ACM digital library and IEEE Xplore as reliable academic databases for blockchain-related literature collection. More detailed search strings for each of the databases are listed in Appendix B. We also created an eligibility criteria protocol for the selection of papers in this review (Table 2).

Table 2. Search protocol.

Category	Inclusion Criteria	Exclusion Criteria	Justification
Language	English	Apart from English	Main academic international language globally
Search fields	Title, abstract and keywords	Other searching field codes	Field codes for effective papers identity
Year of publication	Since 2008 to February 2023	Before 2008	Blockchain was originally introduced in 2008. Last search was conducted on 1 March 2023
Publication type	Research articles and research reviews	Other papers	Peer-reviewed academic literature with related case studies provides increased authenticity
Availability	Full text available	Full text not available	A necessary condition of screening for selected literature
Subject	Related to the topic of blockchain	Not related to the topic of blockchain, or only mentioned it in abstract	To study blockchain specifically
Context	Carbon markets, carbon credits/ETS, carbon offset projects	Not related to carbon markets, carbon credits/ETS and carbon offsets	To study specifically blockchain in carbon markets (including carbon credits/ETS and carbon offsets) as per the research questions defined

3.3. Data Selection

Initially, this study was supposed to conduct a search using the above protocol in four databases. However, during the search in the ACM digital library, it was discovered that access to their full contents was not provided for the 10 manuscripts found. Thus, the data from this database was not included in the identification stage. After searching in three databases, we retrieved 138 records from Web of Science, 134 records from Scopus, and 15 records from IEEE Xplore. Figure 5 is the flowchart of the PRISMA 2020 guideline [62]. As Figure 5 shows, it includes identification, screening and inclusion steps. The total number of search results from three databases was 287; 116 duplicate records were removed and 171 remained for screening stage. According to the PRISMA 2020 guideline, this stage consists of two steps: (1) titles and abstracts eligibility screening; and (2) full text eligibility screening. Therefore, 111 articles were excluded after the first step. The main reasons for records exclusion: (1) unrelated to either topic of blockchain or carbon markets (including carbon credits under ETS and carbon offsets); or (2) only related to one topic. During the next step, we assessed the remaining 60 articles for full-text eligibility. A total of 21 records were excluded for specific reasons, including: (1) superficial overview of blockchain, in some cases mixed with other Industry 4.0 technologies (e.g., IoT, AI, Big Data etc.); and (2) full-text content was not consistent with the topic of carbon markets (including carbon credits under ETS and carbon offsets). Thus, 39 records were included in the dataset of this SLR for further data extraction, analysis and synthesis.

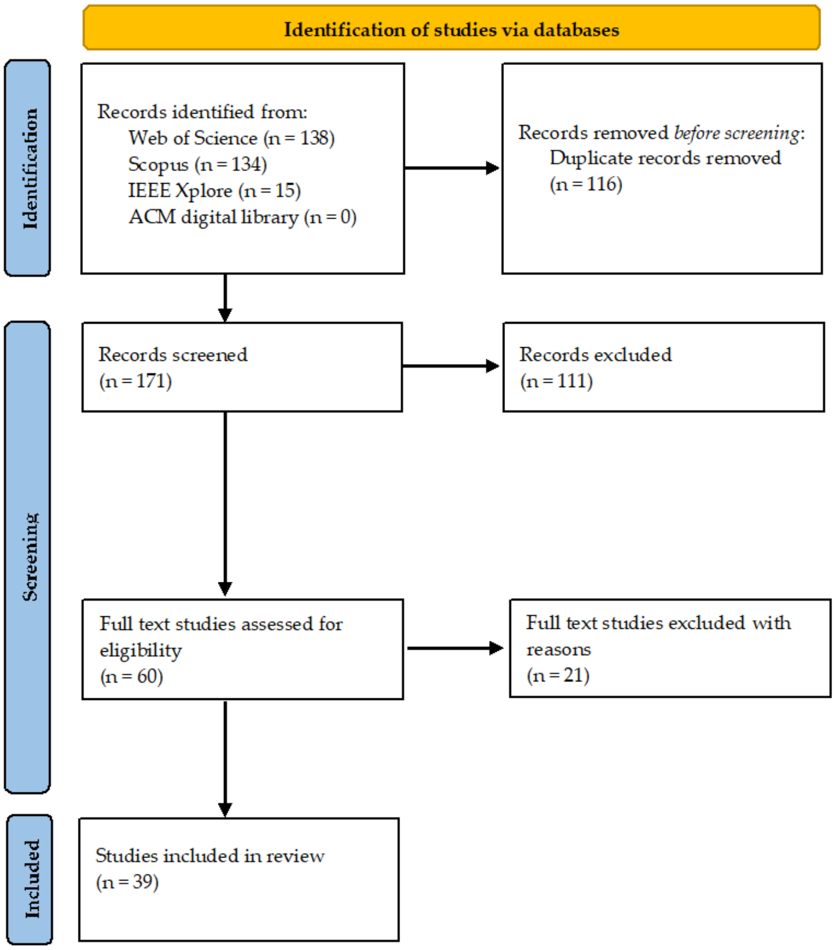

Figure 5. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of this systematic literature review, based on the PRISMA 2020 guideline.

3.4. Data Extraction

According to the research objectives, the next step was data extraction from the included studies. During the process of data categorization, we revealed that some of them combined several topics of carbon offset projects that blockchain could be implemented for. Thus, this aspect presented some difficulty in classifying some of the included studies under certain categories presented in Figure A1 of Appendix A. We highlighted the following domains of blockchain implementation in carbon markets (including ETS and carbon offset projects):

- ETS;
- Forestry and Land Use;
- Renewable Energy;
- Household and Community;
- Transportation;
- Household/Transportation/Renewable Energy;
- Renewable Energy/Transportation.

Figure 6 shows the distribution and domains of publications by year. It is noteworthy that the topic of blockchain implementation for carbon markets became attractive for researchers only in 2018. Despite that fact, in 2019 the topic also was not comprehensively studied. However, starting in 2020, the number of relevant publications began to increase. As a result, the number of publications for 2022 was the number for 2020 and 2021 combined. This indicates the increasing interest in the possible implementation of blockchain technology in carbon markets. Nonetheless, results show that it is still in the early stage of development, since the related topic received scholars' attention only in 2018. Table A1 in Appendix C shows category, author(s), year, title and journal of the articles included in this SLR.

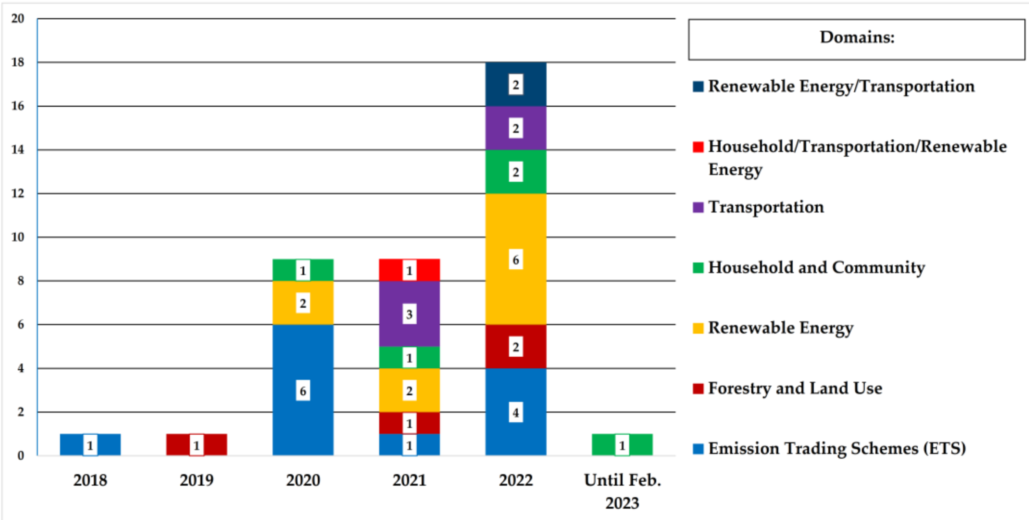

Figure 6. Distribution and domains of publications by years. ETS: emissions trading schemes.

3.5. Analysis, Synthesis and Reporting

In the final step, we extracted the data from each included study and then conducted the analysis based on the research questions. In order to answer them, the basic characteristics of the included studies were extracted and thoroughly analyzed. To answer the first research question, the operating mechanisms for carbon credits considered in articles from the ETS domain were extracted for analysis. The answer to the second research question was already partially given in Section 3.4. However, it is necessary to synthesize the included studies for a full-format presentation of carbon offsets that enable the possible implementation of blockchain for various carbon offset projects. As the answer to the third research question, a qualitative assessment of blockchain for the effective functioning of carbon offset projects was conducted. The answer to the fourth research question presents obstacles to and challenges of blockchain technology that hinder its possible implementation in carbon markets, which were considered in the articles included in this SLR. The findings of this literature review are presented in Section 4. The results are presented based on the content analysis of the selected papers.

4. Results and Discussion

4.1. RQ1: What Are the Operation Features of Blockchain in ETS?

Considering the composition of blockchain in the framework of carbon credits distribution, the degree of predisposition of this technology to this operational format should be assessed.

4.1.1. Public, Private and Consortium Blockchains in ETS

Zhou and Zhang [63] conducted a simulation study of carbon emissions trading based on different types of blockchains: public and private. The simulation results of this research showed that the time cost of private carbon emissions trading mechanism is lower than in public-based ETS. Due to the time-consuming responsibilities of network-wide certification in public-based ETS, the performance of private-based ETS is more suitable for implementation in China's carbon market. Hartman and Thomas [64] suggest that private blockchain is also more suitable for implementation in the Australian carbon market. The national registry of carbon emission units should operate as a private ledger, allowing the regulator to retain its eligibility and access management role due to existing legislation requirements. Comparing the suitability of two different blockchain platforms, Ethereum (public and permission-less) and Hyperledger Fabric (private and permissioned), Franke et al. [65] highlighted the advantages of both systems. The Hyperledger Fabric maintains control over the technological infrastructure for the network authority of the UNFCCC during carbon management accounting. Meanwhile, the Ethereum platform encourages bottom-up and democratic system governance through public transparency. Kim and Huh [66] proposed consortium (hybrid) blockchains for carbon accounting integration. It is responsible for carbon credits verification with hybrid structures that are beyond traditional private and public limits. Mandaroux et al. [67] also proposed a consortium blockchain for enhancing EU ETS. It is a suitable decentralized platform for a user group that is only partly public and, hence, it is of great benefit for organizational cooperation.

4.1.2. Main Actors (Nodes)

Khaqqi et al. [68] proposed a blockchain reputation-based emission trading scheme for participants' (nodes') interaction. Within this scheme, the Auditor (reputation rating agency) evaluates the Firm's (business') carbon reduction strategy represented by the Project (CDM project) with subsequent carbon credits issuing by the Authority (government). The quality of the trade offers and the speed of the transaction depends on the reputation of the participants. Hu et al. [69] also adhered to a similar approach in the reputation assessment of enterprises for emissions. Zhang et al. [70] highlighted, as did Zhou and Zhang [63], the government, investors and company agents as the main actors within blockchain-based ETS. Zhao and Chan [71] proposed a scheme with the interaction of Organizers (supervision), Validators (NGOs or academic institutions) elected by participants, and users (carbon traders). Shokri et al. [72] also adhered to a similar approach, highlighting Creators (organizers), purchasers (users) and market facilitators (verification). Franke et al. [65] and Schletz et al. [31] describe nodes interaction within the blockchain-based Article 6.2 architecture, including the UNFCCC secretariat, technical experts, and participating Parties (countries and non-state actors).

4.1.3. Consensus Mechanisms

Hu et al. [69] proposed a Delegated Proof of Reputation (DPoR) consensus mechanism for the effective assessment of the reputation value of the emitting enterprises. Therefore, fewer reputation points leads to more transaction fees and weaker voting power. Hartman and Thomas [64] proposed a proof-of-authority (PoA) consensus protocol for implementation in the Australian carbon market. Therefore, the Regulator met its legislative responsibilities for updating the national carbon registry. Zhao and Chan [71] suggested that the proof of work (PoW) protocol is not suitable for the purpose of a blockchain-based CAT scheme. The authors considered a practical Byzantine fault tolerance (pBFT) protocol for possible implementation. Kim and Huh [66] proposed a DPoS (Delegation Proof of Stake) protocol for carbon emissions verification under UN. Sipthorpe et al. [73] highlighted that proof-of-stake and proof-of-authority are more appropriate consensus mechanisms than the energy-demanding proof-of-work.

4.2. RQ2: What Is the Scope of Blockchain in Carbon Offset Projects?

In Figure 6 we presented the number and categories of the studies included in this SLR. Obviously, the majority of carbon offset projects with the proposed use of blockchain technology include renewable energy sources (RES) development. Due to the fact that blockchain operations demand large computing power, its application in the transformation, distribution and use of energy resources is natural. Furthermore, it allowed the expansion of the possible application of blockchain in such categories as household and community, and transportation. It is noteworthy that some studies covered several areas of blockchain interaction with energy, including combinations of RES and transport, as well as RES, households and transport.

In general, RES-related studies on blockchain proposed peer-to-peer trading frameworks integrating energy and carbon credits [74–76]. The same mechanism was also proposed for peer-to-peer transaction in virtual power plant [77]. The power-to-gas technology provides to wind farms the ability to absorb carbon for further trade in multiple energy markets [78]. By an automated scheduling framework enabled by smart contracts, it becomes possible to establish reliable coordination between wind farms and multiple energy markets [79]. Several studies observed opportunities for microgrids energy management based on blockchain [80,81]. Blockchain also could be implemented in the bilateral bidding market for carbon allocation, from electricity generation by different units [82]. Finally, a blockchain for distinguishing energy transitions between renewables capacities and power plants by "guarantees of origin" issuing was proposed [83].

For the cultivation of "citizen energy communities", and in order to improve life standards and provide low-carbon facilities, blockchain also could be implemented for peer-to-peer energy trade [84–87], and for the energy efficiency control of residential buildings [88].

Blockchain also does not bypass the transport sector, whose greenhouse gas emissions account for about 45% [89]. With the gradual increase in the share of electric vehicles (EVs) and charging stations, the transport segment has become more tied to the renewable energy market. Therefore, a framework for the charging management of electric vehicles [90–92] with subsequent peer-to-peer energy trading optimization [93] was proposed for blockchain implementation. In addition, a hybrid blockchain was proposed by Subramanian and Thampy [89] for the life cycle supply chain management of pre-owned EVs.

The possible application of blockchain in energy trading also involves the integration of renewable energy and transport in the bidding model of the power grid that considers carbon emissions [94,95]. In addition, blockchain is an integral part of the model of a decentralized energy community involving RES, energy-positive buildings and electric vehicles [96].

A number of papers considered the application of blockchain in natural-based solutions, notably in forestry and land use. Forests that are carbon sinks need effective management, since the amount of carbon absorbed and the quality of carbon offset projects depend on it. Therefore, blockchain is introduced as the integral part of modern forest carbon sinks management [97]. In theory, it could provide optimal control of emission reduction efforts between forest farmers and emission-controlled enterprises. In addition, Reducing Emissions from Deforestation and Forest Degradation (REDD+) has been considered as a platform for the implementation of blockchain to improve forest management practices [98,99]. Blue carbon, as large and unexplored carbon storage, has also been proposed for carbon market integration through the blockchain [100].

4.3. RQ3: How Does Blockchain Address the Criteria of Quality in Carbon Offset Projects?

In order to make a real contribution to mitigating climate change, carbon offset projects must meet a number of criteria. As noted in the introduction, the quality criteria include: (1) baseline and measurement; (2) verifiability and transparency; (3) additionality; (4) permanence; (5) double-counting avoidance; (6) co-benefits provision; and (7) carbon leakage avoidance. Due to the fact that not all of them are applicable for each group of carbon offset projects, we consider the blockchain's ability to address the quality issues based on the literature included in this SLR. There are several examples of how these criteria are used in practice.

4.3.1. Renewable Energy

The validated transactions of proposed peer-to-peer energy and carbon allowance joint trading are structured in publicly available blocks [74,80]. Within this process, smart contracts provide transparent transactions from the initialization of bids and offers, to the selection of the winning bid, to the subsequent exchange of ownership [74,82]. Carbon emissions caused by electricity generation, transmission and consumption are measured by smart meters. The consensus of proof-of-work is proposed for collectively validating transactions by all nodes [74]. However, if the power transmission and distribution transactions are on the public blockchain, the transaction data is transparent and privacy cannot be guaranteed [76]. In order to demonstrate renewable purchases and compliance with carbon standards, proofs of origin (i.e., renewable certificates) can be obtained through the implementation of smart contracts and digital signatures [83].

The double-counting issue in guarantees of origin allocation under renewable energy trade can be avoided by producing unique identifiers for each transaction [83]. This may increase credibility in the renewable energy trading market.

In the case of peer-to-peer energy trading, it is hard to determine the additionality of RES projects, since their installation may have legislative or economic justifications that encourage the enforcement of laws or cost reduction and are not aimed at reducing emissions.

The co-benefits of peer-to-peer energy trading basically include bill-saving or cost-saving for personal benefits [74–77,79–83,95]. The development of renewable energy sources is also closely linked to the power grid and can provide energy for electric vehicles (EV) via charging stations, which consider carbon emissions [94].

4.3.2. Household and Community

Peer-to-peer energy trading for flexible energy exchange across multiple sectors and local communities involves a verification process based on smart contracts [85,86]. Smart meters connected to home energy systems (nodes) measure consumption data, while sensors display data readings [84,86]. Therefore, smart contracts provide transactions between parties [86,88]. Thus, transactions can be aggregated into timestamped and cryptographically linked blocks, forming a blockchain [84,88]. However, the transparency of transactions presents challenges regarding privacy [84].

Household energy trading based on roof solar and wind turbines, in addition to gaining revenue, helps to shift loads and power peaks and reduce customer costs [84,87]. Moreover, energy trading provides an opportunity for the synergy of renewable energy, home energy consumption and the charging of EVs [93,96].

4.3.3. Transportation

Energy trading based on the blockchain network ensures data authenticity and transparency of transactions obtained for electric vehicles [93]. EVs can also sell energy to the grid and buildings through smart charging [96]. The blockchain can help certify and manage renewable energy transfers in each transaction within it. Proposed vehicle-to-grid (V2G) and vehicle-to-building (V2B) energy transaction mechanisms could increase decarbonization flexibility [96].

4.3.4. Forestry and Land Use

Since trees in carbon offset projects performed as physical assets, monitoring their state of growth or decline can be conducted through the "camera oracle" [98]. In turn, the verification process continues with the tokenization of each of the plants (physical assets) and is updated according to their condition (through the synchronization with "camera oracle"). The oracles of blockchain are also able to collect other data from forests (e.g., data on forest cover, land-use changes from drones, satellites or on-the-ground verifiers) [99]. Data can only be recorded in the blockchain after it has been verified by most of the nodes in the entire network [100].

It is found that blockchain cannot entirely address the additionality issue of forest carbon offset projects. In order to be additional, forest carbon sink projects should not be performed as an effort to meet government regulations or be profitable without the intention to offset emissions ("business-as-usual" practices). However, smart contracts are able to capture and process relevant information about the origins of carbon credits obtained through the forest carbon sequestration activities [99]. In the context of REDD+, a blockchain using oracles is able to collect, process and communicate information about deforestation drivers (e.g., prices of beef, palm oil, soya). Therefore, if the profit of deforestation is great, REDD+ projects are likely to be additional [99].

Carbon sequestered in forests is inherently unstable due to its possible emissions through forest degradation or deforestation actions [98,99]. Thus, the permanence of such projects may be questioned, also negating the validity of credits previously issued. The solution proposed by the blockchain is to collect updated data on the state of the forest area, followed by the formation of related tokens [99]. It is assumed that the information on the amount of sequestered carbon is adjusted by carrying out activities related to the forest carbon stocks assessment. External data collected from satellite images and drones can be transmitted through oracles that guarantee the validity and transparency of the information [99].

The double-counting issue in forest carbon offset projects could be potentially solved by the introduction of NFTs, based on the certain carbon stock of individual trees [99]. In turn, blockchain provides the opportunity for users to adjust the distribution of NFTs, with the subsequent avoidance of double-counting in carbon markets.

Blockchain, as a decentralized and transparent technology, is able to enforce the verifiability (via smart contracts) and provide the reduction of labor costs involved in the forest management practices of measuring and monitoring [97,99]. The co-benefits of possible blockchain implementation in the context of REDD+ activities include poverty alleviation and improved governance ensured by the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). The upholding of community rights could require the involvement of relevant jurisdictions, by translating and programming these standards as conditions into the smart contracts [99]. In addition, considering the importance of blue carbon, the potential use of blockchain could bring more efforts to the development and utilization of marine resources (e.g., mangroves, seaweed beds, salt marshes, etc.) [100].

For blockchain technology, dealing with the carbon leakage issue in the context of forestry seems to be very limited. Carbon leakage most often occurs in the buffer areas of projects and depends on their scale. Technically, the blockchain is able, through the mechanism of smart contracts, to revoke the issuance of carbon credits associated with the leakage of a certain amount of carbon. The anti-leakage mechanism can also be improved by introducing a threshold in the buffer zone of the project [99]. However, the process of combating carbon leakage within the framework of offset projects in forests at the regional or state level could require the consolidation of great efforts, using a wide range of other approaches.

4.4. RQ4: What Are the Obstacles and Challenges of Blockchain Implementation in Carbon Markets?

In addition to its advantages, blockchain also has a number of drawbacks that hinder its implementation in various sectors of the economy. Being a complex technology with great potential, its application requires a thorough risk analysis. Since the carbon markets (including ETS and carbon offset projects) have different mechanisms of functioning, we highlighted general challenges of blockchain, and grouped challenges that were similar for both blockchain-enabled ETS and carbon offset projects, as shown in Figure 7.

4.4.1. General Challenges of Blockchain

In the case of the PoW consensus mechanism, blockchain requires high energy and computing costs [45]. That, in turn, leads to the carbon footprint of blockchain itself. Such high computation power is needed to solve the hash puzzle, and this consumes a large amount of electrical energy [95]. However, this issue can be tackled by using other consensus algorithms (PoS, PoA, pBFT) which are less energy-demanding.

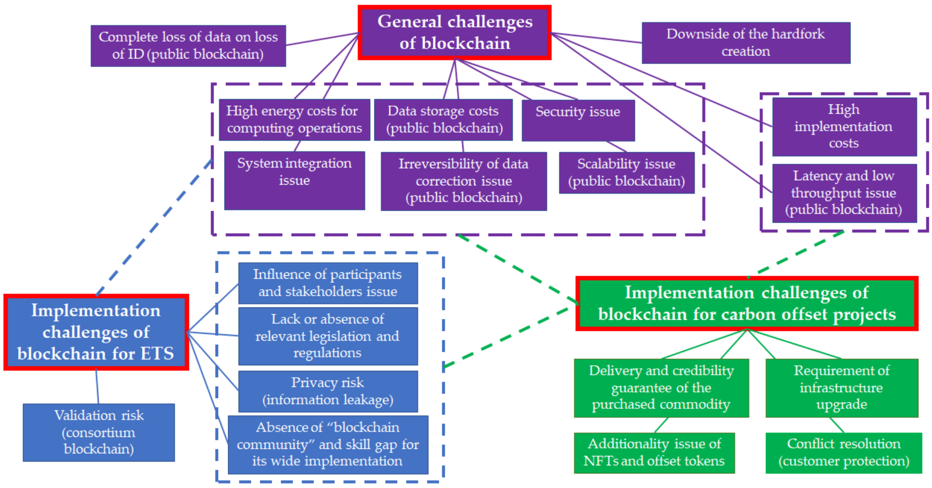

Figure 7. Blockchain implementation challenges in carbon markets. ETS: emissions trading schemes; NFTs: non-fungible tokens.

As new transactions are processed and added to blocks, the data storage decreases. This is because each node has a copy of the data of each transaction. The number of copies increases with the addition of new blocks [95]. This is especially typical for public blockchains.

The cyber-attack resistance of the blockchain is not completely proven yet. However, in practice, if potential malicious users gain control of 51% of the computation capacity (in the case of PoW) or 51% of the network stakes (in the case of PoS), then they could manipulate and change the block data [95]. Thus, the so-called "51% attack" is a significant security issue of blockchain.

Currently, there are relatively few successful cases of blockchain interoperability with other digital technologies. Being an integral part of Industry 4.0, blockchain perhaps cannot conduct digitalization alone. The technological gap still remains by the absence of the integration with other DLT systems [45,95].

Data immutability is a key feature of public blockchains. However, it also eliminates any necessary changes in previous blocks, in the case of bugs or errors [95]. Therefore, the irreversibility of data correction issue hinders the large-scale adoption of public blockchains.

The scalability issue of blockchain requires additional efforts to modify the system to be able to cope with the increased amount of participants and transactions [45,90]. Theoretically, for the perfect functioning of blockchain, it should remain decentralized, secure and scalable [71,83]. In turn, the so-called "scalability trilemma" forms contradictory trade-offs associated with each objective [45].

Another issue with public blockchains is latency and the low throughput of transactions. The trustless nature of the PoW consensus algorithm makes the work of processing transactions time-consuming [45,95].

Being a new and constantly evolving technology, blockchain has not yet reached maturity and has not been widely implemented. Thus, the costs of installing the appropriate equipment are still considered high [45,95].

The hardfork creation is a way to make significant changes to the program code of a project based on blockchain technology [95]. It is activated if the majority of participants agree to its use. In PoW blockchains such as Bitcoin, miners must also express their readiness to upgrade. However, in some cases, the creation of the hardfork can cause a split in the community: some participants support the update, and some do not. This can lead to the division of the blockchain into two chains: some participants use the updated version, while others continue to work on the old version, making their own changes [95].

One more drawback of public blockchains lies in the inability to recover the access to an account in the case of its loss (e.g., by losing or forgetting the wallet password) [95]. Therefore, all data and cryptocurrency belonging to the lost ID will be permanently lost.

4.4.2. Implementation Challenges of Blockchain for ETS (Carbon Credits)

Khaqqi et al. [68] suggest the blockchain-enabled ETS has equal implementation challenges as the blockchain technology itself. In particular, these include: high energy costs for computing operations [45,69]; big data storage requirements [71,95]; the data correction irreversibility issue [71,95]; security issues [45,65,71,95]; the system integration issue [71,73]; and the scalability issue [71].

A central authority should be established for blockchain regulation in ETS [52]. Without it, the legal liability of smart contracts operations remains unclear. Moreover, the regulatory entity should enforce the property rights of carbon credits in a cap-and-trade system [71]. Enterprises will perhaps not hasten to adopt blockchain for automatic carbon accounting, considering the possible leakage of commercially sensitive data (such as production and operation data) [71]. On the global level, blockchain should also enforce the security and integrity of political and sensitive data to create an accountable and incentive consensus mechanism between the participating parties [65]. It is noteworthy that if ETS is based on the consortium blockchain, then validation could be damaged by mistakenly selected malicious peers [71].

Due to the lack of widespread use of blockchain technology, a "blockchain community" is not being formed to support and promote its implementation, in particular, in such important initiatives as the fight against climate change [65,66]. The issue is largely determined by the quality of specialists in programming languages. In addition, it was revealed that the demand for programming skills is outstripping supply [73].

The scaling issue raised earlier mainly concerned the number of nodes in the blockchain network. However, the issue of their influence is also important. In the classical blockchain system, all its participants appear as stakeholders with the task of verifying the block and its subsequent addition to the chain. However, in the case of the proposed implementation of blockchain in ETS, the number of stakeholders, including miners (or validators), developers, coin holders and investors, all of whom have different interests, makes it quite difficult to coordinate and reach an agreement [66]. The further coordination of actions may include informing each of the participants, taking into account their demands [67], or dividing them into full and light nodes [65].

4.4.3. Implementation Challenges of Blockchain for Carbon Offset Projects

Some similar implementation challenges of blockchain-enabled ETS and blockchain itself are relevant to technology adoption in carbon offset projects. There are high energy costs for computing operations [45,84,87,93,95,98]; storage constraints [83]; security issues [45,76,83,84,93]; lack of system integration [45,91,95,96,99]; the data correction irreversibility issue [83]; and the scalability issue [45,84,90,91].

Several implementation challenges of proposed carbon offset projects based on blockchain are similar to those the blockchain-enabled ETS has. For instance, to create incentive mechanisms in blockchain adaptation for peer-to-peer energy trading, the interests of all stakeholders should be met [96]. A lack of regulation, legislation and business models for blockchain use in the electricity sector also could postpone its vast application [95]. Privacy-sensitive data stored in a blockchain of energy consumption transactions could be revealed by network participants, especially in the case of the public blockchain [84,95]. In addition, the skill gap for large-scale deployment of blockchain in the electricity sector is deepened by the uncertainty of using it for a specific application by startups [95]. It is also crucial for the implementation of forest carbon offset projects to attract experienced developers with adequate understanding of forestry and its challenges [99]. Therefore, the majority of pilot projects are still on the "proof of concept" stage [90,91].

In contrast to blockchain-enabled ETS, carbon offset projects based on blockchain additionally suffer from two challenges the technology itself has. First, the latency and low throughput issue is unacceptable for blockchain implementation in peer-to-peer energy trading [83,90,95]. Second, blockchain adoption could require re-equipment with high subsequent implementation costs [83].

In order to reflect a product of equal value in real, delivery guarantee of the purchased renewable electricity volume [83], as well as credibility guarantee of carbon credits gained from blockchain-based forest-offset projects [99], both of which can be challenging issues. In the first case, failure to deliver can have serious repercussions for the balancing of the electricity grid, even though transactions are demonstrably easily and securely traced [83]. In the second case, due to the uncertain baseline and measurement, it becomes difficult to determine which companies provide credible credits [99].

For blockchain integration into the energy system, it should be considered an infrastructure upgrade, in particular for the development of EV charging stations [91,95]. Smart contracts in energy trading also potentially endanger customer protection. Technically, smart meters are able to disconnect the customer from the grid remotely for unpaid electricity bills [84]. Eventually, it can deprive the buyer of basic needs (i.e., heating or cooking). Therefore, conflict resolution and customer protection must be considered and enforced [76].

Finally, considering additionality as a criterion of quality, NFTs and offset tokens should be issued, with social tokens strengthening the relationships between forestry communities and investors to boost local economies [99]. Otherwise, "business-as-usual" practices in forest carbon offset projects based on blockchain could lead to the isolation of local communities in social aspects such as education, healthcare and governance.

5. Theoretical Implications and Further Research Directions

Blockchain is able to promote the digitalization of carbon credits for their subsequent implementation in ETS under CCM. Private and consortium blockchains are suitable solutions for national and global carbon credits allocation. This is also confirmed by proposed participants, operating as verification nodes within blockchain. In turn, practical Byzantine fault tolerance (pBFT), proof-of-authority (PoA), proof-of-reputation (PoR), proof-of-stake (PoS) and their variations, are proposed as the consensus mechanisms.

According to the review of the included studies, such categories as "energy efficiency" (e.g., fuel switching), "chemical processes and industrial manufacturing" (e.g., carbon capture and storage), "waste disposal" (e.g., recycling), and "agriculture" (e.g., methane capture), do not have their own blockchain-led case studies. Thus, at present, blockchain can theoretically be implemented in four categories of carbon offset projects: "renewable energy", "household and community", "transportation", and "forestry and land use".

Despite its potential, blockchain cannot entirely address all quality criteria in carbon offset projects of the above-mentioned groups. Firstly, to our strong belief, not all criteria are applicable to conduct comprehensive quality assessment for each group of carbon offset projects. Secondly, our data extraction step showed that in the case of blockchain application in renewable energy projects, there is a synergy of renewables (photovoltaics), combined with households (energy-positive buildings), and transportation (electric vehicles), in the context of transactive energy (peer-to-peer energy trading). In that case, household and transportation carbon offset projects based on blockchain cannot be considered as independent of renewables. Therefore, renewable energy projects based on blockchain are potentially able to address measurement and verification issues (by smart meters), the transparency issue (by smart contracts), and the double-counting issue (via application of unique identifiers for each transaction), and bring co-benefits (bill-saving or cost-saving). At the same time, the technology is unable to fix the additionality issue, permanence, and carbon leakage in renewable energy projects. In the case of forest carbon offset projects, blockchain could improve verifiability and transparency (via smart contracts), fix the double-counting issue (by the introduction of NFTs), and bring co-benefits (poverty alleviation and possible governance improvement). However, for nature-based solutions, blockchain cannot fully improve carbon sequestration measurement techniques (perhaps, because of its technical drawback of limited computational capabilities), meet the additionality and permanence criteria, as well as help to avoid carbon leakage. Nonetheless, forestry and land use carbon offset projects could be more enhanced and modernized with blockchain implementation.

Various drawbacks of blockchain hinder the implementation of the technology in carbon markets. This is also compounded by the fact that the majority of obstacles to the implementation of blockchain in ETS and carbon offset projects are also those common to its general challenges; implementation challenges of blockchain in carbon offset projects are similar with some of its general drawbacks and drawbacks of blockchain-enabled ETS (Figure 7). That makes the possible implementation of the technology more complicated and costly.

Based on the above-mentioned theoretical implications, our SLR provides the research agenda on the topic of blockchain in carbon markets (including ETS and carbon offset projects). Table 3 shows proposed research gaps and possible further research directions. In total, we present five aspects of research gaps with possible research directions.

Table 3. Research agenda for future research. ETS: emissions trading schemes.

Research Gaps	Further Research Directions
Suitable allocation mechanism for emission allowances (carbon credits) in blockchain-enabled ETS	To develop a mechanism for carbon credits allocation between participants in blockchain-enabled ETS
Blockchain-led case studies in carbon offset projects	To investigate blockchain implication potential in priority order for the following categories of carbon offset projects: "energy efficiency"; "chemical processes and industrial manufacturing"; "waste disposal"; and "agriculture". To develop blockchain implication potential for the following categories of carbon offset projects: "renewable energy", "household and community", "transportation" and "forestry and land use".
Quality assessment of blockchain-enabled carbon offset projects	To develop and conduct comprehensive quality assessment of blockchain-led carbon offset projects based on blockchain.
Synergy among blockchain-enabled ETS and carbon offset projects	To develop a framework for effective cooperation between blockchain-enabled ETS and carbon offset projects based on blockchain.
Risks, threats, and challenges of blockchain implementation in carbon markets (including ETS and carbon offset projects)	To investigate potential threats, challenges, and pitfalls of blockchain implementation in carbon markets and identify possible solutions to overcome these drawbacks.

6. Conclusions

In today's state of climate emergency, carbon markets must provide real contribution. In particular, ETS globally should enforce transparent carbon credits allocation, whereas carbon offset projects both in CCM and VCM should fulfill criteria of quality for efficient carbon reduction or sequestration. Obviously, the current system of carbon markets should be thoroughly improved, considering "3D's concept" of the low carbon economy (decentralization, decarbonization and digitalization). Blockchain has a pronounced potential for implementation as a new model in the architecture of Article 6 of the Paris Agreement. It is able to combine national parties' registries and the voluntary mitigation contributions of non-state actors by token allocation in order to meet long-term climate mitigation goals [31].

In this paper, we investigated the implications of blockchain technology in carbon markets (including ETS and carbon offset projects). To address the research objectives, a systematic literature review was performed. A total of 287 studies were retrieved from three scientific databases. Through the specific and careful selection steps, 39 articles were included in this SLR with subsequent analyses and discussion.

Our findings indicate that blockchain has great potential to be adopted in ETS and carbon offset projects. In addition to existing studies [5,32–38] about the possible adoption of blockchain in carbon markets, our systematic review not only considers blockchain-based ETS of CCM, but also various blockchain-led carbon offset projects of VCM. It also highlights more specific features of their functioning, based on the relevant research questions. However, there is a lack of information of blockchain use cases in such categories of carbon offset projects as "energy efficiency", "chemical processes and industrial manufacturing", "waste disposal", and "agriculture". Household (energy-positive buildings) and transportation (EVs) carbon offset projects based on blockchain cannot be considered as independent of renewables for the reason of energy trading. Renewables and forestry are the most appropriate domains for blockchain adoption, considering various criteria of quality for carbon offset projects. However, blockchain is not a panacea for all carbon markets' issues. According to He and Turner [39], it is only on the fourth stage of its evolution, and develops constantly. In addition, blockchain is currently immature in carbon markets, because the majority of projects are at or before the "proof-of-concept" step [73]. Obviously, the technology has its own drawbacks and challenges. Thus, decision- and policy-makers, startups, stakeholders, and others involved in the field of "3D's concept", should consider that blockchain implementation in ETS and carbon offset projects could create new pitfalls. In that case, all risks and opportunities of the technology should be assessed, as performed in our previous study [101].

Our study has several limitations. Firstly, there was no opportunity to gain full text access for 10 manuscripts found in the ACM digital library database. These articles could potentially make a contribution to our findings and theoretical implications. Secondly, although we spent a considerable amount of time on article searching and selection, we do expect that some potential flaws that could have occurred in the data selection and extraction steps.

The main contribution of this study is to highlight blockchain's scope and purpose in carbon markets (including ETS and carbon offset projects). The systematic literature review we performed could help decision- and policy-makers, startups, stakeholders and others involved or interested in the field of "3D's concept" to better understand blockchain's role and significance in carbon markets. This study also highlights research gaps and offers research directions. To our strong belief, the results we summarized could inspire researchers to conduct related investigations.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figure A1. Ecosystem Marketplace carbon offset projects typology, adapted from [10].

Appendix B

- Search Strings: Web of Science

TS = (((“blockchain*” OR “block chain”) AND (“*carbon*”))) and 2011 or 2013 or 2014 or 2015 or 2016 or 2017 or 2018 or 2019 or 2020 or 2021 or 2022 or 2023 (Publication Years) and Review Article or Article (Document Types) and All Open Access (Open Access) and English (Languages)

- Search Strings: Scopus

TITLE-ABS-KEY ((“blockchain*” OR “block chain”) AND (“*carbon*”)) AND (LIMIT-TO (OA, “all”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010)) AND (LIMIT-TO (LANGUAGE, “English”))

- Search Strings: IEEE Xplore

((“blockchain*” OR “block chain”) AND (“*carbon*”)) Content Type: Journals

- Search Strings: ACM digital library

[[[Title: “blockchain*”] OR [Title: “block chain”]] AND [Title: “*carbon*”]] OR [[[Abstract: “blockchain*”] OR [Abstract: “block chain”]] AND [Abstract: “*carbon*”]] OR [[[Keywords: “blockchain*”] OR [Keywords: “block chain”]] AND [Keywords: “*carbon*”]]

Appendix C

Table A1. The list of included studies. ETS: emissions trading schemes.

Domain	No.	Author(s)	Year	Title	Journal
ETS	[68]	Khaqqi, K.N. et al.	2018	Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application	*Applied Energy*
	[64]	Hartmann, S. and Thomas, S.	2020	Applying Blockchain to the Australian Carbon Market	*Economic Papers*
	[31]	Schletz, M. et al.	2020	Blockchain Application for the Paris Agreement Carbon Market Mechanism—A Decision Framework and Architecture	*Sustainability*
	[66]	Kim, S.-K. and Huh, J.-H.	2020	Blockchain of Carbon Trading for UN Sustainable Development Goals	*Sustainability*
	[69]	Hu, Z. et al.	2020	Delegated Proof of Reputation Consensus Mechanism for Blockchain-Enabled Distributed Carbon Emission Trading System	*IEEE Access*
	[65]	Franke, L. et al.	2020	Designing a Blockchain Model for the Paris Agreement's Carbon Market Mechanism	*Sustainability*
	[71]	Zhao, F. and Chan, W.K.	2020	When Is Blockchain Worth It? A Case Study of Carbon Trading	*Energies*
	[67]	Mandaroux, R. et al.	2021	A European Emissions Trading System Powered by Distributed Ledger Technology: An Evaluation Framework	*Sustainability*
	[73]	Sipthorpe, A. et al.	2022	Blockchain solutions for carbon markets are nearing maturity	*One Earth*
	[72]	Shokri, A. et al.	2022	EnviroCoin: A Holistic, Blockchain Empowered, Consensus-Based Carbon Saving Unit Ecosystem	*Sustainability*
	[63]	Zhou, Q. and Zhang, Q.	2022	Simulation research on carbon emissions trading based on blockchain	*Journal of Environmental Engineering and Landscape Management*
	[70]	Zhang, J. et al.	2022	The Impact of Digital Economy of Resource-Based City on Carbon Emissions Trading by Blockchain Technology	*Computational Intelligence and Neuroscience*
Forestry and land use	[98]	Howson, P. et al.	2019	Cryptocarbon: The promises and pitfalls of forest protection on a blockchain	*Geoforum*
	[97]	Sun, R. et al.	2021	Mechanism Analysis of Applying Blockchain Technology to Forestry Carbon Sink Projects Based on the Differential Game Model	*Sustainability*
	[100]	Zhao, C. et al.	2022	Research on the Blue Carbon Trading Market System under Blockchain Technology	*Energies*
Forestry and land use	[99]	Kotsialou, G. et al.	2022	Blockchain's potential in forest offsets, the voluntary carbon markets and REDD+	*Environmental Conservation*
Renewable energy	[74]	Hua, W. et al.	2020	A blockchain based peer-to-peer trading framework integrating energy and carbon markets	*Applied Energy*
	[75]	He, H. et al.	2020	Joint Operation Mechanism of Distributed Photovoltaic Power Generation Market and Carbon Market Based on Cross-Chain Trading Technology	*IEEE Access*

Table A1. *Cont.*

Domain	No.	Author(s)	Year	Title	Journal
	[78]	Ji, Z. et al.	2021	Automated scheduling approach under smart contract for remote wind farms with power-to-gas systems in multiple energy markets	*Energies*
	[80]	Su, J. et al.	2021	Practical Model for Optimal Carbon Control With Distributed Energy Resources	*IEEE Access*
	[81]	Zhong, X. et al.	2022	A Local Electricity and Carbon Trading Method for Multi-Energy Microgrids Considering Cross-Chain Interaction	*Sensors*
	[76]	Wang, X. et al.	2022	Applications of Blockchain Technology in Modern Power Systems: A Brief Survey	*Energies*
	[82]	Luo, R. et al.	2022	Blockchain-based bilateral bidding market mechanism with carbon allocation on both supply and demand sides	*Frontiers in Energy Research*
	[79]	Hua, W. et al.	2022	Consumer-centric decarbonization framework using Stackelberg game and Blockchain	*Applied Energy*
	[77]	Li, B. et al.	2022	Research on key technologies of P2P transaction in virtual power plant based on blockchain	*IET Smart Grid*
	[83]	Delardas, O. and Giannos P.	2022	Towards Energy Transition: Use of Blockchain in Renewable Certificates to Support Sustainability Commitments	*Sustainability*
Household and community	[84]	Deconinck, G. and Vankrunkelsven F.	2020	Digitalised, decentralised power infrastructures challenge blockchains	*Proceedings of the Institution of Civil Engineers-Smart Infrastructure and Construction*
	[88]	Kolahan, A. et al.	2021	Blockchain-Based Solution for Energy Demand-Side Management of Residential Buildings	*Sustainable Cities and Society*
	[85]	Wu, Y. et al.	2022	Towards collective energy Community: Potential roles of microgrid and blockchain to go beyond P2P energy trading	*Applied Energy*
	[86]	Prabhakar, A. and Anjali, T.	2022	URJA: A sustainable energy distribution and trade model for smart grids	*Blockchain: Research and Applications*
	[87]	Wang, B. et al.	2023	CE-SDT: A new blockchain-based distributed community energy trading mechanism	*Frontiers in Energy Research*
Transportation	[90]	Dorokhova, M. et al.	2021	A blockchain-supported framework for charging management of electric vehicles	*Energies*
	[91]	Khan, P.W. and Byun, Y.-C.	2021	Blockchain-based peer-to-peer energy trading and charging payment system for electric vehicles	*Sustainability*
	[89]	Subramanian, G. and Thampy, A.S.	2021	Implementation of Hybrid Blockchain in a Pre-Owned Electric Vehicle Supply Chain	*IEEE Access*
Transportation	[93]	Kakkar, R. et al.	2022	Blockchain and Double Auction-Based Trustful EVs Energy Trading Scheme for Optimum Pricing	*Mathematics*
	[92]	Liang, Y. et al.	2022	V2GNet: Robust Blockchain-Based Energy Trading Method and Implementation in Vehicle-to-Grid Network	*IEEE Access*

Table A1. *Cont.*

Domain	No.	Author(s)	Year	Title	Journal
Renewable energy/ Transportation	[94]	Wen, Y. et al.	2022	Photovoltaic-electric vehicles participating in bidding model of power grid that considers carbon emissions	*Energy Reports*
	[95]	Nour, M. et al.	2022	Review of Blockchain Potential Applications in the Electricity Sector and Challenges for Large Scale Adoption	*IEEE Access*
Household/ Transportation/ Renewable energy	[96]	Wu, Y. et al.	2021	Decentralized transactive energy community in edge grid with positive buildings and interactive electric vehicles	*International Journal of Electrical Power and Energy Systems*

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