碳市场应用区块链技术的文献综述研究 *

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摘 要:【目的】碳市场，尤其是碳排放交易系统（ETS）和碳补偿项目，都是减缓气候变化的重要机制。区块链作为"3D概念"的核心（包括分散化、脱碳和数字化）可以被视为碳市场进一步改进的候选解决方案。【方法】通过对相关研究内容的分析和讨论，将研究结果分类探讨，对区块链在 ETS 和碳补偿项目中的作用、关键特征、实施挑战和拟议应用进行系统性的文献综述。【结果】通过大量文献的研究结果表明，区块链在碳市场中具有巨大的应用潜力。然而，区块链在能源效率、化学过程和工业制造、废物处理和农业方面的研究应用案例数量匮乏。通过能源贸易活动将基于区块链的家计和交通碳补偿项目与可再生能源紧密联系在一起。考虑到碳补偿项目的各种质量标准，可再生能源和林业是应用区块链技术最合适的领域。【结论】除了现有关于区块链在碳市场中可能采用的研究外，本文系统地综述了基于区块链的符合规定的碳市场排放各种交易方案的设想和研究方向，还综合考虑了自愿碳市场的各种区块链主导的碳补偿项目。我们的研究还基于相关领域的研究现状，强调了应用区块链技术功能的更加具体特征与方式。由于区块链技术自身的缺陷和挑战，区块链技术目前在碳市场上应用还不是特别成熟。本文通过文献综述，还强调了该项研究的差距，并提供了今后的研究方向，以鼓励相关的研究人员进行相关进一步的调查与研究。

关键词: 区块链；碳市场；碳信用；碳补偿项目；碳排放交易

Blockchain in carbon markets: A Systematic Literature Review

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Abstract: [Objective] Carbon markets, in particular, emission trading schemes (ETS) and carbon offset projects, are significant mechanisms of 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. **[Method]** 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, grouping results into domains. **[Results]** The study findings show that blockchain has great potential to be adopted in carbon markets. However, there is no data of 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 the energy trading. Renewables and forestry are the most appropriate domains for blockchain adoption, considering various criteria of quality for carbon offset projects. **[Conclusion]** In addition to existing studies about possible adoption of blockchain in carbon markets, our systematic review not only considers blockchain-based emission trading schemes of compliance carbon market, but also various blockchain-led carbon offset projects of voluntary carbon market. Our study also highlights more specific features of their functioning, based on the relevant research questions. Blockchain is currently immature in carbon markets, because of its own drawbacks and challenges. The study also highlights research gaps and offers research directions to inspire researchers for conducting related investigations.

Key words: blockchain; carbon markets; carbon credits; carbon offset projects; emissions trading scheme

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1 Carbon markets overview

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. Carbon tax became the first form of regulation and subsequent reduction of 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 (Torrens, Cichanowicz, and Platt 1992). The Kyoto Protocol, adopted in 1997 and launched into force in 2005, was the first attempt aimed to reduce and regulate GHGs internationally (Breidenich et al. 1998). Based on cap-and-trade system, emission trading has actually transformed carbon into commodity (Figure 1). 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) and emission trading schemes (ETS) worldwide (Figure 2). According to Jiang et al. (Jiang et al. 2022), the ETS of CCM globally share in 2021 was approximately 270 billion USD, representing the equivalent of 15.8Gt CO_2-e traded on them. According to Refinitiv (Refinitiv 2023), the total compliance carbon market value in 2021 was 762 billion EUR, or approximately 850 billion USD, up 164% from 2020 on higher carbon prices. In 2022, CCM value maintained the growth trend, reaching 865 billion EUR (nearly 924 billion USD) (Refinitiv 2023).

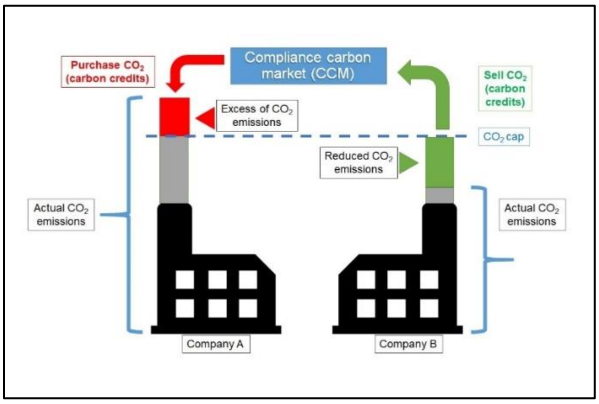

Fig. 1 The operating principle of ETS under CCM

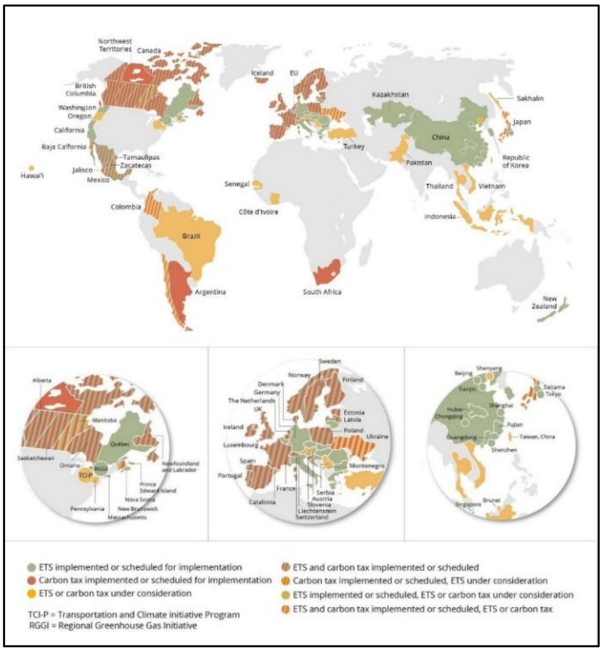

Fig. 2 The world map of carbon taxes and emissions trading schemes, adapted from (*State and Trends of Carbon Pricing 2021* 2021)

In addition to trading carbon emissions quotas on national, regional or international markets, the Kyoto Protocol also provided so-called "flexibility mechanisms": Clean Development Mechanism (CDM) and Joint implementation (JI) projects (United Nations Climate Change (UNFCCC) n.d.; n.d.). The resulting certified emission reductions (CERs), then can be used by the Annex I Party to help meet its emission reduction target. Thus, it became possible to expand carbon credits creation by 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) (Nguyen 2023). Therefore, it also created the basis for voluntary carbon markets (VCM) emergence worldwide. Most often, in such markets, companies are guided by the principles of ESG and CSR in order to decrease their carbon footprint (Franki 2022). In contrast to carbon credits generated in CCM through the ETS, verified emission reductions (VERs) or carbon credits of VCM are flow horizontally. They issuing determined by cultivation of carbon offset projects in order to purchase carbon credits that therefore could be traded on carbon markets (Figure 3). In comparison to the compliance markets, voluntary carbon markets are developing rapidly. However, the recent Ecosystem Marketplace report (Forest Trends' Ecosystem Marketplace 2022) reveals that VCM value in 2021 was only 2 billion USD (Figure 4). Also about 500 million carbon credits were traded in the same year, surpassing the previous year by 66%. The Ecosystem Marketplace report generally identifies eight categories of carbon offset projects in VCM (Table 1). The respective typology is shown in Figure A1 in Appendix A.

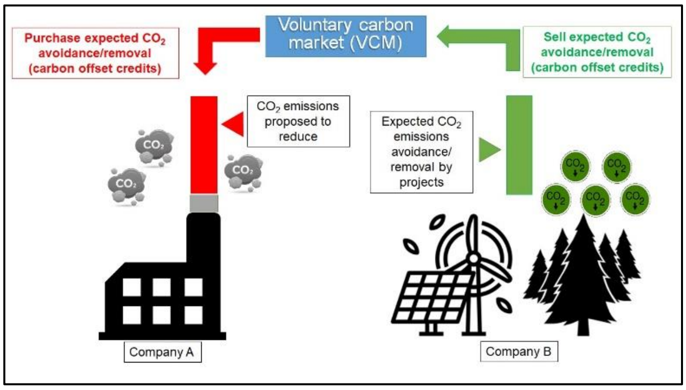

Fig. 3 The operating principle of VCM

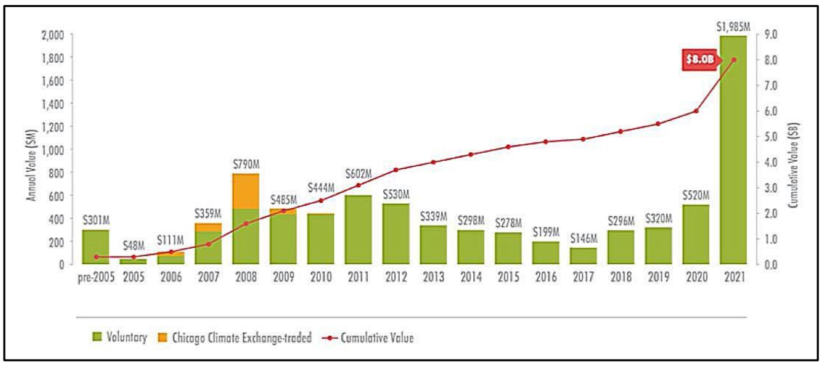

Fig. 4 VCM size by value on traded carbon credits, pre-2005 to 31 Dec. 2021, adapted from (Forest Trends' Ecosystem Marketplace 2022)

Tab. 1 VCM transaction volumes, prices, and values by category in 2020-2021, adapted from (Forest Trends' Ecosystem Marketplace 2022)

Categories	2020			2021		
	Volume (million	Price (USD)	Value (million	Volume (million	Price (USD)	Value (million

	MtCO$_2$e)		USD)	MtCO$_2$e)		USD)
Forestry and land use	57.8	5.40	315.4	227.7	5.80	1 327.5
Renewable energy	93.8	1.08	101.5	211.4	2.26	479.1
Chemical processes	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	30.9	0.98	30.4	10.9	1.99	21.9
Household/ Community	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

Along with the diversity and opportunities of carbon markets, there are still a number of unresolved issues regarding their attractiveness and harmonious, efficient functioning. With the establishment of CCM, carbon prices have been far too low to motivate companies for making efforts to reduce their emissions (i.e. companies have to invest more in the purchase of carbon credits rather than in emission reduction technologies or projects) (Jeffery R. Williams, Jeffrey M. Peterson, and Siân Mooney 2005; World Bank Group 2019; Kaufman et al. 2020; *How to Mitigate Climate Change* 2019; IMF/OECD 2021). 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 the auctions (Cason and de Vries 2019). 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 (Cramton and Kerr 2002). When credits are grandfathered, this puts new or growing companies at a disadvantage relatively to more established and well-known companies (Reichle 2020). Thus, this could be perceived as a protectionist obstacle for new participants in their markets. Alternatively, the emission allowances can be distributed through the auctioning by selling to the highest bidders, rather than allow polluters to receive carbon credits for free (Cramton and Kerr 2002).

The JI projects and CDM under Kyoto Protocol, created the opportunity for huge businesses or whole industries to transfer their production facilities in other countries, that have low environmental-regulation standards. Thus, if divisions of these kind of company or industry make the same product and emit the same GHG volumes, they can avoid having to pay for its carbon emissions on the territory of countries with more relaxed carbon emission policy. The direct result of this patchwork of mechanisms is known as "carbon leakage". According to the UNFCCC (United Nations Climate Change (UNFCCC) 2023), as of February 28, 2023, 7845 CDM projects were registered. However, in 2012 it was reported (The Guardian 2012; The Economist 2012), that the CDM has "essentially collapsed" and "global carbon market is in need of a radical overhaul", due to the prolonged downward trend in the price of CERs, which had been traded for as much as 20 USD per a tonne before the global financial crisis to less than 3 USD. With such low CER prices, potential projects were not commercially viable and gradually decreased to be registered by UNFCCC (Figure 5). Thus, CDM has failed to consistently deliver development and sustainability benefits.

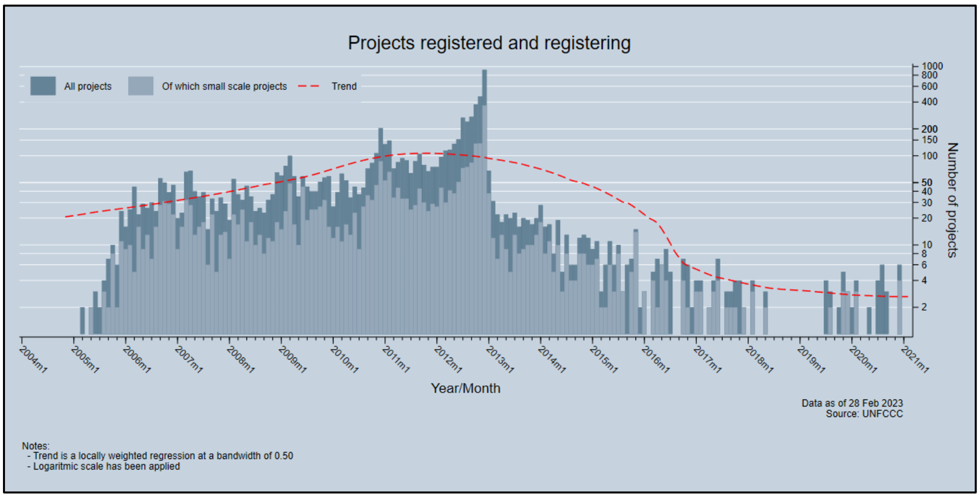

Fig. 5 Monthly registered CDM projects in 2005–2021, adapted from (United Nations Climate Change (UNFCCC) 2023)

Notably, the size of the voluntary market for carbon offset projects is still quite low (2 billion USD in 2021 compared to 851 billion USD for mandatory projects in the same year) (Refinitiv 2023; Forest Trends' Ecosystem Marketplace 2022). 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, baseline and measurement criterion. Baseline setting means the amount of emissions 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 (Bento, Kanbur, and Leard 2016).

Secondly, carbon offset projects should be verifiable and transparent. Projects need to have carbon storage verified by third-party experts and according data should have open-access for stakeholders (Rawhouser, Cummings, and Marcus 2018). The fulfillment of this criterion could ensure the credibility of the project, which is the key to the inflow of investments and obtaining financing.

The additionality is also considered equally important criterion. Carbon offset projects could be recognized "additional" if emissions reduction and/or an increase of GHGs absorption was formed due to measures taken in addition to or in contrast to what is the business-as-usual practice in accordance with current legislation and accepted business norms (Mason and Plantinga 2013). 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 (either because the equipment would pay for itself or because regulation compelled the owner to do so).

Fourthly, the criterion of permanence. In the case of forest carbon offset projects, being as option of nature-based solutions (NBS), there is a risk of deforestation and forest degradation factors i.e., pests and diseases outbreak; forest fires; unsustainable logging (Richards and Huebner 2012). 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 loss.

Next important criterion of quality is double-counting issue. The fact is that carbon reductions are essentially air, the physical transmission of which cannot be fixed. And 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 them from its volume - record the transfer of reductions for use elsewhere. But in practice, it may turn out like the emissions reductions will be taken into account twice – both the seller and the buyer (Lucatello 2022).

Possible co-benefits of carbon offset projects are also considered to be 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, brings other socio-economic benefits (Grafton Q. R.; Chu L. H.; Nelson H.; Bonnis, G. 2021). 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. A classic example of leakage is when large reforestation plantations displace subsistence agriculture for native communities and lead to new deforestation elsewhere to compensate for the lost cropping area (Coulter, Canadell, and Dhakal 2007).

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, has also taken into account the role of carbon markets (Article 6) (United Nations Climate Change (UNFCCC) 2015). The establishment of 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, protectionist measures such as a carbon tax are put into effect (European Union Customs Union (EUCU) n.d.). At the same time, the main issue about the real carbon emissions reduction due to the measures taken remains open. Thus, for each party in this process to make a measurable impact is a must. In order to mitigate climate change and global warming, regulate carbon credits transactions and their allocation, improve carbon offset projects management, blockchain could be considered as a candidate solution.

In this article, authors performed systematic literature review (SLR) to understand the role of blockchain in two forms of carbon markets (including ETS and carbon offset projects), identify its key features, implementation challenges and proposed applications by reviewing the 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 have been inspired by reviewing the study of He and Turner (Z. He and Turner 2022). The authors conducted SLR for the assessment of blockchain possible implementation in forestry, also highlighting its benefits, opportunities, and challenges.

The research objectives of this study are to investigate the operation features of blockchain in ETS; to reveal the scope of blockchain in carbon offset projects; to assess technology’s potential to meet criteria of quality in carbon offset projects; and to identify the obstacles and challenges of its implementation in carbon markets. The contribution of this study is to provide a guidance for decision and policy-makers, start-upers, 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 and structured as follows: Section 1 introduces 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 with 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

(Nakamoto 2008). Because of its origin, it is referred to as cryptocurrency transactions, but the scope of the technology is noticeably wider. Blockchain is a system of records on the transfer of any value on the principle of "peer-to-peer". This means that there is no need for intermediaries such as banks, brokers or other escrow services that serve as a trusted third party.

According to Mougayar (Mougayar 2016), 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”(Mougayar 2016). Business-wise, “the blockchain is an exchange network for moving transactions, value, assets between peers, without the assistance of intermediaries”(Mougayar 2016). Legally, “the blockchain validates transactions, replacing previously trusted entities”(Mougayar 2016).

As shown in Figure 6, the first block in the chain is called "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 — hence the name of the technology. The chain of blocks is constantly growing while each new block is added. Each block (block n) holds hashed code of the previous block (hash of block n-1). In this DLT system, each block consists of two parts: the header and the body of the block (Morkunas, Paschen, and Boon 2019). The header refers to the previous block in the chain. Each block header contains a hash of the previous block, so there is no opportunity imperceptibly change the transaction in the previous block (Thwin and Vasupongayya 2019). The block body contains a list of verified transactions, their amounts, addresses of the parties and some other details (Dinh et al. 2018). Thus, having the last block, it is possible to get sequential access to all the previous blocks in the block chain.

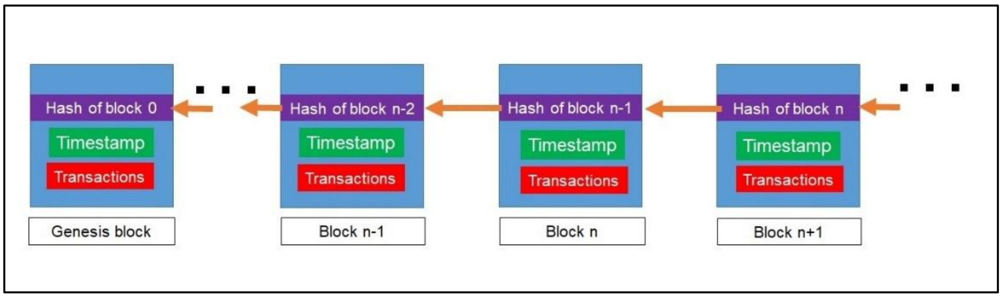

Fig. 6 The operation principle of blockchain

Basically, there are two main types of blockchain: public (permission-less) and private (permissioned) (Ismail and Materwala 2019). Public blockchains can be read by any user, each of whom has the right to form transactions (Buterin 2015). Bitcoin and Ethereum are examples of such type of permission-less blockchain (Nakamoto 2008; Wood 2022). 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 (Buterin 2015). Some researchers (Z. He and Turner 2022; Ismail and Materwala 2019) and Ethereum founder Vitalik Buterin (Buterin 2015) 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 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 (Nakamoto 2008; Mougayar 2016; Wood 2022). 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) are working 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 (Mougayar 2016; Buterin 2015).

Proof of Stake (PoS) is an alternative method that does not require special equipment (Mougayar 2016; Ismail and Materwala 2019). 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. So, in a way, the process is similar to a lottery. PoS is considered as a more sustainable and environmentally friendly alternative to PoW, as well as more protected from "51% attack" (Buterin 2015). 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. Well-known PoS platforms include Ethereum (after the Merge update). Practical Byzantine Fault Tolerance (pBFT) consensus algorithm requires a ⅔ majority of members to reach consensus (Mougayar 2016; Ismail and Materwala 2019).

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 (Mougayar 2016; Ismail and Materwala 2019). 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

A "smart contract" is a certain business logic that works on the network, moving value in a semi-autonomous mode and ensuring the fulfillment of payment agreements between the parties (Mougayar 2016; Buterin 2014). 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 7). One famous example of platforms to implement smart contracts is Ethereum proposed in 2013 (Buterin 2014).

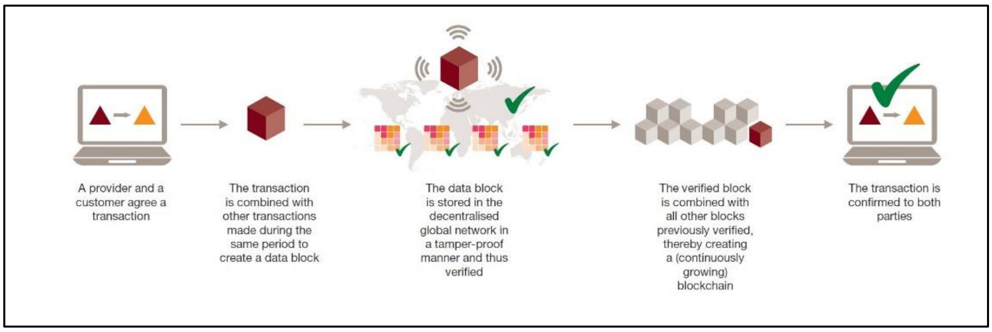

Fig. 7 Smart-contract process principle in blockchain, adapted from (PricewaterhouseCoopers (PwC) 2016)

Special services are used to connect smart contracts with the outside world. Oracle is a tool for smart contracts to access data from the world outside the blockchain (Mougayar 2016). Being a type of the "smart" contract itself, "oracles" take data from the outside world and put it into the blockchain to fulfill conditions under other "smart" contracts. In other words, oracle is a service that provides "trusted" data for a smart contract through transactions (Mougayar 2016). Oracles make the data usable in the blockchain. This allows 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, goods (Mougayar 2016; OECD 2020). Unlike cryptocurrencies, tokens can be issued and managed completely centrally. The token is inextricably linked with the initial coin offering (ICO) (OECD 2020). If companies enter initial public offering (IPO) on the stock exchange in order to receive investments, then 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 are known security, utility, debt, asset-backed and non-fungible tokens (NFT).

Security tokens are created to simplify the work of investors and are essentially company shares (Momtaz 2021). They certify ownership and make it possible to receive dividends. Utility tokens are used within the framework of a single blockchain project and grant investors the right to access the products or services of the project that could be created in the future (Pazos 2018). Debt tokens are crypto assets confirming obligations on mortgages, corporate bonds and other common lending mechanisms (Ooi 2022). Asset backed tokens are backed by tangible assets, as gold, oil, stocks, real estate (OECD 2020). One of the advantages of tokens is that they give the investor the right to use the material means with which the assets are secured (OECD 2020). The uniqueness of non-fungible tokens is that they are not interchangeable (Mougayar 2016). This property makes NFT a great way to capture uniqueness and establish one person's ownership of a digital object.

There is a significant difference between tokens and cryptocurrency. According to Mougayar (Mougayar 2016), the issue and verification of token transactions can be centralized and decentralized, cryptocurrencies can only be decentralized; 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; tokens do not necessarily have to be launched on their own blockchain, cryptocurrencies they always have their own blockchain (Gatabazi et al. 2022).

In some ways, tokens are analogs of company shares (OECD 2020). 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 (OECD 2020). As for the cryptocurrency, here it is a virtual tool that allows you to quickly and conveniently transfer value, while it is often used on the Internet (Mougayar 2016).

3 Research methodology

To address the research objectives within the topic, a systematic literature review was performed. This technique lies in evidence-based literature review, that helps collect and summarize relevant studies and identify the state-of-art data of the research topic by conducting analysis and synthesis of the current literature findings without bias (Mallett et al. 2012).

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 (Moher et al. 2009), combined with SLR guide proposed by Okoli and Schabram (Okoli and Schabram 2010). 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 blockchain addresses 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, included variations of keywords, relevant to this section: "blockchain*" and "block chain". In 'carbon' domain, keyword "*carbon*" was added. The search string was formed by combination of two domains by 'AND' as 'blockchain'-group keywords AND "*carbon*" keyword:

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

In order to provide comprehensive overview, we conducted multiple searches on different databases. These included 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 peer-reviewed high-quality studies. Blockchain, being an integral part of information technologies (IT) and computer engineering, lies in the field of high-tech. Thus, we have considered 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. Also we created eligibility criteria protocol for papers selection in this review (Table 2).

Tab. 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 originally was introduced in 2008. Last search was conducted on March 1, 2023
Publication type	Research articles and research reviews	Other papers	Peer-reviewed academic literature with related case studies provides more 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, car-bon 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, it 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 8 is the flowchart of PRISMA 2020 guideline (Page et al. 2021). As Figure 8 shows, it includes identification, screening and inclusion steps. The total number of searching results from three databases was 287. 116 duplicate records were removed and 171 remained for screening stage. According to 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 of records exclusion were: (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 remained 60 articles for full-text eligibility. A total of 21 records were excluded for specific reasons, included: (1) superficial overview of blockchain, in some cases mixed with other Industry 4.0 technologies (e.g. IoT, AI, Big Data etc.); or (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 as the dataset of this SLR for further data extraction, analysis and synthesis.

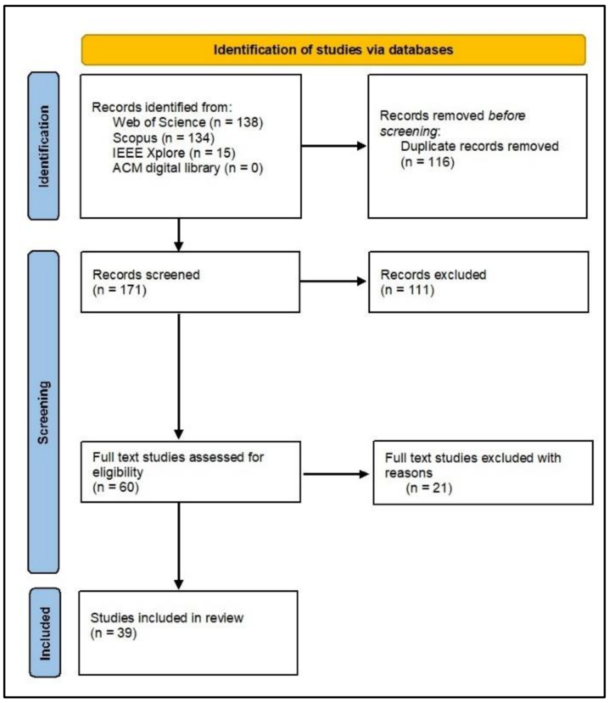

Fig. 8 The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of this systematic literature review, based on the PRISMA 2020 guideline.

3.4 Data extraction

According to the research objectives, next step was data extraction from the included studies. During the process of data categorization, we revealed that some of them combining 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 Table 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 9 shows the distribution and domains of publications by years. 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 became both for 2020 and 2021 combined. It means, the increasing interest in blockchain technology for its possible implementation 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 C1 in Appendix C shows category, author(s), year, title and journal of the articles included in this SLR.

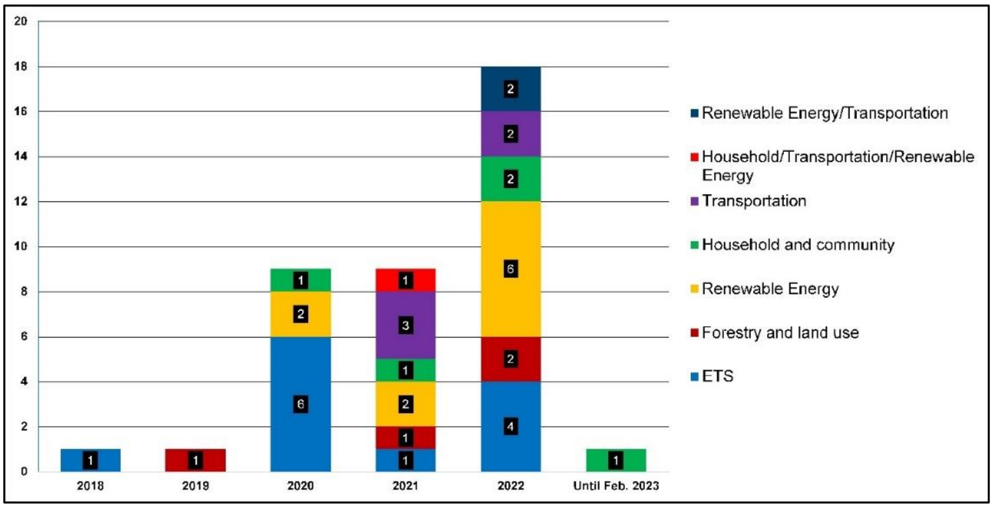

Fig. 9 Distribution and domains of publications by years

3.5 Analysis, Synthesis and Reporting

In the final step, we extracted the data from each included study and then conduct the analysis based on the research questions. In order to answer on them, the basic characteristics of included studies were extracted and thoroughly analyzed. To answer the first research question, the operating mechanisms for carbon credits considered in articles from ETS domain were extracted for analysis. The answer to the second research question has already been 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 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 and challenges of blockchain technology, that hinder its possible implementation in carbon markets considered in 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 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, it should be assessed the degree of predisposition of this technology to this operational format.

4.1.1 Public, private and consortium blockchains in ETS

Zhou and Zhang (Zhou and Zhang 2022) conducted simulation study of carbon emissions trading based on different types of blockchains: public and private. Simulation results of this research showed that time cost of private carbon emissions trading mechanism is lower than in public-based ETS. Due to the time-consuming responsibilities dedicated by network-wide certification in public-based ETS, performance of private-based ETS more suitable for implementation in China’s carbon market. Hartman and Thomas (Hartmann and Thomas 2020) suggest that private blockchain is also more suitable for implementation in Australian carbon market. National registry of carbon emission units should operate as a private ledger, allowing Regulator retain its eligibility and access management role due to existing legislation requirements. Comparing the suitability of two different blockchain platforms, Ethereum (public and permissionless) and Hyperledger Fabric (private and permissioned), Franke et al. (Franke, Schletz, and Salomo 2020) highlighted the advantages of both systems. Hyperledger Fabric provides maintain control over the technological infrastructure for the network authority of the UNFCCC during carbon management accounting. While Ethereum platform encourages bottom-up and democratic system governance through public transparency. Kim and Huh (Kim and Huh 2020) propose consortium (hybrid) blockchain 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. (Mandaroux, Dong, and Li 2021) also propose consortium blockchain for EU ETS enhancing. It is suitable decentralized platform for a user group that is only party public and, hence, is of great benefit for organizational cooperation.

4.1.2 Main actors (nodes)

Khaqqi et al. (Khaqqi et al. 2018) propose blockchain reputation-based emission trading scheme for participants (nodes) interaction. Within this scheme the Auditor (reputation rating agency) evaluates the Firm (business) carbon reduction strategy represented by the Project (CDM project) with subsequent carbon credits issuing by Authority (government). Based on the reputation of the participants, the quality of the trade offers and the speed of the transaction depends. Hu et al. (Hu et al. 2020) also adhere to a similar approach in reputation assessment of enterprises for emissions. Zhang et al. (Zhang et al. 2022) as Zhou and Zhang (Zhou and Zhang 2022) highlighted government, investors and company agents as main actors within blockchain-based ETS. Zhao and Chan (F. Zhao and Chan 2020) propose the scheme with interaction of Organizers (supervision), Validators (NGOs or academic institutions) elected by participants, and users (carbon traders). Shokri et al. (Shokri et al. 2022) also adhere to a similar approach, highlighting Creators (organizers), purchasers (users) and market facilitators (verification). Franke et al. (Franke, Schletz, and Salomo 2020) and Schletz et al. (Schletz, Franke, and Salomo 2020) describe nodes interaction within blockchain-based Article 6.2 architecture, including UNFCCC secretariat, technical experts, and participating Parties (countries and non-state actors).

4.1.3 Consensus mechanisms

Hu et al. (Hu et al. 2020) propose a Delegated Proof of Reputation (DPoR) consensus mechanism for effective assessment of reputation value of the emitting enterprises. Therefore, lower reputation points lead to more transaction fees and weaker voting power. Hartman and Thomas (Hartmann and Thomas 2020) propose proof-of-authority (PoA) consensus protocol for implementation in Australian carbon market. Therefore, the Regulator meet its legislative responsibilities for updating the national carbon registry. Zhao and Chan (F. Zhao and Chan 2020) suggest that proof of work (PoW) protocol is not suitable for purposed blockchain-based CAT scheme. Authors consider practical Byzantine fault tolerance (pBFT) protocol for possible implementation. Kim and Huh (Kim and Huh 2020) propose DPoS (Delegation Proof of Stake) protocol for carbon emissions verification under UN. Sipthorpe et al. (Sipthorpe et al. 2022) highlight that proof-of-stake and proof-of-authority are more appropriate consensus mechanisms, than energy-demanded proof-of-work.

4.2 RQ2: What is the scope of blockchain in carbon offset projects?

Previously, in Figure 9, we presented number and categories of 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 to expand the possible application of blockchain in such categories as household and community, and transportation. Noteworthy, that some studies cover 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 propose peer-to-peer trading framework integrating energy and carbon credits (Hua et al. 2020; H. He et al. 2020; X. Wang, Yao, and Wen 2022). Same mechanism was also proposed for peer-to-peer transaction in virtual power plant (Li et al. 2022). The power-to-gas technology provides to wind farms to absorb carbon for further trade in multiple energy markets (Ji et al. 2021). It becomes possible by automated scheduling framework enabled by smart contract is established for reliable coordination between wind farms and multiple energy markets (Hua et al. 2022). Several studies observe opportunities for microgrids energy management based on blockchain (Su, Li, and Jin 2021; Zhong et al. 2022). Blockchain also could be implemented in bilateral bidding market for carbon allocation from electricity generation by different units (Luo et al. 2022). Finally, blockchain proposed for distinguishing energy transitions between renewables capacities and power plants by "guarantees of origin" issuing (Delardas and Giannos 2022).

For "citizen energy communities" cultivation, in order to improve life standards and provide low-carbon facilities, blockchain also could be impended for peer-to-peer energy trade (Deconinck and Vankrunkelsven 2020; Wu, Wu, Cimen, et al. 2022; Prabhakar and Anjali 2022; B. Wang et al. 2023), and for energy efficiency control of residential buildings (Kolahan et al. 2021).

Blockchain also does not bypass the transport sector, whose greenhouse gas emissions account for about 45% (Subramanian and Thampy 2021). 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, the framework for charging management of electric vehicles (Dorokhova et al. 2021; Khan and Byun 2021; Liang, Wang, and Abdallah 2022) with subsequent peer-to-peer energy trading optimization (Kakkar et al. 2022) was proposed for blockchain implementation. In addition, a hybrid blockchain was proposed by Subramanian and Thampy (Subramanian and Thampy 2021) for 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 bidding model of power grid that considers carbon emissions (Wen et al. 2022; Nour, Chaves-Avila, and Sanchez-Miralles 2022). In addition, blockchain is an integral part of the model of a decentralized energy community involving RES, energy-positive buildings and electric vehicles (Wu, Wu, Guerrero, et al. 2022).

A number of papers consider 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 introduced as the integral part of modern forest carbon sinks management (Sun et al. 2021). In theory, it could provide optimal emission reduction efforts control between forest farmers and emission-controlled enterprises. In addition, Reducing Emissions from Deforestation and Forest Degradation (REDD+) considered as a platform for blockchain implementation to improve forest management practices (Howson et al. 2019; Kotsialou, Kuralbayeva, and Laing 2022). Blue carbon as large and unexplored carbon storage, also proposed for carbon market integration through the blockchain (C. Zhao et al. 2022).

4.3 RQ3: How blockchain addresses criteria of quality in carbon offset projects?

In order to make a real contribution to mitigate climate change, carbon offset projects must meet a number of criteria. As noted in the introduction part, the quality criteria include: (1) baseline and measurement; (2) verifiability and transparency; (3) additionality; (4) permanence; (5) double-counting avoidance; (6) co-benefits provision; (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.

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 (Hua et al. 2020; Su, Li, and Jin 2021). Within this process smart contract provides transparent transactions from initialization of bids and offers, to winner of bidding selection, and subsequent ownership exchange (Hua et al. 2020; Luo et al. 2022). Carbon emissions caused by electricity generation, transmission, and consumption are measured by smart meters. The consensus of proof-of-work is proposed for collectively validation of transactions by all nodes (Hua et al. 2020). However, if the power transmission and distribution transactions are on the public blockchain, the transaction data is transparent and privacy cannot be guaranteed (X. Wang, Yao, and Wen 2022). 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 (Delardas and Giannos 2022).

Double-counting issue in guarantees of origin allocation under renewable energy trade can be avoided by producing unique identifiers for each transaction (Delardas and Giannos 2022). 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.

Co-benefits of peer-to-peer energy trading, basically include bill-saving or cost-saving for personal benefits (Hua et al. 2020; H. He et al. 2020; X. Wang, Yao, and Wen 2022; Li et al. 2022; Hua et al. 2022; Su, Li, and Jin 2021; Zhong et al. 2022; Luo et al. 2022; Delardas and Giannos 2022; Nour, Chaves-Avila, and Sanchez-Miralles 2022). Development of renewable energy sources is also closely linked to the power grid and can provide the energy for electric vehicles (EV) via charging stations, that considers carbon emissions (Wen et al. 2022).

4.3.2 Household and community

Peer-to-peer energy trading for flexible energy exchange across multiple sectors and local communities involves verification process, based on smart contracts (Wu, Wu, Cimen, et al. 2022; Prabhakar and Anjali 2022). Smart meters connected to home energy systems (nodes) performed to measure consumption data, while sensors display data readings (Deconinck and Vankrunkelsven 2020; Prabhakar and Anjali 2022). Therefore, smart contracts provide transactions between parties (Prabhakar and Anjali 2022; Kolahan et al. 2021). Thus, transactions can be aggregated into timestamped and cryptographically linked blocks, forming a blockchain (Deconinck and Vankrunkelsven 2020; Kolahan et al. 2021). However, transparency of transactions presents challenges regarding privacy (Deconinck and Vankrunkelsven 2020).

Household energy trading based on roof solar and wind turbines in addition to gain revenue also helps to shift loads and power peaks and reduce customer costs (Deconinck and Vankrunkelsven 2020; B. Wang et al. 2023). Moreover, energy trading provides an opportunity for the synergy of renewable energy, home energy consumption and charging of EVs (Kakkar et al. 2022; Wu, Wu, Guerrero, et al. 2022).

4.3.3 Transportation

Energy trading based on the blockchain network provides to electric vehicles ensure data authenticity and transparency of transactions obtained (Kakkar et al. 2022). EVs can also sell energy to grid and buildings through the smart charging (Wu, Wu, Guerrero, et al. 2022). Blockchain can help certify and manage renewable energy transfers in each transaction among them. Proposed vehicle-to-grid (V2G) and vehicle-to-building (V2B) energy transaction mechanisms could increase decarbonization flexibility (Wu, Wu, Guerrero, et al. 2022).

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" (Howson et al. 2019). 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) (Kotsialou, Kuralbayeva, and Laing 2022). Data can only be recorded in the blockchain after they have been verified by most nodes in the entire network (C. Zhao et al. 2022).

It is found, that blockchain can not entirely address the additionality issue of forest carbon offset projects. In order to be additional, forest carbon sink projects should not to 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 (Kotsialou, Kuralbayeva, and Laing 2022). In the context of REDD+, 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, thus REDD+ projects are likely to be additional (Kotsialou, Kuralbayeva, and Laing 2022).

Carbon sequestered in forests is inherently unstable due to its possible emissions through forest degradation or deforestation actions (Howson et al. 2019; Kotsialou, Kuralbayeva, and Laing 2022). Thus, the permanence of such projects may be questioned, also negating the validity of credits issued before. The solution proposed by blockchain is to collect updated data on the state of the forest area, followed by the formation of related tokens (Kotsialou, Kuralbayeva, and Laing 2022). 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 information (Kotsialou, Kuralbayeva, and Laing 2022).

The double-counting issue in forest carbon offset projects could be potentially solved by the introduction of NFTs, that are priced differently based on the carbon stock of individual trees (Kotsialou, Kuralbayeva, and Laing 2022). In turns, blockchain provides the opportunity for users to adjust the distribution of NFTs, with subsequent double-counting avoidance in carbon markets.

Blockchain, being decentralized and transparent technology is able to enforce the verifiability (via smart contracts) and provide the reduction of labor costs involved in measuring and monitoring under forest management practices (Sun et al. 2021; Kotsialou, Kuralbayeva, and Laing 2022). Co-benefits of possible blockchain implementation in the context of REDD+ activities could include poverty alleviation and improved governance ensured by United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). Upholding of community rights could require the involvement of relevant jurisdictions, by translating and programming these standards as conditions into smart contracts (Kotsialou, Kuralbayeva, and Laing 2022). 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.) (C. Zhao et al. 2022).

Dealing with carbon leakage issue in the context of forestry for blockchain technology 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 (Kotsialou, Kuralbayeva, and Laing 2022). 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 the 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, grouped its similar challenges for both blockchain-enabled ETS and carbon offset projects and between them as shown in Figure 10.

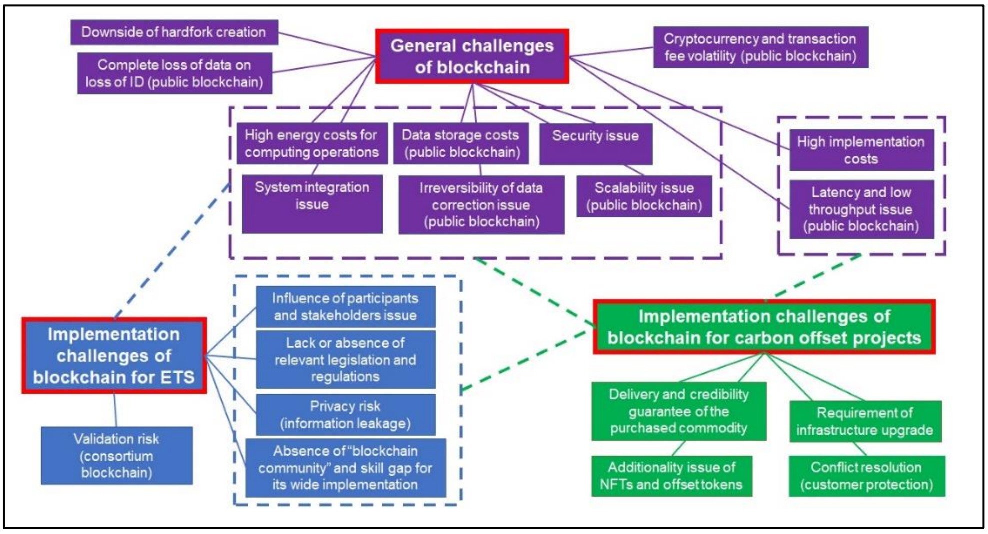

Fig. 10 Blockchain implementation challenges in carbon markets

4.4.1 General challenges of blockchain

In the case of PoW consensus mechanism, blockchain requires high energy and computing costs (Mougayar 2016). That in turns, leads to carbon footprint of blockchain itself. Such high computation power needs to solve the hash puzzle, and it consumes a large amount of electrical energy (Nour, Chaves-Avila, and Sanchez-Miralles 2022). However, this issue can be tackled by using other consensus algorithms (PoS, PoA, pBFT), which are less energy-demanded.

As new transactions are processed and added to blocks, the data storage decreases. This is because each node has a copy of each transaction and data. The number of copies increases with the addition of new blocks (Nour, Chaves-Avila, and Sanchez-Miralles 2022). This is especially typical for public blockchain.

Cyber-attack resistance of blockchain is not completely proven yet. However, in practice, if potential malicious users gain control of 51% of computation capacity (in case of PoW) or 51% of the network stakes (in case of PoS), then they could manipulate and change block data (Nour, Chaves-Avila, and Sanchez-Miralles 2022). Thus, so-called "51% attack" is a significant security issue of blockchain.

Currently, there is not many 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 is still remains by the absence of integration with other DLT systems (Mougayar 2016; Nour, Chaves-Avila, and Sanchez-Miralles 2022).

Immutability of data is a key feature of public blockchain. However, it also eliminates to make any necessary changes in previous blocks in case of bugs or errors (Nour, Chaves-Avila, and Sanchez-Miralles 2022). Therefore, irreversibility of data correction issue hinders public blockchain large-scale adoption.

Scalability issue of blockchain requires additional efforts to modify the system to be able to cope with the increased amount of participants and transactions (Mougayar 2016; Dorokhova et al. 2021). Theoretically, for the perfect functioning of blockchain, it should remain decentralized, secure and scalable (F. Zhao and Chan 2020; Delardas and Giannos 2022). In turn, so-called “scalability trilemma” forms contradictory trade-offs associated with each objective (Mougayar 2016).

Another issue of public blockchain is latency and low throughput of transactions. Trustless nature of PoW consensus algorithm brings time consuming principle of work to process transactions (Mougayar 2016; Nour, Chaves-Avila, and Sanchez-Miralles 2022).

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 as high (Mougayar 2016; Nour, Chaves-Avila, and Sanchez-Miralles 2022).

A hardfork is a way to make significant changes to the program code of a project based on blockchain technology (Nour, Chaves-Avila, and Sanchez-Miralles 2022). 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, a hard fork 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: one part of them use the updated version, while others continue to work on the old version, making their own changes (Nour, Chaves-Avila, and Sanchez-Miralles 2022).

Cryptocurrency frequently suffers from high volatility (Mougayar 2016). That makes blockchain-based applications risky for investment and creates uncertainty for blockchain network users (Nour, Chaves-Avila, and Sanchez-Miralles 2022). Moreover, for smart contract execution in public blockchain, miners should receive a fee to process transactions (Hu et al. 2020). The price of the fee is also variable and unpredictable (Nour, Chaves-Avila, and Sanchez-Miralles 2022).

One more drawback of public blockchain lie in inability to recover the access to account in the case of its loss (e.g. by losing or forgetting the wallet password) (Nour, Chaves-Avila, and Sanchez-Miralles 2022). Therefore, all data and cryptocurrency belongs to the lost ID will be permanently lost.

4.4.2 Implementation challenges of blockchain for ETS (carbon credits)

Khaqqi et al. (Khaqqi et al. 2018) suggest the blockchain-enabled ETS has equal implementation challenges of the blockchain technology itself. In particular, they include: high energy costs for computing operations (Mougayar 2016; Hu et al. 2020); big data storage requirements (F. Zhao and Chan 2020; Nour, Chaves-Avila, and Sanchez-Miralles 2022); data correction irreversibility issue (F. Zhao and Chan 2020; Nour, Chaves-Avila, and Sanchez-Miralles 2022); security issues (Mougayar 2016; Franke, Schletz, and Salomo 2020; F. Zhao and Chan 2020; Nour, Chaves-Avila, and Sanchez-Miralles 2022); system integration issue (F. Zhao and Chan 2020; Sipthorpe et al. 2022) and scalability issue (F. Zhao and Chan 2020).

A central authority should be established for blockchain regulation in ETS (Hartmann and Thomas 2020). Without it, the legal liability of smart contracts operations consequences remains unclear. Moreover, the regulatory entity should enforce the property right of carbon credits in cap-and-trade system (F. Zhao and Chan 2020).

Enterprises, perhaps, could demonstrate unwillingness to adopt blockchain for automatic carbon accounting, because of commercially sensitive data (such as production and operation data) leakage concerns (F. Zhao and Chan 2020). On the global level, blockchain also should enforce security and integrity of political and sensitive data to create an accountable and incentive consensus mechanism between the participating Parties (Franke, Schletz, and Salomo 2020).

If ETS is based on consortium blockchain, then validation could be damaged by mistakenly selected malicious peers (F. Zhao and Chan 2020).

Due to the lack of widespread use of blockchain technology, "blockchain community" is not being formed to support and promote its implementation, in particular, in such important initiatives as the fight against climate change (Franke, Schletz, and Salomo 2020; Kim and Huh 2020). 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 (Sipthorpe et al. 2022).

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, a number of stakeholders, including miners (or validators), developers, coin holders and investors, all of whom have different interests, which makes it quite difficult to coordinate and reach an agreement (Kim and Huh 2020). Further coordination of actions may include informing each of the participants, taking into account their demands (Mandaroux, Dong, and Li 2021), or dividing them into full and light nodes (Franke, Schletz, and Salomo 2020).

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 (Mougayar 2016; Deconinck and Vankrunkelsven 2020; B. Wang et al. 2023; Kakkar et al. 2022; Nour, Chaves-Avila, and Sanchez-Miralles 2022; Howson et al. 2019); storage constraints (Delardas and Giannos 2022); security issues (Mougayar 2016; X. Wang, Yao, and Wen 2022; Delardas and Giannos 2022; Deconinck and Vankrunkelsven 2020; Kakkar et al. 2022); lack of system integration (Mougayar 2016; Khan and Byun 2021; Nour, Chaves-Avila, and Sanchez-Miralles 2022; Wu, Wu, Guerrero, et al. 2022; Kotsialou, Kuralbayeva, and Laing 2022); data correction irreversibility issue (Delardas and Giannos 2022) and scalability issue (Mougayar 2016; Deconinck and Vankrunkelsven 2020; Dorokhova et al. 2021; Khan and Byun 2021).

Several implementation challenges of proposed carbon offset projects based on blockchain are similar to 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 (Wu, Wu, Guerrero, et al. 2022). Lack of regulation, legislation and business models for blockchain use in electricity sector also could postpone its vast application (Nour, Chaves-Avila, and Sanchez-Miralles 2022). Privacy-sensitive data stored in blockchain of energy consumption transactions could be revealed by network participants especially in the case of the public blockchain (Deconinck and Vankrunkelsven 2020; Nour, Chaves-Avila, and Sanchez-Miralles 2022). In addition, skill gap for large-scale deployment of blockchain in electricity sector deepens by uncertainty of using it for a specific application by startups (Nour, Chaves-Avila, and Sanchez-Miralles 2022). It is also crucial for forest carbon offset projects implementation to attract well-experienced developers with adequate understanding of forestry and their challenges (Kotsialou, Kuralbayeva, and Laing 2022). Therefore, majority of pilot projects are still on the "proof of concept" stage (Dorokhova et al. 2021; Khan and Byun 2021).

In contrast to blockchain-enabled ETS, carbon offset projects based on blockchain additionally suffer from two challenges of the technology itself has. First, latency and low throughput issue is unacceptable for blockchain implementation in peer-to-peer energy trading (Delardas and Giannos 2022; Dorokhova et al. 2021; Nour, Chaves-Avila, and Sanchez-Miralles 2022). Second, blockchain adoption could require re-equipment with subsequent high implementation costs (Delardas and Giannos 2022).

In order to reflect a product of equal value in real, delivery guarantee of the purchased renewable electricity volume (Delardas and Giannos 2022), as well as credibility guarantee of carbon credits gained from blockchain-based forest-offset projects (Kotsialou, Kuralbayeva, and Laing 2022), 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 (Delardas and Giannos 2022). In the second case, due to uncertain baseline and measurement, it becomes difficult to determine which companies provide credible credits (Kotsialou, Kuralbayeva, and Laing 2022).

For blockchain integration into the energy system, it should be considered infrastructure upgrade, in particular for EV charging stations development (Khan and Byun 2021; Nour, Chaves-Avila, and Sanchez-Miralles 2022). Smart contracts in energy trading also potentially can endanger customer protection. Technically, smart meters are able to disconnect the customer from the grid remotely for unpaid electricity bill (Deconinck and Vankrunkelsven 2020). 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 (X. Wang, Yao, and Wen 2022).

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 (Kotsialou, Kuralbayeva, and Laing 2022). Otherwise, "business-as-usual" practices in forest carbon offset projects based on blockchain could lead to isolation of local communities in social aspects as education, healthcare and governance.

5 Theoretical Implications and Further Research Directions

Blockchain is able to promote 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 the 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 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 criteria of quality in carbon offset projects of about-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, data extraction step showed that in the case of blockchain application in renewable energy projects, it also provides the synergy of renewables (photovoltaics), combining with household (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), transparency issue (by smart contracts), 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 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 double-counting issue (by the introduction of NFTs), 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 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 modern with blockchain implementation.

Various drawbacks of blockchain are hinder the implementation of the technology in carbon markets. This is also compounded that majority of implementation obstacles of blockchain in ETS and carbon offset projects are factually consisting from some of its general challenges. Interestingly, that implementation challenges of blockchain in carbon offset projects are similar with some of its general drawbacks and drawbacks of blockchain-enabled ETS. That makes possible implementation of the technology more complicated and costly.

Based on the above-mentioned theoretical implications, this 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.

Tab. 3 Research agenda for future research

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 be-tween 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 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 low carbon economy (decentralization, decarbonization and digitalization). Blockchain has a pronounced potential for implementation into a new model in the architecture of Article 6 of the Paris Agreement, combining national Parties' registries and voluntary mitigation contributions of non-state actors by tokens allocation in order to meet long-term climate mitigation goals (Schletz, Franke, and Salomo 2020).

In this paper, we investigated blockchain technology implication in carbon markets (including ETS and carbon offset projects). To address the research objectives, a systematic literature review was performed as the research methodology. 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 analysis and discussion.

Our findings indicate that blockchain has great potential to be adopted in ETS and carbon offset projects. 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. Therefore, 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 (Z. He and Turner 2022), it is only on the fourth stage of its evolution, but develops constantly. In addition, blockchain is currently immature in carbon markets, because majority of projects are at or before "proof-of-concept" step (Sipthorpe et al. 2022). Obviously, the technology has its own drawbacks and challenges. Thus, decision and policy-makers, start-upers, 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 it performed in our previous study (Vilkov and Tian 2019).

There are several limitations in our study. Firstly, there was no opportunity to gain full text access for 10 manuscripts found in ACM digital library database. These articles potentially could make a contribution to our findings and theoretical implications. Secondly, despite we spent a considerable amount of time on article searching and selection, we do not exclude some potential flaws that could be occurred in the data selection and extraction steps.

The main contribution of this study was 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, start-upers, stakeholders and others involved or interested in the field of "3D's concept" to better understand blockchain's role and significance in carbon markets. The study is also highlights research gaps and offers research directions. To our strong belief, the results we summarized could inspire researchers to conduct related investigations.

Appendix A

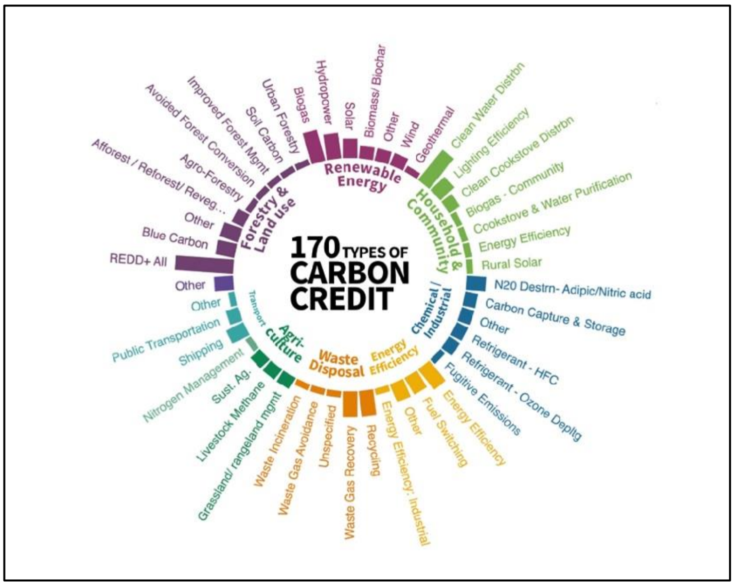

Figure A1 Ecosystem Marketplace carbon offset projects typology, adapted from (Forest Trends' Ecosystem Marketplace 2022)

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*"]]

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