Received: 22 September 2023 | Revised: 14 January 2024 | Accepted: 26 January 2024

DOI: 10.1002/ese3.1697

REVIEW

Towards the net zero carbon future: A review of blockchain-enabled peer-to-peer carbon trading

Mohammad Parhamfar[1] | **Iman Sadeghkhani**[1,2] | **Amir Mohammad Adeli**[1]

[1]Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran

[2]Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

Correspondence
Iman Sadeghkhani, Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad 85141-43131, Iran.
Email: sadeghkhani@pel.iaun.ac.ir

Abstract

The increasing trend of energy generation and management systems towards decentralized structures such as using renewable energy resources makes it necessary to use digital and smart platforms for exchanging information and even conducting financial transactions in a decentralized manner, known as the peer-to-peer model. The decentralized transaction verification of cryptocurrencies makes it possible to use these encrypted currencies and decentralized blockchain networks in energy management systems and carry out financial transactions related to carbon trading. Carbon and other greenhouse gas (GHG) emission trading systems reduce the competitiveness of fossil fuel projects in the market and accelerate investment in low-carbon energy sources such as wind and photovoltaic power generation units. This market mechanism allows large entities such as countries and companies that emit GHGs into the atmosphere to buy and sell these gases. This paper reviews the blockchain solutions developed for carbon markets. Studies related to the design of smart contracts in the platform of blockchain are investigated. Special cryptocurrencies that are used in the field of green energy transactions and carbon trading are introduced. In addition, the application of artificial intelligence and game theory in energy trading is stated. The study of different blockchain frameworks for carbon trading shows that the use of decentralized platforms in carbon trading can have a significant impact on the trend towards low-carbon measures and achieving the goals of the Kyoto Treaty, increasing the value of green cryptocurrencies and the volume of transactions. These technologies offer a promising avenue for creating a more decentralized, efficient, and environmentally conscious energy ecosystem.

KEYWORDS

artificial intelligence, blockchain, carbon trading, game theory, green cryptocurrency, renewable energy

1 | INTRODUCTION

Greenhouse gases (GHGs) trap the heat and make the planet warmer.[1] Human activities have been almost responsible for the increase of GHGs in the atmosphere during the last 150 years.[2] Figure 1 shows the amount of CO_2 emission change by separating each part of human activities. The most important activity is the burning of fossil fuels for electricity and heat generation, and transportation. It contributes significantly to global warming, climate change, and a wide range of environmental impacts.[3] According to the international energy agency (IEA) report,[4] global CO_2 emissions associated with the energy sector grew by about 0.9% in 2022, reaching an all-time high of more than 36.8 gigatons. The significant growth of electricity generation from wind turbines and solar photovoltaic (PV) systems has prevented the emission of about 465 million tons of CO_2 in the power sector. Other clean energy technologies, including heat pumps, electric vehicles, and other renewables, helped prevent an increase of about 85 million tons of CO_2 emissions. Without this increased growth in the deployment of clean energy technologies, the annual increase in emissions related to the energy sector would have almost tripled. Therefore, effective international measures should be taken to deal with the increase in GHG emissions.

The Kyoto Protocol is one of the first international coordinated agreements that was approved by the United Nations (UN) in Kyoto, Japan, in which industrialized economies agreed to reduce their GHG emissions during 2012–2018 by 5.2% compared to levels measured in 1990.[5,6] Based on empirical evidence, the Kyoto Protocol has been effective in reducing GHG emissions in committed countries. It is a market-based mechanism that forms the framework of the international climate change response system, as described by the UN. This protocol includes carbon emission trading, a clean development mechanism, and a joint implementation system. Carbon trading is an approach adopted for reducing the global emission of GHGs such as CO_2.[7,8] In the Kyoto Protocol, the market mechanism is introduced as a new way to solve the problem of reducing GHG emissions; the emission of carbon dioxide is considered as a commodity that forms a trading system for carbon.[9]

Blockchain technology has found a transformative application in carbon trading, revolutionizing the way emissions are monitored, recorded, and traded. It has the potential to accelerate the global deployment of an emissions trading system (ETS) and improve the efficiency of existing systems.[10] With this technology, verification of transmitted data and information is no longer done through a central actor, but through a peer-to-peer (P2P) network.[11] By providing a decentralized and immutable ledger, blockchain ensures transparency, security, and accountability in carbon markets. Through smart contracts, emission reduction targets and commitments can be automatically executed, streamlining the verification and certification processes. This enables stakeholders to have real-time access to accurate emissions data, reducing the risk of fraud and inaccuracies. Additionally, blockchain facilitates fractional ownership of carbon credits, enabling wider participation in the market and unlocking opportunities for smaller players. Ultimately, the integration of blockchain technology in carbon trading has the potential to accelerate the transition toward a more sustainable and low-carbon future by creating a robust and efficient marketplace for emissions reductions. The objectives of this review article are as follows: (i) Review of blockchain-based P2P carbon trading schemes, (ii) review of the application of artificial intelligence (AI) and game theory in energy trading that includes the role of AI and game theory in optimizing the energy trading, facilitating the decision-making,

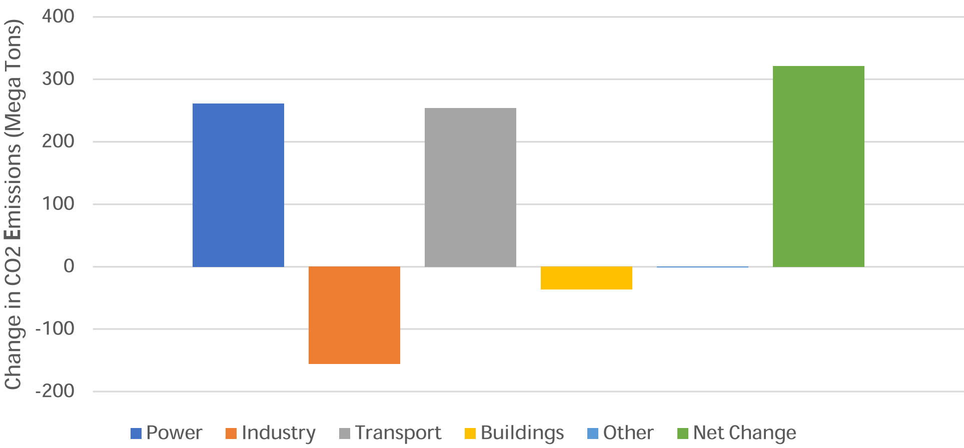

FIGURE 1 Carbon dioxide emissions change by sector during 2021–2022.[4]

predicting the energy consumption, and enhancing efficiency in energy transactions, and (iii) identifying future research directions that are forward-looking and aims to propose potential future avenues for research and development in the application of blockchain, AI, and game theory in carbon trading and energy markets.

2 | CARBON TRADING

Carbon emissions can be rooted in the source of energy or its consumption. There are two types of carbon sources: direct and indirect.[12] The former is the carbon that is released directly from chemical reactions on site, such as fuel burning (crude oil, paraffin, coal, and natural gas), decomposition, fermentation, decay and organic matter, and production of chemical products such as oil and coal stone. The latter mainly includes carbon outside a specific site. The most important measure for carbon reduction is the use of clean energy sources and the efficiency improvement of energy consumption.[13]

With emissions of more than 10,065 million tons of CO_2 in 2019, China accounts for about 30% of the world's carbon emissions and ranks first in the list of top polluters.[14] Figure 2 shows the share of CO_2 emissions by country in 2021.

In commitments to gradually eliminate the use of coal and reduce GHGs, world leaders at the UN climate change conference (COP26) in Glasgow agreed to reform global carbon markets and improve carbon trading laws. Proponents of this system state that carbon trading will ultimately increase investment in environmentally friendly solutions; because the carbon price makes fossil fuel projects more competitive and at the same time encourages low carbon energy sources such as wind and solar.[16] COP26 participants agreed on a clear and uniform set of rules for international GHG trading. This means that countries that are trying to reduce their emissions can partially meet their climate goals by buying offset credits from other countries that have successfully reduced their emissions. The process also allows for the forming of a Un-monitored carbon sequestration market, where governments and private entities can trade GHG emission credits from low-carbon projects.

Each company/country is given a certain number of permits based on the standards set to emit carbon dioxide at a certain level. If a company/country does not consume all its permits (emit less CO_2), it can sell the unreleased permits to another company/country that wants to consume more carbon than its released permits. The point is that every year fewer permits are granted to each company/country.

Countries worldwide are increasingly committing to the ambitious goal of achieving net-zero carbon emissions. This objective involves balancing the release of carbon dioxide into the atmosphere with its removal, ultimately resulting in no net increase. Table 1 shows the target date of some countries and large companies that have a net zero carbon program to end their contribution to global warming.

Carbon emission trading (trading of pollutants) refers to the market in which GHG emission rights (emission trading) are acquired.[19] Carbon emission rights can be sold in different markets—some at the international

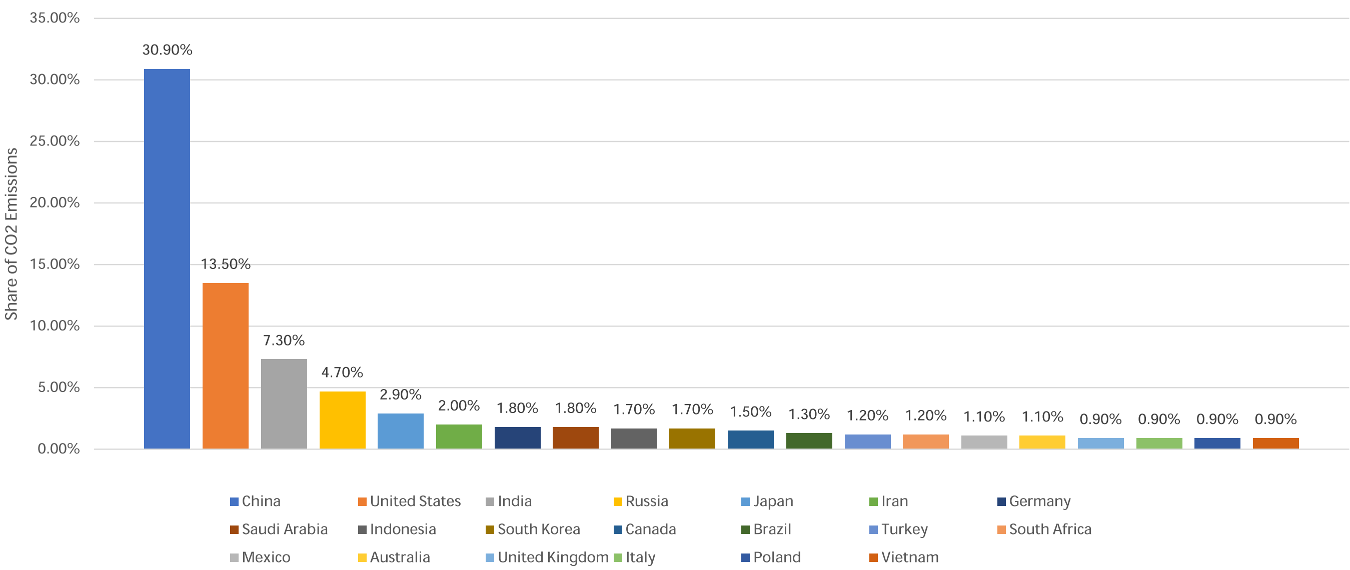

FIGURE 2 Share of CO_2 emissions by country in 2021.[15]

TABLE 1 Net zero carbon target date of some countries and companies.[17,18]

Country	Target date	Company	Target date
Argentina	2050	Allianz	2030
Austria	2040	Alphabet	2030
Brazil	2060	Amazon	2040
Bhutan	Currently carbon negative	Apple	2030
Canada	2050	AT&T	2035
Chile	2050	AXA	2050
China	2060	BP	2050
Colombia	2050	Cardinal Health	2030
Costa Rica	2050	China Construction Bank	2060
Denmark	2050	China State Construction	2060
European Union	2050	Cigna	2040
Fiji	2050	Costco	2030
Finland	2035	CVS Health	2050
France	2050	Daimler AG	2039
Germany	2045	Deutsche Telekom AG	2040
Grenada	2050	EXOR	2025
Hungary	2050	Exxon Mobil	2050
Iceland	2040	Ford Motor Company	2050
Ireland	2050	General Motors Company	2040
Japan	2050	Glencore International	2050
Maldives	2030	Home Depot	2035
Laos	2050	Hon Hai Precision	2050
Marshall Islands	2050	ICBC	2060
Nepal	2050	Kroger	2030
New Zealand	2050	Microsoft	2030
Panama	2050	Mitsubishi	2050
Portugal	2050	PetroChina Co	2050
Slovakia	2050	Ping An Insurance	2030
South Africa	2050	Royal Dutch Shell	2050
South Korea	2050	Samsung Electronics Co	2050
Spain	2050	Saudi Aramco	2050
Sweden	2045	Sinopec	2050
Switzerland	2050	Toyota Motor	2050
Turkey	2053	UnitedHealth	2035
Ukraine	2060	Verizon	2035
United Kingdom	2050	Volkswagen	2050
United States of America	2050	Walgreens Boots Alliance	2030
Uruguay	2030	Walmart	2040

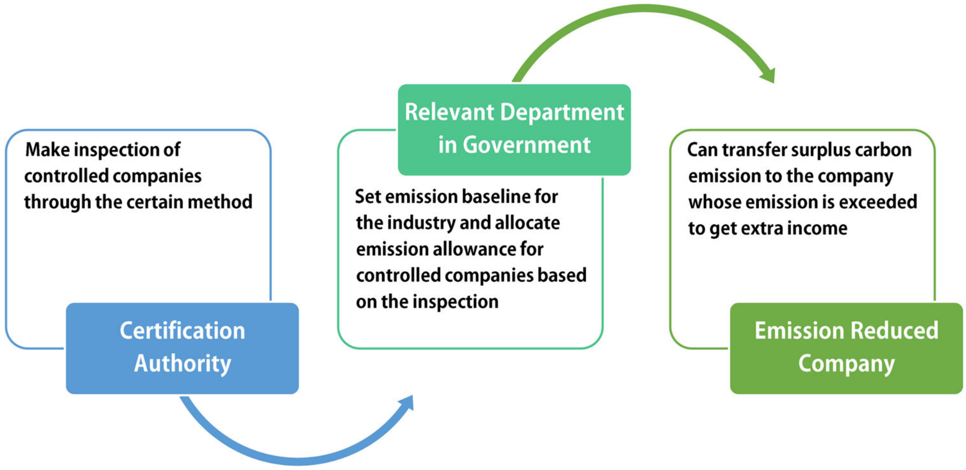

FIGURE 3 Carbon trading process.[22]

markets, some at the national level, and some at the state or local level, such as California's cap-and-trade system.[20] China is the largest operating market for GHG trading in the world.[21] The ETS of this country, which was introduced in July 2021, covers about 4800 million tons of GHGs equivalent to carbon dioxide.

The carbon trading process is shown in Figure 3. The emission of GHGs has decreased in companies that have paid attention to the development of energy saving or upgrading technology and equipment. The companies whose emissions are more than the allowed limit must buy the remaining emission quota from them. In this way, awareness of low-carbon goals will be strengthened. As a result, equipment, technologies, structural energy saving, and energy management will be improved to increase the effect of energy saving and reduce emissions.

Construction sectors around the world consume a lot of energy. Also, buildings account for 30% of the total global final energy consumption and 27% of all harmful emissions from the energy sector.[23] Therefore, the importance of this sector in terms of reducing emissions by optimizing energy consumption and using renewable energy sources should be considered. In,[24] technical-economical-environmental analysis was performed on building integrated photovoltaic (BIPV) systems for decarbonization purposes in Australia. The results showed that BIPVs are one of the effective solutions to reduce carbon emissions by 28% less than in 2005 until 2030.

Liu et al.[25] investigates a P2P energy trading system based on hydrogen vehicles in a set of net zero energy buildings. According to the presented model, energy transaction price can reduce electricity costs by 14.54% and carbon emissions by 8.93%. Zhou[26] presents a new spatiotemporal energy network in the Guangdong-Hong Kong-Macao Greater Bay Area with the participation of electric vehicles. Regional pricing policy is very important in creating economic incentives for all stakeholders. Lyu et al.[27] present a decentralized P2P energy-sharing framework with privacy protection and high-level autonomy in middle coordinators for smart buildings, considering several dynamic components, including heating, ventilation, air conditioning, battery energy storage systems, and electric vehicles. The results show that the presented framework can admirably improve the overall well-being of the involved smart buildings.

2.1 | UN carbon offset platform

The UN carbon offset platform is an e-commerce platform where a company, an organization, or an ordinary citizen can buy a currency (carbon credits) to save GHG emissions or to support environmental actions.[28] The carbon offset process in this platform is shown in Figure 4.

2.2 | Carbon footprint calculation

One of the key elements of the carbon offset platform is the possibility to calculate the carbon footprint. This calculator is made as a simple questionnaire in which each company provides information about its activities and gets an estimate of its emissions, that is, its carbon footprint. The amount of GHG emissions is estimated by the UN based on the latest available country data. All data is obtained from reliable sources such as electronic data gathering, analysis, and retrieval system (EDGAR), environmental protection agency (EPA), climate watch, and the international civil aviation organization (ICAO). These data are supplemented by internal estimates made

FIGURE 4 The process of offsetting the emissions by UN.[28]

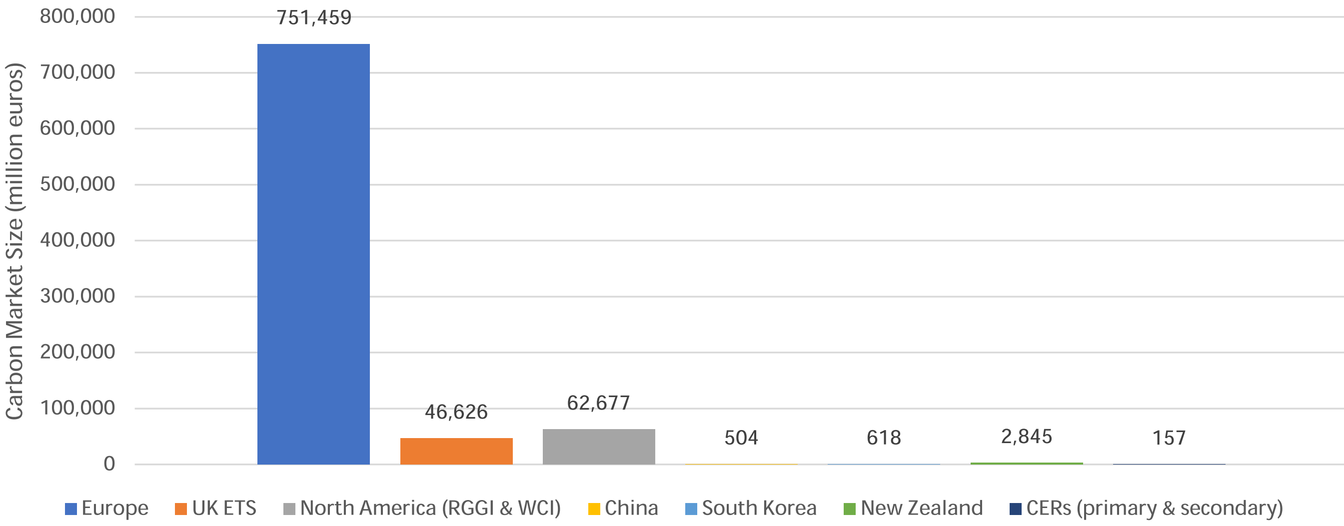

FIGURE 5 Carbon market size in 2022. CER, certified emission reductions; RGGI, regional greenhouse gas initiative; WCI, western climate initiative.[34]

by UN experts.[29] This organization uses various tools to check the validity of the data and ensure the highest possible degree of accuracy. To provide a uniform result, GHG emissions related to different activities are calculated with their CO_2 equivalent. To make calculations easier, default values are used in certain cases. For the final calculation, in addition to the data provided, each country's specific reference values for public services and activities that are not considered as carbon footprints from the country's point of view will also be applied. Therefore, all three categories of emissions of household, transportation, and lifestyle have a certain ratio in the final result. This organization updates the data used in calculations as much as possible over time.

2.3 | Glasgow carbon trading agreement

After much study, global carbon market rules were established at the Glasgow climate change conference in November 2021; a global integrated approach was established for the first time in the Paris Climate Agreement in 2015. The agreed framework known as Article 6 includes a centralized system and a separate bilateral system.[30] The centralized system is for the public and private sectors, while the bilateral system is designed for countries to exchange carbon offset credits to help them meet their emissions targets. According to the new agreement, those who generate carbon credits will pay 5% of the proceeds into a fund to help developing countries deal with climate change. Also, 2% of the credits will be canceled to ensure the overall emission reduction.[31]

2.4 | Carbon trading market

In 2022, the traded value of the worldwide carbon credit market amounted to US$978.56 billion; it is anticipated that this market will grow and attain a value of US$2.68 trillion by 2028.[32] Figure 5 shows the carbon market size for some countries/regions in 2022. According to the report of the international carbon action partnership (ICAP) in 2023,[33] about 28 ETSs are currently active in the world, covering about 17% of global emissions. Also, 20 other markets are in the consideration or development stage. The coverage volume of the global carbon markets compared to 2005, when the European Union (EU) emission trading scheme was launched and covered only 5% of global emissions, has increased to more than three times in 2022. The ICAP report states that the global sales amount of emission permits in 2021 was about US$58 billion, which has increased by more than 132% compared to 2020 with a sales value of US$25 billion. In 2021, the price of carbon permits in the EU emissions trading market increased by 150% at the end of the year to around €80 per ton; the main reason for this was the increase in the EU emission reduction target from 40% to 55% by 2030 compared to 1990 emissions. It is €87 per tonne in 2023. The price of one ton of carbon in the emission trading market of California and Quebec, which are connected, increased from $18 in 2020 with a 55% increase to $28 at the end of 2021. In China, the carbon market closed at around $8.5 in December 2021, which was about 13% higher than the price at the time of the opening of this market in July 2021.

According to the ICAP report, ETS play a key role in the century challenge of achieving net zero carbon emissions by 2050 and are increasingly becoming the adopted policy tool to guide decarbonization programs globally. Countries' net zero emissions commitments cover approximately 70% of global GHG emissions, but many are not supported by short-term policies. Achieving the long-term climate goal requires strengthening existing ETS.

As of March 31, 2023, Uruguay has the highest carbon tax rate worldwide at nearly US$156 per ton of CO_2 equivalent (USD/tCO_2e). Uruguay's carbon tax was first introduced in January 2022. In comparison, Poland's tax rate was less than 1 USD/tCO_2e. In addition, Finland—the first country in the world to introduce a carbon tax in 1990—had a carbon tax rate of about 84 USD/tCO_2e as of March 31, 2023.[35] Carbon prices in multiple ETSs worldwide are expected to increase during 2026–2030 compared to 2022–2026. It is expected that the average carbon price of the EU will reach 84.4 euros per ton of CO_2 during 2022–2025.[36] Figure 6 shows the carbon tax rate in Europe in 2022 and Figure 7 shows the allowance price for some ETSs.

2.5 | Various viewpoints on carbon trading

Proponents of carbon trading have concluded that this trade is a cost-effective solution to the problem of climate change and provides an incentive to adopt renewable energy technologies. However, carbon emissions trading has been widely and increasingly criticized. Sometimes this trade is considered as a half-baked measure and a distraction to solving the big and urgent problem of global warming. Despite these criticisms, carbon trading is a central concept in many proposals to mitigate climate change and global warming.[39]

2.6 | Internet of Vehicles (IoV) application in carbon trading

The IoV has a significant potential to reduce carbon emissions by optimizing transportation efficiency. Through IoV's interconnectedness that can be secured using blockchain technology, vehicles can access real-time traffic data, leading to smoother routes and reduced

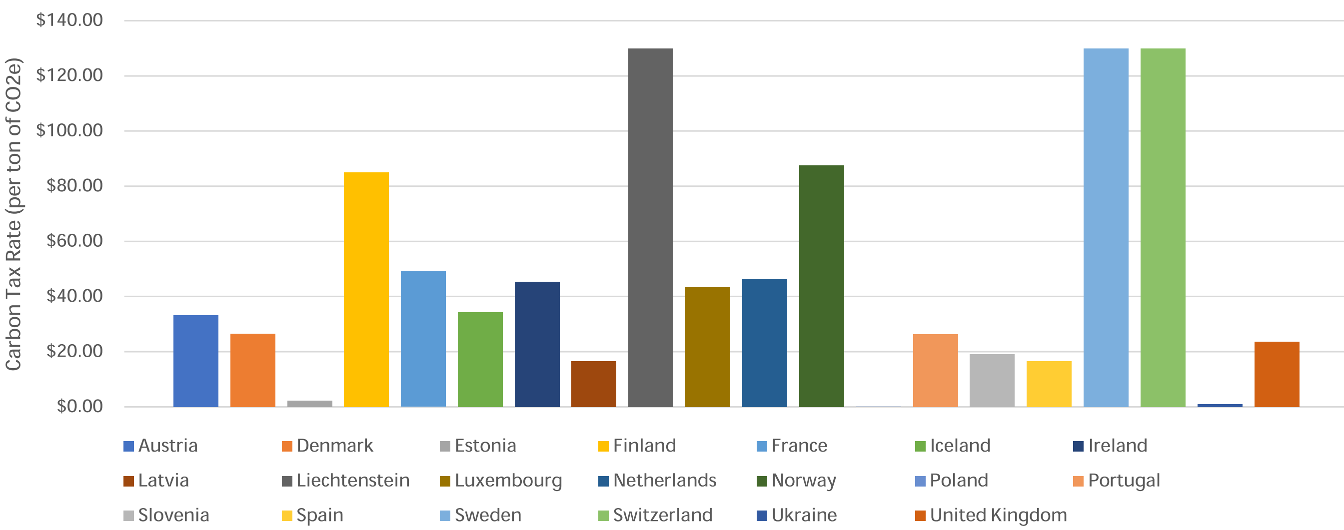

FIGURE 6 Carbon tax rate in Europe in 2022.[37]

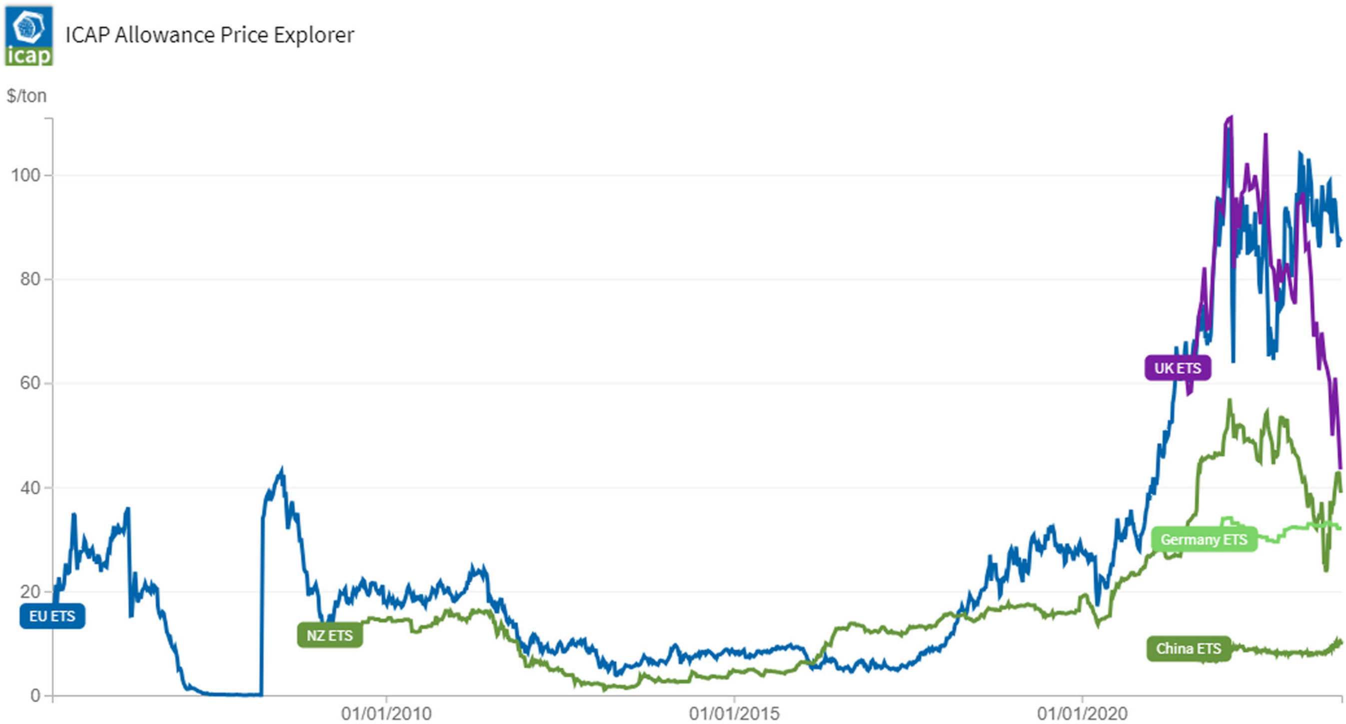

FIGURE 7 Allowance price for some ETSs.[38]

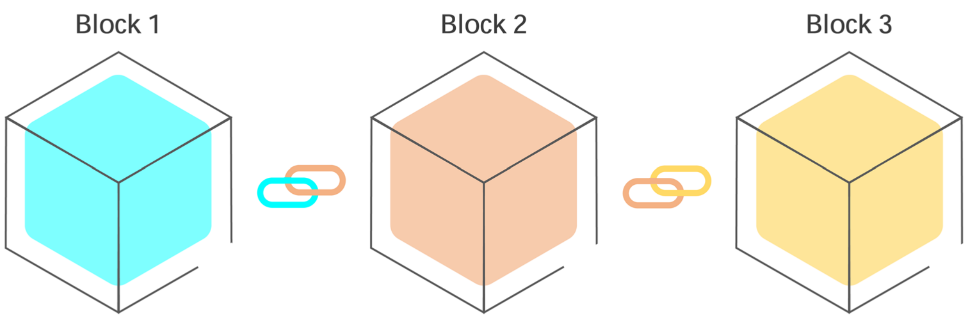

FIGURE 8 Blockchain structure.

idling time, thus minimizing fuel consumption and emissions.[40–43] Additionally, IoV enables intelligent traffic management, promoting better traffic flow and decreased congestion, further contributing to lower carbon emissions by reducing the time vehicles spend in traffic jams. IoV's ability to optimize transportation efficiency, reduce fuel consumption, and minimize emissions aligns with carbon trading objectives focused on decreasing overall carbon footprints. By leveraging IoV technologies to enhance transport systems and reduce emissions, companies and industries could potentially earn carbon credits or allowances through carbon trading, incentivizing the adoption of IoV technologies as part of broader strategies for reducing GHG emissions.

3 | BLOCKCHAIN TECHNOLOGY

Blockchain, sometimes referred to as distributed ledger technology (DLT), records the history of any digital asset using a decentralized network and chained blocks through encrypted hashes.[44] This system is completely immutable and transparent. A decentralized network is something similar to the Google Doc.[45] When a Google Doc is created and shared with a group of people, the document is distributed instead of being copied or transferred. This system creates a decentralized distribution chain of consecutive blocks that allows everyone to access the basic document at the same time. Each block contains a cryptographic hash of the previous block, a timestamp, and transaction data.[46] As shown in Figure 8, cryptographic concepts are used to protect and link each of these data blocks. This design makes it extremely difficult for malicious actors to alter historical data, providing a high level of trust in the information stored on the blockchain.

For the first time, David Chaum in 1982 managed to develop an infrastructure or protocol similar to blockchain based on an encryption algorithm called RSA.[47] He submitted an article to a conference on security in the banking field, and this is how the cornerstone of this technology was formed in the 1980s. The first decentralized blockchain was conceptualized by a person (or a group of people) named Satoshi Nakamoto in 2008. Nakamoto improved the design in a significant way by using a hash-like method to time-stamp blocks without requiring a trusted party to sign them.[48] The hash cache is a proof-of-work system used to limit email spam and denial-of-service attacks. The hash cache was proposed by Adam Beck in 1997.[49] In 2019, it was estimated that about US$2.9 billion were invested in blockchain technology, which represents an increase of 89% compared to the previous year.[50] In addition, the international data corp has estimated that corporate investment in blockchain technology will reach US$12.4 billion by 2022.[51]

One of the notable features of blockchain technology is the smart contract, self-executing, and programmable agreements encoded within the blockchain. Smart contracts automate and enforce predefined conditions, streamlining processes and reducing the need for intermediaries. The combination of blockchain's transparent and secure ledger with the programmability of smart contracts enhances efficiency and trust in transactions across various sectors, collectively contributing to the evolution of the broader concept of DLT.

3.1 | Smart contract

In the traditional electricity market, electricity flows from large power stations and through national/regional transmission grids to local distribution systems that are connected to the end consumers. Network operators ensure the matching of demand and supply and maintain the quality of electricity at all times. This includes ensuring that the frequency of the system is maintained within the permitted range, the balance of supply and demand instantaneously, and the existence of sufficient storage capacity in the system in case of significant unforeseen changes in supply or demand by providing “ancillary services.” Network operators can be considered as intermediaries between producers and consumers. In traditional systems, the balance is managed at the transmission level, while in today's networks, this management is done at the local distribution level. The rapid integration of intermittent and often very distributed renewable generations in the system, as well as the integration of products and services based on information and communication technologies, have increased the need to use an intelligent platform for energy management and balance of supply and demand. The need to implement such a system is to use smart technical tools, smart interaction initiatives, and smart monitoring tools like smart contracts.[52]

Smart contracts are simple codes that can be executed to perform a specific function.[53] These contracts are equivalent to paper contracts, but they eliminate the need for an enforcement agency to ensure compliance because once the contract is executed, it is completed exactly as planned, regardless of any additional human input. A carbon credit ecosystem based on blockchain technology is created in Saraji and Borowczak[54] that includes four smart contracts: (i) recording the essential data using a registry system on the blockchain, (ii) mining carbon tokens, (iii) multisignature contract, and (iv) automated market maker. Various works have studied how to use smart contracts and their effects in different smart grids.[55–57] Richter and Pollitt[58] studies the heterogeneity of home consumers' preferences for smart contracts for electricity services in the context of a smart grid. The results show that smart electricity service providers can significantly reduce their customer acquisition costs by targeting customers with special characteristics. In Foroozandeh et al.,[59] a contract for energy management of a smart residential building with PV production, electric vehicles, and a battery energy storage system is presented. In this building, each customer has a flexible contract power and the entire residential building has a single contract power. The results indicate that by using the optimal amount of contracted power of the unit and intelligent management system, the electricity cost of the building is reduced significantly by 47%. Table 2 reviews some previous works on smart contracts.

3.2 | Distributed ledger

DLT stands as the cornerstone of blockchain systems, revolutionizing the traditional approaches to data management and verification. Within the realm of carbon trading, DLT offers a decentralized, transparent, and immutable ledger, facilitating secure and efficient transactions while eliminating the need for intermediaries. The P2P nature of DLT ensures that transaction records are simultaneously stored across a network of

TABLE 2 Some previous works on smart contracts.

Reference	Proposed scheme	Features
[60]	• Decentralized execution of economic dispatch by using smart contracts	• Facilitates the distribution of surplus energy among neighboring structures to decrease the energy transmission requirements of conventional power grid management
	• Provides an incentive mechanism based on the reputation value	• Can significantly guarantee the adherence of all involved parties to the dispatching plan
	• The multilateral transaction based on reputation and billing value	• Eliminates the need for participants to engage in bidding, thus saving time and preventing transaction conflicts
[61]	• Evaluates the present and future status of carbon trading within the power industry, examining growth patterns and obstacles	• Enhances the security and efficiency of carbon trading
	• Develops a diagram outlining a process optimization framework for carbon trading using blockchain technology, along with a smart carbon trading system	• Enhances the mechanism for storing carbon trading data
	• Develops a model for smart contracts within the smart carbon trading system	• Evaluates the credibility of trading participants
		• Precisely maintains records of transactions
		• Offers a high degree of automated settlement capabilities
[62]	• Introduces an innovative smart contract framework within smart cities	• Explores the process of enrolling IoT devices into heterogeneous networks
	• Implements a dynamic service security protocol that is practical and viable	• Explores the establishment of secure communication across multiple heterogeneous networks
	• Demonstrates the practicality of the decentralized service security architecture for diverse IoT devices, showcasing its feasibility	• Examines the procedures involving registration, communication, and the execution of dynamic service security protocols among IoT devices within a heterogeneous network
[63]	• Expansion of the decentralized peer-to-peer market framework	• Facilitates product distinctiveness via bilateral negotiations
	• Incorporation of the Hyperledger Fabric blockchain framework with a customized smart contract	• Makes participant trust and preserves privacy during bilateral negotiations
	• Documenting the multi-step market clearing process for a day	• Examines the effect of product distinctiveness in peer-to-peer markets on the revenue and dispatch of renewable energies
[64]	• A thorough examination of energy-related smart contract research, encompassing benefits and constraints	• Offers a prospective foundation for the initiation of smart contract deployments
	• Introduces a six-layer architecture and an energy smart contract	• Delivers a structured exposition of the advantages and drawbacks associated with smart contracts
	• Conducts an assessment of diverse real-world applications of smart contracts drawn from industrial contexts and pilot demonstration initiatives	

nodes, fostering a tamper-resistant ecosystem where each participant possesses a synchronized and continuously updated ledger. This decentralized consensus mechanism not only enhances data integrity and security but also engenders trust among participants, paving the way for innovative and transparent carbon trading platforms.

The distributed ledger is an immutable historical record; in fact, all blockchain transactions are recorded in an immutable ledger and distributed throughout the network.[65] In general, there are three types of distributed ledger: (i) single-entry ledger includes one-way entry in the credit or debit column, (ii) double-entry ledger includes simultaneous tracking of debts and credits, and (iii) triple-entry ledger includes an advanced double entry system where all transaction inputs are verified and secured by a cryptographic system. In the blockchain, a triple ledger is used, which includes debt, credit, and links between previous blocks.

4 | APPLICATION OF BLOCKCHAIN IN ENERGY TRADING

Energy is a natural resource that has fueled the growth of countries' economies in the past few decades. As society moves towards digitalization, the reliance on energy also increases increasingly. According to the statistical review of the World Energy Report by British Petroleum, global primary energy demand rose 5.8% and carbon emissions from energy consumption increased by 5.9% in 2021.[66] The shortage of fossil fuels and the known environmental issues related to carbon emissions have helped to increase the focus on discovering alternative energy sources, the most important of which are renewable energy sources such as solar and wind energy.[67]

Extracted energy from different sources (conventional and renewable sources) is generated on the supply side and is delivered to consumers on the demand side. Management of increasing energy demand on the supply side is limited due to the limitations of network infrastructure and resources. One way to manage energy on the demand side is to use distributed renewable energy sources, which is known as cloud energy.[68] This method creates new challenges for the smart grid.

With the decentralization of the energy sector, many issues such as time-varying renewable generation, distributed storage, control, management, and trading must be considered. These problems cannot be solved by traditional energy systems, while blockchain features can provide suitable solutions.

The carbon trading system is a market mechanism that is used to promote the reduction of global GHG emissions. It allows businesses that cannot reduce their GHG emissions to offset these emissions by purchasing credits from others that meet their targets. Previous discussions emphasize the importance of decentralization, a feature commonly associated with blockchain. In recent years, the application of blockchain has increased in many fields, including energy management. Figure 9 shows the application of blockchain in various fields, including the energy area.

4.1 | P2P energy trading system

With the emergence of modern energy technologies, the smart energy market is moving from a centralized form to a decentralized one which is known as the P2P model. The main challenges in a P2P energy market are scalability, robustness, security, and privacy issues.[69] In Khalid et al.,[70] a blockchain-based solution is presented to implement a combined energy trading market. It shows that a blockchain-based system is completely decentralized and allows market members to interact with each other and trade energy without the intervention of a third party. In Kang et al.,[71] a P2P electricity trading model based on blockchain is presented for plug-in hybrid electric vehicles. Instead of the traditional method of importing electricity from a distant power source, this model focuses on the demand response, and by offering various incentives, it attracts consumers to participate in this program. Each participant who works in this system can balance his electricity demand with the supply to get the maximum incentive. A blockchain-based smart contract framework for retail P2P energy trading is designed in Han et al.[72] It introduces a double-auction mechanism for direct trading control, utilizes a multidimensional blockchain platform for user-friendly interfaces and complete cyber-physical communication, and outlines a smart contract architecture feasible for decentralized energy trading in small-scale integrated systems. Suthar and Pindoriya[73] presents a blockchain and smart contract-driven trading platform for local energy trading, utilizing blockchain to record power transactions and smart contracts for pretransaction checks.

Blockchains are usually managed by a P2P computer network as a public distributed ledger. In this network, all nodes have access to the consensus algorithm protocol to add and confirm new transaction blocks.[74] In P2P

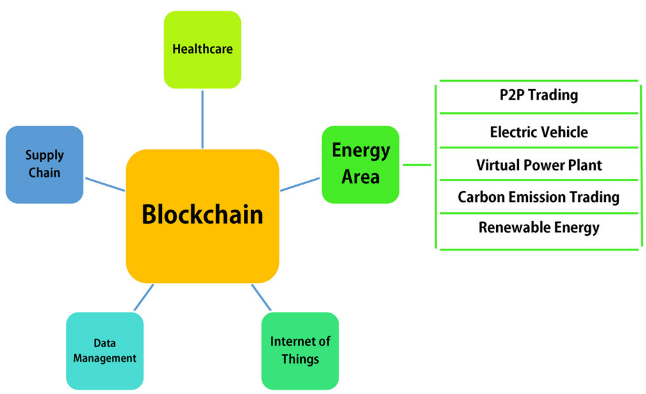

FIGURE 9 Application of blockchain.[67]

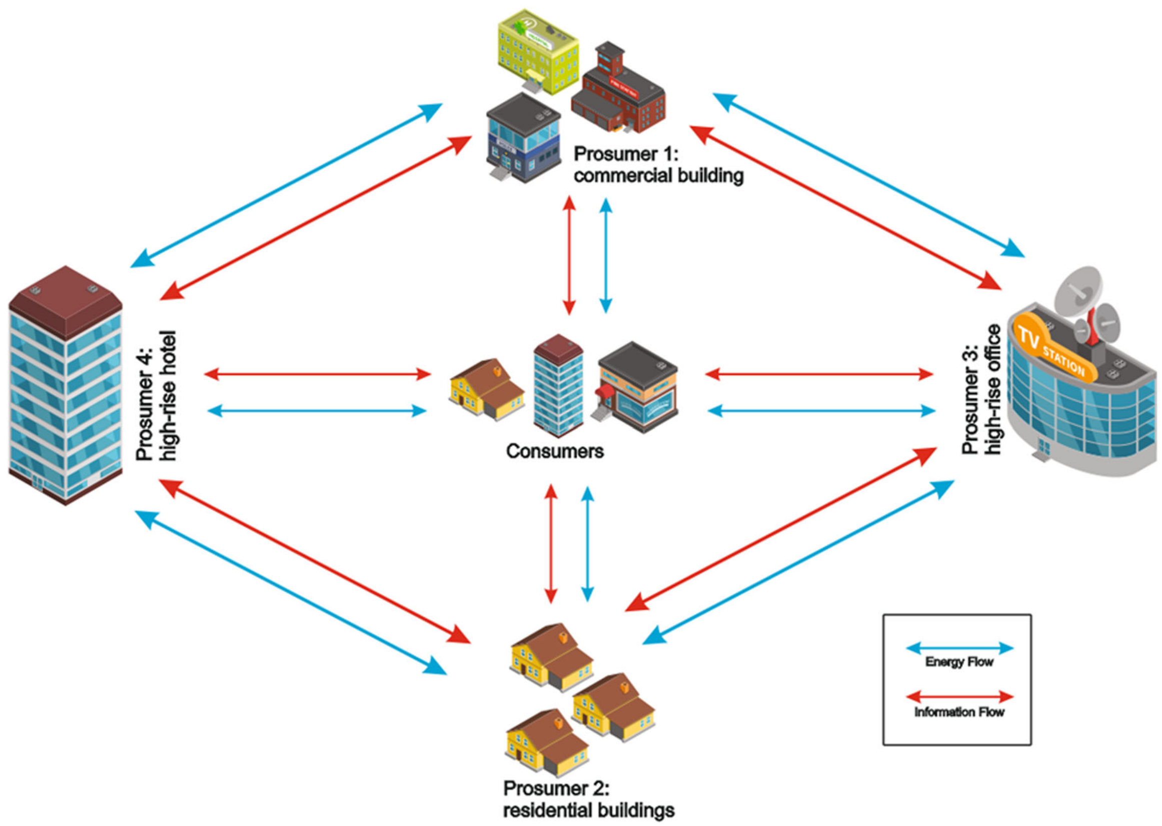

FIGURE 10 P2P energy trading in a small area.[75]

energy trading, internal consumption can be effectively increased with the high penetration of renewable energies, reducing pressure on the electrical grid and promoting decarbonization. Figure 10 shows P2P energy trading in a small area.

4.2 | Renewable energies

Renewable energy sources are intermittent in nature; the coalition between multiple microgrids based on a P2P energy trading system can solve this problem. A P2P energy trading system for microgrids is proposed in Thakur and Breslin[76] where a blockchain-based coalition formation method is presented in which several coalition algorithms are executed in parallel, which reduces computing time and allows microgrids to exchange energy more often. The decentralized nature of this system makes it scalable and the algorithms converge quickly. In Wang et al.,[77] a dynamic energy management approach is designed for distributed energy resources with high penetration of renewable energies where a real energy blockchain project with 300 renewable energy prosumers has been investigated. This method can reduce network latency to less than 2000 ms, which will double the efficiency of energy trading operations. In Song et al.,[78] a secure P2P energy trading system using an Ethereum-based smart contract is developed, featuring dynamic pricing for microgrid balance, autonomous operation, and prevention of double sales.

Basic knowledge about blockchain technology shows the connection of this technology with digital currencies such as Bitcoin and Ethereum. It has caused the development of digital currencies in the field of renewable energy trade in recent years. Several companies are using cryptocurrencies to attract new investors and organize additional financing options in this area. Some examples of cryptocurrencies related to renewable energies are presented in Table 3.

4.3 | Virtual power plant (VPP)

Changing the style of the traditional energy management system to a decentralized power system with a two-way flow of power and information for the integration of distributed generation (DG) units is essential in moving towards smart energy networks. VPPs are known as a promising technology for managing DG units and increasing participation in improving the power system performance. Figure 11 shows the conceptual model of a VPP.

TABLE 3 Some cryptocurrencies in renewable energy trading.

References	Cryptocurrency	Summary
[79, 80]	SolarCoin	• SolarCoin was proposed by Nick Gogerty along with Joseph Zitoli and was launched in January 2014 • SolarCoin incentivizes solar energy generation by rewarding solar electricity producers with tokens. For every MWh of generated solar energy, participants can receive SolarCoins, providing a financial incentive for adopting clean energy practices • SolarCoin utilizes blockchain technology to verify and record energy production, ensuring transparency, immutability, and accuracy in the reward distribution process
[81]	EECoin	• EECoin was developed by a team led by Dr. Anna Martinez and was launched in March 2022 • EECoin incentivizes energy efficiency improvements by rewarding individuals and businesses that reduce their energy consumption. Participants earn EECoins based on the degree of efficiency achieved, promoting sustainable energy practices and enhancing the attractiveness of energy efficiency measures • Built on a secure blockchain, EECoin ensures transparency and traceability of energy-saving actions. This technology verifies and records energy consumption reductions, preventing fraudulent claims and ensuring accuracy
[82, 83]	EcoCoin	• The EcoCoin was introduced to the public in September 2021 • EcoCoin serves as a cryptocurrency that rewards individuals, organizations, and communities for adopting eco-friendly behaviors. By engaging in activities such as recycling, reducing waste, and conserving resources, participants earn EcoCoins that represent their positive environmental impact • Built upon a decentralized blockchain, EcoCoin ensures transparency and security in tracking environmentally conscious actions. This tamper-resistant technology verifies and records each activity
[84, 85]	NRGcoin	• NRGCoin was the brainchild of a group led by Dr. Sarah Greenfield and was introduced to the public in May 2020 • NRGCoin serves as a cryptocurrency that channels funds directly into sustainable development initiatives. Individuals, corporations, and governments can contribute to these projects by purchasing NRGCoins, supporting endeavors like renewable energy installations, afforestation efforts, and clean water initiatives • NRGCoin operates on a transparent and secure blockchain, ensuring the traceability and accountability of funds allocated to sustainable projects
[86]	EverGreenCoin	• EverGreenCoin was conceived by a community of environmental enthusiasts, blockchain developers, and sustainability advocates, and was launched in December 2015 • EverGreenCoin is a cryptocurrency that actively supports environmental initiatives. A portion of each block reward generated by the blockchain is dedicated to funding projects focused on sustainability, renewable energy, conservation, and other eco-friendly causes • EverGreenCoin's blockchain technology ensures transparency and traceability for its transactions and fund allocations. This immutable ledger validates the utilization of funds in various environmental projects

VPPs represent the future of power generation because they enable intelligent energy consumption in a distributed environment through optimal management of demand and power generation.[88] This means that each user can produce and consume their energy at the same time, which leads to the active participation of consumers in decision-making. In addition, VPPs are a useful tool for integrating renewable energies in helping to balance the grid. VPPs can also be used to integrate the load management of electric vehicles.[89–91]

In Yang et al.,[92] an energy management platform for VPPs based on blockchain is simulated to facilitate energy transactions between residential users with renewable energy sources, energy storage systems, and flexible loads. It shows that the blockchain-based VPP energy management platform reduces the cost of users by

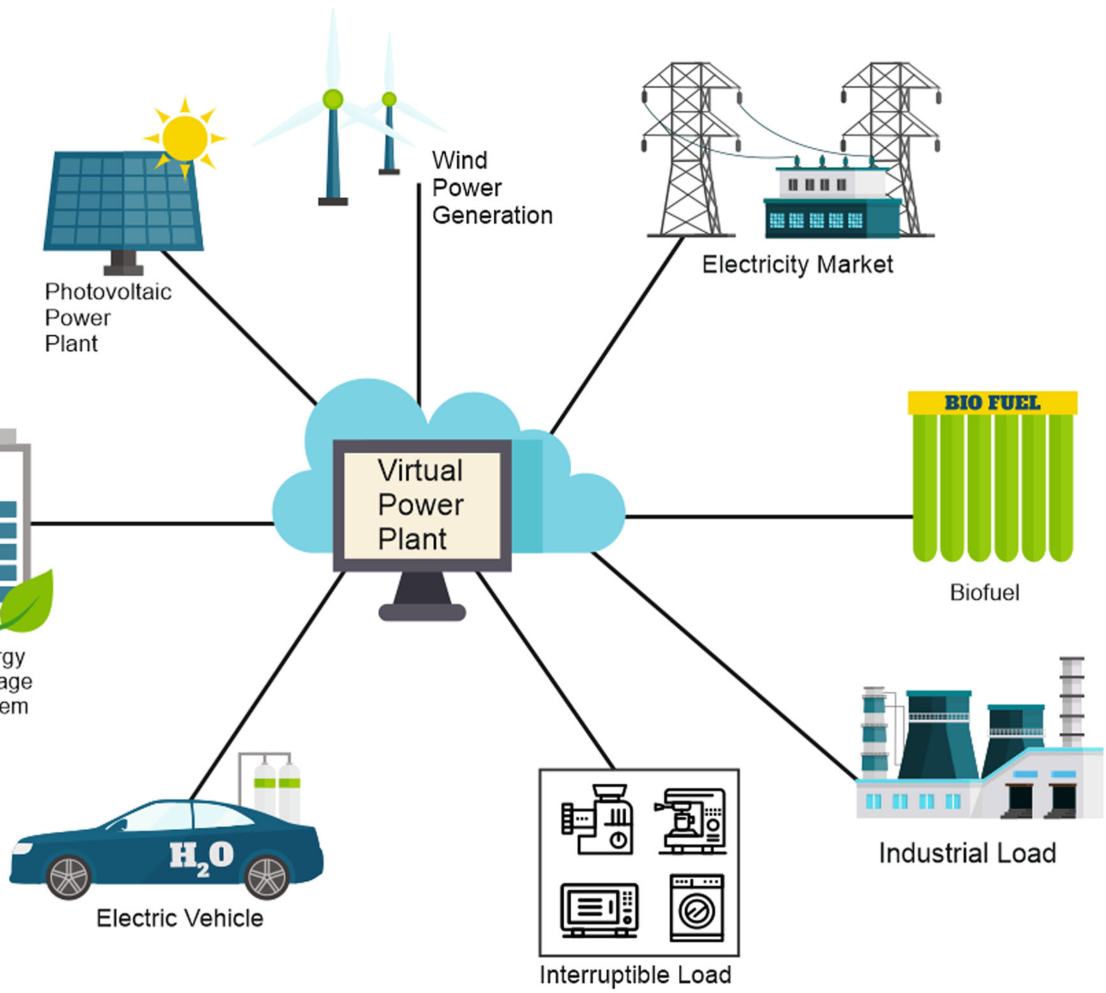

FIGURE 11 Conceptual model of a VPP.[87]

38.6% and the overall cost of the system by 11.2%. In Yin et al.,[93] a trading mode for VPPs is designed to solve the problems of multi-layer coordination and lack of trust between market institutions, which has more studied the trading behavior of aggregators. A power energy transaction scheme under VPPs based on the Ethereum network-based blockchain is proposed in Wang et al.[94] In Wang et al.,[95] a decentralized credit system is designed to simulate real-world trust in blockchain-based P2P energy trading. The decentralized credit system helps to implement a consensus algorithm for blockchain and an algorithm based on seller/buyer credit. Some works in the field of using blockchain in power management of VPPs investigate the implementation of operation and transaction system,[96,97] blockchain-based demand response for a residential complex in a VPP,[98] hierarchical blockchain consensus algorithm for VPP transactions,[99,100] blockchain-based VPP coordination control system,[101] and application of blockchain technology in VPP considering distributed PV generation.[102] Seven et al.[103] introduces an efficient P2P energy trading scheme in a VPP using Ethereum-based smart contracts. The approach ensures transparency and cost-effectiveness through blockchain-based bidding, addressing both security and cost. Notable features include smart contract implementation for bidding, withdrawal, and control modules within the VPP framework.

4.4 | Blockchain in carbon trading

Carbon trading is a market-based tool to reduce climate change caused by GHG emissions. This tool was first introduced as part of the Kyoto Protocol. Currently, there are several national carbon tax and pollutant trading systems that cover about one-fifth of global GHG emissions.[53] The use of blockchain in the carbon industry is inevitable. Many features of the carbon trading market are similar to the blockchain mechanism. The nature of blockchain is a decentralized database while the essence of carbon trading is the assessment, storage, trading, and management of carbon emissions. A blockchain is a form

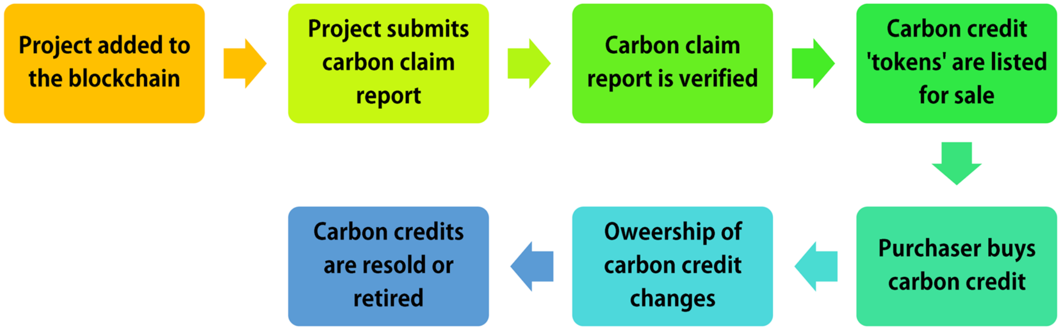

FIGURE 12 Carbon trading on a blockchain platform.

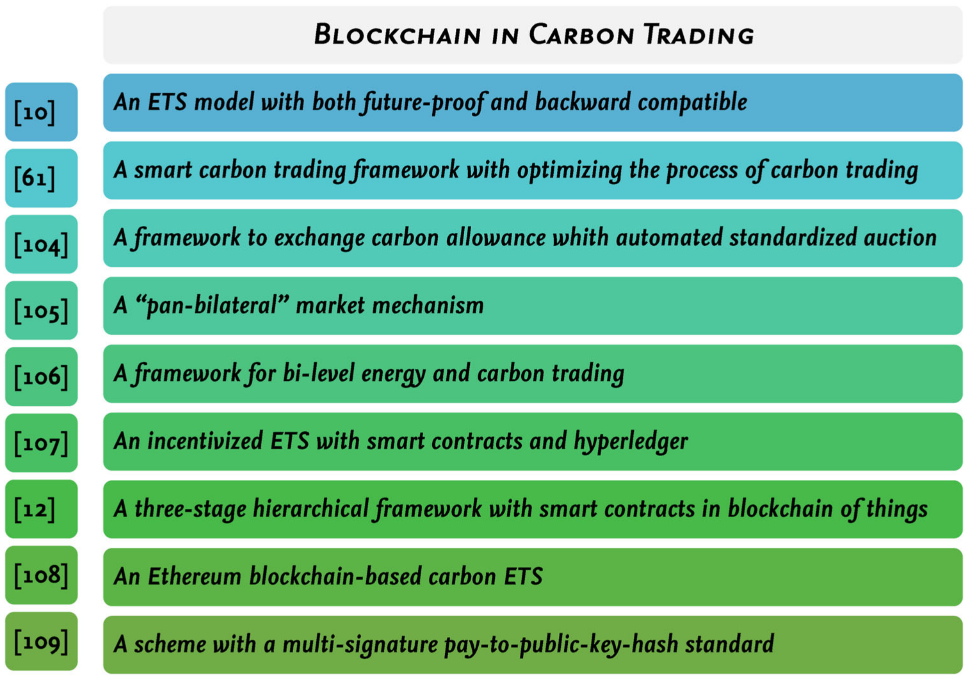

FIGURE 13 Previous works on carbon trading in blockchain systems.

of data existence, while carbon trading is the use of data.[22] Figure 12 shows the simplified steps required to conduct carbon trading on a blockchain platform, whereby project owners create tokens for carbon-saving projects that are then traded through a decentralized marketplace.

Various works are presented in the literature on carbon trading in blockchain systems, as shown in Figure 13. Richardson and Xu[10] implements a permissioned blockchain and present an ETS model with both future-proof and backward compatible. In Zhang et al.,[61] a smart carbon trading framework based on blockchain is presented where the process of carbon trading is optimized and the smart contract is employed. A P2P trading framework based on blockchain is presented in Hua et al.[104] to exchange carbon allowance and energy where the standardized auction is automated using smart contracts and presumption behaviors are reshaped. Zhang et al.[105] develop an electricity carbon rights trading market mechanism based on the blockchain where a "pan-bilateral" market mechanism is presented. A distributed market framework based on blockchain for bi-level energy and carbon trading is presented in Huang et al.[106] where the trading problem is formulated as a Stackelberg game, and the PV uncertainties and participants' privacy are considered. In Muzumdar et al.,[107] smart contracts and hyperledger-based incentivized ETS are developed where a priority-based auction is applied and both carbon credit sellers and buyers are incentivized. Sadawi et al.[12] present an efficient and transparent carbon emission trading system with automated controls. It suggests a three-stage hierarchical blockchain framework with smart contracts in the blockchain of things, reaching fair trade status and ensuring system integrity.

The Ethereum blockchain-based carbon ETS in Al Sadawi et al.[108] utilizes smart contracts to automate Kyoto unit trading and to decrease operational costs. The system enables buyer registration and Ether cryptocurrency payments for Kyoto units directly through smart contracts and blockchain, eliminating the need for intermediaries. In Hua and Sun,[109] a decentralized blockchain scheme for P2P trading in energy and carbon markets that enhances transaction security with a multisignature pay-to-public-key-hash standard, reducing sender storage burden. To protect privacy, a script during wallet address generation is hashed. Also, a novel carbon accounting method with an incentive mechanism for carbon reduction is developed for distributed prosumers, evaluating emission behaviors efficiently.

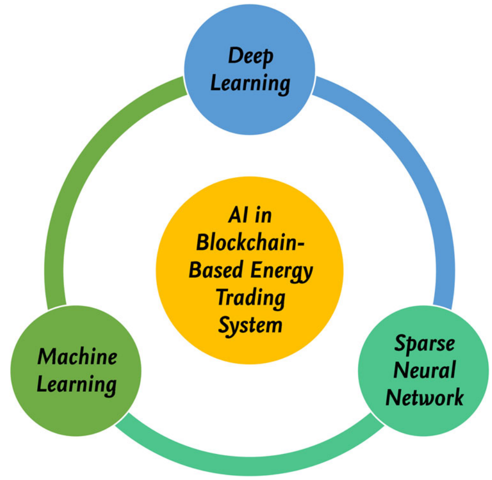

FIGURE 14 Various AI technologies in blockchain-based energy trading.

5 | APPLICATION OF ARTIFICIAL INTELLIGENCE IN BLOCKCHAIN-BASED ENERGY TRADING SYSTEM

The information infrastructure of the current power systems cannot manage the increasing information flows caused by the decision-making and transactions of a large number of decentralized consumers and distributed renewable energy sources. Due to limited budgets for control systems of small or medium consumers, it is difficult for them to exploit historical data for optimal planning of generation and consumption according to specific energy patterns.[110] Also, considering the uncertainties caused by the intermittency of distributed renewable energy sources and flexible demand, accurate prediction of default behaviors is a challenging task. Flexible structures of energy markets and intelligent operation of power systems are two essential factors to address these challenges. These two factors can be met with recent scientific innovations in the field of blockchain and AI.[111] From an energy market perspective, blockchain provides a trading platform and technical support for decentralized energy markets that provide automation, security, and improved privacy for individual buyers. From an operational point of view, AI supports control systems for making strategic decisions in optimizing system operations and achieving certain goals such as saving electricity bills, improving profit generation, reducing carbon emissions, and predicting system uncertainties.

Figure 14 shows various AI technologies that are employed in blockchain-based energy trading. Hua et al.[111] combines blockchain and AI in smart grids to facilitate customer participation in energy markets. Gupta et al.[112] investigates a P2P sustainable energy exchange system using blockchain and deep learning algorithms, providing a general framework for designing such a system with various advanced components and their interactions. To ensure reliable performance and efficient use of energy resources, AI models predict energy consumption, load profiles, and resource status. Li et al.[113] provides a comprehensive view of the application of AI, blockchain, Internet of Things (IoT) devices, and big data technologies in smart energy management. It states that the efficient integration of these technologies will be an important factor in transitioning the energy sector to a low-carbon system. To address the privacy problem in the energy trading system based on the IoT, Yi et al.[114] investigates a secure energy trading method based on blockchain technology and homomorphic encryption technology. Compared to other similar systems, this energy trading system can provide more secure user services. In addition, this system can better preserve the privacy of users. Samuel et al.[115] presents a secure blockchain-based energy trading system for residential homes, introducing a proof-of-computational closeness consensus protocol. To enhance efficiency, an improved sparse neural network facilitates computation offloading to cloud servers. In Jamil et al.,[116] an intelligent P2P energy trading is presented that predicts short-term energy demand using machine learning to minimize electrical energy delivery costs for consumers. An energy trading architecture, employing smart contracts and an efficient machine learning algorithm is developed in Rahman et al.[117] to optimize participants' energy productions and streamline the auction process. The experiments affirm the random forest model's superior accuracy in predicting power production.

6 | APPLICATION OF GAME THEORY IN ENERGY TRADING

Game theory, as a branch of modern mathematics, is one of the main tools for studying the current world economy. The energy trade market belongs to the economic field. Therefore, game theory can be used in the energy trading market to analyze the strategies of the participants. The two main classical models of game theory are known as Cournot and Stackelberg models.[111] The theory of the Cournot game is that market players supply homogeneous products and compete with independent and simultaneous decisions on the quantity of products supplied. The Stackelberg model has a two-level or multilevel hierarchical sequential decision-making process. For two-level decision-making, players are classified into a leader level that decides first and a follower level that makes subsequent decisions in response to the leader's strategies. For multilevel decision making, after the first level of followers makes responsive decisions, they become a leader level to make decisions with priority over the decisions of the next level of followers. This process continues until the last level of followers makes their responsive decisions. Stackelberg game theory is one of the most effective methods for realizing the energy management system of energy microgrids with a leader-follower structure.[118]

Figure 15 shows previous work on the application of game theory in energy trading. In Zheng et al.,[119] a Stackelberg game model is proposed to address the energy trading management problem, considering the energy trading management system as the leader and all the distributed generation in the microgrid as followers, which can reduce the dependency of microgrids on the upstream power grid based on making more profit. A decentralized trading scheme based on game theory is presented in Luo et al.[120] to investigate the effects of ownership of distributed generations on the interests of each participant in the P2P trading market. This study also emphasizes self-sufficiency and reducing the dependency of the microgrid on the upstream network. Chen et al.[121] proposes a decentralized energy business scheme based on consortium blockchain and game theory. It optimizes the price and transaction amount in transaction matching, which has high security among decentralized energy transaction scenarios. A system for integrating cooperative game theory and blockchain technology in the energy trading process is presented in Moniruzzaman et al.[122] to stimulate users to maximize their profit and secure trading. In this model, users can store renewable energy credits as assets in the blockchain and trade with others. This scheme improves the financial benefits of customers by 6.5% in terms of energy savings compared to the base model. Malik et al.[123] presents a cooperative game theory framework for efficient trading algorithms, incentivizing individual users. The algorithm prioritizes based on parameters like location, energy demand, generation, and pricing. In Devi et al.,[124] a smart grid energy trading model using the multistage Nash Bargaining solution based on game theory is presented that enables utility, private parties, and prosumers to decide on a mutually acceptable price.

FIGURE 15 Previous works on the application of game theory in energy trading.

A game-theoretic model for P2P energy trading among community prosumers is presented in Paudel et al.[125] Evolutionary game theory captures buyer dynamics, while an M-leader and N-follower Stackelberg game method models buyer–seller interactions.

7 | FUTURE RESEARCH DIRECTIONS

Several areas of potential future directions that researchers can explore to further advance the field of carbon trading are as follows:

- Scalability and performance optimization: As blockchain networks grow, addressing scalability issues becomes critical. Future research can focus on developing efficient consensus mechanisms and network architectures that can handle a larger number of transactions without compromising speed, security, or energy efficiency.
- Energy efficiency and environmental Impact: While blockchain has transformative potential, its energy consumption remains a concern. Investigating innovative consensus algorithms, proof-of-stake mechanisms, and energy-efficient network designs can contribute to reducing the carbon footprint associated with blockchain systems.
- Interoperability and standards: The development of common standards and protocols is essential to enable interoperability between different blockchain platforms and carbon market systems. Future efforts could explore creating industry-wide standards that facilitate seamless integration and information exchange.
- Regulatory frameworks and compliance: Given the global nature of carbon trading and the varying regulatory landscapes, more research is needed to navigate legal and regulatory challenges. Developing adaptable frameworks that align with diverse regulatory environments while ensuring transparency and accountability will be crucial.
- Behavioral and economic insights: Understanding how participants in blockchain-based carbon trading systems behave and make decisions is an area ripe for exploration. Behavioral economics can provide insights into incentive structures that encourage active participation and sustainable practices.
- Governance and decentralization: Designing effective governance models for decentralized carbon trading platforms is a complex task. Future research can delve into mechanisms that balance decentralization with governance controls, ensuring the systems remain resilient and trustworthy.
- Real-world implementation and case studies: While theoretical frameworks and prototypes exist, more real-world implementations and case studies are needed to validate the feasibility, scalability, and impact of blockchain-based carbon trading across various industries and regions.
- Data security and privacy: Ensuring the security and privacy of sensitive environmental and financial data in blockchain networks is paramount. Further research can explore advanced encryption techniques, zero-knowledge proofs, and other methods to enhance data protection.
- Public awareness and education: The success of blockchain-based carbon trading relies on widespread adoption and understanding. Initiatives to educate stakeholders about the benefits, mechanics, and potential risks of these systems can facilitate informed decision-making and participation.
- Integration with emerging technologies: Investigating how blockchain technology can synergize with other emerging technologies, such as IoT devices, AI, and data analytics, can enhance the overall effectiveness of carbon trading systems.
- AI-enabled carbon offset matching: AI can facilitate the matching of carbon offset buyers and sellers by analyzing their preferences and requirements. This could create more efficient and effective carbon offset markets.
- Personalized carbon footprint tracking: AI-powered tools could provide individuals and organizations with personalized carbon footprint tracking, offering insights into their emissions and suggesting tailored strategies for reducing their carbon impact.
- AI for impact assessment: AI algorithms can assess the impact of blockchain-based carbon trading initiatives on emissions reduction. By analyzing historical data and outcomes, these algorithms could provide insights into the effectiveness of different strategies.
- AI-enhanced carbon credit generation: AI algorithms can identify new opportunities for generating carbon credits by analyzing emissions reduction initiatives. This could incentivize innovation and the development of new sustainable practices.
- City data collection for AI-based prediction: An extensive data set from a city can be gathered to develop predictive algorithms utilizing AI. The aim is to predict carbon production and storage.
- Efficient blockchain network for carbon trading: The transfer of digital currency through the blockchain network involves costs. Therefore, to expand this business, it is necessary to consider an efficient network for the fast transfer of digital currency with the lowest tariff.

- Integrated carbon trading system across sectors: Currently, there are some platforms for carbon trading and some startups have been developed in this field. However, there is a need to have platforms that cover the building and industrial sectors in an integrated manner and cover different conditions of carbon tax, carbon trading, or a combination of both. Using AI can help to determine which modes will be more useful.

8 | CONCLUSION

This paper aims to present the potential of the blockchain network for use in the carbon trading system, managing intermittent renewable generations, and creating a decentralized trading platform for financial transactions related to energy activities. The blockchain platform can facilitate the process of carbon trading under the provisions of the Kyoto Treaty. The integration of decentralized blockchain technology and energy trading systems paves the way for the emergence of VPPs, empowering consumers to actively engage as energy producers. Various types of green cryptocurrencies used in carbon trading and the management of renewable generations are introduced. Furthermore, the concept of smart contracts has been introduced as a robust solution to decentralize the energy sector and harness the capabilities of blockchain platforms. In addition, the application of AI and game theory in energy trading is presented. The blockchain framework and decentralized carbon trading can have a significant effect on reducing carbon emissions. The privacy and information preservation issues are addressed to a large extent in the platform of blockchain due to decentralization, elimination of middlemen, and the chain structure of blockchain, which facilitates irreversible and unchangeable transactions.

The potential impact of these technologies on reducing carbon emissions and accelerating the transition to cleaner energy sources is a powerful incentive. With continuous innovation, informed decision-making, and strategic implementation, the fusion of blockchain and AI holds the promise of reshaping carbon trading into a more transparent, efficient, and sustainable practice. As we stand at the crossroads of technological advancement and environmental stewardship, the journey towards a greener future through P2P carbon trading driven by blockchain and AI is an exciting one, building a more resilient and eco-conscious world. This review paper serves as a foundational resource for researchers, practitioners, and stakeholders venturing into the uncharted territory of blockchain and AI-enabled carbon trading. It elucidates the intricate interplay of these technologies and their transformative potential, encouraging further exploration and collaboration to realize a sustainable energy future.

ORCID

Iman Sadeghkhani http://orcid.org/0000-0002-8410-2068

REFERENCES

1. Qi Y, Yuan M, Bai T. Where will corporate capital flow to? Revisiting the impact of China's pilot carbon emission trading system on investment. *J Environ Manage*. 2023;336(1):117671.
2. Intergovernmental Panel on Climate Change. Climate Change 2013: The Physical Science Basis—Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2013. Accessed 2023. https://www.ipcc.ch/report/ar5/wg1
3. Tang YE, Fan R, Cai AZ, et al. Rethinking personal carbon trading (PCT) mechanism: a comprehensive review. *J Environ Manage*. 2023;344:118478.
4. International Energy. CO_2 Emissions in 2022. 2023. Accessed 2023. https://www.iea.org/reports/co2-emissions-in-2022
5. Najarzadeh R, Dargahi H, Agheli L, Khameneh KB. Kyoto protocol and global value chains: trade effects of an international environmental policy. *Environ Dev*. 2021;40:100659.
6. Deng M, Zhong S, Xiang G. Carbon emission reduction effect of China's final demand structure change from 2013 to 2020: a scenario-based analysis. *Carbon Manage*. 2019;10(4):387-404.
7. Fang G, Tian L, Liu M, Fu M, Sun M. How to optimize the development of carbon trading in China—enlightenment from evolution rules of the EU carbon price. *Appl Energy*. 2018;211:1039-1049.
8. Cong R, Lo AY. Emission trading and carbon market performance in Shenzhen, China. *Appl Energy*. 2017;193:414-425.
9. Kuriyama A, Abe N. Ex-post assessment of the kyoto protocol-quantification of CO_2 mitigation impact in both annex B and non-annex B countries. *Appl Energy*. 2018;220:286-295.
10. Richardson A, Xu J. Carbon trading with blockchain. In: *2nd International Conference on Mathematical Research for Blockchain Economy*. Springer; 2020:105-124.
11. Patsonakis C, Terzi S, Moschos I, Ioannidis D, Votis K, Tzovaras D. Permissioned blockchains and virtual nodes for reinforcing trust between aggregators and prosumers in energy demand response scenarios. In: IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe); 2019.
12. Sadawi AA, Madani B, Saboor S, Ndiaye M, Abu-Lebdeh G. A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. *Technol Forecasting Social Change*. 2021;173:121124.

13. Levin RB, Waltz P, LaCount H. Chapter 9—Betting blockchain will change everything-SEC and CFTC regulation of blockchain technology. In: LeeKuoChuen D, Deng R., eds. *Handbook of Blockchain, Digital Finance, and Inclusion*. Vol 2. Academic Press; 2018:187-212.
14. ClimateTrade. Which countries are the world's biggest carbon polluters? 2021. Accessed 2023. https://climatetrade.com/which-countries-are-the-worlds-biggest-carbon-polluters
15. Statista. Distribution of Carbon Dioxide Emissions Worldwide in 2021, by Select Country. 2023. Accessed 2023. https://www.statista.com/statistics/271748/the-largest-emitters-of-co2-in-the-world
16. Parhamfar M, Sadeghkhani I, Adeli AM. Towards the application of renewable energy technologies in green ports: technical and economic perspectives. IET Renew Power Generation. 2023;17(12):3120-3132.
17. Darby M, Gerretsen I. Which Countries Have a Net Zero Carbon Goal? 2019. Accessed 2023. https://www.climatechangenews.com/2019/06/14/countries-net-zero-climate-goal
18. Net Zero Tracker. Accessed 2023. https://zerotracker.net
19. Zhang S, Chen W. Assessing the energy transition in China towards carbon neutrality with a probabilistic framework. *Nat Commun*. 2022;13(1):87.
20. California Air Resources Board. Cap-and-Trade Program. Accessed 2023. https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program
21. Statista. Coverage of Largest Emissions Trading Systems (ETS) Worldwide as of 2022. 2023. Accessed 2023. https://www.statista.com/statistics/1315109/largest-ETS-markETS-by-coverage
22. Pan Y, Zhang X, Wang Y, et al. Application of blockchain in carbon trading. *Energy Proc*. 2019;158:4286-4291.
23. International Energy Agency. Buildings. 2023. Accessed 2023. https://www.iea.org/energy-system/buildings
24. Alim MA, Tao Z, Hassan MK, et al. Is it time to embrace building integrated photovoltaics? A review with particular focus on Australia. *Solar Energy*. 2019;188:1118-1133.
25. Liu J, Yang H, Zhou Y. Peer-to-peer energy trading of net-zero energy communities with renewable energy systems integrating hydrogen vehicle storage. *Appl Energy*. 2021;298:117206.
26. Zhou Y. Energy sharing and trading on a novel spatio-temporal energy network in Guangdong-Hong Kong-Macao Greater Bay Area. *Appl Energy*. 2022;318:119131.
27. Lyu C, Jia Y, Xu Z. Fully decentralized peer-to-peer energy sharing framework for smart buildings with local battery system and aggregated electric vehicles. *Appl Energy*. 2021;299:117243.
28. United Nations. Framework Convention on Climate Change. United Nations Carbon Offset Platform. Accessed 2023. https://unfccc.int/climate-action/united-nations-carbon-offset-platform
29. United Nations. Carbon Offset Platform. How to Offset. Accessed 2023. https://offset.climateneutralnow.org/howtooffset
30. Paris Agreement: Article 6. Accessed 2023. https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf
31. Watson F. COP26: Nations Strike Deal on International Carbon Markets at Glasgow Summit. 2021. Accessed 2023. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/111421-cop26-nations-strike-deal-on-international-carbon-markets-at-glasgow-summit,
32. Yahoo! Finance. Global Carbon Credit Market 2023: Sector to Reach $2.68 Trillion by 2028 at a CAGR of 18.23%. 2023. Accessed 2023. https://finance.yahoo.com/news/global-carbon-credit-market-2023-104800429.html
33. International Carbon Action Partnership. Emissons Trading Worldwide: Status Report 2023. 2023. Accessed 2023. https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-2023-icap-status-report
34. Statista. Carbon Market Size Worldwide from 2019 to 2022, by Region. 2023. Accessed 2023. https://www.statista.com/statistics/1335923/carbon-market-size-by-region-worldwide
35. Statista. Carbon Tax Rates Worldwide as of March 31, 2023, by country. 2023. Accessed 2023. https://www.statista.com/statistics/483590/prices-of-implemented-carbon-pricing-instruments-worldwide-by-select-country
36. Statista. Average Carbon Price Expectations Worldwide from 2022 to 2030, by Trading System. 2023. Accessed 2023. https://www.statista.com/statistics/1334906/average-carbon-price-projections-worldwide-by-region
37. Bray S. Carbon Taxes in Europe. 2022. Accessed 2023. https://taxfoundation.org/data/all/eu/carbon-taxes-in-europe-2022
38. ICAP Allowance Price Explorer. 2023. https://icapcarbonaction.com/en/ets-prices
39. Kenton W. Carbon Trade: Definition, Purpose, and How Carbon Trading Works. 2022. Accessed 2023. https://www.investopedia.com/terms/c/carbontrade.asp
40. Wang Y, Cao Y, Lv C, Zhang Y, Zhou B, Wan S. PDTM: a provenance-driven dynamic trust management model for IoVs. *Sustain Energy Technol Assess*. 2023;60:103496.
41. Mollah MB, Zhao J, Niyato D, et al. Blockchain for the Internet of Vehicles towards intelligent transportation systems: a survey. *IEEE Internet of Things J*. 2021;8(6):4157-4185.
42. Lin Y, Gao Z, Du H, et al. DRL-based adaptive sharding for blockchain-based federated learning. *IEEE Trans Commun*. 2023;71(10):5992-6004.
43. Hildebrand B, Baza M, Salman T, et al. A comprehensive review on blockchains for Internet of Vehicles: challenges and directions. *Comput Sci Rev*. 2023;48(4):100547.
44. Morris DZ. Leaderless, blockchain-based venture capital fund raises $ 100 million, and counting. *Fortune* (magazine). 2016:5-23.
45. Daley S. What is Blockchain? 2022. Accessed 2023. https://builtin.com/blockchain
46. Narayanan A, Bonneau J, Felten E, Miller A, Goldfeder S. *Bitcoin and Cryptocurrency Technologies: A Comprehensive Introduction*. Princeton University Press; 2016.
47. Sherman AT, Javani F, Zhang H, Golaszewski E. On the origins and variations of blockchain technologies. *IEEE Security Privacy*. 2019;17(1):72-77.
48. The Economist. The Great Chain of Being Sure About Things. 2015. Accessed 2023. https://www.economist.com/briefing/2015/10/31/the-great-chain-of-being-sure-about-things

49. Back A. Hashcash—A Denial of Service Counter-Measure. 2002. Accessed 2023. http://www.hashcash.org/papers/hashcash.pdf
50. Castillo dM. Blockchain 50: Billion Dollar Babies. 2019. Accessed 2023. https://www.forbes.com/sites/michaeldelcastillo/2019/04/16/blockchain-50-billion-dollar-babies
51. Mearian L. Global Blockchain Spending to Hit $12.4B by 2022; Finance Sector Leads Growth. 2019. Accessed 2023. https://www.computerworld.com/article/3356502/global-blockchain-spending-to-hit-124b-by-2022-finance-sector-leads-growth.html
52. Anaya KL, Pollitt MG. Going smarter in the connection of distributed generation. *Energy Policy*. 2017;105(C):608-617.
53. Sipthorpe A, Brink S, Van Leeuwen T, Staffell I. Blockchain solutions for carbon markets are nearing maturity. *One Earth*. 2022;5(7):779-791.
54. Saraji S, Borowczak M. A blockchain-based carbon credit ecosystem. 2021. https://doi.org/10.48550/arXiv.2107.00185
55. Oprea SV, Bâra A, Diaconita V. A motivational local trading framework with 2-round auctioning and settlement rules embedded in smart contracts for a small citizen energy community. *Renew Energy*. 2022;193:225-239.
56. Ebrahimi M, Sheikhi A. A local integrated electricity-heat market design among multi smart energy hubs with renewable energy generation uncertainty. *Electric Power Syst Res*. 2023;218(11):109217.
57. Vieira G, Zhang J. Peer-to-peer energy trading in a microgrid leveraged by smart contracts. *Renew Sustain Energy Rev*. 2021;143:110900.
58. Richter LL, Pollitt MG. Which smart electricity service contracts will consumers accept? The demand for compensation in a platform market. *Energy Economics*. 2018;72:436-450.
59. Foroozandeh Z, Ramos S, Soares J, Vale Z, Dias M. Single contract power optimization: a novel business model for smart buildings using intelligent energy management. *Int J Electr Power Energy Syst*. 2022;135:107534.
60. Zhao S, Zhu S, Wu Z, Jaing B. Cooperative energy dispatch of smart building cluster based on smart contracts. *Int J Electr Power Energy Syst*. 2022;138:107896.
61. Zhang yT, Feng tT, Cui lM. Smart contract design and process optimization of carbon trading based on blockchain: the case of China's electric power sector. *J Clean Product*. 2023;397(9):136509.
62. Siddiqui S, Hameed S, Shah SA, Khan AK, Aneiba A. Smart contract-based security architecture for collaborative services in municipal smart cities. *J Syst Architect*. 2023;135:102802.
63. Chandra R, Kaippilly Radhakrishnan K, Panda SK. Privacy protected product differentiation through smart contracts based on bilateral negotiations in peer-to-peer transactive energy markets. *Sustain Energy Grids Netwk*. 2023;34:100997.
64. Kirli D, Couraud B, Robu V, et al. Smart contracts in energy systems: a systematic review of fundamental approaches and implementations. *Renew Sustain Energy Rev*. 2022;158:112013.
65. Sudeep J, Girish SC, Ganapathi K, Raghavendra K, Lin H, Subramanya P. *Blockchain: A New Era of Technology*. Springer International Publishing; 2022.
66. British Petroleum. Statistical Review of World Energy. 2022. Accessed 2023. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
67. Bao J, He D, Luo M, Choo KKR. A survey of blockchain applications in the energy sector. *IEEE Syst J*. 2021;15(3):3370-3381.
68. Kumari A, Gupta R, Tanwar S, Kumar N. Blockchain and AI amalgamation for energy cloud management: challenges, solutions, and future directions. *J Parallel Distribut Comput*. 2020;143:148-166.
69. Zanghi E, Do Coutto Filho MB, Stacchini de Souza JC. Conceptual framework for blockchain-based metering systems. *Multiagent Grid Syst*. 2019;15(1):77-97.
70. Khalid R, Javaid N, Javaid S, Imran M, Naseer N. A blockchain-based decentralized energy management in a P2P trading system. In: IEEE International Conference on Communications (ICC); 2020.
71. Kang J, Yu R, Huang X, Maharjan S, Zhang Y, Hossain E. Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains. *IEEE Trans Industr Inform*. 2017;13(6):3154-3164.
72. Han D, Zhang C, Ping J, Yan Z. Smart contract architecture for decentralized energy trading and management based on blockchains. *Energy*. 2020;199:117417.
73. Suthar S, Pindoriya NM. Blockchain and smart contract based decentralized energy trading platform. In: 2020 21st National Power Systems Conference (NPSC); 2020.
74. Iansiti M, Lakhani KR, et al. The truth about blockchain. *Harvard Business Rev*. 2017;95(1):118-127.
75. Zhou Y. Worldwide carbon neutrality transition? Energy efficiency, renewable, carbon trading and advanced energy policies. *Energy Rev*. 2023;2(2):100026.
76. Thakur S, Breslin JG. Peer to peer energy trade among microgrids using blockchain based distributed coalition formation method. *Technol Econ Smart Grids Sustain Energy*. 2018;3:1-17.
77. Wang L, Jiang S, Shi Y, et al. Blockchain-based dynamic energy management mode for distributed energy system with high penetration of renewable energy. *Int J Electr Power Energy Syst*. 2023;148:108933.
78. Song JG, Kang Es, Shin HW, Jang JW. A smart contract-based P2P energy trading system with dynamic pricing on ethereum blockchain. *Sensors*. 2021;21(6):1985.
79. Johnson L, Isam A, Gogerty N, Zitoli J. Connecting the blockchain to The Sun to save the planet. *Available at SSRN 2702639*, 2015. https://doi.org/10.2139/ssrn.2702639
80. SolarCoin. Accessed 2023. https://solarcoin.org
81. Dispenza J, Garcia C, Molecke R. Energy Efficiency Coin (EECoin)—A Blockchain Asset Class Pegged to Renewable Energy Markets. 2017. Accessed 2023. https://enledger.io/Energy_Efficiency_Coin_Whitepaper_v1_0.pdf
82. The Eco Coin. Introducing a Digital Crypto Agora. Accessed 2023. https://www.ecocoin.com/blog-posts/the-return-of-direct-democracy-introducing-a-digital-agora-to-the-crypto-world
83. Next Nature Network. The ECo Coin—A Cryptocurrency Backed by Sustainable Assets. Accessed 2023. https://uploads-ssl.webflow.com/5c1b58255c613376879c2558/5c4970105b4d237571564f43_ECOcoin_white_paper_v1.0.pdf

84. Mihaylov M, Jurado S, Avellana N, et al. Virtual currency for trading of renewable energy in smart grids. In: International Conference on the European Energy Market, EEM.
85. NRGcoin—Smart Contract for Green Energy. Accessed 2023. https://nrgcoin.org
86. EverGreenCoin—Environmental Green Causes, Nurtured by Cryptocurrency. Accessed 2023. https://evergreencoin.org
87. Bai H, Miao S, Ran X, Ye C. Optimal dispatch strategy of a virtual power plant containing battery switch stations in a unified electricity market. *Energies*. 2015;8(3):2268-2289.
88. Naval N, Yusta JM. Virtual power plant models and electricity markets—a review. *Renew Sustain Energy Rev*. 2021;149:111393.
89. Chen Y, Niu Y, Du M, Wang J. A two-stage robust optimization model for a virtual power plant considering responsiveness-based electric vehicle aggregation. *J Clean Product*. 2023;405:136690.
90. Yang X, Zhang Y. A comprehensive review on electric vehicles integrated in virtual power plants. *Sustain Energy Technol Assess*. 2021;48:101678.
91. İnci M, Savrun MM, Çelik Ä. Integrating electric vehicles as virtual power plants: a comprehensive review on vehicle-to-grid (V2G) concepts, interface topologies, marketing and future prospects. *J Energy Storage*. 2022;55:105579.
92. Yang Q, Wang H, Wang T, Zhang S, Wu X, Wang H. Blockchain-based decentralized energy management platform for residential distributed energy resources in a virtual power plant. *Appl Energy*. 2021;294:117026.
93. Yin S, Ai Q, Li J, Li D, Guo Q. Trading mode design for a virtual power plant based on main-side consortium blockchains. *Appl Energy*. 2022;325:119932.
94. Wang X, Zhang J, Jia Z, Hu A, Li D, Wu X. A new energy trading model for virtual power plants based on blockchain. In: IEEE International Conference on Emergency Science and Information Technology (ICESIT). 2021:93-99.
95. Wang T, Guo J, Ai S, Cao J. RBT: A distributed reputation system for blockchain-based peer-to-peer energy trading with fairness consideration. *Appl Energy*. 2021;295:117056.
96. Li D, Guo Q, Bai D, Zhang W. Research and implementation on the operation and transaction system based on blockchain technology for virtual power plant. In: International Conference on Blockchain Technology and Information Security (ICBCTIS); 2022:165-170.
97. Ma R, Zhou H, Qian W, Zhang C, Sun G, Zang H. Study on the transaction management mode of virtual power plants based on blockchain technology. In: 12th IEEE PES Asia-Pacific Power and Energy Engineering Conference (AP-PEEC). 2020.
98. Lv R, Guo M, Wang X, et al. Blockchain-based demand response for aggregated residential users in a virtual power plant. In: 8th Asia Conference on Power and Electrical Engineering (ACPEE). 2023:1108-1112.
99. Jing W, Xuefeng B, Bin L. Research on consensus algorithm of hierarchical partition blockchain for virtual power plant transactions. In: 2nd International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE). 2022:1613-1617.
100. Xiang J, Zhao J, Zhou W. Consensus mechanism of virtual power plant transaction blockchain based on credit value. In: 4th International Academic Exchange Conference on Science and Technology Innovation (IAECST). 2022:527-533.
101. Li Y, Teng Y, Cao R, Li N. Research on coordination control system of virtual power plant based on blockchain. In: IEEE 8th International Conference on Advanced Power System Automation and Protection (APAP). 2019:1377-1383.
102. Guo L, Du Y, Yang X, Su L. Application of blockchain technology in virtual power plant considering distributed photovoltaic generation. In: *CSAA/IET International Conference on Aircraft Utility Systems (AUS 2022)*. vol. 2022; IET; 2022:189-192.
103. Seven S, Yao G, Soran A, Onen A, Muyeen SM. Peer-to-peer energy trading in virtual power plant based on blockchain smart contracts. *IEEE Access*. 2020;8:175713-175726.
104. Hua W, Jiang J, Sun H, Wu J. A blockchain based peer-to-peer trading framework integrating energy and carbon markets. *Appl Energy*. 2020;279:115539.
105. Zhang Q, Sun Y, Gu W, Jing F, Jin P, Jia Y. Electricity carbon emission trading market mechanism based on blockchain technology. In: *6th International Conference on Wireless Communications and Applications (ICWCAPP)*; 2022:245-249
106. Huang H, Li Z, Sampath LPMI, et al. Blockchain-enabled carbon and energy trading for network-constrained coal mines with uncertainties. *IEEE Trans Sustain Energy*. 2023;14(3):1634-1647.
107. Muzumdar A, Modi C, Vyjayanthi C. A permissioned blockchain enabled trustworthy and incentivized emission trading system. *J Clean Product*. 2022;349:131274.
108. Al Sadawi A, Ndiaye M. Blockchain-based carbon trading mechanism to elevate governance and smartness. In: 14th International Conference on Theory and Practice of Electronic Governance. 2021:34-43.
109. Hua W, Sun H. A blockchain-based peer-to-peer trading scheme coupling energy and carbon markets. In: International Conference on Smart Energy Systems and Technologies (SEST). 2019.
110. Mahmud K, Khan B, Ravishankar J, Ahmadi A, Siano P. An Internet of energy framework with distributed energy resources, prosumers and small-scale virtual power plants: an overview. *Renew Sustain Energy Rev*. 2020;127:109840.
111. Hua W, Chen Y, Qadrdan M, Jiang J, Sun H, Wu J. Applications of blockchain and artificial intelligence technologies for enabling prosumers in smart grids: A review. *Renew Sustain Energy Rev*. 2022;161:112308.
112. Gupta Y, Javorac M, Cyr S, Yassine A. HELIUS: a blockchain based renewable energy trading system. In: 2021 4th International Seminar on Research of Information Technology and Intelligent Systems (ISRITI). 2021:287-292.
113. Li J, Herdem MS, Nathwani J, Wen JZ. Methods and applications for artificial intelligence, big data, Internet of things, and blockchain in smart energy management *Energy AI*. 2023;11:100208.
114. Yi H, Lin W, Huang X, Cai X, Chi R, Nie Z. Energy trading IoT system based on blockchain. *Swarm Evolut Computat*. 2021;64:100891.
115. Samuel O, Javaid N, Alghamdi TA, Kumar N. Towards sustainable smart cities: a secure and scalable trading system for residential homes using blockchain and artificial intelligence. *Sustain Cities Society*. 2022;76:103371.

116. Jamil F, Iqbal N, Imran, Ahmad S, Kim D. Peer-to-peer energy trading mechanism based on blockchain and machine learning for sustainable electrical power supply in smart grid. *IEEE Access*. 2021;9:39193-39217.
117. Rahman M, Chowdhury S, Shorfuzzaman M, Hossain MK, Hammoudeh M. Peer-to-peer power energy trading in blockchain using efficient machine learning model. *Sustainability*. 2023;15:18.
118. Palensky P, Dietrich D. Demand side management: demand response, intelligent energy systems, and smart loads. *IEEE Trans Industr Inform*. 2011;7(3):381-388.
119. Zheng X, Li Q, Bai C, Nie Y, Huang C. Energy trading management based on stackelberg game theory to increase independence of microgrids. *Energy Reports*. 2022;8:771-779. 5th International Conference on Renewable Energy and Environment Engineering.
120. Luo X, Shi W, Jiang Y, Liu Y, Xia J. Distributed peer-to-peer energy trading based on game theory in a community microgrid considering ownership complexity of distributed energy resources. *J Cleaner Product*. 2022;351:131573.
121. Chen Y, Li Y, Chen Q, Wang X, Li T, Tan C. Energy trading scheme based on consortium blockchain and game theory. *Comput Standards Interfaces*. 2023;84:103699.
122. Moniruzzaman M, Yassine A, Benlamri R. Blockchain and cooperative game theory for peer-to-peer energy trading in smart grids. *Int J Electr Power Energy Syst*. 2023;151:109111.
123. Malik S, Duffy M, Thakur S, Hayes B, Breslin J. A priority-based approach for peer-to-peer energy trading using cooperative game theory in local energy community. *Int J Electr Power Energy Syst*. 2022;137:107865.
124. Devi NN, Thokchom S, Singh TD, Panda G, Naayagi RT. Multi-stage bargaining of smart grid energy trading based on cooperative game theory. *Energies*. 2023;16(11):4278.
125. Paudel A, Chaudhari K, Long C, Gooi HB. Peer-to-peer energy trading in a prosumer-based community microgrid: a game-theoretic model. *IEEE Trans Industr Electron*. 2019;66(8):6087-6097.

How to cite this article: Parhamfar M, Sadeghkhani I, Adeli AM. Towards the net zero carbon future: a review of blockchain-enabled peer-to-peer carbon trading. *Energy Sci Eng*. 2024;12:1242-1264. doi:10.1002/ese3.1697