BLOCKCHAIN APPLICATIONS IN THE ENERGY SECTOR

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Abstract

As fossil fuel resources are gradually depleting, countries are increasingly focusing on developing renewable energy as a sustainable alternative. A trend is the shift of the energy market towards a decentralized model, where renewable energy can be traded flexibly. This is partly evidenced by the rise of blockchain-based solutions in the energy sector. Blockchain technology garners attention due to its outstanding advantages such as anonymity, decentralization, and transparency. Therefore, this study explores the application of blockchain in the energy sector. We shed light on four main areas: energy management, peer-to-peer (P2P) trading, applications related to electric vehicles, and carbon credit trading. This paper provides insights into how blockchain technology can act as a catalyst for revolutionizing the energy sector in both management and control.

Keywords: blockchain, carbon certificate, distributed energy, energy trading, smart grid management

1. Introduction

Fossil energy is an important natural resource that has fueled the world economy throughout much of history. Today, as society becomes increasingly digital, the demand for energy increases. According to the "BP Statistical Review of World Energy" (BP, 2022), primary energy demand increased by 5.8% in 2021, exceeding the 2019 level of 1.3%. Global natural gas demand grew 5.3% in 2021, recovering above pre-pandemic 2019 levels and crossing the 4 Tcm mark for the first time. Although primary renewable energy is still growing rapidly (15%) (BP, 2022), fossil fuels are limited and will be exhausted by the early 22nd century if current consumption continues (Hossain, 2016).

This shortage and also environmental issues have prompted the search for alternative energy sources such as solar and wind power. Households can install solar power systems to use and sell excess electricity to the grid. However, managing a large number of prosumers is a big challenge for traditional power grids with centralized management systems that are not flexible enough. This creates a need to design an efficient, safe, and sustainable smart grid system to meet increasing demand.

Additionally, the increasing use of electric vehicles will create a major challenge for smart grid systems in the near future. Electric vehicle sales are forecast to increase from nearly 30 million in 2022 to about 240 million in 2030, reaching an average annual growth rate of about 30%. In this scenario, electric vehicles account for more than 10% of the road vehicle fleet by 2030. Total electric vehicle sales reach more than 20 million in 2025 and more than 40 million in 2030, accounting for more than 20% and 30% of the total car sales (IEA, 2023). Current challenges include inadequate charging infrastructure, especially mobile and fast charging stations, due to high implementation costs. This highlights the importance of developing decentralized mobile charging systems while also considering the related management, pricing, and privacy protection issues.

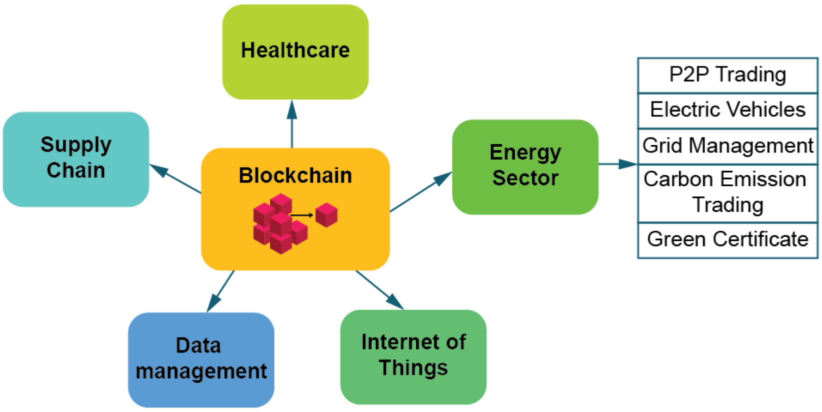

Figure 1. Applications of blockchain (Bao et al., 2020)

Carbon and green certificate trading systems are market mechanisms to reduce global greenhouse gas emissions (Xu et al., 2023). Carbon trading allows organizations that cannot reduce their emissions to offset by buying credits from others. Green certificates provide financial support to companies using renewable energy to produce electricity. During this process, users need to pay attention to safety, transparency, and credit data registration of participating parties.

All of the above issues show that the operating model of the energy industry requires a shift from centralized decentralization to decentralization; this is a prominent feature of blockchain (Efanov & Roschin, 2018; He et al., 2024). Recently, blockchain has been widely applied in many fields such as data management (Deepa et al., 2022; Hasan et al., 2022), supply chain (Sahoo et al., 2022), healthcare (Sahu et al., 2024; Shinde et al., 2024), Internet of Things (IoT) (Atlam et al., 2020), and cybersecurity (Mahmood et al., 2022; Wylde et al., 2022), etc (Figure 1).

Blockchain technology is applied in the energy sector due to its outstanding advantages, such as decentralization, transparency, and high reliability (Kaur et al., 2022). The energy industry is becoming increasingly decentralized, leading to numerous issues that need to be addressed, such as distributed storage, control, management, and trading. Traditional energy systems cannot effectively meet these challenges, whereas blockchain, with its distinctive features, can provide optimal solutions.

This article surveys the applications of blockchain in the energy industry, specifically focusing on four key areas: energy management, P2P trading, electric vehicles (EVs), and carbon certificate trading. The rest of the paper is organized as follows: Part 2 provides an overview of blockchain technology and a brief introduction to the energy industry; Part 3 explores the applications of blockchain in the electricity sector; Part 4 summarizes and discusses the potential benefits and challenges of implementing blockchain in the energy field; and finally, Part 5 concludes the paper.

2. Background

2.1. Basics of the energy sector

Regardless of the generation source, electricity is distributed to consumers through the transmission grid. Electricity is generated by different producers in different regions or countries. The electricity is then traded through an exchange. To provide electricity to consumers, two service providers are needed. One is the power system operator, providing electricity transportation and distribution services, distributing from producers to consumers, and monitoring the energy consumption of each customer. Second are the wholesalers. The most developed countries (like Europe) are using a full, open electricity market. That means consumers cannot choose the electricity network operator, but they can choose the electricity seller according to the proposed purchase price (Naraindath et al., 2023). The energy sector has a peculiarity: electricity is difficult to store as a physical commodity on a large scale. The main problem is that the power system always needs to meet the balance between total energy generation and consumption. Therefore, it is required that all stages of power system operation must ensure reliability, accuracy, and high automation from consumption planning and distribution at the micro level. With the increasing participation of distributed sources, the above tasks become more complicated.

Currently, there are many problems in the energy system, such as cost and security problems caused by centralized management. Furthermore, as many scenarios in the energy sector are shifting to distributed structures, the traditional centralized management model has many limitations. The advent of blockchain technology provides solutions to these problems. With the application of blockchain technology in management, transactions, tracking, and other links in the energy field, the management efficiency of the new distributed energy network has been significantly improved.

2.2. Brief introduction to blockchain fundamentals

2.2.1 Blockchain

Blockchain is a distributed data structure containing blocks chained together in chronological order. It is a technology that allows secure data transmission through encrypted transactions. Blockchain networks implement smart contracts and rely on consensus mechanisms to ensure data consistency. Transactions are fundamentally verified through participant consensus, recorded, and added to the ledger (Zheng et al., 2017). These transactions and/or data are organized into units known as blocks. Each block not only contains data but also includes its own hash and the hash of the preceding block, thereby connecting the blocks in a chain (Figure 2). A hash function maps data of arbitrary size to fixed-size values, with the resulting values known as hashes. Functions are deterministic, ensuring that the same input consistently yields the same output, while even minor changes in input can cause significant variations in the output. Moreover, reverse-engineering the input from a given output is time-consuming, challenging, and nearly impossible. This design makes it exceptionally challenging for malicious actors to modify historical data, thereby ensuring a high level of trust in the information stored on the blockchain. Based on access permissions and alteration capabilities, there are three types of blockchain: permissionless (public), consortium, and private blockchain (Goranovic et al., 2017).

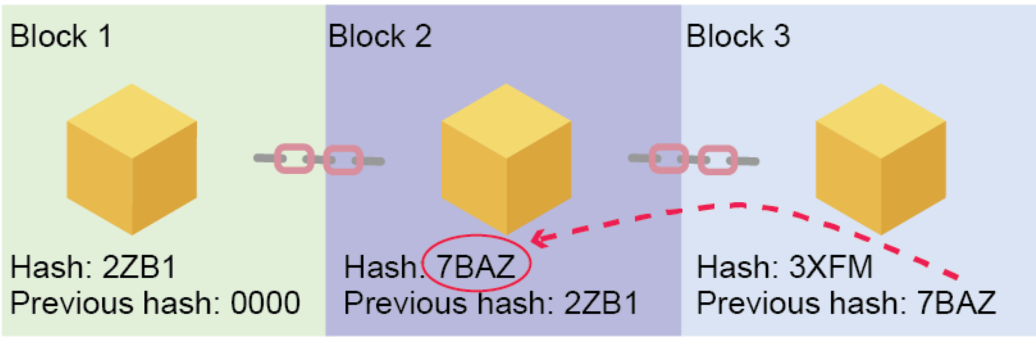

Figure 2. Blockchain structure

2.2.2 Consensus mechanism

In traditional payment systems, banks act as trusted third parties to manage transactions and maintain account balances. In contrast, blockchain operates as a distributed consensus system, requiring no trust from third parties to carry out transactions. Every participant can verify information because each person owns a copy of the blockchain. To ensure consistency throughout this system, a consensus mechanism is needed. Consensus mechanisms (also known as consensus protocols) are applied to ensure general agreement on the state of the chain and confirm the validity of transactions on the network. These protocols help all nodes in the blockchain network reach agreement on the state of the chain and the data it contains. Common consensus mechanisms include Proof of Work (PoW) (Aggarwal & Kumar, 2021; Wendl et al., 2023), Proof of Stake (PoS) (Wendl et al., 2023), Delegated Proof of Stake (DPoS) (Saad et al., 2021) and Practical Byzantine Fault Tolerance (PBFT) (Marcozzi & Mostarda, 2024).

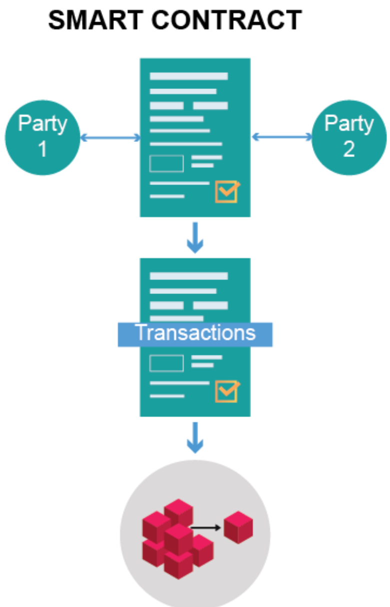

Figure 3. Working of a smart contract (Bhavana et al., 2024)

2.2.3 Smart contract

A smart contract is a digital agreement signed and stored on the blockchain. Unlike traditional contracts, smart contracts operate automatically without the need for intermediaries or judicial intervention, helping to reduce transaction costs and increase network efficiency. These contracts are accessible to all members of the network and cannot be tampered with at any time. They enforce any provisions regarding payment and transfer of assets that all parties have agreed to (Bhavana et al., 2024; Wu et al., 2024). Figure 3 illustrates how a smart contract works: once both parties have fully met the terms, the transaction automatically takes place and is recorded on the blockchain ledger.

3. Blockchaın Applıcatıons in The Energy Sector

3.1. Blockchain's work in energy sector

Blockchain technology is increasingly asserting its position in the modern world, especially in the energy sector, with many diverse applications. There are two main factors promoting the implementation of projects applying blockchain technology in the energy sector (Kaur et al., 2022; Wu & Tran, 2018):

• Energy liberalization, including significant participation of private renewable power generation facilities, which is a shift from centralized to distributed electricity markets;

• Smart electrical system with automatic measurement system.

In this section, how blockchain is applied in the energy sector as presented below:

3.1.1 Electric vehicles

The invention of the automobile has made people's daily travel more convenient but also brought some challenges, especially the consumption of fossil energy that causes environmental problems. The transportation sector is often the sector that consumes fossil energy the fastest and emits the most greenhouse gases, so many countries are making efforts to replace vehicles using internal combustion engines with electric vehicles. Large-scale use of electric vehicles not only significantly reduces greenhouse gas emissions but also reduces fuel costs for drivers while promoting the development of renewable energy technology. According to IEA forecasts, electric vehicle sales will reach nearly 45 million in 2030 and reach nearly 65 million in 2035, up from about 14 million in 2023. The sales market share of electric vehicles increased from about 15% in 2023 to nearly 40% in 2030 and more than 50% in 2035 (IEA, n.d.).

Electric vehicles are considered one of the most effective solutions to today's environmental problems. Although electric cars have some disadvantages, notably the lack of charging stations, blockchain technology can improve this situation through the establishment of individual charging stations based on smart contracts and distributed ledgers. The idea of applications developed for electric cars is that people can register their charging stations and rent them out to other electric car users. Electric car users will pay for charging time through smart contracts.

(Hua et al., 2018) introduced a battery exchange mechanism utilizing a decentralized blockchain system. In this, battery information is securely stored on the blockchain, and smart contracts facilitate the automatic completion of payment processes, including adjustments for price differences. This method effectively addresses fairness issues that may arise during transactions.

(Kim et al., 2017) proposed a lightweight charging system leveraging blockchain technology. This system uses simple payment verification (SPV) technology, allowing nodes to download only the header to verify transaction existence, thereby minimizing storage space and reducing the terminal's burden. Additionally, a technique is introduced to decrease block data size, addressing the issue of accumulating blockchain data. Within this system architecture, mobile chargers are organized into groups, each with a parent node. Only the parent node maintains a complete blockchain, while the other nodes function as SPV nodes, further alleviating their load.

Knirsch et al. (2018), a blockchain-based platform for electric vehicle (EV) charging is proposed, emphasizing reliability, automation, and privacy preservation. In this system, EVs send out requests for charging services, and charging stations respond with their quotes. EVs can then select the most suitable charging stations based on factors such as price and proximity. The use of blockchain technology enhances the reliability and transparency of transactions. Additionally, the platform ensures that the geographical location information of EVs remains confidential, safeguarding user privacy.

3.1.2 P2P Energy trading in smart grid

Traditional energy transactions are typically managed through a centralized organization. The energy market will become increasingly more complex as a larger number of consumers are reached. And consumer-to-consumer transactions will also become more complicated.

Currently, the electricity industry is often a monopoly industry in many countries. All consumers must purchase electricity through the electric company. And electricity prices are uniform, so consumers cannot independently choose the most economical energy purchasing option. Blockchain technology brings a new opportunity to the decentralized market. Blockchain technology can help build a transparent and trustworthy market for electricity trading. Consumers and prosumers can participate in electricity business in the form of distribution.

The advent of a new decentralized energy trading system powered by blockchain technology is set to transform the role of traditional companies in the energy market. These will no longer need to invest heavily in infrastructure management facilities to serve large numbers of consumers. Consumers and prosumers will gain greater flexibility in selecting energy purchasing programs within a genuinely low-cost trading environment. The implementation of blockchain technology addresses potential transaction issues in the distributed energy market while offering several additional benefits. For instance, it enhances transparency in the trading process, ensures smooth grid operations during peer-to-peer energy exchanges, optimizes demand response and billing, and streamlines other transactions—all while safeguarding privacy and security (Alam et al., 2024; Kyriakarakos & Papadakis, 2018).

Centralized systems often face challenges like high costs and information insecurity. However, the emergence of blockchain technology addresses drawbacks. The figure 4 illustrates the sales process utilizing blockchain technology (PwC Global Power & Utilities, n.d.).

(Mengelkamp et al., 2018) introduced a decentralized energy auction system leveraging blockchain technology. This system enables buyers and sellers to conduct online auctions, facilitating reliable, secure, and transparent electricity exchanges. The system primarily involves two types of participants: sellers and bidders, and incorporates two key technologies: smart meters and smart contracts. When a seller has surplus power to sell, they can initiate a new auction by publishing their available power on the blockchain.

Contractors with electricity needs can bid after receiving the new auction. Auction and payment processes are automated by smart contracts. The smart meter detects and reports electricity flow during the transaction, verifying that the transaction is complete. All data from suppliers, contractors, and smart meters will be stored on the blockchain. Privacy issues are not covered in this article. But if auction data from sellers, auctioneers, and smart meters stored on the blockchain is not encrypted, some personal information could be compromised. And if the final price of each auction can be traced in the blockchain, subsequent auctions can be affected.

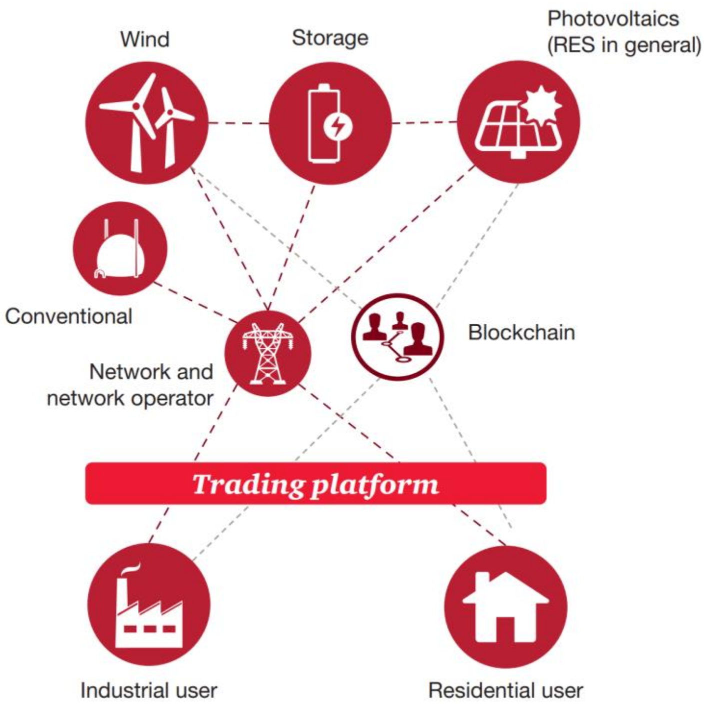

Figure 4. Market structures of decentralised transaction model (PwC Global Power, n.d.)

Saxena et al. (2019) introduces a permissioned solution for a P2P energy trading system tailored for residential communities. In this system, individual homeowners can submit energy bids for their distributed energy resources on the blockchain ledger for specific time intervals. Once all bids are collected, the market is cleared using a double auction method implemented as a smart contract. This process sends control signals to individual distributed energy resources, determining their settings for the specified market interval. Simulation results indicate that the platform achieves a 46% reduction in community peak demand and offers weekly savings of 6%. Additionally, the platform is tested on a real-world Canadian microgrid using the Hyperledger Fabric blockchain framework, demonstrating seamless connectivity between smart home distributed energy resources and the platform.

3.1.3 Carbon emission trading and green certificate

In 1997, over 100 countries signed the Kyoto Protocol in response to global warming. The protocol outlines the responsibilities of developed nations to reduce carbon emissions and introduces three flexible mechanisms for emission reduction, with carbon emissions trading being one of them.

Carbon emissions trading serves as a market mechanism aimed at reducing global carbon emissions and mitigating climate change. Under this system, government agencies allocate emission quotas to companies. Companies vary in their ability to manage emissions; some may struggle to stay within their limits, while others might have excess capacity. Those unable to meet their reduction targets can buy permits from companies that exceed their goals, facilitating compliance through the carbon trading market.

Currently, the carbon emissions trading market faces several challenges, including the allocation of low carbon emissions, accurate detection of emissions, and the establishment of effective trading rules and pricing, and regulatory. With numerous companies involved, certifying each power producer's carbon emission quota presents a significant workload for the government. Furthermore, government agencies must verify the authenticity of emission quotas submitted by all companies. The frequent trading of carbon emission permits complicates the traceability process. Consequently, records of carbon emission quotas must be both traceable and tamper-proof.

Blockchain technology can offer carbon markets a robust system for tracking carbon flows, transactions, and certificates. By storing, timestamps, and records on the blockchain, carbon trading can be efficiently managed through smart contracts.

Khaqqi et al. (2018) proposed an emissions trading system leveraging blockchain technology, utilizing the trading system as its trading mechanism. In this framework, smart devices monitor emissions transactions, while blockchain technology is employed to report, verify, and record emissions transfers, ensuring transparency and preventing forgery.

Imbault et al. (2017) developed a blockchain-based stamp system to manage environmental certificates and emission permits. By integrating blockchain technology into industrial operating systems, the system facilitates energy asset transactions with enhanced traceability.

Castellanos et al. (2017) designed and simulated a Guarantees of Origin (GoO) trading platform utilizing Ethereum and smart contracts. This platform enables the trading of GoOs, allowing producers and consumers to financially support renewable energy producers and promote the development of renewable energy. GoOs serve as a type of green certificate.

3.1.4 Energy management

As discussed in Part 1, the energy market is shifting towards a distributed model, with the solar photovoltaic industry gaining significant attention. However, the increasing number of consumers poses management challenges, particularly in storing the vast amounts of data generated. Centralized storage leads to higher costs, limited access to historical data, and risks of data breaches. In contrast, blockchain technology provides real-time operations and ensures data integrity through its decentralized nature, preventing unauthorized alterations or deletions.

Blockchain technology and smart contracts are increasingly used to monitor power consumption and manage demand in decentralized energy systems. By facilitating demand-side management within smart grids, these technologies help balance supply and demand, preventing overloads and blackouts. Blockchain stores large data volumes securely, protects consumer information, and supports decision-making through consensus mechanisms. This approach streamlines management, reduces costs, and remains effective as the number of participants grows.

Wu et al. (2017), a hybrid blockchain system is developed for data storage within the Energy Internet. This innovative system combines public and private blockchains, leveraging the benefits of both to create a smart, efficient, and secure energy management framework. It effectively meets the demands for safe and efficient data storage, ensuring robust data management even as the number of participants in the Energy Internet grows significantly.

Mannaro et al. (2017) introduced a cryptocurrency trading project focused on utilizing blockchain and smart contracts to develop smart grids. These smart grids aim to balance electricity supply and demand, facilitating the creation of distributed energy markets. In such markets, consumers can manage their own energy supplies and sell any excess energy. Within this project, blockchain serves two primary functions: first, as a distributed ledger to record all data during energy transactions, and second, as a control system for managing smart meters.

Gao et al. (2018) developed a smart grid management system using sovereign blockchain technology to protect data, ensure transparency, and prevent tampering. This system securely records electricity data, allowing consumers to maintain control over their while preventing unauthorized alterations. Smart meters offer detailed insights into energy consumption by device, and smart contracts automatically monitor grid activities to detect any malicious use or tampering with electricity data.

3.2. Known projects in energy sector

Blockchain technology has been tested and deployed in various power generation environments. Some of these tests have been conducted in controlled laboratory settings, while others have taken place in real-world environments. Different stakeholders have shown interest and invested in using blockchain to address smart grid challenges. In this section, we highlight some active projects in the energy sector.

3.2.1 PowerLedger

Powerledger has developed Australia's first peer-to-peer (P2P) blockchain energy trading network, enabling seamless interaction between market mechanisms and electricity units (kWh) through pre-purchased tokens. It uses a dual-token system: POWR tokens, issued on Ethereum as ERC-20 tokens, grant access to the platform, while Sparkz tokens, derived from POWR via smart bonds, facilitate transactions. The POWR token is currently ranked #375 among all cryptocurrencies, with a market cap of $160.7 million (Powerledger, n.d.-b). Headquartered in Zug, Switzerland, Powerledger operates in over 10 countries and aims to modernize the electric grid by empowering consumer choice and promoting energy democratization. The platform also leverages a native Solana blockchain for scalable energy transaction processing (Powerledger, n.d.-a).

3.2.2 Energy Web Token

The Energy Web Token (EWT) is the native cryptocurrency of the Energy Web Chain, an open-source platform aimed at enhancing energy sector applications by creating a more traceable and sustainable energy system. Currently, EWT token is ranked #668 among cryptocurrencies with a market cap of $55.7 million (Energy Web, n.d.-b). EWT operates on the Energy Web (EW) Chain. This chain is a unique public, Proof-of-Authority blockchain supporting commercial applications with reputable organizations as validator nodes. Unlike many smart energy solutions built on Ethereum, Energy Web uses its own blockchain and offers EW-DOS, a decentralized operating system providing open-source software and standards for digital participation in smart energy markets(Energy Web, n.d.-a).

3.2.3. KlimaDAO

KlimaDAO is a decentralized platform revolutionizing climate finance by addressing global coordination issues. Governed by the KLIMA token, it promotes a sustainable digital economy and ranks #1241 among cryptocurrencies with a market cap of $9.83 million (KlimaDAO, n.d.-b). Founded in 2021 by experts in carbon markets, technology, and finance, KlimaDAO aims to enhance market efficiency and scale climate finance.

The platform boosts climate action by raising carbon offset prices and tokenizing carbon credits for a transparent market. In 2022, it launched a tool for individuals and organizations to offset emissions easily. Operating on the Polygon blockchain reduces transaction fees and speeds up processing.

KlimaDAO uses blockchain to create efficient carbon markets, promoting public goods through cryptocurrency. Its goal is to expand global climate finance impact by building transparent infrastructure for voluntary carbon markets, pioneering in the ReFi (Renewable Finance) sector to lower entry barriers and grow environmental markets (KlimaDAO, n.d.-a).

4. Dıscussıon

In the energy sector, both management and business operations are gradually transitioning from centralized to decentralized models. In a decentralized energy system, several challenges arise, such as storing consumer data and ensuring data security, fairness, and transparency in transactions. Blockchain technology plays a crucial role in managing user data storage and enhancing data security and privacy within distributed power system management and operations. In P2P transactions, blockchain facilitates price setting, regulates supply and demand, and ensures transparency, security, and consumer privacy throughout the transaction process. When applied to the electric vehicle sector, blockchain is primarily used for selecting charging stations and determining charging prices. Pricing can be established through bidding or controlled by smart contracts that automatically adjust to market conditions. In carbon emission trading and green certificate trading, blockchain technology is utilized for traceability and privacy protection during transactions. Blockchain's extensive applications in the energy sector are due to its ability to meet the requirements of distributed energy systems with characteristics such as decentralization, anonymity, transparency, democracy, and security.

The alignment of blockchain's characteristics with the needs of the distributed energy market suggests that its application in the energy field will continue to expand, and related technologies will become increasingly sophisticated. However, there are also several challenges and issues to consider when applying blockchain to the energy sector:

• One of the primary challenges currently facing blockchain technology is the lack of standardization. As the technology is relatively new, standards are still in development, necessitating more time for observation and evaluation.

• Due to its novelty, blockchain technology is not widely understood, and there are legal barriers that complicate its application.

• Another significant challenge is the shortage of skilled human resources. Although blockchain has been around for about a decade and intensive research began roughly five years ago, there remains a demand for well-trained technicians. These professionals must not only be capable of deploying systems using blockchain technology but also proficient in maintaining them, addressing any issues that arise, and optimizing system operations to maximize efficiency and profitability.

5. Conclusıons

On the basis of the findings of this study, several recommendations could be made for future translation practices and research. First, translators working in specialized fields should receive comprehensive training in linguistic theories such as the SFL, which could provide valuable insights on the structure and function of the texts they the translate. Second, translation practices should be continuously updated and refined to reflect the latest developments in both language and subject matter expertise.

Finally, further research should be conducted into the application of the SFL in other areas of translation, particularly in fields where linguistic and cultural differences are likely to pose significant challenges. By expanding our understanding of how language functions in different contexts, we could continue to improve the quality and effectiveness of translations across a wide range of disciplines.

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