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Research Article

Blockchain-Enabled Integrated Energy System Trading Model for CCS-P2G-Coupled Operation: Enhancing Energy Trading Efficiency and Carbon Emission Reduction

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The need for sustainable integrated energy systems to mitigate environmental impact is hindered by challenges in fluctuating demand, trading reliability, and trustworthiness. This paper proposes an innovative approach to tackle these challenges by introducing a blockchain-based integrated energy system trading model with smart contracts. It is intricately linked with the operation of carbon capture and storage (CCS) technology and power-to-gas (P2G) equipment. The CCS-P2G-coupled operation principle is first outlined, followed by the presentation of a comprehensive system model. The peer-to-peer (P2P) energy trading algorithm is enhanced using the Bloom filtering technique. Leveraging smart contracts, a distributed energy trading mechanism is employed, resulting in a meticulously constructed integrated energy system trading model for CCS-P2G-coupled operation. The proposed model is rigorously evaluated for energy trading efficiency and system performance, revealing significant improvements compared to prior studies and showcasing substantial cumulative benefits. Three operation scenarios are examined, with experimental results highlighting the model's superior carbon emission reduction capacity. This study introduces an innovative paradigm for trading and managing integrated energy systems, holding potential implications for the sustainable development and decarbonization transition of future energy systems.

1. Introduction

The pollution caused by the energy production process and how to make full use of new clean energy sources in the context of the nonrenewable traditional fossil energy sources are the focus of the world's concern today. However, the traditional fossil energy sources are finite and not renewable. Therefore, it is necessary to break the traditional monopolistic energy service system of separate development, separate operation, and separate maintenance of energy sources and build a unified integrated energy service system in which the whole society participates in operation and maintenance. Additionally, in the realm of oil and gas reservoir engineering, integrating sustainable energy practices is vital for the evolution of a unified, environmentally responsible energy infrastructure [1]. The application of integrated energy services and the reduction of emissions within this field can significantly contribute to constructing multiprincipal, diversified, cleaner, and regenerative integrated supply systems.

In traditional energy trading paradigms, energy trading and risk management tools are primarily used. Classical energy dispatching and trading methodologies exhibit challenges stemming from insufficient information communication within photovoltaic, wind power, natural gas, and other energy frameworks [2]. Such insufficiencies can precipitate "energy islands," resulting in significant power system losses and suboptimal energy utilization efficiency [3]. These challenges pose considerable impediments to the high-quality progression of urban energy systems. In contemporary times, advancements in the energy sector, driven by Internet technology, have considerably reshaped societal lifestyles and economic development paradigms [4]. The hallmark of next-generation energy interconnection technology is the integration of blockchain technologies rooted in Internet infrastructures [5]. Within the energy Internet paradigm, the modality of energy trading is shifting from a centralized to a distributed approach. Consequently, the scheduling, monetary transactions, and information security in energy deals will increasingly rely on third-party intermediaries [6]. Relying on third parties for opaque energy trading raises security concerns. Inherently, centralized systems exhibit scalability challenges and intrinsic vulnerabilities such as single points of failure and deficits in privacy and anonymity. This manuscript introduces an innovative energy trading mechanism tailored for demand-side management within cellular networks [7]. Drawing upon the Stackelberg game theory, the proposed system facilitates the collaboration of energy storage providers, optimizing revenue via establishing energy trading prices with the grid [8]. Concurrently, burgeoning research has advanced a novel framework for dual settlement P2P energy markets, often applied to the joint scheduling and trading activities of producers and consumers within community microgrids [9].

Blockchain technology, with its distributed data storage, peer-to-peer transmission capabilities, consensus mechanisms, and encryption algorithms, offers significant advancements [10]. Distinctive attributes of blockchain include its decentralized nature, anonymity, tamper resistance, and its commitment to openness and transparency [11]. Energy trading, in its essence, is a multifaceted process [12]. Relying solely on antiquated systems for energy trading is increasingly untenable in light of contemporary shifts within the energy sector. However, blockchain technology presents the potential to streamline and revolutionize energy trading practices [13]. The blockchain industry in China has seen notable growth, with expectations that blockchain will be pivotal in realizing the infrastructure of the energy Internet [14]. Beyond its original applications in digital currency, blockchain's potential is increasingly recognized in areas such as smart contracts, rendering it a vital technology for intricate energy trading agreements [15]. Research indicates that within an energy Internet environment, blockchain nodes can be harnessed for energy trading by third-party institutions [16]. Blockchain can archive energy trading data in the form of smart contracts, facilitating the automated execution of trade schemes and fund transfers [17]. Hence, there is potential to establish a secure energy Internet sharing network supported by blockchain technology. Importantly, energy exhibits unique characteristics that set it apart from standard commodities, thereby giving rise to distinct trading dynamics [18]. The advent of energy blockchain has garnered significant academic interest, with particular emphasis on distributed energy sharing network architectures based on blockchain [19]. Empirical research has proposed a trusted distributed energy sharing network architecture undergirded by side chains, characterized by its efficiency, security, and transparency, ensuring user privacy [20]. In addressing information security and loss concerns within the scheduling process of the integrated energy system, researchers have put forth an optimization model for service scheduling. This model is founded on the principles of energy blockchain [21]. Furthermore, certain scholars have introduced a credit scoring mechanism, drawing inspiration from the conventional carbon emission trading system. They have defined a trading priority value and established a sophisticated smart contract model. This innovative model facilitates the automatic quantification of both carbon emission rights and currency [22].

CCS technology is one of the main means to reduce CO_2 emissions. In the short term, it is difficult to rapidly change China's coal-based energy consumption structure, and CCS technology is suitable for China's coal-based energy utilization system, as it transforms fossil fuels into clean energy with zero carbon emission without changing the type of energy utilization. P2G can convert surplus electricity power into natural gas for storage or use, realizing the consumption of renewable energy and providing important technical support for realizing the low-carbon potential of the integrated energy system. CCS can be converted into a carbon capture unit, which can provide a high-quality carbon source for the P2G equipment while reducing the carbon emissions of the system. The combination of CCS and P2G can not only reduce the carbon emissions of the system but also supply CO_2 raw materials for P2G to reduce the cost of purchasing carbon and realize the local utilization of CO_2 to reduce the cost of carbon transportation and storage.

In order to further explore the environmental benefits of integrated energy system, some scholars have introduced CCS technology into the scheduling process and carried out related research on carbon trading models. Lyu et al. [23] introduced CCS system and P2G to reduce CO_2 emissions and improve wind power utilization. Liu [24] investigated the impacts of a unified carbon trading model and a stepped carbon trading model on the operation of an integrated energy system with P2G and gas-fired units. Li et al. [25] constructed a multistage planning model of an integrated energy system under the stepped carbon trading mechanism. The results show that the carbon trading benchmark price is the main factor affecting the planning results.

Based on the above research and analysis, this paper couples the operation of CCS and P2G and constructs an integrated energy system trading model for CCS-P2G-coupled operation based on blockchain technology. Within this framework, a Bloom filter-based P2P energy trading algorithm is optimized to improve the proficiency of the integrated energy system trading infrastructure.

The novelty of this paper is as follows:

(1) Coupled CCS-P2G operation: the coupling of CCS technology with P2G equipment presents a novel approach, contributing to the advancement of integrated energy systems

(2) Optimized P2P energy trading algorithm: the application of the Bloom filtering technique to optimize the P2P energy trading algorithm adds a unique dimension, enhancing reliability and timeliness

(3) Distributed energy trading mechanism: the utilization of smart contracts in a distributed energy trading mechanism establishes an innovative framework, meeting high requirements for trading reliability

This paper consists of five main components. Specifically, the first part is the introduction, the second part is the state of the art, the third part is methodology, the fourth part is the result analysis and discussion, and the fifth part is the conclusion.

2. State-of-the-Art

2.1. Energy Routing Mechanism in the Integrated Energy System. In the integrated energy Internet paradigm, establishing multiple transmission pathways between source and load nodes is feasible. This is akin to the communication domain, where information routers ensure precise information delivery to designated destinations. The energy routing mechanism, integral to the energy Internet, strategically interconnects stakeholders through specific routing methodologies, facilitating coordinated operations aligned with predetermined objectives. Consequently, the desired energy flow stipulated by the end user is accurately channeled to the load terminus. Within a market-oriented environment, the disseminated energy pricing information encapsulates variations in energy supply-demand dynamics and potential transmission bottlenecks. This crucial intel augments the foundational premise for the energy routing mechanism. Through the energy routing apparatus, one can actualize the synergistic coordination and optimization of multiple energy forms. Moreover, it furnishes end users with a diverse array of energy utilization services. In the context of this study, we introduce a value stream cultivated from the mutual pursuit of maximal profitability by transactional entities. This value stream-driven energy routing mechanism amplifies trading gains through an enhanced centralized bidding approach that duly considers transmission losses intrinsic to both transactional parties. Equations (1) and (2) delineate the profit structures for the respective sides of the trading.

$$m_{s,t} = \sum_{t=1}^{T} (\rho - \rho_s)(E_{sh} - E_{\text{loss}}), \quad (1)$$

$$m_{h,t} = \sum_{t=1}^{T} (\rho_h - \rho)(E_{sh} - E_{\text{loss}}), \quad (2)$$

where $m_{s,t}$ and $m_{h,t}$ are the profits of the energy seller and the energy buyer within the period t; ρ_s and ρ_h are the energy selling price of the energy selling party and the energy purchasing price of the energy buying party within the t period, respectively; ρ is the energy trading price; E_{sh} indicates the number of energy sources traded in period t; and E_{loss} refers to the loss generated during energy transmission.

The Power Routing Decision Center (PRDC) serves as the nexus for comprehensive control and strategic scheduling optimization. This infrastructure assimilates data pertaining to the output capacity of individual energy sources, prevailing energy prices, and purchase rates at the load terminus. Leveraging the underpinnings of the integrated energy routing framework, the trading's maximum profitability is employed as a pivotal benchmark and a foundation for swift computations. As a consequence, user energy consumption strategies are meticulously refined, and the paramount integrated energy routing modality is discerned for each transactional dyad.

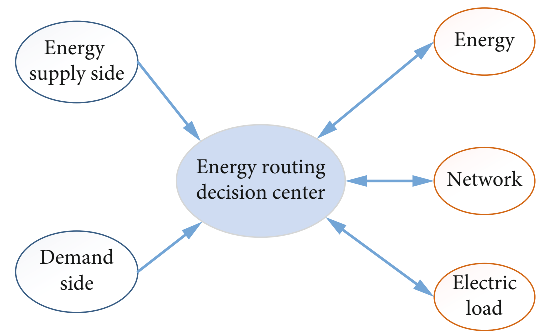

Figure 1: Integrated energy routing mechanism driven by value flow.

Each originating node operates as a market energy purveyor, delineating prices for varied energy mediums such as electricity, petroleum, and natural gas. Meanwhile, these sources remain receptive to the PRDC's judicious online quotations for surplus energy. Energy suppliers, while navigating diverse markets, tailor their engagement to distinct business paradigms to optimize their vested interests.

On the demand side, consumers relay their energy requisites and anticipated energy price thresholds to the PRDC. Users, in leveraging the capabilities of the PRDC, pinpoint the optimal routing configuration—essentially, the trajectory with minimal losses. Within this schema, the trajectory of integrated energy routing undergoes a paradigm shift from the conventional "source-network-load" model towards a more inclusive and diversified stakeholder-based routing.

The intricacies of the value stream-driven integrated energy routing mechanism are visually encapsulated in Figure 1.

2.2. Blockchain-Based Integrated Energy System Trading Architecture. Blockchain technology has the characteristics of decentralization, data tampering, and openness. Therefore, the application of blockchain technology is conducive to improving the security of the integrated energy trading network and realizing anonymous mutual trust between the nodes of the two parties to the trading. Since the subjects and services in the integrated energy system have different requirements for the privacy and decentralization of trading information, the blockchain network of integrated energy system is constructed in the form of a "multichain" (see Figure 2). The energy blockchain network is mainly divided into four types of master nodes: source-side master nodes, grid-side master nodes, sales-side master nodes, and load-side master nodes. Each type of master node holds the management right for the corresponding slave node. This includes summarizing the trading information of the slave node, publishing it to the blockchain network, receiving information from other master nodes, and engaging in communication with other master nodes. Each slave node can

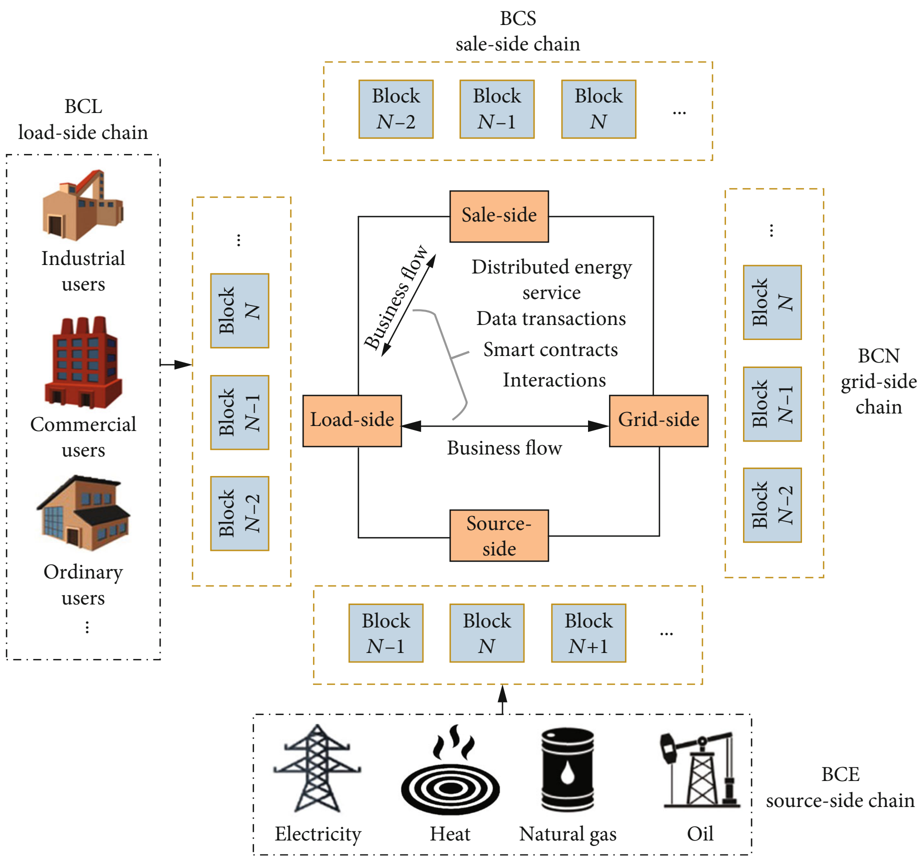

Figure 2: Integrated energy system trading architecture.

only interact with the relevant master node in the information flow and encrypt the relevant trading information to the slave chain after the completion of the trading. The source-side subordinate nodes include electricity, heat, natural gas, and oil supply. The grid-side subordinate nodes consist of power grid companies responsible for energy dispatching and comprehensive services. Sales-side slave nodes are mainly electricity selling companies, which mainly carry out energy trading functions between subjects. The load-side slave nodes mainly include industrial users, commercial users, ordinary users, and electric vehicle energy storage users.

In the blockchain network of integrated energy systems, there is a two-way flow of integrated energy trading business between the master node at the network side and the master node at the load side and between the master node at the sales side and the master node at the load side. This kind of business mainly includes as follows: (1) data transactions: including all kinds of electricity consumption data and energy saving data and other valuable data that can be traded; (2) distributed energy services: for power users to screen more energy efficient distributed energy generators, mainly distributed photovoltaic power generation and nearby energy trading; (3) interactions: integrated energy service providers can also sell the stored power to users who cannot participate in P2P trading, realizing extensive interaction between distributed power and users at all levels; and (4) smart contracts: the smart contract in the blockchain can act as an auction institution in the trading process of each user, thus replacing the "third-party intermediary" of the traditional "centralized" auction and realizing the aggregated auction trading in which the users are of equal status, information is symmetric, and transparency is open.

3. Methodology

3.1. Optimization of CCS-P2G Integrated Energy System Trading

3.1.1. CCS-P2G-Coupled Operation Model. For an integrated energy system incorporating CCS and P2G devices, CCS is capable of capturing CO_2 emissions from coal-fired units through absorption towers, regenerating towers, and subsequent compression and storage processes. This enables low-carbon operation of coal-fired units. P2G devices utilize surplus wind power to electrolyze water and produce hydrogen, which is then used in a methane-producing reaction with CO_2 to obtain methane. However, the cost of CO_2 feedstock can impact the operation of P2G devices. The coupling of CCS with P2G devices through the compression and supply of captured CO_2 significantly enhances the economic viability and low-carbon performance of the system. Given that P2G devices typically operate with limited CO_2 from conventional CCS during regular operation, the carbon source supplied to P2G devices is constrained. To address this, a liquid storage system is introduced between the

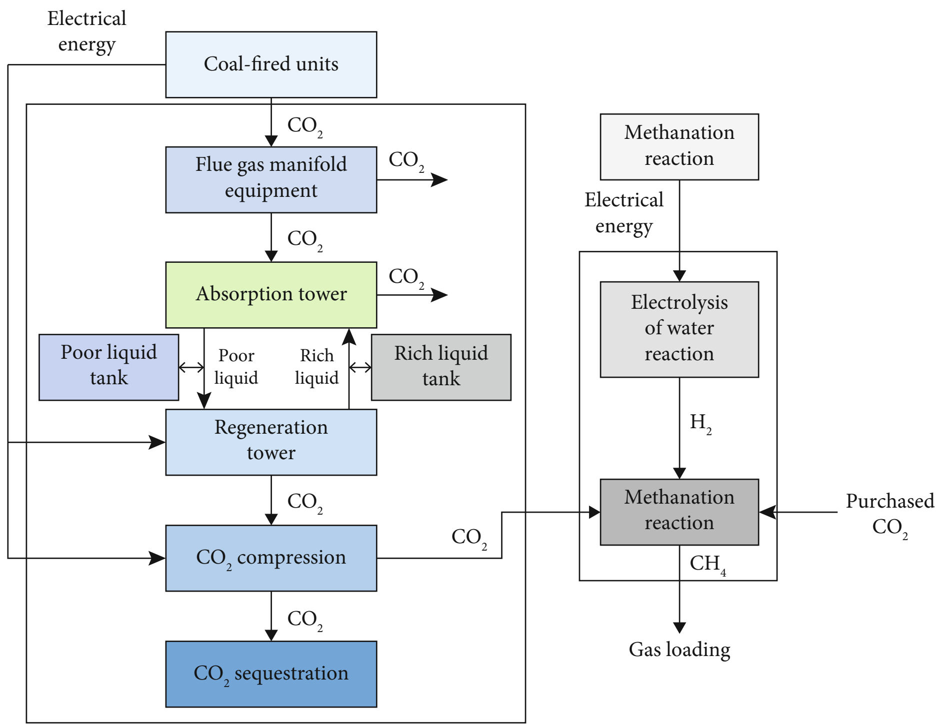

FIGURE 3: CCS-P2G coupling operation system.

absorption and regeneration sections of CCS to decouple the CO_2 absorption and solvent regeneration steps. This operational mode allows carbon capture units to transfer rich liquid for treatment from peak output periods to off-peak periods. A schematic of the CCS-P2G-coupled operation is depicted in Figure 3.

CCS consumes a portion of the output power of a coal-fired unit and captures compresses and stores the CO_2 produced by the coal-fired unit. The energy consumption of CCS is as follows:

$$U_{\mathrm{CCS},n} = U_{C,n} - U_{T,n} = U_H + U_{J,n}, \tag{3}$$

where $U_{\mathrm{CCS},n}$ is the energy consumption of carbon capture in time period n; $U_{C,n}$ is the total power of coal-fired units in time period n; $U_{T,n}$ is the net output of coal-fired units in time period n; U_H and $U_{J,n}$ are the fixed energy consumption of CCS and the operation energy consumption, respectively; $U_{J,n}$ is related to the amount of CO_2 processed in the regeneration tower in time period n, and the calculation equations are as follows:

$$\begin{aligned}
&U_{J,n} = e_C E_{2,n},\\
&E_{2,n} = E_{1,n} + E_{CJ,n},\\
&E_{1,n} = \alpha \eta_{\mathrm{CCS}} E_{C,n},\\
&E_{C,n} = \gamma_C U_{C,n},\\
&0 \leqslant E_{2,n} \leqslant \omega \eta_{\mathrm{ccs}} \gamma_C U_C^{\max},
\end{aligned} \tag{4}$$

where e_C is the energy consumption required to capture CO_2 per unit mass, $E_{1,n}$ is the mass of CO_2 absorbed by the absorber tower at time n, $E_{2,n}$ is the mass of CO_2 processed by the regeneration tower at time n, α is the flue gas split ratio, η_{ccs} is the carbon capture efficiency, $E_{C,n}$ is the total CO_2 emission from the coal-fired unit at time n, $E_{CJ,n}$ is the mass of CO_2 supplied by the storage tank at time n, γ_C is the carbon intensity of the coal-fired unit, ω is the maximum operating condition factor of the regeneration tower and compressor, and $U_C^{\max}$ is the maximum total power of the coal-fired unit. Considering that the energy consumption of CCS operation is constrained by the optimal operational settings of the regeneration tower and compressor, there exists an upper limit for the amount of CO_2 processed by the regeneration tower within time period n. The interval for the quantity of CO_2 available for capture provided by the liquid storage tank in time period n is as outlined below:

$$-\alpha \eta_{\mathrm{CCS}} E_{C,n} \leqslant E_{CJ,n} \leqslant \omega \eta_{\mathrm{CCS}} \gamma_C U_C^{\max} - \alpha \eta_{\mathrm{CCS}} E_{C,n}. \tag{5}$$

After CCS is introduced into the reservoir, the volume of the stored ethanolamine solution needs to be considered about the mass of CO_2, and therefore, $E_{CJ,n}$ needs to be converted to solution volume.

$$Q_{CG,n} = \frac{E_{CJ,n} W_{\mathrm{MEA}}}{W_{CO_2} \theta \psi_R \rho_R}, \tag{6}$$

where $Q_{CG,n}$ is the volume of solution required to release CO_2 from the reservoir at time n; W_{MEA} and W_{CO_2} are the molar mass of ethanolamine solution and CO_2, respectively; θ is the regeneration tower resolving volume; ψ_R is the concentration of ethanolamine solution; and ρ_R is the density of ethanolamine solution. The storage volume constraints of the reservoir are shown below:

$$\begin{cases} Q_{FJ,n} = Q_{FJ,n-1} - Q_{CG,n}, \\ Q_{UJ,n} = Q_{UJ,n-1} + Q_{CG,n}, \\ 0 \leqslant Q_{FJ,n} \leqslant Q_{CR}, \\ 0 \leqslant Q_{UJ,n} \leqslant Q_{CR}, \\ Q_{FJ,0} = Q_{FJ,24}, \\ Q_{UJ,0} = Q_{UJ,24}, \end{cases} \tag{7}$$

where $Q_{FJ,n}$ and $Q_{UJ,n}$ are the volume of solution stored in the rich liquid tanks and the poor liquid tanks, respectively, at time n; Q_{CR} is the capacity of the tanks; $Q_{FJ,0}$ and $Q_{UJ,0}$ are the initial volume of solution stored in the rich and poor liquid tanks, respectively; and $Q_{FJ,24}$ and $Q_{UJ,24}$ are the volumes of solution stored in the rich and poor liquid tanks, respectively, at the end of the scheduling cycle.

The amount of CO_2 consumed by the P2G equipment at time period n comes from two sources: one is supplied by the CCS in the system; the other is purchased from the carbon source material market.

$$z_{CO_2} U_{P2G,n} = E_{CU,n} + E_{BUY,n}, \tag{8}$$

where z_{CO_2} is the amount of CO_2 required by the P2G device per unit of electrical power, $U_{P2G,n}$ is the operating power of the P2G device at time period n, $E_{CU,n}$ is the amount of CO_2 supplied by the CCS to the P2G device at time period n, and $E_{BUY,n}$ is the amount of CO_2 purchased at time period n.

CCS supplies the captured CO_2 to the P2G plant as feedstock for the methanation reaction, thereby reducing CO_2 sequestration.

$$E_{FC,n} = E_{2,n} - E_{CU,n}, \tag{9}$$

where $E_{FC,n}$ is the amount of CO_2 sequestration at time n.

In the methanation reaction, the volume of methane produced by the P2G device equals the volume of CO_2 consumed; therefore,

$$E_{CU,n} = \rho_{CO_2} Q_{CO_2,n} = \rho_{CO_2} Q_{CH_4,n}, \tag{10}$$

where ρ_{CO_2} is the CO_2 density, $Q_{CO_2,n}$ is the volume of CO_2 consumed at time n, and $Q_{CH_4,n}$ is the volume of methane produced at time n.

The relationship between the volume of methane generated by the P2G device and the electrical power consumed is as follows:

$$Q_{CH_4,n} = \frac{(\eta_{P2G} U_{P2G,n} B_e)}{B_a}, \tag{11}$$

where η_{P2G} is the energy conversion efficiency of the P2G device and B_e and B_a are the calorific value of electricity and natural gas, respectively.

3.1.2. Structure of P2P Energy Trading System. P2P energy trading refers to the decentralized exchange of energy between individual participants within a network. The principle of P2P energy trading involves the direct buying and selling of excess energy between producers and consumers without the need for intermediaries. P2P energy trading leverages decentralized networks, blockchain, and smart contracts to create a transparent, efficient, and trustless system for the direct exchange of energy between producers and consumers. The P2P energy trading paradigm can be conceptualized as a composite of discrete yet interrelated units. Collectively, these units constitute the entirety of the P2P energy trading infrastructure, as illustrated in Figure 4. Each of these units functions as an autonomous entity, operating independently yet collaboratively within the broader system. Furthermore, these units can be augmented with specific energy storage systems, such as wind energy infrastructure. The system is fundamentally segmented into three critical components:

(1) Producers. These are pivotal actors within the system. Operating as both buyers and sellers in the trading landscape, their role is indispensable. Users can selectively assume roles predicated on the efficiency criteria of energy and other pertinent performance indicators of the energy trading

(2) System Operators. These form the bedrock of the energy trading marketplace. Their primary mandate is to oversee and facilitate energy trading, rendering essential trading services. Additionally, they grant stakeholders the capability to administrate the trading system via dedicated software interfaces

(3) Intelligent Controller. This component is instrumental in the overarching coordination and dissemination of trading-related information. It primarily oversees information exchange processes. As such, consumers harness this functionality to frequently engage in information sharing within the energy marketplace

In this paper, B represents the set of producers and consumers in the system. H and S represent groups of buyers and sellers, respectively. $T = |B|$ said production quantity, elimination $T_H = |H|$ says the number of buyers, and $T_S = |S|$ says the number of sellers. Each producer and consumer generates energy $E_{t,n}^{UQ}$ and consumes energy $i_{t,n}$ in time period n. $E_{t,n}^{UQ}$ represents energy generation, and $i_{t,n}$ represents energy consumption. $E_{t,n}^{UQ} - i_{t,n} > 0$, the producer will become the seller selling their energy in time period n. Otherwise, consumers will become buyers and choose to purchase energy sources to meet their needs in time period n. In this study, the discrete time system is considered and the running time

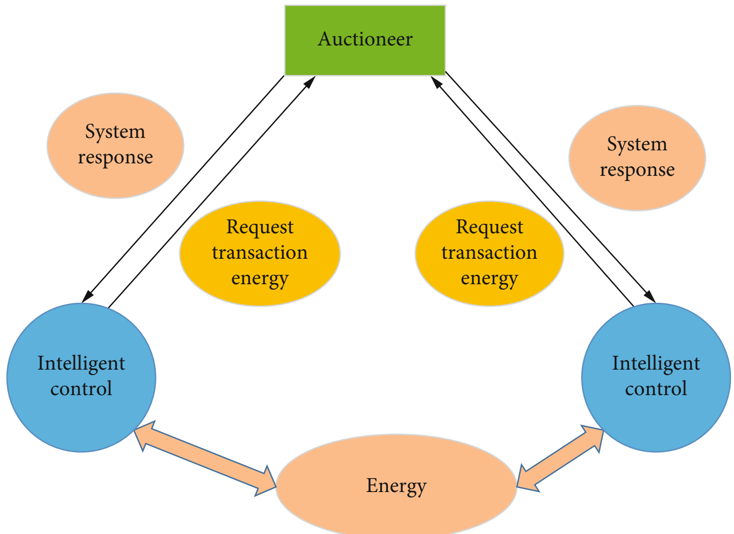

Figure 4: P2P energy trading system.

is divided into the same interval; the interval is $n = 5 \sim 15$ min. $n = \{1, 2, \cdots, N\}$ represents the set of run intervals.

Demand-responsive buyers can adjust their load demand based on price or benefit incentives. The buyer's profit is a utility function. By function calculation, the utility function is not decreasing all the time. The change in the value of the function is a curve, first decreasing and then increasing. Utility functions can also be used in energy purchasing behavior of consumers. Usually, you use the logarithmic utility function and the quadratic utility function. As this paper is an energy trading, timeliness needs to be considered. Therefore, quadratic utility function is used to optimize energy loss and income for energy trading. The optimization method is shown in

$$P(i_{x,n}) = g_{x,n} i_{x,n} - \frac{\theta_{x,n}}{2} (i_{x,n})^2 \; 0 \le i_{x,n} \le i_{x,n}^{\max}, \tag{12}$$

where $i_{x,n}$ is the bid of producer x at time n and $\theta_{x,n}$ represents the satisfaction degree of producer x consuming a specific amount of energy during a period n. For higher $\theta_{x,n}$ values, producers are willing to reduce their energy consumption; otherwise, they will consume more energy. When $i_{x,n}$ changes, through change of sensitive index, $i_{x,n}$ is the energy demand of producer x. $i_{x,n}^{\max}$ is the maximum load of producer x at time n. The utility function employed in this study reflects the dynamic nature of demand-responsive buyers' profit calculations. The function's curve, initially decreasing and then increasing, captures the nuanced response of buyers to price or benefit incentives. The quadratic utility function, introduced in Equation (12), serves as an optimization method tailored for energy trading. It efficiently balances the trade-off between energy loss and income, ensuring timely decision-making in the dynamic energy market.

If the consumer is the buyer, the buyer's profit is shown in

$$M_{x,n} = P(i_{x,n}) - u_n i_{x,n}, \tag{13}$$

where u_n is the price determined by the auctioneer at the time period n and $M_{x,n}$ represents the buyer's way of making a profit. The strategy of the producer to maximize his profit function is shown in

$$i_{x,n}^{*} = gra \max_{i_{x,n}} M_{x,n}(i_{x,n}) \; 0 \le i_{x,n} \le i_{x,n}^{\max}. \tag{14}$$

From Equation (15), we can get $i_{x,n}$, where buyer x gets the maximum benefit.

$$i_{x,n} = \frac{g_{x,n} - u_n}{\theta_{x,n}}. \tag{15}$$

$i_{x,n}^{*}$ can be calculated by Equation (16) and condition $0 \le i_{x,n} \le i_{x,n}^{\max}$.

$$i_{x,n}^{*} = \begin{cases} i_{x,n}^{\max}, & i_{x,n} \ge i_{x,n}^{\max}, \\ i_{x,n}, & 0 \le i_{x,n} < i_{x,n}^{\max}. \end{cases} \tag{16}$$

To comprehend the objective function in Equation (15), consider a scenario where all other parameters are held constant. The benefits for consumers with different $\theta_{x,n}$ and u_n values are explored. At the beginning, as $i_{x,n}$ increases, the overall payoff continues to increase. If $i_{x,n}$ continues to increase, the yield increases to a maximum and then decreases. For lower satisfaction $\theta_{x,n}$ and price u_n, customers are willing to buy more energy. Otherwise, as the satisfaction degree and price u_n increase, the customer's demand for energy purchase will decrease

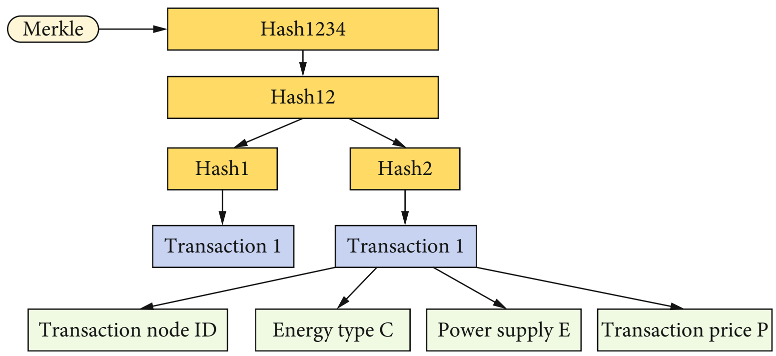

Figure 5: Merkle tree data structure of distributed generation trading.

accordingly, and the cost and energy consumption will be considered.

Different from the buyer, the seller will sell the surplus energy to customers, including the grid and other buyers. In general, the cost of buying energy for the grid will be lower. The seller mainly sells its surplus energy to the P2P market at the price u_n. The seller's profit function can be determined as shown in

$$M_{y,n} = -q_{y,n} i_{y,n} + u_n i_{y,n}, \tag{17}$$

where $q_{y,n}$ is the asking price of seller y at time n and $i_{y,n}$ is the surplus energy that the seller can sell on the market.

3.1.3. Optimization Strategy for Integrated Energy System Trading Network. The conventional P2P energy trading infrastructure encounters inherent performance constraints. Specifically, as the number of nodes in the system escalates, the latency in data transmission correspondingly surges, while the data throughput diminishes. Such a scenario implies that a substantial increment in nodes can critically attenuate communication efficacy, especially when myriad users engage in distributed energy trading. To address these challenges, this study proposes an integrated energy system trading network underpinned by the Bloom filters. Initially, every block node is interfaced to facilitate users in registering their instantaneous energy demands or excess energy contributions. Subsequently, an information exchange network is architected among users, thereby fostering seamless communication between energy producers and consumers. This design ethos aligns with the imperatives of minimal memory footprint and reduced energy expenditure characteristic of terminal nodes in multienergy grids. Efficient information exchange can be achieved through the introduction of the Bloom filters while minimizing the burden on individual nodes. Equations (18) and (19) mathematically elucidate this energy-information exchange, ensuring a balanced approach that meets the requirements of reduced memory usage and efficient energy communication in multienergy grids.

$$w = -\frac{t \ln u}{(\ln 2)^2}, \tag{18}$$

$$z = \frac{w}{t} \ln 2, \tag{19}$$

where w is the length of the Bloom filter, t is the number of inserted elements, u is the false alarm rate, and z is the number of hash functions. According to the data structure of distributed energy trading data, this model selects appropriate parameters and designs a data type sensing mechanism. By constructing the Bloom filter, invalid information is filtered. Further, improve the data query and insertion efficiency of integrated energy system network. This mechanism can reduce disk IO and network requests, reduce the pressure of data transmission, and realize the interconnection of energy blockchain network nodes.

3.2. Construction of Distributed Energy Trading Mechanism. Utilizing the optimized integrated energy system trading network, transactional data is propagated to a blockchain-based distributed energy trading system, heralding the onset of energy trading. Conventional centralized energy trading platforms demand significant resources to engender trust among participants. Centralized repositories for transactional data also render themselves susceptible to cyberattacks, thereby compromising data integrity. In response to these challenges, this study introduces a decentralized energy trading framework underpinned by smart contracts. This framework capitalizes on the automated enforcement capabilities of smart contracts.

Simultaneously, the mechanism utilizes the Merkle tree data structure (see Figure 5) to autonomously record transactional details on the blockchain through smart contracts. This promotes a trustless trading environment and enhances data security. The smart contract within this model is divided into three distinct segments: the load verification smart contract, the economic regulation smart contract, and the cost reconciliation smart contract. This design ensures modularity and templated structures for smart contracts, making the system accessible even to users devoid of programming expertise. The Merkle tree data structure plays a crucial role in enhancing transparency and accountability within the decentralized energy trading framework. Each transaction is cryptographically hashed and linked within the Merkle tree, creating a hierarchical structure. This ensures that any tampering with transactional details would be immediately detectable, promoting transparency in the

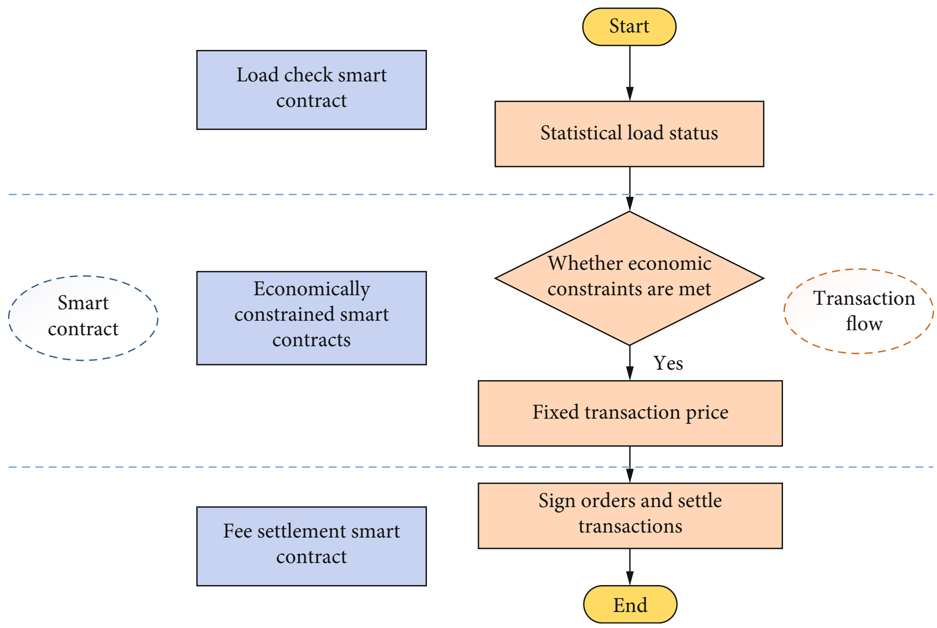

Figure 6: Trading process based on smart contract.

transactional process. Moreover, the Merkle tree's structure enables efficient verification of the transactional history, contributing to the overall accountability of the energy trading system.

As depicted in Figure 6, the transactional procedure predicated on smart contracts unfolds as follows:

(1) The load verification smart contract initiates by aggregating data pertaining to the distribution network as well as procurement and divestment requests from producers and consumers within the integrated energy system trading network

(2) Subsequent to this data acquisition, the security verification smart contract undertakes an initial assessment

(3) Building upon pre-established algorithms within the smart contract, processes such as power flow intersection examinations and congestion oversight are performed for distributed energy assets, encompassing photovoltaic systems and electric vehicles

(4) Concurrently, the economic regulation smart contract operates based on its intrinsic algorithm. Evaluating the load status of the transmission and distribution network in conjunction with localized energy consumption, users are subjected to economic stipulations. Only those adhering to these fiscal constraints are permitted to engage in trading, thereby determining the transactional price point

(5) Culminating the process, the cost reconciliation smart contract autonomously records the transactional data within the Merkle tree data framework. This facilitates the market reconciliation and effectuates value exchanges between producers and consumers, thus finalizing the energy trading. The entire operational continuum is characterized by its verifiability, traceability, and its capability to modulate energy supply and demand from a demand-centric perspective

The incorporation of the Bloom filter technology into the P2P energy trading algorithm is a pivotal aspect of our model. The Bloom filter is employed to optimize the query efficiency of the algorithm by mitigating the false positive rate, thereby augmenting the overall speed and responsiveness of the P2P energy trading system. Specifically, the Bloom filter is strategically utilized to check whether a particular transaction has occurred previously, facilitating a more efficient validation process in the energy trading network. The Bloom filter technology in the P2P energy trading algorithm is designed to enhance scalability by efficiently managing and querying transactional data. An adaptive mechanism is implemented to dynamically adjust Bloom filter parameters based on evolving network conditions and user demands. This adaptability ensures optimal performance as the number of nodes and the complexity of energy transactions within the network change over time. The dynamic adjustment of parameters contributes to the scalability and responsiveness of the P2P energy trading algorithm in diverse operational scenarios.

4. Result Analysis and Discussion

This section presents the results of simulation analysis and evaluates the performance of the proposed method. In this section, the energy trading efficiency of different methods and the performance of the energy trading system are analyzed and verified.

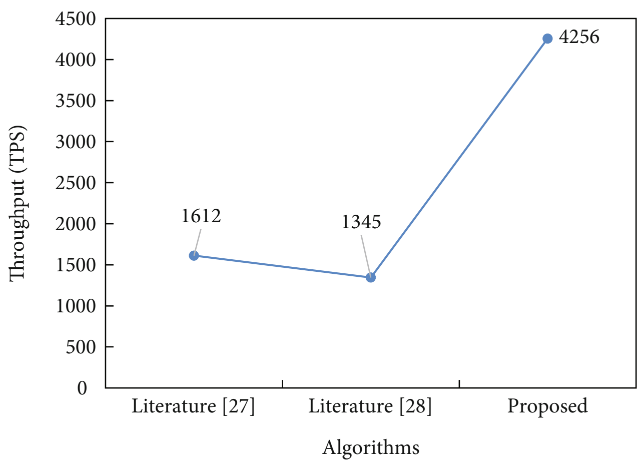

Figure 7: Throughput comparison of classical consensus algorithm.

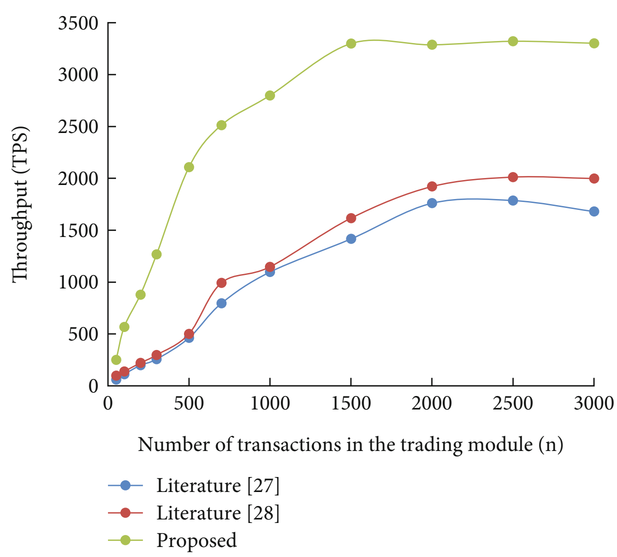

Figure 8: Throughput comparison between the proposed algorithm and other algorithms with different block sizes.

First, the performance of the blockchain-based energy trading system was tested. The system is analyzed by comparing the throughput and delay of different schemes. Figure 7 reveals a substantial enhancement in the average throughput of our proposed scheme compared to other classical consensus algorithms, as exemplified in literature [26] and literature [27]. As a result, the proposed method significantly reduces the overall time required for transaction processing. This research result finding not only emphasizes the superior performance of our method but also has far-reaching implications for the field of consensus algorithms and blockchain technology.

Select block sizes that contain 50, 100, 200, 300, 500, 700, 1000, 1500, 2000, 2500, and 3000 transactions. The proposed algorithm and the time delay and throughput of the algorithm in literature [26] and literature [27] are analyzed experimentally. The specific experimental results are shown in Figures 8 and 9.

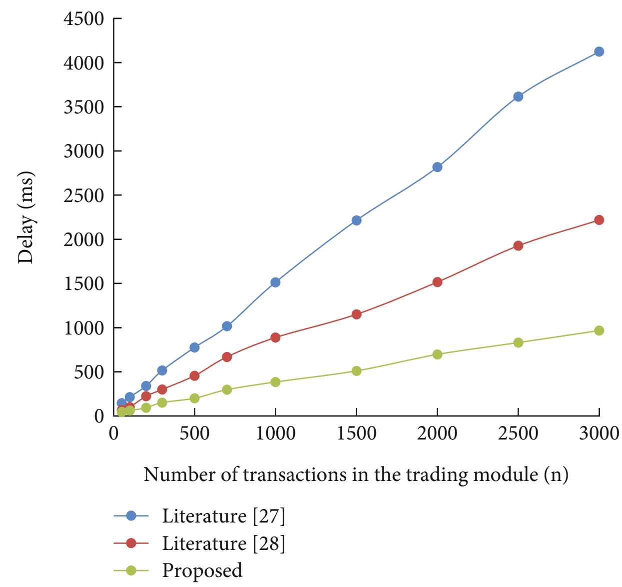

Figure 9: Time delay comparison between the proposed algorithm and other algorithms when block size changes.

As can be seen from Figures 8 and 9, compared with the algorithm in literature [26] and literature [27], the proposed scheme has higher throughput and lower delay. In both scenarios, throughput initially increases as the number of transactions in the block increases. However, after the block size reaches a certain value, the throughput increases slowly or even decreases. The delay increases with the size of the block. Therefore, the block size should be selected as an optimal value to obtain the best performance. An important insight derived from the analysis emphasizes the selection of an optimal block size. This consideration stems from the observed saturation point, where further increases in data block size do not linearly improve throughput and, in fact, may lead to performance degradation. The method proposed in this paper achieves a balance between transaction volume and system efficiency, thus exhibiting superior performance compared to the algorithms in literature [26] and literature [27].

In Figures 10 and 11, the proposed method is compared with the methods in literature [26, 27].

Figure 10 shows the social benefits of market transactions for all participants, where the proposed approach achieves higher benefits than the other two alternatives. In literature [26], the energy trading algorithm for smart grid networks is based on isolated forests. In literature [27], the energy trading algorithm of adaptive marketized combined double auction resource allocation in cloud computing is presented. The cumulative benefit of the proposed method is 118.32% higher than that of the literature [26] and 25.82% higher than that of the literature [27]. The proposed algorithm maximizes the social benefit of consumers by incorporating a dynamic pricing strategy. This strategy is designed to adapt to varying conditions in the energy market, aiming to balance consumer welfare and overall social efficiency. By considering the given price and dynamically adjusting transaction parameters, the proposed algorithm seeks to optimize the distribution of benefits among consumers participating in the energy trading

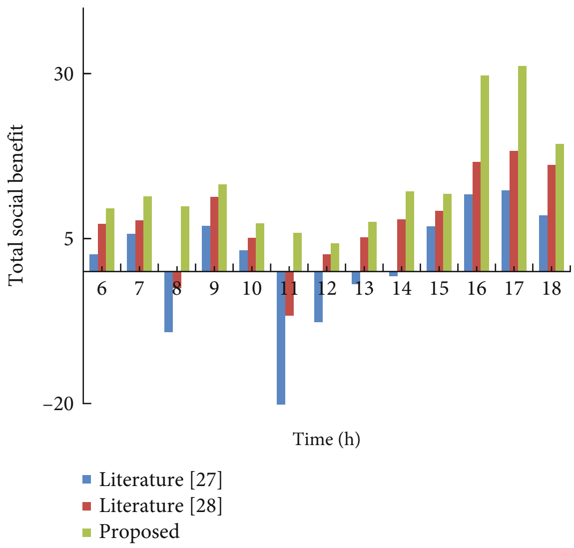

Figure 10: Comparison of social benefits of different methods.

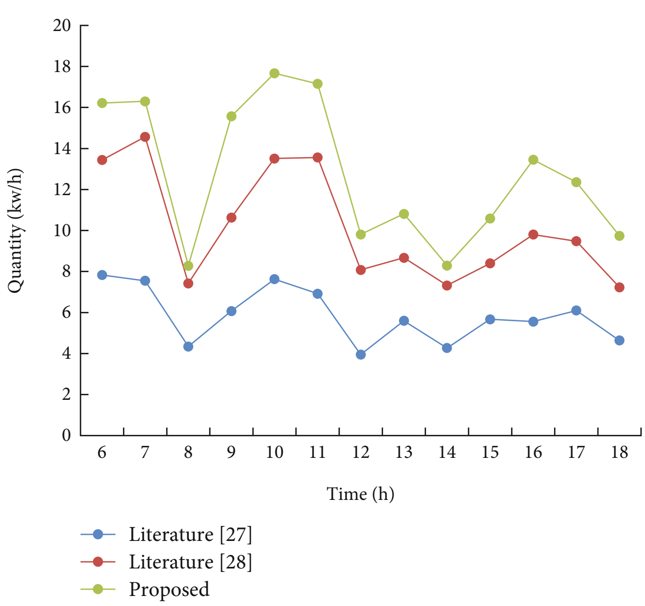

Figure 11: Comparison of trading quantity of different methods.

system. This is because the proposed approach is flexible, allowing the buyer to benefit by adjusting energy consumption. This is because of the flexibility of the proposed approach. This will adjust energy consumption and reduce costs so that the buyer can profit from it. The auctioneer makes the decision on behalf of the seller. As a result, the scheme creates maximum social benefits for each seller.

Figure 11 shows the total amount of energy traded on the market. The other two methods consume more energy than the one proposed in this paper. Our algorithm evaluates the performance of the blockchain platform by focusing on two key indicators: throughput and delay. Through rigorous analysis, we observed a notable enhancement in the average throughput of our proposed scheme, indicating improved transaction processing efficiency. Additionally,

Table 1: Comparison of net carbon emissions under three scenarios.

Time	Net carbon emissions/t		
	Scenario 1	Scenario 2	Scenario 3
0:00	7	5.1	3.5
2:00	5.5	5.3	4
4:00	6.2	5.4	3.3
6:00	4.5	5.5	3.7
8:00	7.1	5.7	3.9
10:00	7.1	5.9	4.1
12:00	7.1	6.1	4.3
14:00	6.8	5.6	4.5
16:00	7.1	5.8	3.8
18:00	7.1	5.5	3.6
20:00	7.1	5.4	3.5
22:00	6.8	5.4	4.2
24:00	7.1	5.2	4

our algorithm significantly reduces the time required for the entire trading process in the energy trading system. Even with a substantial number of trading modules, our algorithm maintains a low delay, showcasing its efficiency in handling diverse and concurrent energy trading activities.

In order to further compare and verify the rationality and effectiveness of the model in this paper, the following three operation scenarios are set up for comparative analysis. Table 1 shows the net carbon emissions of the system under the three scenarios.

Scenario 1: CCS is not included, and only P2G is considered

Scenario 2: no joint operation of CCS and P2G equipment is considered, and each equipment operates independently

Scenario 3: coupled operation of CCS and P2G, i.e., the model proposed in this paper

As shown in Table 1, the net carbon emission of scenario 1 is higher than that of scenarios 2 and 3, and the net carbon emission in most of the periods is 7t. The reason is that compared to scenarios 2 and 3, the system in scenario 1 does not have CCS and cannot achieve CO_2 recycling, resulting in higher carbon emissions. The overall carbon emissions of scenario 2 are higher than scenario 3. The net carbon emissions for each period in scenario 2 are 5-6t, while the net carbon emissions for each period in scenario 3 are all below 5t. The CCS in the model supplies captured CO_2 to the P2G plant as feedstock for the methanation reaction, reducing carbon emissions and promoting CO_2 reuse. Upon a comprehensive comparison of the system carbon emissions across the three scenarios, it is evident that the coupled CCS-P2G operation model proposed in this paper is effective in achieving low-carbon economic dispatch.

5. Conclusion

P2G equipment realizes the mutual coupling of electric energy and natural gas and plays an important role in improving the economy of multienergy system and reducing the carbon emission of the system. In this study, CCS technology is coupled with P2G for operation, and an integrated energy system trading model is constructed based on blockchain technology. The energy trading efficiency of the model and the performance of the energy trading system are analyzed and verified. The performance test is analyzed based on two performance metrics: throughput and latency. Through a series of experimental analyses, it is demonstrated that our method has higher throughput and lower latency relative to other methods. At the same time, our approach achieves higher energy trading benefits, and the cumulative benefits are significantly better than other methods. In addition, by setting different scenarios for research, it was found that the scenarios under this paper's scheme are superior in terms of reducing system carbon emissions compared to other scenarios.

While the presented integrated energy system trading model exhibits promising results in terms of throughput, latency, energy trading benefits, and cumulative benefits, there are certain limitations and areas for future exploration. Specifically, (1) the analysis and experimental results are based on certain assumptions and idealized conditions. Future research could delve into the robustness of the proposed model under more realistic and dynamic scenarios, considering factors like market uncertainties, regulatory changes, and external disturbances. (2) The study primarily focuses on the internal dynamics of the integrated energy system. Future research may explore the impact of external factors, such as market fluctuations, geopolitical events, or technological advancements, on the efficiency and benefits of energy trading within the proposed model.

Data Availability

The labeled datasets used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares no competing interests.

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