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Research on an Integrated Internet of Things and Blockchain-based Industrial Energy Trading System

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Abstract: **With the development of the national economy and the introduction of zero-carbon campuses, distributed energy is gradually becoming a significant component of the energy market. Based on this, this study proposes a set of solutions for campus energy transactions based on blockchain technology. Mathematical models for lighting, air conditioning, and fresh air are developed, and blockchain technology is used to store information about each energy transaction. This ensures the secure transmission and real-time sharing of distributed energy transaction information. Point-to-point energy transaction smart contracts are also designed. Through performance testing, the system was validated to have a high transaction success rate in most batches, providing a new approach for securing blockchain energy transactions.**

Keyword: Blockchain Technology; Campus Energy Transactions; Distributed Energy; Secure Transmission

1. Research Background

Distributed energy primarily refers to comprehensive energy management platforms deployed at various user endpoints. Due to their advantages of high efficiency, low pollution, and significant economic benefits, these platforms play a crucial role in modern energy networks. Consequently, the transition of distributed energy toward the development of primary energy sources has become an inevitable trend [1]. The blockchain technology, with its features of decentralization, transparency, security, and smart contracts, perfectly aligns with the needs of distributed energy trading, making it an ideal solution for optimizing energy trading models. This study therefore designed a blockchain-based distributed energy trading system, aiming to empower various processes of energy trading through information technology.

1.1 Zero-carbon Industrial Park

A zero-carbon industrial park is a specific area where carbon emissions are minimized through the use of new energy sources, new information technologies, and innovative business models, with the goal of achieving zero carbon emissions. The construction of a zero-carbon industrial park integrates the concept of carbon reduction into every aspect of urban development. It coordinates the use of energy, transportation, architecture, manufacturing, and other fields to create a new model of industrial development that is low-carbon, environmentally friendly, and resource-efficient. This model is in full alignment with the country's "dual carbon" strategic goals, working hand in hand to reduce greenhouse gas emissions, protect the natural ecological environment, and promote the transformation of the economy and society towards green and sustainable development. It is a concrete manifestation of the optimization of energy structures and the high-quality development of the economy [2].

1.2 Blockchain Technology

Blockchain technology facilitates the secure storage of distributed energy by deploying integrated smart contract chip devices. As energy data is generated, it can be encrypted and written to the blockchain network simultaneously, effectively preventing data tampering and fraudulent activities, thereby significantly enhancing the timeliness, accuracy, and reliability of the data [3].

Blockchain technology provides strong guarantees for the secure circulation of data. By allowing data owners to use private keys for signing and authorizing, it enables precise control over data access permissions. This allows for both the temporary disclosure of specific data and the assurance of the security and controllability of energy data during the sharing process.

2. Model Establishment

2.1 Lighting System Model

The brightness of indoor lighting in the park is maintained through a combination of the performance of the lighting system and the intensity of natural sunlight. While ensuring that the indoor lighting meets the required standards, if the lighting equipment can respond to power demands and effectively utilize natural light, it is possible to reduce the output power of the lighting devices during periods when electricity costs are higher during the day. To achieve this goal, this study constructed a lighting system model, the formula for which is as follows:

$$P_{light,t} = F_{in}R_{light}IL_{in,t} \tag{1}$$

In equation (1), $P_{light,t}$ and $IL_{in,t}$ represent the power output of the lighting system at a particular moment and the corresponding level of brightness it produces, R_{light} refers to the power consumption required to achieve a unit of brightness, F_{in} indicates the total area of the enclosed spaces involved.

To better align with practical applications, we have specifically designed a constraint function:

$$IL_{min} \leq IL_{in} + IL_{out,t} \leq IL_{max} \tag{2}$$

In equation (2), IL_{min} and IL_{max} represent the minimum and maximum permissible levels of illumination brightness, respectively, $IL_{out,t}$ represents the intensity of outdoor light at time t.

2.2 Air Conditioning System Model

The air conditioning system ensures that the indoor temperature remains within the comfortable range for humans, while the building's inherent thermal storage capacity works in conjunction with the air conditioning system. Based on this, the study aims to optimize the performance of the air conditioning equipment by establishing a model of the air conditioning system, whose heat balance equation is expressed as follows:

$$\rho_a CV \frac{d\theta_t}{dt} = B(\theta_t^{out} - \theta_t^{in}) + Q_{solar,t} + Q_{infle,t} + Q_{light,t} + Q_{crowd,t} + Q_{new,t} - Q_{AC,t} \tag{3}$$

In equation (3), ρ_a represents air density, C denotes the specific heat capacity of air, V represents the overall volume of the building, θ_t represents the indoor temperature at time t ; B is the thermal conductivity of the wall; θ_t^{out} represents the external air temperature at time t; $Q_{solar,t}$, $Q_{infle,t}$, $Q_{light,t}$, $Q_{crowd,t}$, $Q_{new,t}$ and $Q_{AC,t}$ t

represent the solar thermal energy at time t, the heat generated by non-elastic electrical loads, the heat generated by lighting equipment, the heat emitted by humans, the heat emitted by ventilation systems, and the cooling heat generated by the air conditioning system, respectively.

2.3 Model of the New Air System

The operating power of the new air system is related to the number of people passing through. Based on the actual situation, this study established a model, the formula for which is as follows:

$$P_{new,t} = n_{crowd,t}R_{new}E \tag{4}$$

In equation (4), $P_{new,t}$ represents the total energy consumption of the new air system at time t , $n_{crowd,t}$ denotes the total number of occupants in the building at time t , R_{new} represents the energy consumption per unit of new air volume, and E is the minimum required amount of new air per person per hour. To balance ventilation needs with energy consumption, the value of E must be determined in conjunction with the building's energy efficiency goals, as specified in the "Code for Design of Heating, Ventilation, and Air Conditioning for Civil Buildings" (GB50736-2022): the new air volume per person for office buildings should not be less than 30 m³/h.

3. The Proposal is Presented

This study proposes a blockchain-based energy trading solution for industrial parks. Through hardware devices, energy data from buildings is collected and uploaded. The data is then accessed via an intelligent gateway and stored on the blockchain, where it is verified, processed, and stored automatically by smart contracts.

3.1 Overall Architecture

The overall architecture is primarily divided into five layers: data acquisition, data layer, network layer, core layer, and application layer, as shown in Figure 1 below. Among these, the data acquisition layer is responsible for collecting energy data and market information in real-time[4].The data layer stores transaction records, smart contracts, and ownership information for energy assets, employing a hybrid storage strategy that combines chain-based hashing with off-chain databases to balance efficiency and security. The network layer builds a P2P communication network,

utilizing a consensus mechanism for distributed validation, and supports cross-chain interactions to connect grid management systems or carbon trading platforms. The core layer relies on smart contracts to automate transactions, including order matching, real-time settlement, and default handling, while incorporating off-chain computations to meet the physical constraints of the grid. The application layer provides transaction interfaces and value-added services to end-users, enhancing user experience and market participation.
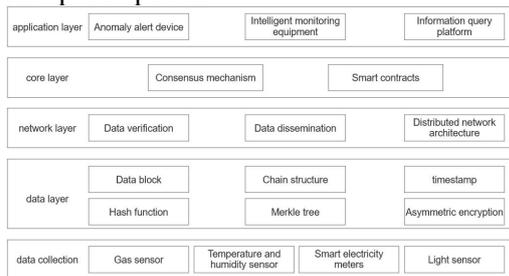

Figure 1. Framework of the Industrial Park Energy Trading System

3.2 Functional Module

This study has divided the functions of blockchain in energy trading systems into several modules. A detailed diagram of the modules is shown in Figure 2.

(1) In the proof of origin module, data on energy production, consumption, and transactions is fully recorded, ensuring its immutability. This feature supports cross-chain transaction tracing, making building energy transactions more transparent and trustworthy;

(2) The identity authentication module ensures the legitimate identity of participants, guaranteeing that only authorized users can participate in energy transactions and preventing malicious nodes from causing interference;

(3) The privacy encryption and decryption module safeguards users' sensitive data, striking a balance between transparency and privacy needs;

(4) The smart contract module automates the execution of energy transactions, enabling automatic triggering of transactions and completion of settlements, thereby significantly enhancing efficiency;

(5) The module for data pricing and transaction incentive mechanisms dynamically adjusts energy prices based on economic principles and optimization theories, and incorporates a feedback trust mechanism to incentivize users to participate in distributed energy sharing;

(6) The interaction between end-user devices and blockchain ensures the real-time and authenticity of data, thereby guaranteeing the genuine and reliable origin of the data;

(7) The cross-chain and cloud interaction module supports coordinated management between different energy networks;

(8) The trusted management module reduces the risk of cooperation by evaluating the historical behavior of nodes, thereby further enhancing the reliability of the system.
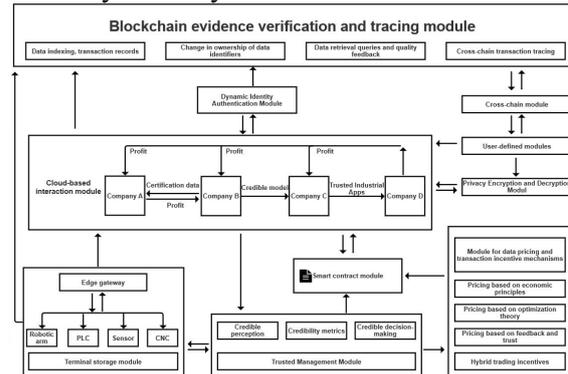

Figure 2. Functional Modules of a Blockchain Energy System

3.3 Design of the Transaction Process

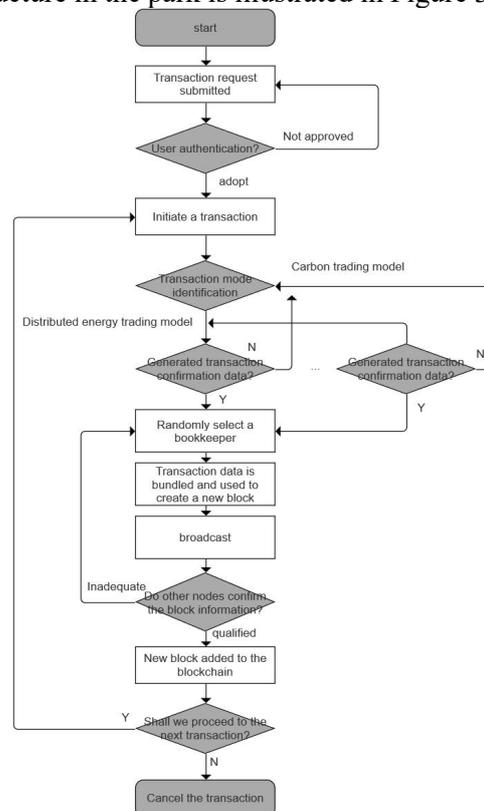The design concept for the energy blockchain structure in the park is illustrated in Figure 3.

Figure 3. Flowchart of the Energy Trading Process within the Campus

Energy traders must first apply to join the park's energy blockchain platform system and complete real-name authentication. After passing the authentication, they can initiate energy transactions. Once other users respond to the transaction and confirm the relevant information, the system generates corresponding transaction data. A blockchain network randomly selects a bookkeeper to pack the transaction data into a new block, which is then broadcasted to other nodes in the network. Each node verifies the transaction information within the block. Once verified, the new block is officially added to the blockchain, and the current round of energy transactions is concluded. If a subsequent round of transactions needs to be conducted, the process remains the same as described above [5].

4. System Design

4.1 System Hardware Design

The hardware system employs a multi-layered optimization design approach, achieving technological innovation in three critical areas: signal processing, data transmission, and intelligent control [6].

At the level of signal processing, an heterogeneous computing architecture is employed, integrating the collaborative processing capabilities of digital signal processors (DSPs), field-programmable gate arrays (FPGAs), and graphics processing units (GPUs). DSPs are responsible for accurately capturing and analyzing energy parameters, FPGAs handle real-time processing of transaction signals, and GPUs are used for deep learning analysis of energy usage patterns. This architecture design reduces signal processing delays related to energy trading by more than 35%, while also allowing for flexibility in adapting to varying demands for transaction data processing.

The intelligent control terminal is centered around a high-performance embedded system, which integrates key components such as temperature and humidity sensors, gas sensors, and light sensors. The data collection and control logic can be implemented using programmable logic controllers (PLCs). The design and application of such controllers already have a well-established technical framework [7]. By introducing machine learning-based predictive maintenance algorithms, we can identify potential equipment failures in advance through trend analysis of sensor historical data, thereby extending the Mean Time Between Failures (MTBF) of the system by 25% [8]. Additionally, the system features real-time energy efficiency optimization capabilities, which can automatically adjust operational parameters based on trading needs and energy consumption patterns, resulting in a 20% improvement in energy utilization efficiency. This provides precise measurement and control support for distributed energy trading.

4.2 System Software Design

The software system employs a layered optimization design, achieving technological innovation in four dimensions: task scheduling, message processing, service architecture, and intelligent algorithms.

The task scheduling layer employs a hybrid scheduling algorithm that integrates priority scheduling and time slice rotation mechanisms. For high-priority real-time transaction tasks, it employs preemptive scheduling to ensure immediate response to critical transaction instructions. For ordinary monitoring tasks, it employs dynamic time slice allocation to optimize the utilization of system resources.

The message broker layer is built on top of Apache Kafka as a distributed message bus. It incorporates a machine learning-driven adaptive routing mechanism and real-time monitoring of network topology and load conditions.

The service layer employs a microservices architecture, utilizing Docker containers for elastic scalability, to create an intelligent service communication layer.

The intelligent algorithm layer, combined with deep reinforcement learning algorithms, constructs an optimized model for energy trading operations. This model aims to reduce overall energy consumption while maintaining service quality. Specialized transaction feature extraction algorithms have been developed for blockchain transactions to enhance the efficiency of smart contract execution.

4.3 Smart Contract Design

The design is programmed using the Solidity language to create an efficient smart contract. This study focuses on a peer-to-peer energy trading mechanism. Under the condition that both parties' identities have been authenticated, the seller calls the trade Energy() method, inputs the corresponding parameters, and the smart

contract automatically verifies them. If the seller's energy balance is greater than the transaction amount and the buyer's account status is valid, the transaction is established, energy is transferred, and a notification is sent to the entire network on the chain. Finally, the token settlement takes place on the chain.

Algorithm 1: Smart Contract for Peer-to-Peer Energy Trading

```
struct Transaction {
address seller;
address buyer;
uint256 amount;
uint256 price;
uint256 timestamp; }
function tradeEnergy(address _buyer, uint256 _amount, uint256 _price) external onlyRegistered {
buildings[msg.sender].energyBalance -= _amount;
buildings[_buyer].energyBalance += _amount;
transactions.push(Transaction(
msg.sender, _buyer, _amount, _price, block.timestamp ));
emit EnergyTraded(msg.sender,_buyer,_amount,_price,block.timestamp);}
```

4.4 Database Design

To meet the requirements of real-time data availability, transaction consistency, and high concurrent access in a distributed energy system, three types of databases were designed: a real-time database (InfluxDB), a cache database (Redis), and a relational database (MySQL).

Table 1. Transaction Log Table

Field Name	Data Type	Explanation
t_hash	varchar	Blockchain transaction hash
timestamp	datetime	Trading hours
energy	float	Volume of energy traded
price	decimal	Unit Price
seller_id	int	Seller ID
buyer_id	int	Buyer ID

Table 2. Equipment Information Table

Field Name	Data Type	Explanation
device_id	varchar	Equipment ID
device_type	varchar	Type of equipment
location	varchar	Installation location
owner_id	int	Associated user ID
Field Name	Data Type	Explanation

This study leverages InfluxDB's efficient storage mechanism and robust indexing capabilities to effectively manage parameters such as power, voltage, and temperature, and to support rapid writing of large amounts of time-series data. At the same time, we utilize Redis' data persistence feature to store cached information such as real-time energy levels, user balances, and device statuses at predetermined intervals, ensuring that this data is stored on the server's disk before user data is written, thereby achieving data backup [10].Utilize the MySQL database to manage data such as transaction records and equipment information, As shown in Tables 1 and 2 above.

5. System Performance Testing

To test the performance of a distributed energy trading system based on blockchain technology, this study devised an experimental plan. By simulating a blockchain network environment, smart contracts were executed to handle and store transaction information. The transaction data included information on energy demand, transaction prices, and other relevant content. Evaluation metrics primarily focused on key parameters such as transaction success rate, system response latency, and network throughput capacity.

Among these, the success rate of transactions refers to the proportion of successfully completed transactions out of the total number of transactions; the system response time represents the average duration from the initiation of a transaction to its confirmation; and the network throughput denotes the total number of transactions that the network can handle within a given time period. Transactions were divided into three batches, and the experimental results are shown in Tables 3 and 4.

Table 3. Test Results for Transaction Success Rates and Average Response Times

Transaction batch	Number of successful attempts	Total transaction count	Transaction success rate (%)	Average response time (s)
Batch1	1968	2000	98.40	1.32
Batch2	1943	2000	97. 15	1.24
Batch3	1884	2000	94.20	1.27

Table 4. Number of Transactions Processed and Throughput Test Results for Each Time Period

Time frame	Number of transactions processed	Throughput (transactions/s)
09:00-11:00	500	8.25
11:00-13:00	540	9.04
13:00-15:00	520	8.72

As shown in Tables 3 and 4 above, the system maintains a high transaction success rate in most batches, demonstrating excellent processing efficiency and stability. Some batches approach 99%, indicating that the system is capable of performing efficiently under ideal conditions. However, the batch completion rate is slightly lower, suggesting that optimization is needed in extreme scenarios to enhance stability. The system's response time is relatively short, meeting the requirements for real-time transactions. The network throughput remains high, indicating the system's ability to handle high concurrent transactions.

6. Epilogue

This study proposes an innovative design for distributed energy trading in industrial parks based on blockchain technology. By constructing models, proposing solutions, and designing systems, we aim to improve the energy trading service system. Ultimately, through system performance testing, we found that the system maintains a high transaction success rate across multiple batches, demonstrating excellent processing efficiency and stability. In the future, as technology advances and applications grow, blockchain-based energy trading solutions will play an increasingly critical role in the energy industry, making significant contributions to the establishment of a sustainable energy ecosystem.

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