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Distributed Settlement Mechanism Design for Carbon Market Based on Blockchain-enabled Edge Intelligence

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***Abstract*—The trend towards decarbonizing the power industry is accelerating due to the environmental crisis. The development of carbon markets as one of the solutions for decarbonization has received more attention. The current annual carbon market widely adopts the method of calculating carbon emission according to the average carbon emission factor. The roughness of the average carbon emission factor and the long carbon market cycle lead to some problems in carbon market settlement in the carbon market at present. In this paper, we propose a blockchain-based scheme for real-time local settlement of carbon emissions. The system obtains accurate carbon emission information of generating units calculated from real-time power information through IoT devices. The digital carbon asset stored in the unit's account are written off in a short period through a blockchain smart contract. The above scheme eases the communication burden caused by accurate carbon emission records. With hardware devices, we verify the feasibility and operability of the scheme.**

***Index Terms*—blockchain, carbon emission, digital carbon asset, edge intelligence.**

I. Introduction

The global pursuit of carbon peaking and carbon neutrality necessitates reducing carbon-intensive practices. Among various industries worldwide, the power industry stands out for its substantial carbon emissions. Thus, it becomes imperative to transition towards a low-carbon power industry to ensure sustainable future development [1]. To effectively curb carbon emissions from the power industry, many countries have put forth proposals and initiatives. In Ref. [2], it is highlighted that implementing carbon quotas and establishing carbon quota trading markets are effective long-term measures for reducing regional carbon emissions. An essential foundation for carbon markets is the accurate measurement of carbon emissions.

Currently, carbon measurement is roughly designed at the regional level, and different regions follow the prescribed Carbon Emission Factor (CEF) data for a long time. However, since the current carbon emission measurement method assumes that the characterization of carbon emissions is fixed for large regions and long time scales, the carbon emission situation of different generating units cannot be accurately reflected. Physical measurements allow for continuous monitoring of carbon emissions in real-time, but additional monitoring and analyzing equipment results in higher costs. For most of the carbon markets in the world, the settlement of carbon quota is completed with a sole market operator on a long timescale (e.g., annual) [3]. Generally, such a settlement process relies on two assumptions. First, there is a trusted central authority for whole market management, while such authority is probably an ideal entity that might not exist. Second, the carbon emission of generator units is unaffected by their operating status. However, this assumption may not hold in actual unit operations, as discussed in Ref. [4]. The actual power produced by a generating unit fluctuates, which affects the actual carbon emission [5]. To sum up, the traditional carbon emission quota settlement mechanism faces two critical issues.

On the one hand, the market operator faces two challenges in managing the market, as follows: 1) The communication burden caused by the huge amount of refined information exchange in the long timescale settlement mechanism between each market participant and the central authority. 2) It is difficult for the settlement ledger to be trusted by all market participants. Thus, distributed carbon quota market settlement

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mechanisms and trusted ledger technologies need to be investigated. A decentralized trusted ledger can solve the above problems. Blockchain is a distributed ledger technology for the automatic execution of programs and the secure sharing of data [6].

On the other hand, the CEFs of generation units are not constant. For example, Chen *et al.* [7] proposes a linear function to depict the relation between power generation and carbon emission of different carbon capture power plants. Pourakbari *et al.* [8] further gives a quadratic formulation for the carbon emission of fuel units concerning output power. Therefore, low-time-resolution metering data cannot accurately reflect the mathematic relation between carbon emission and power generation. High-time-resolution power data is needed to capture the time-varying and power-dependent carbon emission better. However, measuring, transmitting, and storing high-time-resolution carbon emission data could cause heavy communication burdens and be very costly for storage. Thus, localized processing of high-time-resolution data for carbon quota settlement needs to be investigated. Edge intelligence is widely applied in localized data processing since it allows interconnected systems and devices to collect, store, and analyze data in the proximity to where it is generated [9]. However, to the best knowledge of the authors, carbon quota settlement methods using edge intelligence have not been reported in the literature.

In this paper, we propose a blockchain-based Digital Carbon Asset (DCA) settlement mechanism enabled by IoT devices, which relieves the communication burden by local settlement with edge intelligence. Real-time power data collected through high-precision sensors is transformed into carbon emission data through edge intelligence. Carbon emissions data is further translated into DCA consumption for units, and DCA settlement is automatically accomplished by blockchain smart contract. Carbon quota becomes digital assets on the blockchain, and blockchain smart contracts allow real-time settlement DCA and deletion of large amounts of used-up data. A series of steps are executed locally at a high frequency without taking up additional communication resources, thereby reducing the stress of storage and data communication and promoting observing the carbon emission status of generators.

The remainder of this paper is organized as follows. Section II presents the framework of the blockchain-based carbon quota settlement mechanism. Section III introduces the proposed settlement process for heterogeneous carbon emission characteristics. Numerical studies and results are presented in Section IV. Finally, Section V concludes the paper.

II. Blockchain-based DCA Settlement Framework

This section first builds the framework of the system. Afterward, a standardized DCA settlement mechanism process based on blockchain is designed.

A. System Structure

The carbon emission data settlement system includes three layers, namely the microgrid layer, the IoT layer, and the

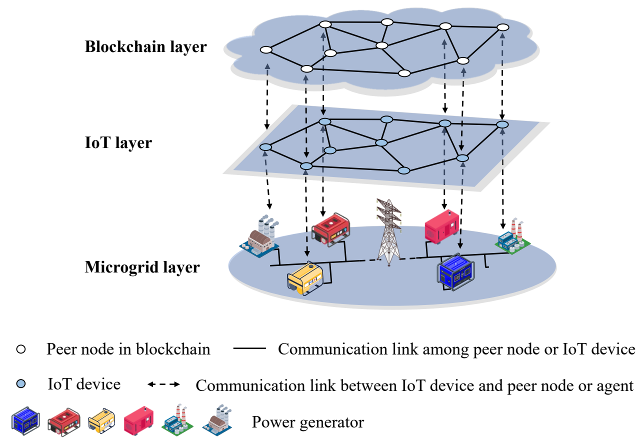

Fig. 1. System schematic.

Blockchain layer. Fig. 1 shows the whole structure of the carbon emission data settlement system. Each generator unit in the microgrid layer corresponds to an IoT device in the IoT layer and a peer node in the Blockchain layer, where power and carbon emission data are obtained. We consider both conventional thermal power units and units with Carbon Capture Systems (CCS) in this paper. Their differences in the relation between power generation and carbon emission and methods of carbon emission calculation are discussed in the next section. In the IoT layer, the Raspberry Pi transmits real-time power data collected by the smart meter to the peer node in the blockchain layer. As a credible and decentralized ledger technology, blockchain is a promising solution to enhance trust relationships between entities in the microgrid [10]. For the microgrid generator units scenario in this paper, we choose the consortium blockchain as a reliable recording platform.

B. Settlement Mechanism

The flow of the DCA settlement mechanism we designed is shown in Fig 2. In the microgrid layer, there are multiple types of power generator units, and the characteristics of each unit are considered. The power data during operation is closely monitored. High-precision meters and Raspberry Pi devices form the IoT layer, where the power data measured by the meters is collected and transmitted by Raspberry Pi to the Blockchain layer for further processing. Peer nodes in the Blockchain layer are responsible for obtaining fine-grained carbon emission data automatically through the smart contract, which automates the process of obtaining refined carbon emission data. In turn, the carbon assets of each unit are written off. The blockchain network is used to trust recording information about the power and carbon emission data. The smart contract can be automatically processed to calculate carbon emission data every minute.

III. Settlement Mechanism of System

The settlement of trades is a critical part of the process after the market has been cleared of trades. Detailed unit power

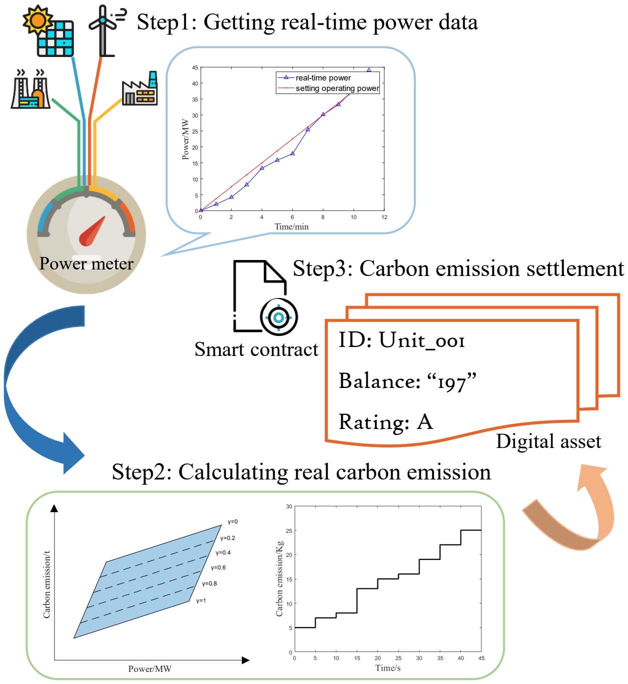

Fig. 2. The whole process of the carbon emission asset settlement mechanism.

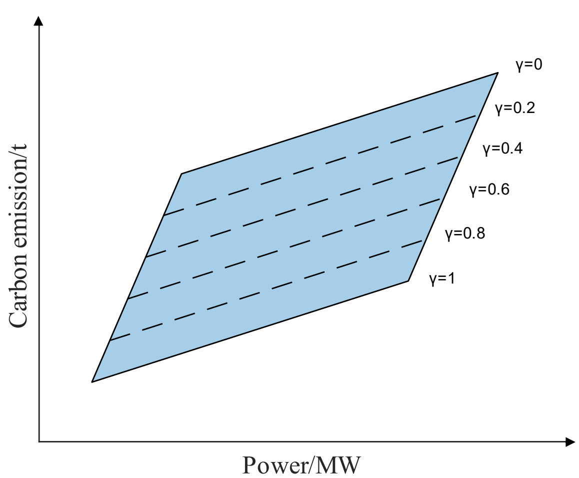

Fig. 3. The relation between power generation and carbon emission of the carbon capture unit. The carbon capture rate $gamma$ corresponds to an electricity-carbon characteristic curve at different values. All the values that can be functioning form the operating range of the generator unit, that is, the entire blue area.

generation and carbon emission data are conducive to a better assessment of the unit's carbon reduction process.

A. Carbon Emission Characteristics

The average CEF is defined by the average emissions generated per unit of electricity produced in a region, which varies over time and across regions. The average CEF is determined by:

$$F_y^{\text{power}} = \frac{\sum_f CE_y{}^{\text{power}}}{\sum_f g_y^{\text{power}}}, \tag{1}$$

where F, CE, and g represent annual total CEF, carbon emission, and power generation for a given region; superscript power represents power plant; subscripts y, f represent the year and fuel type, respectively. Common fuels include coal, natural gas, oil, and so on. The carbon emission quota for each unit is issued at the beginning of each trading cycle based on historical data, which will be reduced year by year according to a descending factorα. For a given power plant, its monthly carbon emission quota is [1]:

$$Emis_m^{\text{power}} = (1-\alpha) \cdot \frac{g_y^{\text{power}} \cdot F_y^{\text{power}}}{12}, \tag{2}$$

where $Emis$ represents the carbon emission quota and subscripts m represents month, respectively. For a given unit, the carbon emission quota for each monthly cycle is:

$$Emis_{i,m} = Emis_m^{\text{power}} \cdot \frac{g_i^{ex}}{\sum_{i=0}^{n} g_i^{ex}}, \tag{3}$$

where g represents the generation of electricity, subscript i represents the unit of the power plant, and superscript ex represents the power output of the unit. We view this carbon emission quota as DCA stored in the blockchain account of each unit. One ton of carbon dioxide emission corresponds to one token in the account. We can use equation. 4 to represent it.

$$Emis_{i,m} = \omega \cdot \pi_{i,m}, \tag{4}$$

where ω, π represent the conversion rate and DCA, respectively. The carbon emission quota is the product of electricity generation and the average CEF:

$$Emis_{i,m} = \sum_{i=0}^{n} g_{i,m} \cdot F_y, \tag{5}$$

which serves as the initial balance of the account of each unit.

B. Carbon Emission Data

Accurate carbon emissions data comes from accurate power data. The relationships between power generation and carbon emission of different units are characterized in the following paragraphs.

1) Carbon Emission Characteristics of Non-capture Units: Obviously, in the basic non-capture generating unit, the gross power generation is equivalent to the net power generation, and this relationship can be expressed by the following equation:

$$g_{i,t} = g_{i,t}^{\text{ex}}, \tag{6}$$

where t represents the time of unit operation.

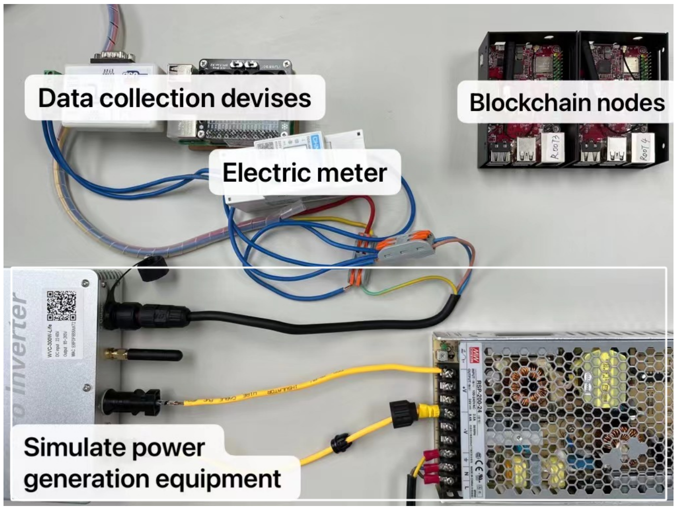

Fig. 4. The whole hardware circuit of the DCA settlement mechanism system.

2) Carbon Emission Characteristics of Capture Units: Through flexible operation, the CO_2 emission intensity of per unit electricity generated by a capture unit can be adjusted to produce different performances in terms of power generation efficiency, net power generation, and power generation costs, as compared to a conventional non-capture unit. In a capture power plant, the efficiency loss is equal to the gross efficiency minus the net efficiency, and the power loss is equal to the gross output minus the net output.

$$g_{i,t} = g_{i,t}^{\text{ex}} - g_{i,t}^{\text{cap}}, \tag{7}$$

where superscript cap represents the power of carbon capture of the unit. When running different CO_2 capture rates of the carbon capture power plant, the relation between power generation and carbon emission of the carbon capture unit is presented as a straight line with a certain slope as shown in Fig. 3. The uppermost line segment in Fig. 3 represents the relation curve between power generation and carbon emission when γ takes the value of zero. As the capture rate increases, the slope of the curve remains unchanged, and the position gradually shifts downward and to the left, which indicates the reduction of CO_2 emission and net power generation.

C. Real-time Carbon Emission Data

The carbon emission level of the unit is affected by the operation state of the unit. Real-time measurement of output power helps with getting the actual carbon emission data. For traditional fossil fuel generators, the carbon emission $Emis_{i,t}^{N}$ is calculated by:

$$Emis_{i,t}^{N} = g_{i,t}^{\text{ex}} F_y^f, \tag{8}$$

where F_y^f and f represent the CEF related to fuel types and type of fuel. For carbon capture generator units, CCS and CCGT units are specifically referred to in this paper, g_M^C is the power consumed by carbon capture and the relationship between their carbon emissions$Emis_{i,t}^{C}$ and power generation is:

$$Emis_{i,t}^{C} = \gamma Qi,t(g_N + g_M^C), \tag{9}$$

where Qi,t is the unit parameter affected by the operating state of the unit.

D. Settlement of DCA

After the carbon emissions data are converted to asset data, corresponding deductions are made for each account. Settlement is made on the last day of each month, and if there are surplus or negative assets, they can participate in the carbon market. For each unit's account, the asset is:

$$\pi_{i,m} = \pi_{i,m} - \sum_{t=0}^{n} Emis_{i,t}. \tag{10}$$

IV. Case Study

Numerical experiment results are presented in this section.

A. Hardware System

To verify that our proposed write-off mechanism is reasonable. We have reproduced all the steps through a set of hardware circuits shown in Fig. 4. Simulate power generation equipment generates power data for random analog unit operation. The data is read by a smart meter and transferred to a Raspberry Pi 4B by a data converter. The data collected by Raspberry Pi 4B is transmitted to the peer node at the blockchain layer via Transmission Control Protocol. Peer nodes in the blockchain layer are operated and maintained by Rock PI X devices.

B. Carbon Emission Data

In the microgrid layer, there are two fossil fuel power generator units, a generator unit with CCS, and a Combined Cycle Gas Turbine. The first type of fossil fuel unit belongs to a conventional power plant, while the other type combining low carbon technology belongs to an innovative power plant. The parameters of the units with the same fuel in our design experiments are the same to facilitate the comparison of differences in carbon emission data. The ramp rate of coal and gas units is 60 and 100 MW/h. We obtained the theoretical and actual measured values of the units' carbon emission using the equations in Section III and plotted Fig. 5. The upper and lower limits of the output of the coal-fired generator unit are 29 and 441 MW. The upper and lower limits of the generator's output with natural gas as a fuel are 34 and 627 MW. Traditional fossil fuel units fluctuate more than carbon capture units during operation. The output is more affected by the operating state of the fossil fuel units. Similarly, in terms of carbon emissions, the trend is the same. Due to the influence of the ramp state, the carbon emission fluctuation of the traditional fossil fuel unit is more obvious. In the early stage of the ramp, the carbon emission of the unit increases sharply from the stable operation state. In Fig. 5, we can observe the obvious fluctuation in the early stage of the ramp. These changes are difficult to reflect in the current rough carbon emissions records.

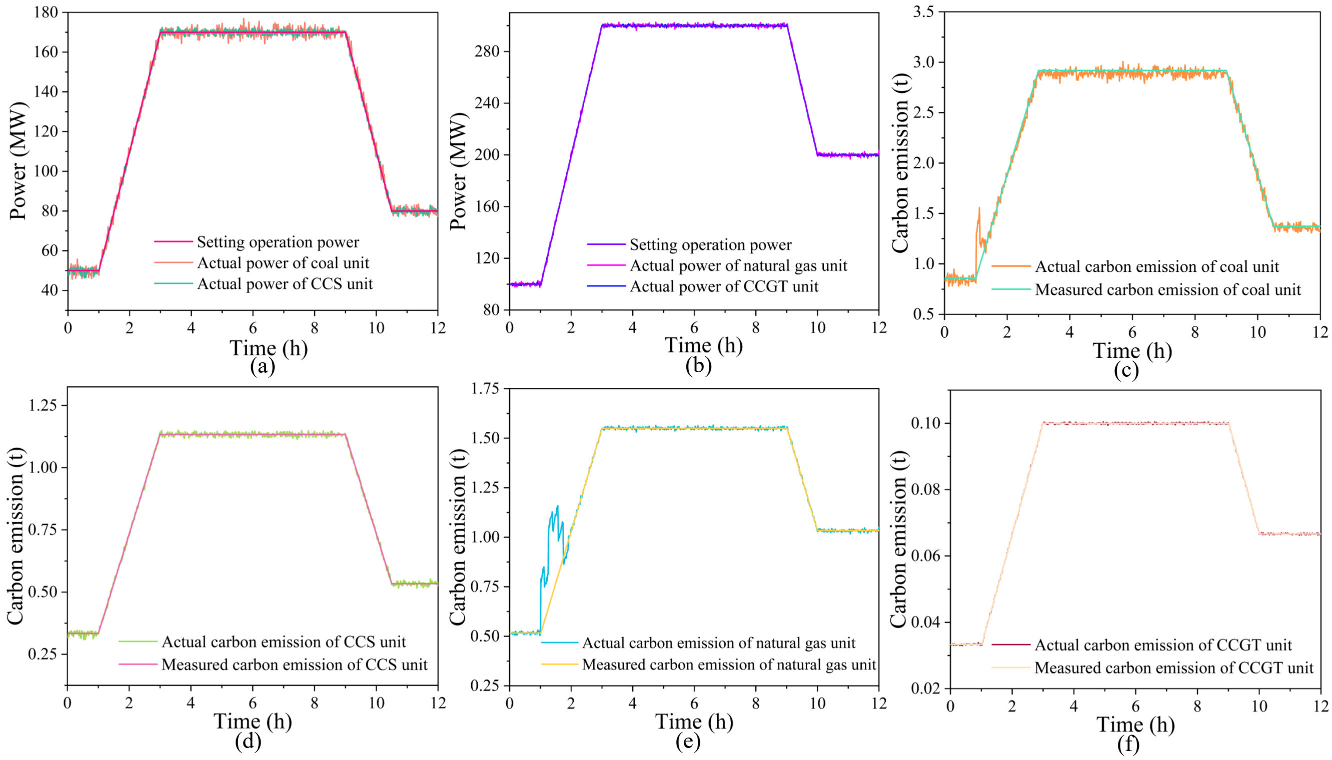

Fig. 5. A and b are the comparison of actual power and set operating power of different units. The c,d,e, and f are the comparison of actual carbon emission and measured carbon emission of different units. CCGT in the figure refers to Combined Cycle Gas Turbine.The carbon emission of the unit is basically consistent with the trend of the unit power. However, some operating conditions will affect the level of carbon emissions.

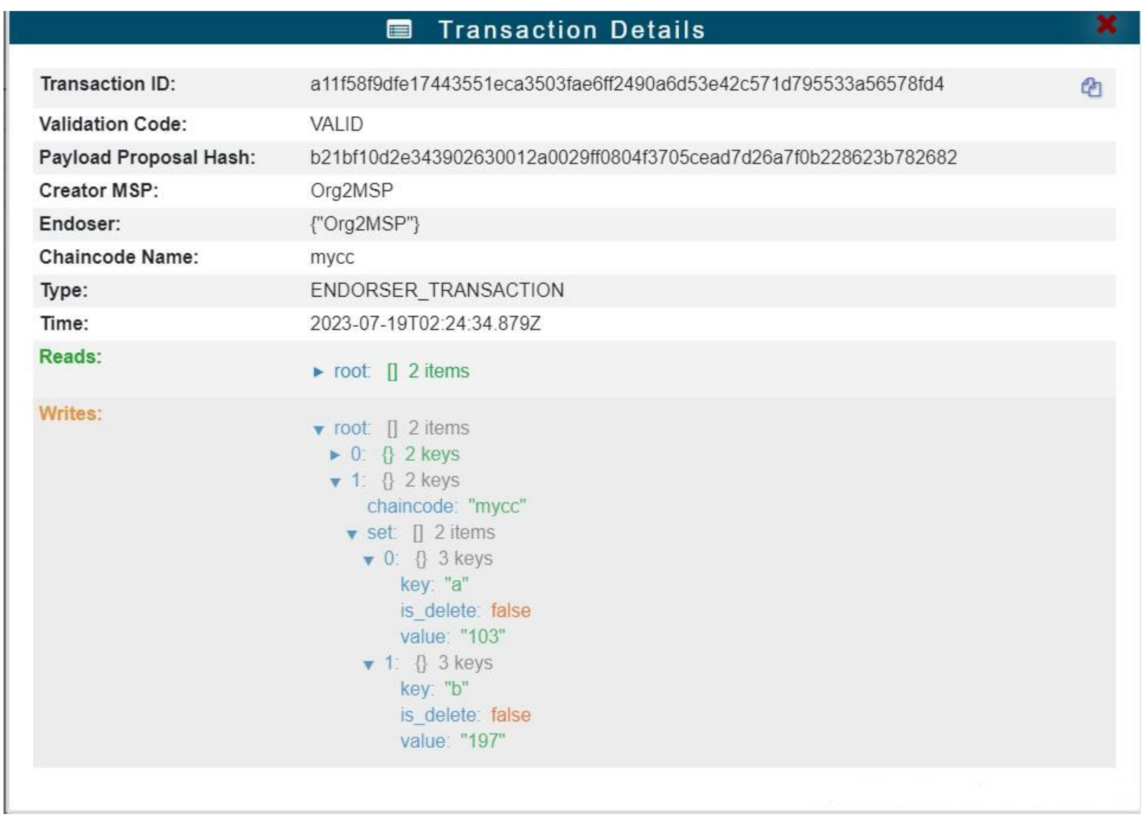

Fig. 6. The result of changing the DCA balances of different units through the smart contract. Carbon asset settlement for each unit account based on real-time carbon emission data calculated by the smart contract.

C. DCA Settlement

We also use hardware types of equipment to demonstrate the DCA settlement process of each unit on a daily cycle. The automated execution of smart contract leverages Rock PI X devices to credibly record the relevant data for each unit. A visualization page is developed, where the query function allows power plants to obtain information about the amount of assets in the account, as shown in Fig. 4. Table I shows the power generation and carbon asset consumption of four units in a settlement cycle. Units using clean energy and low-carbon technologies significantly reduce carbon emissions. Reduced carbon emissions are profited from carbon market transactions, further encouraging development.

TABLE I
CARBON ASSET CONSUMPTION AND POWER OUTPUT OF DIFFERENT UNITS IN BLOCKCHAIN ACCOUNT.

Type of the unit	Electricity generation (MW)	Carbon asset consumption (t)
Coal unit	1573.42	1636.02
Natural gas unit	2886.81	926.33
CCS unit	1571.61	620.71
CCGT unit	2886.38	58.53

V. CONCLUSION

Concerning the centralized carbon market, there has been an inaccurate and untrustworthy problem with the carbon emission quota write-off for the annual cycle. Meanwhile, paying attention only to the high-time-resolution of the unit output information will burden the communication. In this paper, we propose a mechanism design for DCA settlement based on blockchain technology and edge intelligence. The problem of communication burden is solved by intelligently and automatically processing the power information of high acquisition frequency locally. We developed a hardware circuit to verify the effectiveness of the scheme. Several cases are presented to verify the feasibility of the scheme, which provides the following insights. Under the same output, the carbon emissions of clean energy and low-carbon technology units are greatly reduced compared with coal-fired power units. The further development of the carbon market is inseparable from the accurate and fair settlement mechanism.

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