Distributed Multi-Factor Electricity Transaction Matching Mechanism based on Blockchain

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***Abstract*—With the rapid development of the power generation technology of distributed renewable energy, great quantities of prosumers emerged and joined to the regional energy internet (REI), which could lead to challenges for conventional energy transaction matching mechanisms. At the present stage, electricity transaction match mostly adopts traditional mechanisms such as double auction, which may exist problems in practical utilization such as the match of clean energy is relatively difficult and the waste of electricity transmission is hard to be indicated, etc. In addition, the conventional centralized matching platform could face challenges considering the widely deployment of building and even house level prosumers among regions, as well as the instantaneous variable characteristic of clean energy generation such as photovoltaic and wind. Aiming at the challenges, in this paper a blockchain-based multi-factor electricity transaction matching mechanism is proposed. The suitability of multiple factors such as electricity price, transaction volume, transmission distance, and energy type are calculated and compared based on the calculation formula of dissimilarity degree in the K-prototypes clustering algorithm. The seller and the purchaser with the smallest dissimilarity value between electricity sale demands and electricity purchase demands are selected as the matching objects. In addition, corresponding automatic match, signing matching records by private key and settlement of the transactions were designed based on smart contract. The experimental results illustrated that comparing with conventional solutions, by adopting the proposed mechanism, the supply proportion of clean energy in the entire REI increased to 80.40%; the actual unit price gap between clean energy and non-clean energy decreased by 63.00%; the total electricity sale volume in the entire REI increased by 83.37%.**

***Keywords*—blockchain, multi-factor, distributed electricity transaction match, regional energy internet**

I. INTRODUCTION

With the widespread access of distributed renewable energy (DRE) and energy storage, and the continuous advancement of electricity electronics and internet technologies, the concept of regional energy internet (REI) has been proposed [1-4]. From a geographical perspective, the scale span of REI could be flexible. It can cover a collection of multiple microgrids, even cities. Or it could be a microgrid of a community. REI is one of the important means to deal with the problems of high energy consumption and high pollution in the process of urbanization in many countries [5-6]. In addition, the promotion of the power generation technology of DRE has enabled more producers and consumers to access the REI to participate in electricity transactions. Guo et al. conducted a detailed analysis of the user-oriented REI framework and applications based on users' energy demand types [7], which provided technical support for user-oriented REI applications. On the one hand, the REI provides users with renewable energy that meets their preferences; on the other hand, it enables more house level prosumers to actively participate in market transactions. Electricity trading has gradually evolved from traditional single energy centralized trading to diversified comprehensive energy trading [8]. The process of transaction match becomes rather complicated, which makes it difficult for conventional centralized management to be competent for the new scenario.

In the traditional electricity market, consumers trade indirectly with renewable energy suppliers through third-party centralized institutions [9-11]. Although this mechanism solves the problem of trust among consumers, the addition of a third-party centralized organization increases electricity transmission losses and electricity transaction costs, and presents information security risks [12]. Therefore, the traditional mechanism may not apply to the scenario of diversified comprehensive energy trading in the REI.

Therefore, in this paper, a blockchain-based multi-factor electricity transaction matching mechanism is proposed for the scenario of diversified comprehensive energy trading in the REI. Based on blockchain [13] technology, a distributed trust system is established for prosumers. Producers and consumers could freely conduct P2P transactions to reduce transmission losses [14], and the security of transaction information is guaranteed by distributed encrypted storage [15-17]. The suitability of multiple factors such as price, transaction volume, transmission distance, and energy type are calculated and compared based on the calculation formula of dissimilarity degree, which is utilized as the formula for calculating the dissimilarity of mixed attributes in the K-prototypes [18] clustering algorithm. The seller and the purchaser with the smallest dissimilarity value between electricity sale demands and electricity purchase demands are selected as the matching objects. In addition, corresponding automatic match, signing matching records by private key and settlement of the transactions are designed based on smart contract.

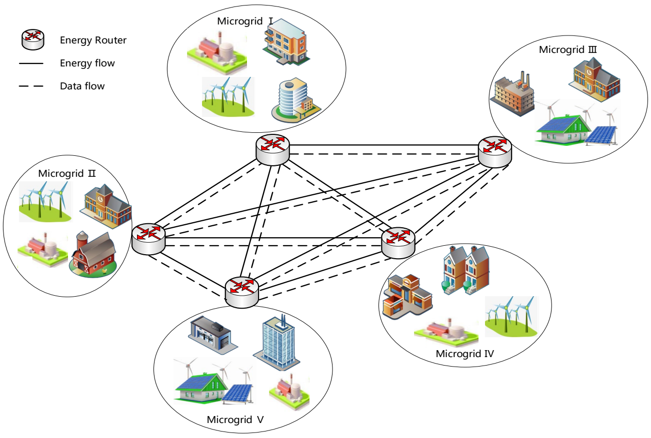

Fig. 1. Mechanism application scene graph.

The rest of this paper is organized as follows. Related researches of this work are introduced in Section II. In Section III, the application scenario and flow of the multi-factor electricity matching mechanism are described. Based on the scenario of REI, the proposed mechanism was experimentally tested and the test results were analyzed in Section IV. This paper is summarized in Section V.

II. Related Works

In response to the increasingly common phenomenon of autonomous trading of user surplus electricity, Pee et al. implemented a smart energy trading platform based on blockchain by using smart contract technology [19], which allows traders to complete electricity trading independently without third-party intervention. Ai et al. implemented an electricity transaction asynchronous settlement system based on blockchain for the REI [20], which established a trust system of mutual trust for traders and used asynchronous settlement to solve the problems of electricity deviation waste. Zeng et al. comprehensively analyzed the problems of information security in the energy internet, and proposed a multi-level, multi-chain information transfer model based on the blockchain [21], and illustrated the technical characteristics of the blockchain in the energy internet information security by the application examples. The above researches proved that the application of blockchain technology to multi-node electricity transactions in the energy internet has become research trend [22].

At the same time, a large number of producers and consumers access REI, resulting in a large number of electricity transactions match. Currently, electricity transactions match in the REI generally uses traditional mechanisms such as double auction (DA), which easily causes the difficulty of clean energy match, the waste of electricity transmission and other issues. Therefore, designing a suitable electricity matching mechanism for REI is essential. Wang et al. analyzed the researches status of blockchain electricity transaction match at home and abroad, and gave suggestions on the construction of blockchain energy transactions in China [23]. However, it was not an available electricity matching mechanism suitable for REI. Mengelkamp et al. proposed a decentralized market trading platform based on blockchain [24], allowing producers and consumers to conduct double trade to consume renewable energy in the market in real-time. However, the platform did not design a corresponding matching mechanism for the price gap between renewable energy and fossil energy. Saxena et al. proposed a blockchain-based peer-to-peer energy trading market platform for the residential community [25], and used a DA mechanism to provide electricity match for users. However, there was no corresponding matching mechanism designed for different types of energy. LO3 Energy and Siemens jointly developed a blockchain-based microgrid trading platform [12], and the matching mechanism of DA is designed. However, the platform did not have the function of blockchain-based direct settlement. Wang et al. proposed a blockchain-based distributed electricity transaction model based on the continuous DA mechanism for the energy internet [26]. However, this model mainly focused on the timely adjustment of quotations based on market changes to promote electricity sales. Zhao et al. proposed a blockchain-based comprehensive energy trading mechanism based on the principle of electricity transaction match [27], which divided the matching process into two stages: centralized match and continuous DA match. The former centrally matched through third-party institutions that do not apply to multi-node free transactions, and the latter mainly ranked and matched based on the price. With the lack of considerations for energy type, transmission loss, and other factors, the mechanism is not conducive to the sale of clean energy, and may cause long-distance transmission, which may cause unnecessary electricity transmission losses and increase transmission costs.

III. Multi-Factor Electricity Transaction Matching Mechanism

A. Application scenario

The proposed multi-factor electricity transaction matching mechanism is designed for the REI scenario, which is demonstrated in Fig. 1. The REI is composed of multiple microgrids, each of which contains many producers, consumers and prosumers. Each microgrid owns a microgrid energy router as well as many sub-routers. Each energy router and sub-router is also a blockchain node. The blockchain nodes are used for data flow transmission, and energy routers are used for energy flow transmission. Compared with a single microgrid, REI may contain more electricity sellers, which could provide more comprehensive and more personal electricity supply options for the electricity purchasers. Compared with many existing mechanisms, the proposed mechanism calculates and compares the suitability of multiple factors by the calculation formula of dissimilarity degree in the K-prototypes clustering algorithm, and the seller and the purchaser with the smallest dissimilarity value between electricity sale demands and electricity purchase demands are selected as the matching objects.

The mechanism sets electricity is traded by cycles. Transaction adopts planned transactions, that is, the energy of the transaction in this cycle is the energy of the next cycle. Before the end of a cycle, if the cycle available electricity is positive, the cycle available electricity will be resold to State Grid Corporation of China at a low price. According to the order of the electricity purchase demands on the chain, the mechanism performs electricity match for electricity purchasers, avoiding the double-spending problem caused by parallel match of electricity purchase demands.

B. Mechanism flow

The specific flow of the multi-factor electricity transaction matching mechanism based on blockchain proposed in this paper is shown in Fig. 2, which mainly includes the following 7 sections and 15 steps.

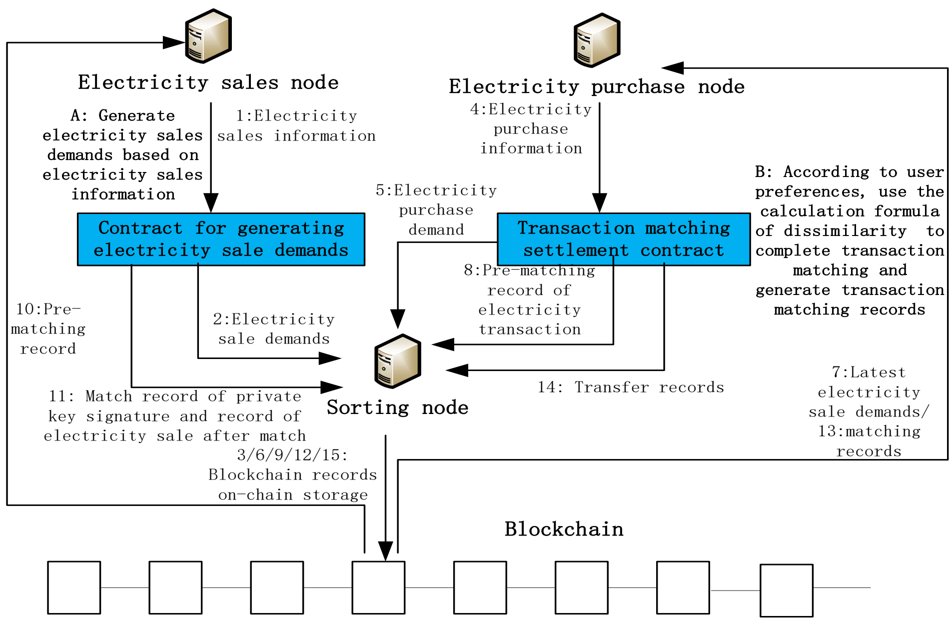

Fig. 2. Electricity transaction matching process based on multiple factors.

TABLE I. ELECTRICITY SALE INFORMATION

User ID	Energy Type	Electricity Selling Price	Cycle Total Electricity Supply	Cycle Available Electricity	Electricity Supply Location

TABLE II. ELECTRICITY SALE DEMANDS

Electricity Sale Demands ID	User ID	Environmental Protection Index	Electricity Selling Price	Cycle Total Electricity Supply	Cycle Available Electricity	Energy Type	Credit Value of Electricity Seller	Electricity Supply Location

TABLE III. ELECTRICITY PURCHASE INFORMATION

User ID	Environmental Protection Index	Electricity Purchase Price	Cycle Demand of Electricity	Estimated Transmission Loss	Energy Type	Electricity Demand Location

TABLE IV. ELECTRICITY PURCHASE DEMANDS

Electricity Purchase Demands ID	User ID	Expected Environmental Protection Index	Electricity Purchase Price	Cycle Demand of Electricity	Energy Type	Credit Value of Electricity Purchaser	Electricity Demand Location

TABLE V. ELECTRICITY TRANSACTION PRE-MATCHING RECORD

Pre-matching Record ID	Electricity seller ID	Private Key Signature of Electricity Purchaser	Trading Price	Electricity for Periodic Trading	Environmental Protection Index	Transmission Loss	Electricity Sale Demands ID	Electricity Purchase Demands ID

TABLE VI. ELECTRICITY TRANSACTION MATCHING RECORD

Matching Record ID	Electrici ty seller ID	Private Key Signature of Electricity seller	Private Key Signature of Electricity Purchaser	Trading Price	Electricity for Periodic Trading	Environment al Protection Index	Transmission Loss	Electricity Sale Demands ID	Electricity Purchase Demands ID

TABLE VII. TRANSFER RECORD

Transfer ID	Electricity seller ID	Matching Record ID	Private Key Signature of Electricity Purchaser	Trading Price	Electricity for Periodic Trading	Transfer Amount

- The electricity seller submits the electricity sale information for the next cycle through the electricity sale node.

The section corresponds to step 1 in Fig. 2. Electricity sellers refer to major electricity generators and ordinary independent electricity generators in the REI. The specific electricity sale information is shown in Table I.

In Table I, Energy Types mainly include wind energy, water energy, fossil energy, solar energy, bioenergy, etc. Electricity Selling Price refers to the unit electricity selling price customized by the electricity seller, that is, the selling price per kW·h. Cycle Total Electricity Supply refers to the total electricity generation of the electricity seller in the next cycle. Cycle Available Electricity refers to the remaining electricity that is not sold in Cycle Total Electricity Supply of the electricity sellers in this cycle.

- Electricity sale demand generation contract (ESDGC) generates electricity sale demands based on electricity sale information and stores them on the chain.

The section corresponds to steps 2-3 in Fig. 2, and the specific information about the electricity sale demands is shown in Table II.

In Table II, Environmental Protection Index refers to the clean energy supply ratio calculated according to the type of energy. Wind energy, water energy, solar energy, and bioenergy are all clean energy. Credit Value of Electricity Seller refers to the Credit Value of Electricity Seller based on the matching records of electricity seller's latest 100 electricity transactions, the calculation method of Credit Value: Credit Value is increased by 1 after completing an electricity transaction, and Credit Value is decreased by 10 after being punished once. Its initial value is 100, and it will not increase after reaching 100.

- The electricity purchaser submits electricity purchase information for the next cycle through the electricity purchase node.

The section corresponds to step 4 in Fig. 2, and the specific information of electricity purchase is shown in Table III.

In Table III, Electricity Purchase Price refers to the unit purchase price customized by the electricity purchaser, that is, the expected purchase price per kW·h. Cycle Demand of Electricity refers to the electricity demand of electricity purchasers in the next cycle. Estimated Transmission Loss refers to the estimated transmission loss caused by the transmission distance that the electricity purchasers can accept.

- Transaction match settlement contract (TMSC) generates electricity purchase demands based on the electricity purchase information and stores them on the chain.

The section corresponds to steps 5-6 in Fig. 2, and the specific information of electricity purchase demands is shown in Table IV.

In Table IV, Expected Environmental Protection Index refers to the electricity environmental protection index expected by the electricity purchaser, which is set by the electricity purchaser. Energy Type refers to the type of electricity generation energy that electricity purchasers expect to purchase first. Credit Value of Electricity Purchaser has the same theory as Credit Value of Electricity Seller, it has already been described in detail in section (2) and will not be described in detail here.

- TMSC acquires the electricity sale demands of the next cycle from the blockchain, according to the electricity purchase demands, the calculation formula of dissimilarity degree in the K-prototypes clustering algorithm is used to match the electricity sale demands. Finally, pre-matching records of electricity transactions are generated and stored on the chain.

The section corresponds to steps 7-9 in Fig. 2, the calculation of dissimilarity degree is shown in formula (1). To ensure that each attribute has the same effect on the total dissimilarity degree when the weights are the same, it is necessary to perform the same-scale digital level conversion on the calculation result of the dissimilarity degree of each attribute.

$$d(X_j, Z_i) = d_m(X_j, Z_i) + d_n(X_j, Z_i) \quad (1)$$

In formula (1), $d(X_j, Z_i)$ is the dissimilarity degree between the electricity purchase demands X_j and the electricity sale demands Z_i, the electricity purchase demands and the electricity sale demands with the smallest dissimilarity value are the best match, and X_j is the jth electricity purchase demands, Z_i is the ith electricity sale demands.

$d_m(X_j, Z_i)$ is the dissimilarity degree of numeric attributes, such as unit price, environmental protection index, the credit value of users, transmission loss, etc. The calculation method is shown in formula (2), P represents the number of numeric attributes, α_l represents the weight of the attribute l, and $(X_{jl}-Z_{il})^2$ represents the Euclidean distance of the attribute l of the electricity purchase demands and electricity sale demands.

$$d_m(X_j, Z_i) = \sum_{l=1}^{P} \alpha_l (X_{jl} - Z_{il})^2 \quad (2)$$

$d_n(X_j, Z_i)$ is the dissimilarity degree of non-numeric attributes, such as energy type, the calculation method is shown in formula (3) and formula (4). In formula (3), Q represents the number of non-numeric attributes and β_q represents the weight of the attribute q.

$$d_n(X_j, Z_i) = \sum_{q=1}^{Q} \beta_q \delta(X_{jq}, Z_{iq}) \quad (3)$$

In formula (4), if the attribute q of the electricity purchase demands X_{jq} and the electricity sale demands Z_{iq} are different, the dissimilarity is 1; otherwise, the dissimilarity is 0.

$$\delta(X_{jq}, Z_{iq}) = \begin{cases} 1, X_{jq} \neq Z_{iq} \\ 0, X_{jq} = Z_{iq} \end{cases} \quad (4)$$

The specific information about electricity transaction pre-matching record is shown in Table V. In the table, the trading price is the Electricity Selling Price in the electricity sale demands. Transmission Loss refers to the actual transmission loss of electricity calculated based on the distance between the electricity supply location and the electricity purchase location.

- The electricity seller obtains the electricity transaction pre-matching record from the blockchain and signs authorization. TMSC generates the electricity transaction matching record and the new electricity sale demands, and stores them on the chain.

The section corresponds to steps 10-12 in Fig. 2, and the specific information of the electricity transaction matching record is shown in Table VI.

In Table VI, Private Key Signature of Electricity seller indicates the permission of the electricity seller for electricity transactions, the matching record without the signature of the electricity seller's private key is not regarded as a valid record. The electricity seller has the right to veto transactions. If he disagrees with the transaction, he may not sign the electricity transaction matching record with his private key.

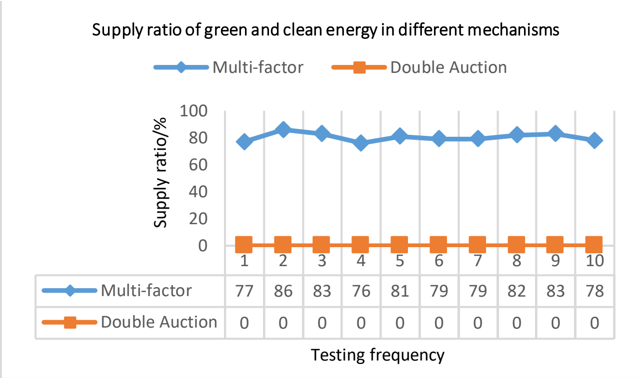

Fig. 3. Supply ratio of clean energy.

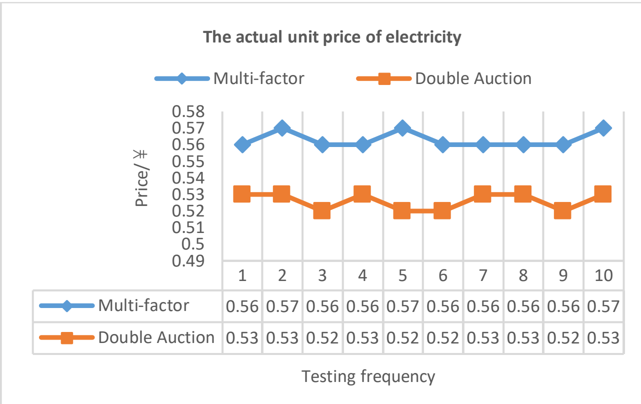

Fig. 4. Comparison chart of actual unit price.

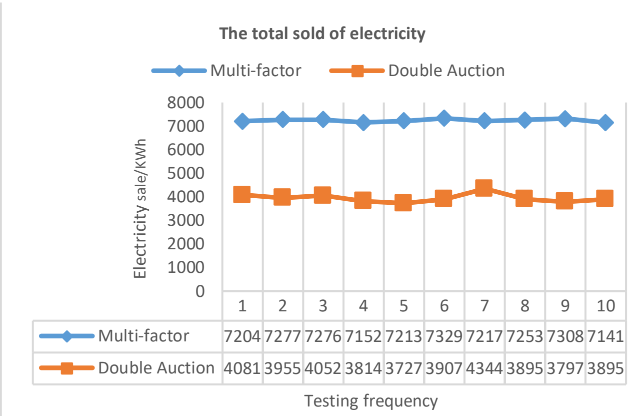

Fig. 5. Overall electricity sale.

- TMSC verifies the private key signature of the electricity seller in the electricity transaction matching record by the public key decryption technology. After the verification is successful, the electricity transaction money transfer is completed, and the electricity transaction money transfer record is generated and stored on the chain.

The section corresponds to steps 13-15 in Fig. 2, and the specific information about the electricity transaction money transfer record is shown in Table VII.

IV. Implementation and Performance Evaluation

A. *Experimental test environment*

The proposed mechanism is implemented and tested based on the Hyperledger Fabric [28] v1.4.4. The experimental equipment consists of 5 virtual machines with 2 core and 2GB. The operating system on the virtual machine is CentOS Linux release 7.7.1908. Each virtual machine is deployed with one Peer node, and each Peer is connected to more users.

In our experiment, it is set that the REI contains 5 microgrids, and each micro-grid is set to have about 200 users in 10 minutes to purchase electricity. To ensure the diversity of electricity sale types, in the REI of this test, it is set that there are about 1000 electricity sale requirements for match at each time point. To compare the transmission loss, in the REI of this test, the maximum distance between users is set to 10000 meters, the user's acceptable electricity transmission loss percentage is set within 10%, and the actual electricity transmission loss percentage is set 1% per 1 kilometer. To calculate the electricity matching amount, the range of electricity seller Cycle Total Electricity Supply is set to 10-50kW·h, and the range of electricity purchaser Cycle Demand of Electricity is set to 10-20kW·h. According to the actual electricity sale price, the Electricity Selling Price range of clean energy is set to ¥0.5-0.6, the Electricity Selling Price range of non-clean energy is set to ¥0.4-0.5. To ensure that the price of clean energy and non-clean energy can be accepted by the purchaser, the Electricity Purchase Price range expected by electricity purchasers is set to ¥0.4-0.6. To ensure the diversity of energy types, the Energy Type is set to five categories, such as wind energy, water energy, fossil energy, solar energy, and bioenergy. To reflect the different preferences of users for multi-factors, the weight range of various factors is set to 0-1. Experimental test data is randomly generated based on the above settings, and a test period of 10 minutes is set. The multi-factor electricity transaction matching mechanism and traditional mechanisms such as DA are tested. The relevant data of the test is obtained from the matching records in this blockchain.

B. *Analysis of results*

A. *Supply ratio of clean energy*

For the promotion of clean energy, the supply ratio of clean energy (SRCE) of the two matching mechanisms is tested. The calculation method of the SRCE is shown in formula (5). The higher the ratio, the better the sale of clean energy, and it is more beneficial to reduce environmental pollution. The SRCE of 1000 transactions is counted. The result after 10 tests is shown in Fig. 3.

$$SRCE = \frac{Total\ supply\ of\ green\ and\ clean\ energy}{Total\ energy\ supply} \tag{5}$$

As can be seen from Fig. 3, the SRCE of the multi-factor matching mechanism is 80.40%, while the SRCE of the DA matching mechanism is 0. Therefore, this mechanism is conducive to promoting small-scale clean energy producers to actively participate in energy transactions in the REI, and promoting the development of clean energy and protecting the environment.

B. *The actual unit price of electricity*

According to the interests of electricity purchasers, the actual unit price of electricity of the single transaction (APET) of the two matching mechanisms is tested. APET is defined as the unit price of the available electricity purchased by a single user. The calculation method is shown in formula (6). The smaller the value, the lower the transmission loss, and the lower the user purchase cost. The average APET of 1000 transactions is counted. The result after 10 tests is shown in Fig. 4.

$$APET = \frac{Total\ purchase\ of\ single\ transaction}{Total\ energy\ of\ single\ transaction - Loss\ energy\ of\ single\ transaction} \quad (6)$$

As can be seen from Fig. 4, the APET of the multi-factor matching mechanism is ¥0.563, the APET of the DA matching mechanism is ¥0.526, and the APET gap is ¥0.037. It can be seen from Experiment A that the SRCE of the DA matching mechanism is 0, so ¥0.526 is only the APET of non-clean energy. It can be seen from the experimental test data set that the gap between the price of clean energy and non-clean energy is ¥0.1, and ¥0.037 is significantly reduced compared with ¥0.1. Therefore, with the proposed mechanism, the APET gap between clean energy and non-clean energy is reduced by 63.00%, which effectively promotes the sale of clean energy.

C. Total sold of electricity

According to the interests of electricity sellers, the total electricity sale volume (TESV) of 1,000 transactions with two matching mechanisms in the test period is counted. The result after 10 tests is shown in Fig. 6.

As can be seen from Fig. 6, the average value of the TESV of the multi-factor matching mechanism is 7237kW·h, and the average value of the TESV of the DA matching mechanism is 3946.7kW·h. The proposed mechanism improves the TESV of electricity sellers by 83.37%, which ensures that electricity sellers can sell more electricity to electricity purchasers at a higher price and avoids selling more surplus electricity to the State Grid Corporation of China at a lower price, which brings greater economic benefits to the electricity sellers.

V. CONCLUSION

In this paper, a blockchain-based multi-factor electricity transaction matching mechanism was proposed for REI. The suitability of multiple factors were calculated and compared based on the calculation formula of dissimilarity degree in the K-prototypes clustering algorithm. The seller and the purchaser with the smallest dissimilarity value between electricity sale demands and electricity purchase demands are selected as the matching objects. In addition, corresponding automatic match, signing matching records by private key and settlement of the transactions were designed based on smart contract. The experimental results illustrated that compared with the conventional solutions, with the premise of using this mechanism, the SRCE increased to 80.40%; the APET gap between clean energy and non-clean energy decreased by 63.00%; the TESV in the entire REI increased by 83.37%.

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