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Smart Micro-GaS: A Cognitive Micro Natural Gas Industrial Ecosystem Based on Mixed Blockchain and Edge Computing

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***Abstract*—With the increase in natural gas consumption, distributed natural gas supply and transaction have become new development goals of the industrial Internet of Things (IoT) for natural gas. However, there are obvious disadvantages of existing natural gas pipeline network in aspects of infrastructure warning, multilevel data transmission, automatic transaction and security. Emerging technologies such as blockchain, edge computing, and AI have been introduced to address these shortcomings. This paper proposes Smart Micro-GaS, i.e., the concept of a cognitive micro natural gas industrial ecosystem based on mixed blockchain and edge computing. Three aspects, multi-level, multi-view and multi-dimension, are put forward for its design and deployment. Then, based on the most important smart contract algorithm in blockchain, a mixed transaction model for natural gas is established. Finally, a case analysis is conducted on a smart natural gas testbed for data prediction and the proposed smart contract algorithm. The framework proposed in this paper makes the natural gas data have multi-level liquidity and realizes diversified transaction.**

***Index Terms*—Artificial intelligence, blockchain, edge computing, industrial Internet of Things, natural gas**

I. INTRODUCTION

With the rapid increase in massive industrial big data, the gradual maturity of AI technology [1], [2], and the popularization of a new generation of heterogeneous IoT [3], Industry 5.0 [4] has gradually become the main development direction for the next generation of smart industry. The core technologies of Industry 4.0 are information and communication technology (ICT) and cyber-physical systems (CPS) [5]. In Industry 5.0, there are new definitions of these two. The ICT in Industry 5.0 means intelligence and connectivity technology, and CPS is changed to cyber-physical social systems (CPSS). The combination of these two technologies shows that industrial information system should be linked up with social groups and users [6].

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Energy internet is an important research field in Industry 5.0. Through the comprehensive application of advanced power and electronic technology, information technology and smart management technology, a large number of energy nodes can be interconnected. Specifically, distributed energy acquisition devices, distributed energy storage devices and various types of load composed of new power, oil and natural gas networks, realize the energy exchange and sharing network of bidirectional flow of energy. According to statistics, the world's total primary energy consumption in 2017 was equivalent to 13,511,000,000 tons of oil, of which natural gas consumption accounted for 23.36% [7]. As a high-quality fuel and chemical raw material, natural gas has four advantages: environmental protection, economy, safety and reliability, and life improvement. Accelerating the development and utilization of natural gas is conducive to propel energy production and the consumption revolution. In addition, it contributes to establish a modern energy system that is clean, safe and efficient, with a low level of carbon consumption. Therefore, our research focuses on the natural gas industry IoT.

Current natural gas industry IoT cannot meet the demand of distributed energy supply. In the existing natural gas industry IoT, traditional methods were adopted, such as network warning with temperature-pressure control [8]–[10], centralized power supply and data transmission, and government regulating pricing and transactions. In recent years, with the development of blockchain, edge computing [11], [12] and AI technologies [13], improved solutions are emerging, such as distributed transactions [14], content caching [15], edge data transmission [16], [17] and future demands prediction of natural gas [18], [19].

Blockchain is a new application that integrates distributed data storage, point-to-point transmission, consensus mechanism [20], smart contract, and encryption algorithm [21], [22]. The features of blockchain, such as decentration, openness, security and anonymity, enable it to be a potential solution for the challenges that are faced in developing a natural gas industrial IoT [23].

Edge computing means the provision of the nearest services in the neighbourhood on an open platform that integrates the network, computing, storage, and applied core-competence on the side near terminals or the data sources [24]. Thus, a quicker network service response is generated to meet the basic demands of the industry in aspects such as real-time service [25], application intelligence [26], security [27], and privacy protection [28], [29].

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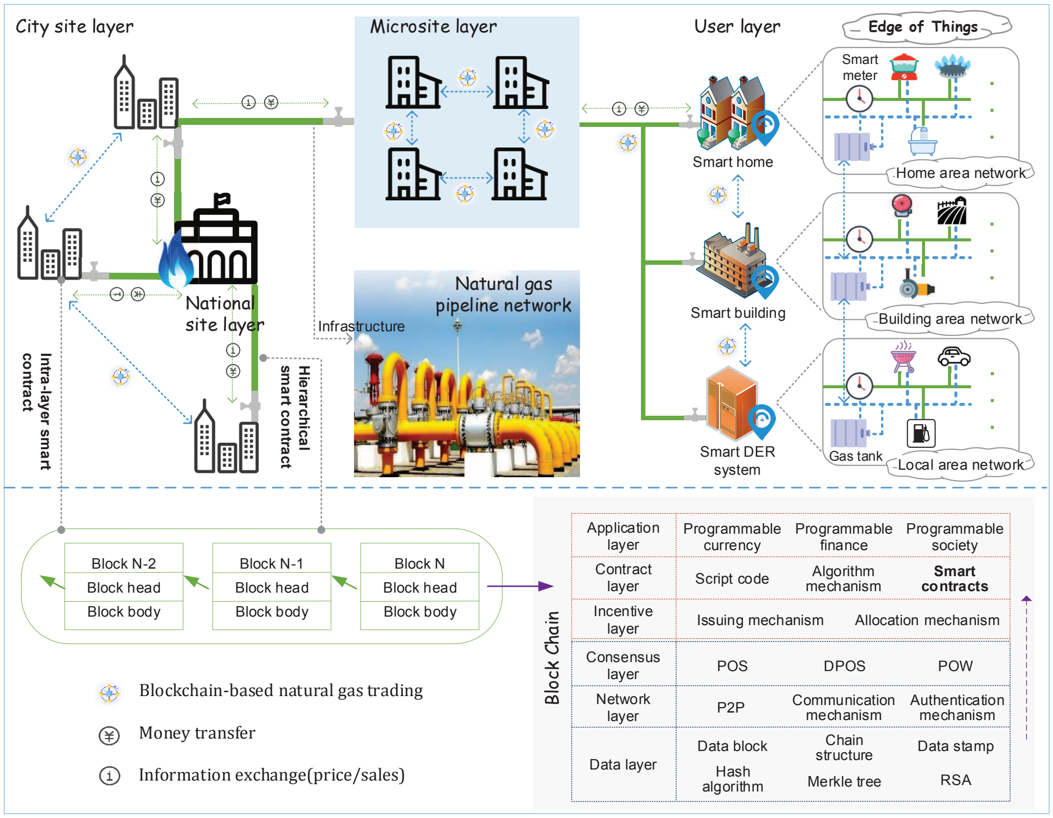

Fig. 1. Architecture of smart natural gas IoT based on multi-level blockchain and edge computing.

AI technologies, such as the linear model and the neural network model, have been established [18], [30]–[32] for the prediction of natural gas demand in static and adaptive conditions. However, various advanced smart technologies have not been deeply integrated into these plans, and thus macro control over the whole natural gas industry system cannot be conducted from multiple angles.

When it comes to the ecological system of natural gas, what we seek is a new type of natural gas IoT with a distributed energy supply infrastructure on the user side. In this new type of IoT, in order to realize an autonomous transaction and secure transmission, transaction methods are determined as per benefit maximization, systematic integration and optimization are conducted to multiple energy demands of the user and the allocation status of resource [33], [34]. Preliminary realization of this has been achieved along with the combination technology advantages in the field of Micro-Grid (distributed power supply system) [35]. However, there has still been no application in the field of natural gas. Therefore, Smart Micro-GaS, i.e., cognitive micro natural gas industrial ecosystem based on mixed block chain and edge computing is proposed in this paper. Blockchain technology [23] is introduced for personalized autonomous transactions and security, edge computing [28] is introduced for multilevel data transmission, and AI technology [36] is introduced for dynamic prediction and warning. Through the combination of three technologies, a smart micro ecological system in the natural gas industry is formed.

The main contributions of this paper can be summarized as follows:

- The framework of Smart Micro-GaS based on mixed blockchain and edge computing is designed, with a focus on addressing the disadvantages of existing natural gas pipeline network. The framework is illustrated in three different aspects of multi-level, multi-view and multi-dimension.
- In combination with distributed solution of blockchain and AI technology, a mixed transaction model for smart natural gas contracts is designed to provide the theoretical basis for multi-view transactions with different demands.
- Through establishing a Testbed for the smart natural gas industrial IoT, performance test and case analysis are conducted regarding the pressure state warning, flow monitoring, and smart contract.

The remainder of this paper is organized as follows: The overall architecture and deployment plan for Smart Micro-GaS are illustrated in Section II. The superiority of this architecture is expressed from three aspects: multi-level, multi-view, and multi-dimension. Section III proposes an optimal and personalized smart contract algorithm based on blockchain, thus providing autonomous transaction solutions for different levels of providers and demanders. A case analysis is conducted in Section IV. A smart industrial IoT testbed is established for natural gas regarding aspects of microsite flow prediction, pressure state warning, and smart transactions. Section V summarizes the paper.

II. Architecture of Smart Micro Natural Gas IoT based on Mixed Blockchain and Edge Computing

In this paper, the design and deployment for Smart Micro-GaS are conducted from three aspects: multi-level, multi-view and multi-dimension.

- Multi-level: The network architecture is shown in Fig. 1. Taking a country as an example, the architecture from large to small is divided into national master site → provincial master site → municipal master site → cell microsite → user. A cell may have more or less area, so the structure of its natural gas IoT can be changed accordingly. The terminal edge devices or communication devices for Smart Micro-GaS are taken into consideration, i.e., the cell microsite and the user devices in Fig. 1. The edge devices compose the Edge of Things (EoT). The architecture of the blockchain and edge computing introduced in this paper enable natural gas data to be multilevel liquidity, and therefore a higher intelligence (when compared with traditional infrastructure) is generated, so as to allow the gas usage to be more intelligent while doing less harm to the environment.
- Multi-view: There are mainly two views in Smart Micro-GaS: provider and demander. In allusion to each level, the smart contract should change in accordance with the demand of the providers and demanders. The emphasis for the optimization algorithm is to make the sales amount of the provider and the expenditure of demander stable in a natural gas management system with mixed blockchain. Modeling is conducted as per the inflow and outflow of the natural gas in each level, and an autonomous transaction is occurred after triggering the pre-agreed conditions of the system.
- Multi-dimension: In our Smart Micro-GaS, analysis can be conducted by the system for natural gas data (such as temperature, pressure, flow and transaction condition) collected at each site, thus guaranteeing infrastructure warning, multi-level data transmission, autonomous transaction and security in the natural gas IoT from multiple dimensions.

From the national master site to the user, the existing infrastructure for the natural gas IoT is still adopted in this paper. Fig. 1 shows the topological structure of the pipeline network. This pipeline network guarantees the physical transmission of natural gas, and will reduce the cost for large-scale pipeline deployment.

In the whole architecture, blockchain technology is adopted to guarantee data storage and autonomous transaction. Blockchain was developed to solve the problem of transaction trust and security. The evolution of blockchain can be divided into the following three stages: blockchain 1.0 (digital currency), blockchain 2.0 (smart contract), and blockchain 3.0 (distributed society). To cope with the challenge of distributed energy supply in a natural gas IoT, a smart contract algorithm will be optimized based on blockchain 3.0. In which, a personalized autonomous transaction is made as an important organizational part and economic development element in the ecosystem of the natural gas industry. Fig. 1 shows the basic structure of the blockchain system. The system is divided into the application layer, contract layer, incentive layer, consensus layer, network layer, and data layer from top to bottom. [35].

In the edge area of the whole architecture (the part nearest to the user), the operation of micro natural gas site integrated blockchain technology is shown in Fig. 1. Edge computing is introduced for various scenarios (terminals) that require a distributed supply of natural gas. These scenarios include s-mart home, data center, industrial park, traffic center, and other industries with high energy efficiency and large installation capacity that are in high demand of unit emission reduction. There are three operation modes for the edge network in Smart Micro-GaS: 1) A microsite or user sends out the application for a natural gas purchase to a site at a higher level. If purchase conditions are met, a personalized smart contract is formulated by the blockchain system. After the two parties confirm the transaction and the payment is made, the balance of natural gas is updated by the system in real time, and the consumption amount of natural gas is monitored. 2) A prediction of the natural gas demand for some time to come is conducted as per the historical sales volume of natural gas at the microsite. If the current selling price for natural gas is relatively low, an advance purchase application will be initiated to a site at a higher level as per the prediction results, and thus the use ratio of the gas storage device is enhanced, the cost is reduced, and the profit is increased. 3) If a microsite or user purchases too much natural gas beyond its consumption level, sales information may be issued through the blockchain system, and thus the cost allowance will be reduced through selling redundant gas, while the natural gas resources are balanced at a certain degree.

III. Smart Micro-GaS based on Mixed Blockchain Smart Contract

A. Smart contract based on mixed blockchain

A smart contract is a kind of agreement, i.e., the contract is spread, verified or executed in an informatization mode. Two parties can conduct a credible transaction in the absence of a third party. Moreover, these transaction records are traceable and irreversible. In the meantime, blockchain, a computer network form where monitoring is conducted in the whole network, can provide a decentralized environment for the smart contract.

The network environment of blockchain is very friendly to the deployment of a smart contract. First, the tamper-resistant feature of the blockchain guarantees that the data cannot be deleted or altered once contract content is published. In the meantime, more terms can be added into the contract, and the historical records are traceable. Secondly, due to the high reliability of the blockchain, there is no need to worry about whether the two parties meet the conditions but do not enforce the contract. The blockchain is decentralized, and there is a backup copy in the whole network. The intact records can support contract auditing, and there are no restrictions imposed by the centralized structure. Due to these features,

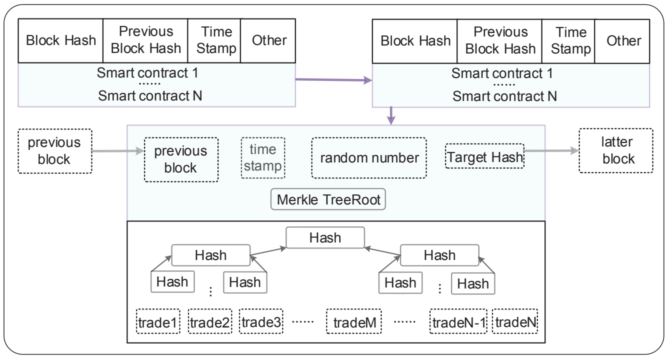

Fig. 2. Structure of blockchain supporting smart contract.

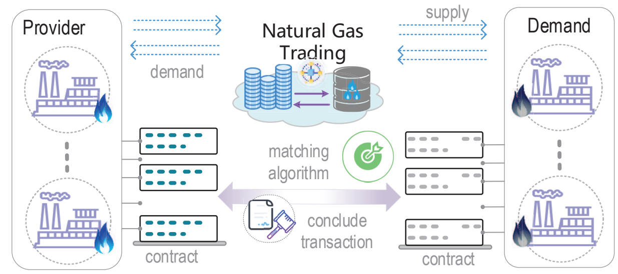

Fig. 3. Transaction chain based natural gas transaction system.

the blockchain can allow full play to the function of the smart contract. Fig. 2 shows the structure of blockchain supporting smart contract.

The construction process of smart contract based on blockchain is as follows:

- Multiple users participate in the formulation of one smart contract.
- Smart contracts are deployed on P2P networks, propagated in the network, and finally linked to the blockchain.
- The storage of a smart contract in the blockchain means that the contract becomes effective, and will be executed automatically.

Currently, blockchain is divided into public chain, private chain and union chain by the industry as per their different mechanisms. The nodes of the public chain are operated on the network. Due to features of its commonality and openness, public chain provides access portal to anyone while tampering cannot be conducted. As for a private chain, some department/organization masters require writing permission while others are not entitled to keep accounts. The concept of union chain is between public chain and private chain. In a union chain, there is the right of keeping accounts for preassigned nodes while other joining nodes only have transaction rights. The union chain has an efficient operation mechanism, which is strictly confidential to the enterprise privacy information and has flexible access rights [37]. However, the fairness and openness of public chain support that all users have access rights.. Thus, the combination of public chain and union chain will be the development trend of blockchain 3.0.

The blockchain-based smart contract can realize the advantages of low cost and efficiency. And the obstruction in the execution of the contract by malicious behaviors can be avoided. The consensus mechanism and relevant algorithms will guarantee that the contract is efficiently executed in a transparent environment.

B. Mixed transaction chain model for Smart Micro-GaS

When applying blockchain technology to natural gas network, the characteristics of natural gas system must be considered. The existing natural gas operation system is highly integrated, where the upstream monopoly restricts the direct purchase transactions between users. In a smart micro natural gas ecosystem, autonomous transaction services for natural gas are deployed into the public chain. In addition, based on the two natural gas operation modes put forth in Section II, two transaction models, the direct transaction model and the forward transaction model are put forward. In this paper, the above mentioned public chain is called a transaction chain, which provides a smart natural gas transaction platform for natural gas sites and users. In the meantime, to adapt to the present integral upstream market structure for natural gas, a union chain is introduced to meet the internal activity environment required by natural gas enterprises and the relevant organizations. As for enterprise members, there is flexible permission setting and safe access. As for government regulatory members, they can monitor the operation of the natural gas industry more efficiently, thus guaranteeing the healthy development of the entire ecosystem.

1) User-oriented transaction chain:

Decentralized natural gas transaction services are deployed on a public chain. In other words, the game process and transaction records of the natural gas transaction are completed by participants on a transaction chain. In circumstances where there is no central authority, a distributed algorithm is adopted in the transaction system to let each node on the network trade autonomously. In addition, there are mainly two kinds of nodes on the transaction chain: transaction nodes and full function nodes. As for full function nodes, except to be available for transactions, they also safeguard the security of the whole transaction chain, i.e., they verify whether a transaction contract in a block is effective. As soon as a transaction contract is confirmed by the full function nodes, this transaction contract is accepted. The block, including multiple confirmed smart contracts, is linked to the blockchain by the system. Fig. 3 shows a transaction chain based natural gas transaction system. The provider and demander release natural gas information onto the blockchain and the contract is reached as per the smart transaction matching algorithm. After confirmation of the two parties, a smart contract is formed and linked to the transaction chain. Finally, the contract is executed to send token money to the provider and natural gas purchase information to the demander.

As per two natural gas operation modes put forth in Section II, to meet the natural gas transaction demand of different users, two transaction models are given for the transaction chain: the direct transaction model and the forward transaction model. A discussion will be conducted based on the transaction chain at some certain level. Regarding transaction users in this area, they can be a demander as well as a provider, whichever the case may be. For the convenience of elaborating the model, users participating in the transaction are divided into the above two identities. It is assumed that M represents for the number of providers, N represents for the number of demanders, $Provider_i$ represents for the i^{th} provider, and $demander_j$ represents for the j^{th} demander. There must be one provider and one demander in each transaction. Next, the transaction models under the two operation modes (given in Section II) for a micro natural gas edge network will be introduced.

a) Direct transaction model:

Users and sites release natural gas purchase or sale information directly on the transaction chain according to their demands. The sales/purchase quantity and price/budget of natural gas are set by the themselves. $Provider_i$ submits relevant information to the natural gas supplier, such as $number_i$ (quantity of natural gas available for sale) and $price_i$. After the information is uploaded to the transaction chain, the corresponding smart supply contract pc_i is generated. $Demander_j$ will also submit the $number_j$ (demand quantity of natural gas) and acceptable $budget_j$ to transaction chain. A smart demand contract dc_j is generated on the transaction chain as per the information that was released. In addition, one demander can purchase natural gas from multiple providers, and one provider can sell natural gas to multiple demanders. It can be seen that multiple contracts will be generated in one-to-many transactions. The two parties of a contract can be one site and another site, one site and one user, or one user and another user.

In this scene, the natural gas price for a specific provider is deterministic. Therefore, the problem is which providers would be chosen by the $demand_j$ to sign a contract. The optimization strategy in this paper is used to control the cost of packing smart contract C^j_{pack} as well as the purchase cost of the $demander_j$. C^j_{pack} can be expressed as follows:

$$C^j_{pack} = Avprice \times \frac{M_j}{M} \times number_j, \tag{1}$$

where, M_j represents for the number of providers who conduct a transaction with $demander_j$. $n_j = \{n^1_j, n^2_j, \ldots, n^m_j \mid n^i_j \geq 0\}$ represents for the amount of natural gas sold to $demander_j$ by $provider_i$. Therefore, $M_j = |\{n^i_j \mid n^i_j \neq 0\}|$. In addition, $Avprice$ represents for the average price for natural gas on the whole network, and the $Avprice$ can be expressed as follows:

$$Avprice = \frac{\sum_1^M number_i \times price_i}{\sum_1^M number_i}. \tag{2}$$

Additionally, the purchase cost of $demander_j$ is $C^j_{purchase}$ which is expressed as follows:

$$C^j_{purchase} = \sum_{i=1}^{M} n^i_j \times price_i. \tag{3}$$

Therefore, the transaction matching problem for the objective of the transaction chain is denoted as $C_{optimize}$:

$$C_{optimize} = \min \sum_{j=1}^{N} C^j_{pack} + C^j_{purchase}$$
$$\text{subject to}: \begin{cases} \sum_{i=1}^M n^i_j = number_j, \\ 0 \leq C^j_{purchase} \leq budget_j, \\ 0 \leq n^i_j \leq number_i \end{cases} \tag{4}$$

The $C_{optimize}$ function is a convex function, and its constraints are inequations with the upper and the lower bound. Therefore, there is an optimal solution to this function. In the direct transaction model, the load of the transaction chain and cost of demander are jointly considered to optimize the contract matching problem between the demander and provider. With universality, this model could be used in any multi-demander-provider contract matching scene. This model could also be used in the contract matching process of the forward transaction model to be introduced in the next subsection.

b) Forward transaction model:

Because the multi-level natural gas framework has a tree structure, a microsite is taken as one of the objects here for illustrating the forward transaction model. It is assumed that $inflow_t$ and $outflow_t$ are the site's predicted natural gas inflow and outflow from time t to time $t+1$. In this paper, the historical flow data of the site are adopted to predict the inflow and outflow in the site at time t, based on LSTM. The LSTM-based site flow prediction model is introduced in detail in Section IV-B. Thus, $netflow_t = inflow_t - outflow_t$, where $netflow_t$ represents for the net growth of traffic at time t. If $netflow_t$ is a positive value, more energy is obtained than output; if $netflow_t$ is a negative value, less energy is obtained than output. Therefore, the total natural gas energy of the site at time t can be expressed as follows:

$$E_t = C_{gas} + \sum_{t=0}^{t} netflow_t, \tag{5}$$

where, C_{gas} is the original gas storage in this site. Due to limited energy storage devices in this site, no matter what value t is, the inequation $E_t \leq C^{max}_{gas}$ must be met. C^{max}_{gas} represents for capacity of gas storage devices. Transaction node will detect the value of E_t in real time based on the predicted value and C^{max}_{gas} of the site. Assuming it is at time t_1, and the inequation $E_{t_1} \geq C^{max}_{gas} \times 0.9$ is predicted, the storage warning shall be given to the site by transaction node, in which the site is suggested to sell excess gas. If the inequation $E_{t_1} \geq C^{max}_{gas} \times 0.1$ applies, a gas supply crisis may be caused. In this case, a pre-order application for natural gas will be submitted to the transaction chain by the site. Different from means of purchase in the direct transaction model, as there

TABLE I
DATA STRUCTURE AND FUNCTION SETTING AT THE TRANSACTION NODES

Supply smart contract $pc_i(provider_i)$	**Demand smart contract** $dc_j(demand_j)$

Contract contract_provider{
// Contract user
user number;
// User ID
gas account;
// Saleable natural gas quantity
gas quantity;
// Unit price of natural gas
gas price;
//Receipt bank account
receipt account list[]; }
	Contract contract_demand{
	// Contract user
	user number;
	// User ID
	gas account;
	// Quantity of natural gas required
	gas quantity;
	// Gas purchase budget
	purchase budget;
	//Payment account
	pay account;
	// Gas collection account
	receipt gas list[]; }

function update_price (){⋯⋯} function update_quantity (){⋯⋯} function update_accountlist (){⋯⋯} function sell_gas (){⋯⋯}	function update_quantity (){⋯⋯} function update_budget (){⋯⋯} function update_gaslist (){⋯⋯} function buy_gas (){⋯⋯}

is no significant influence of the pre-order application on the in-time supply of natural gas, there may be a wait-and-see process for the site. If the price of some natural gas provider meets the selling price requirements of the site, the site will purchase natural gas from this provider. The detailed means of pre-ordering in the forward transaction model is introduced as follows.

The standard value would be set by the site in the pre-order by using $Lowprice$ (low price threshold) and $Targetdate$ (temporal threshold). The lowest unit price low in a successful natural gas auction of recent transactions may be obtained according to the stored records. Then, the low price threshold $Lowprice$ for this site is calculated as follows:

$$Lowprice = low + (high - low) \times \varepsilon, \tag{6}$$

where, ε represents for ratio, and the inequation $0.1 \leq \varepsilon < 0.5$ applies. As shown, when ε is smaller, the value of $Lowprice$ is closer to low. The value of ε and $Targetdate$ are set by site. If the time is before $Targetdate$, the site can purchase natural gas only when the inequation $price \leq Lowprice$ applies for price in provider contract on transaction chain until the pre-order quantity of natural gas is reached. If the time is after $Targetdate$ but the pre-order quantity is still not reached, the direct transaction model is adopted to guarantee the stability of natural gas supply in the site. The site shall send demand contract to transaction chain.

Two operation modes for micro natural gas edge network have been introduced above. Next, the structure of the transaction nodes and transaction process on the transaction chain are introduced. We hope to provide a reference for the transference of the transaction chain to the actual scenario in the future.

Table I shows the data structure and function settings of transaction node. The execution process is given below:

- Gas provider: At first, the supply smart contract pc should guarantee that the limit sale quantity is no more than the available quantity of natural gas for sale. When the two parties have reached an agreement, the remaining gas quantity is renewed by the $provider_i$, and the $provider_i$ will add a token money account sent by the $demander_j$ into the receipt account list. In the meantime, the receipt gas number is generated according to the gas account of the $provider_i$, which will be sent to the $demander_j$. The price of natural gas can also be updated according to the current market.
- Gas demander: After the demand smart contract dc_j is released onto the transaction chain, the most suitable provider or multiple suitable providers are selected for the $demander_j$ for the transaction matching according to the smart transaction selection algorithm. Such a process may generate multiple transaction contracts. The operation for each transaction process is the same. Corresponding to the process of selling natural gas, at first, the receipt account number is generated based on the pay account of the $demander_j$. Then, the gas quantity and purchase budget of the $demander_j$ are renewed. The receipt account number is sent to the $provider_i$ and is added into the $provider_i$ receipt account list.

Fig. 4 shows a sequence diagram of a natural gas transaction. In conclusion, after $demander_j$ receives the optimal purchase plan provided by the transaction chain, it sends the gas purchase request to the corresponding providers. After one $provider_i$ receives gas the purchase request from the $demander_j$, if it agrees with the transaction, a smart transaction contract is automatically generated through the data layer, network layer, consensus layer, and so on. Then, the smart contract is executed. Finally, a natural gas transaction is realized in the application layer to complete the gas supply process.

2) *Supplier-oriented league chain:*

The blockchain system for transactions of natural gas is described above. There are different transaction chains for different natural gas suppliers. However, due to restrictions of factors for different transaction chains, such as network isolation and supervision, commercialized application scenes for natural gas transactions could not be met. Therefore, a private platform must be established to suppliers in emerging natural gas ecosystems. The inter-chain technology is introduced and supplier-oriented league chain is put forward to realize resources transaction, information sharing and other services between suppliers.

The semi-open characteristic of the league chain perfectly matches the robust situation in the upstream market of natural gas. Supplier-oriented league chain is a union ecosystem with information sharing. As per the mode of union chain, all union members in the league chain are certified trusted nodes. With technical features for data on the blockchain, such as tampering resistance, P2P transmission and data sharing, a reliable platform is required by suppliers and energy management departments. For suppliers, information exchange and natural gas transactions can be realized between them by league chain. Government departments have different access rights for natural gas transactions in the league chain, thus realizing transparent market supervision.

Fig. 5 shows the different application scenes of supplier-

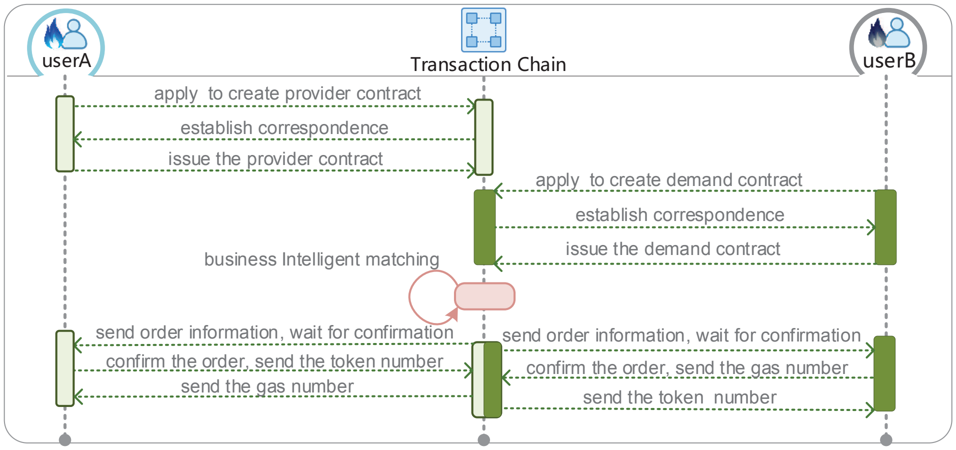

Fig. 4. A sequence diagram of a natural gas transaction.

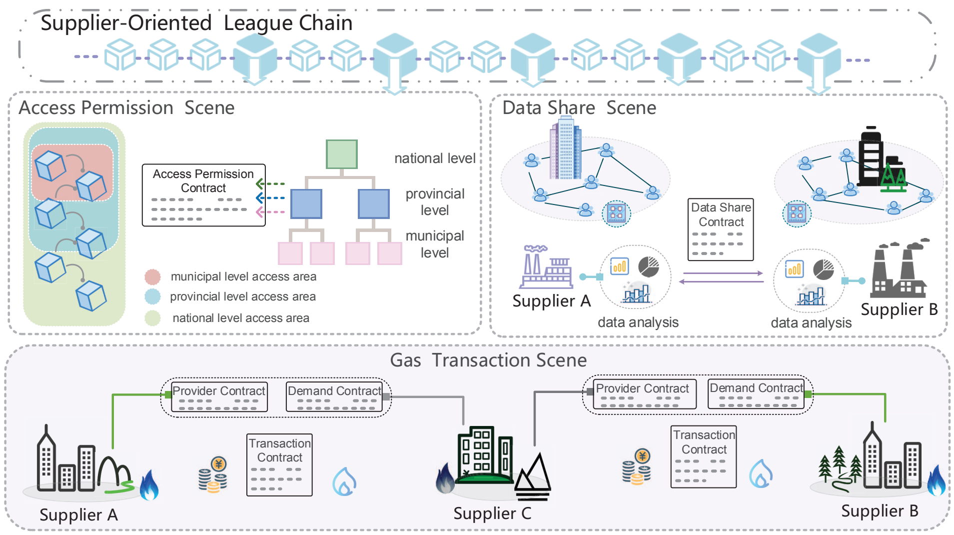

Fig. 5. Application scenes of Supplier-Oriented League Chain.

oriented league chain:

- Gas transaction scene. Suppliers' transaction process in league chain is similar to that of gas users in the transaction chain. Distributed storage technology enables union members to participate in a natural gas transaction. Suppliers with sufficient natural gas storage provide natural gas energy to suppliers with scarce storage. In addition, an optimal gas purchase plan can be provided by league chain in accordance with factors like geographical environment and price to guarantee a stable supply of natural gas in that area.
- Data share scene. To protect the commercial information of enterprises, when information is issued at transaction nodes, the information is encrypted in the form of a public key, and the digital signature is affixed. Only the nodes with the specific private key can decrypt and read the data block information while the other nodes are responsible for verification and recording. This is the technical support of data sharing. When two union members want to exchange enterprise operation information with each other, they can directly exchange the private key of the data. Then, the encrypted data can be downloaded from the blockchain, and the operation information of the opposite side can be obtained.
- Access permission scene. The energy management departments of the government need to conduct supervision for all suppliers. A supervision environment with different degrees of transparency can be provided by league chain. For example, there are different regulatory jurisdictions for the government at different levels, such as national government, provincial government, and county-level government. Government departments at different levels can access to natural gas data information and transaction information of different union members. Specific nodes are set for government departments by the league chain as per the different levels. Identity verification and jurisdiction settings can be realized at these nodes, and part or all of the information for the

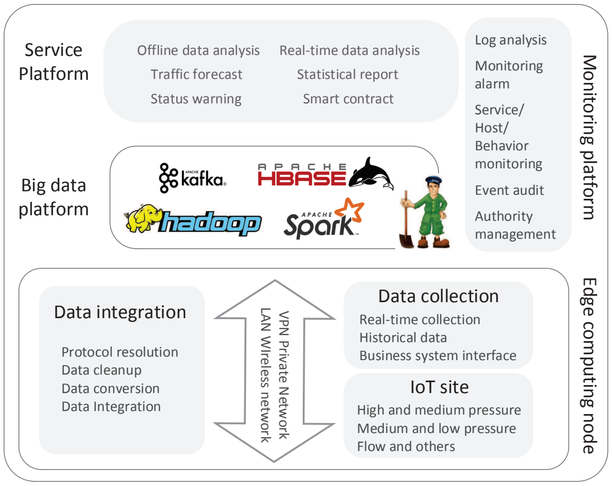

Fig. 6. Architecture for a smart natural gas testbed.

natural gas transaction are read by them.

IV. Testbed and Analysis

A. Smart natural gas Testbed based on mixed blockchain and edge computing

As shown in Fig. 6, the smart natural gas testbed was composed of four parts: edge computing nodes for natural gas, the big data platform, the service platform, and the operation and maintenance monitoring platform. Edge computing nodes consist of natural gas IoT sites, which have the capacity of data collection, data transmission, and data integration. At the edge nodes, sensor devices are deployed to collect the pressure information and flow data of the natural gas pipeline network, so as to generate corresponding indices information. As for data collection, detection data are obtained in real time from natural gas sites, which are converged to the big data platform in a reasonable data format. The data transmission medium provides the infrastructure for data transmission. The efficient transmission for various types of service data is realized based on guaranteeing data communication security. Data integration realizes the extraction of data features, data preprocessing, and data formatting. Thus, the collected data can be efficiently organized and integrated according to the predefined format, and the efficient data management can be realized. For the big data platform, unified storage, organization, and management for various types of heterogeneous, structured, or unstructured data are realized, as well as unified and efficient data service interfaces are provided.

This platform provides a consistent data layer for data analysis [38] and other service applications. The application types of the service platform mainly include offline data analysis, online analysis for real-time data, statistical statements, pressure status warning, gas flow prediction, smart contract, and so on. Basically, services rich in decision value, such as data association analysis, warning and prediction, provide decision-making support and early warnings through monitoring. As for the operation and maintenance of the monitoring platform, efficient monitoring and management of the resource utilization rate, load, service state, user behaviors, incident auditing and jurisdiction management can be realized for the whole platform.

B. Prediction of flow and pressure data in a micro gas site

To cope with a pre-ordered plan in a smart contract, the data value in the future needs to be predicted according to historical logs on flow and pressure at the micro gas site, thus enabling each microsite to purchase gas in advance when the gas selling price is relatively low and to reduce expenditure when the gas selling price is relatively high.

An LSTM-based deep learning algorithm is adopted to predict natural gas flow and pressure. A real flow and pressure data set was obtained from above smart natural gas testbed with a duration of 250 minutes, and it was divided into two parts: the previous 67% was made used as the training data set, and the latter 33% was used as testing data set. The algorithm parameters were as follows: there were four hidden_units (number of units in hidden layer) for LSTM, the duration of time_steps (memory time) was 3 minutes, there were ten batch_size (number of batching times), the epochs (iterative times) were equal to 1,000, and the size of the parameter document was 5 KB. After data normalization processing, the LSTM algorithm was adopted for training. When loss is convergence (loss = 0.0025), the prediction result for natural gas flow was as shown in Fig. 7 (a), and the prediction result for natural gas pressure was as shown in Fig. 7 (b). The blue lines stand for real data, the green lines stand for training results, and the red lines stand for testing results. Experimental results showed that our method could meet prediction demand in circumstances where the internal storage occupation was as little as possible and the operation duration was as short as possible. The adopted method can assist in realizing future transaction decisions for Smart Micro-GaS, and it can also provide a device state warning function.

C. Simulation experiments for mixed chain transaction model

In the actual natural gas transaction scenario, the environment and position of providers and demanders are dynamic. However, due to the delay in the whole network, we did not consider the impact of the transaction chain changing with the time series, and the process of packaging a contract in blockchain was regarded as a state at a certain time. In the experiments, we simulated the transaction environment of providers and demands according to the current natural gas flow data and tested the feasibility of the transaction models under different market scales.

Particle swarm optimization (PSO) was used to solve the optimal solution of the transaction matching model, i.e., finding the optimal solution to Eq. (4). Each particle in the population corresponded to a transaction matching scheme between providers and demanders. The fitness function was the sum of contract packing cost and purchase cost. Fig. 8 shows the optimal solution of the transaction chain with different scales. We selected user number scales of [2-4], [3-6], [4-8], [5-10], [6-12], [7-14], and [8-16] for the experiments. Taking [4-8] as an example, there were 400 gas providers and 800 gas

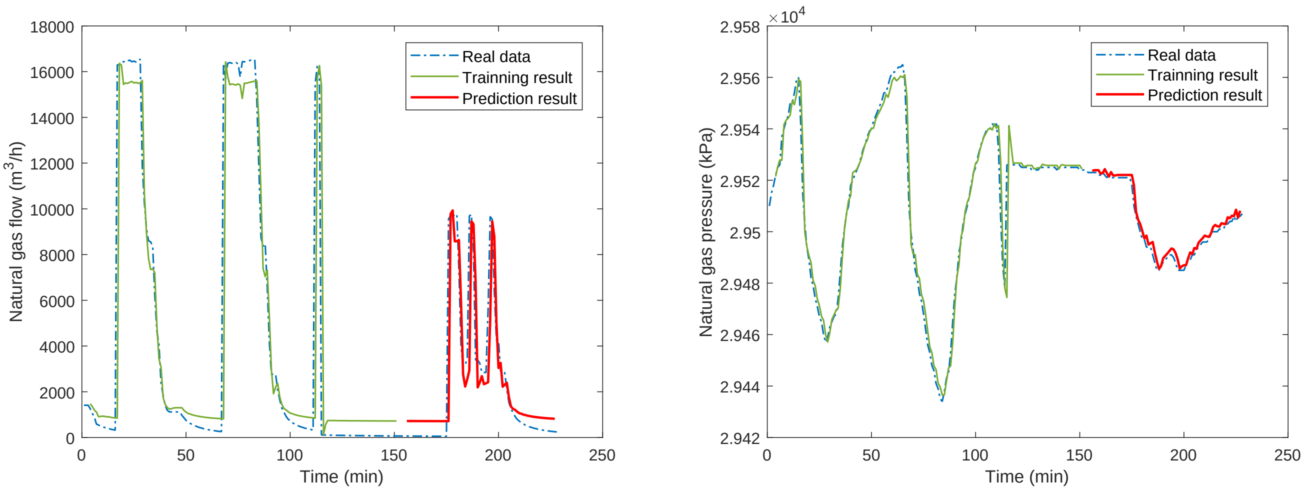

Fig. 7. Natural gas data prediction for a micro gas site: (a) flow; (b) pressure.

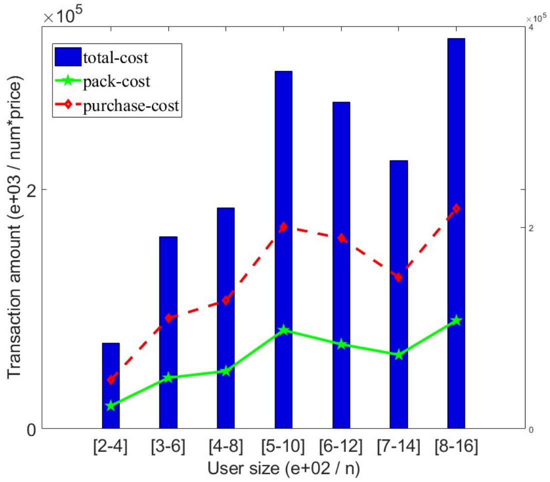

Fig. 8. Contract packaging and purchase costs of optimal solution with different market scales.

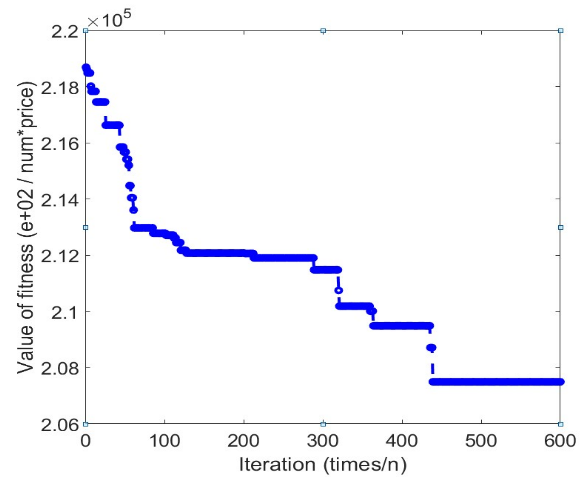

Fig. 9. Particle convergence process solved by particle swarm optimization in [6-12] scale.

demanders in the transaction chain. As shown, for different transaction chain scales, the contract packaging costs account for one-third of the total cost while purchase costs account for two-thirds. The result shows that the model proposed in this paper can be stably adapted in different natural gas transaction markets.

Fig. 9 shows the search process of the transaction matching algorithm for a user group with scale [6-12] on the transaction chain. After more than 400 iterations, the [6-12] scale group searched for the optimal solution of transaction selection, which required about 0.45 ms. Although the transaction time increases with the transaction size, it can still be maintained at the microsecond level, i.e., it has good timeliness. In summary, the experiment proves that the proposed transaction strategy can not only adapt to different scales of natural gas transaction but also meet the requirements of the transaction cycle.

V. Conclusion

In allusion to disadvantages of traditional natural gas IoT in transmission, transaction and analysis, this paper proposes Smart Micro-GaS in combination with distributed storage and the safe transaction function of blockchain technology, multilevel data transmission function of edge computing, and the real-time prediction function of AI technology. Smart micro natural gas IoT is designed and deployed regarding three different aspects of multi-level, multi-view and multi-dimension. In addition, algorithm optimization is conducted to the smart contract module in blockchain, the mixed transaction model for natural gas is established, and a union chain model for natural gas is introduced based on inter-chain technology. To verify the effectiveness and superiority of our solution, a smart natural gas testbed was established and a case analysis was conducted to evaluate the system performance. The results showed that the flow and pressure data at a certain future time quantum can be predicted accurately, while pressure warnings will be given for the device state according to the prediction results. Moreover, the proposed method can assist in realizing diversified smart contracts, which guarantees safe and autonomous transactions.

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