An Optimized GRT Model with Blockchain Digital Smart Contracts for Power Generation Enterprises

Abstract: The traditional power generation rights trading (GRT) market is faced with the problems of weak interconnection of electricity-carbon market and low security. Using smart contracts in the blockchain, the idea of establishing a weakly centralized GRT structure is proposed in this paper. The carbon emission factor was introduced to improve the GRT model, and carbon emission market is used to further stimulate the emission reduction vitality of generating units. The empirical results show that compared with the benchmark model and improved model 1, the improved GRT model proposed by us has the best emission reduction effect. The contribution of this paper is to make up for the existing research that cannot fully consider the impact of carbon peak and carbon neutralization on the GRT market, as well as the information security issues brought by big data trading on the GRT platform. This paper puts forward some policy implications for the decarbonization and green development of the electricity market advocated by the Chinese government.

Key words: big data; blockchain; digital smart contract; generation rights transaction (GRT); power generation enterprises

1. Introduction

In order to achieve carbon peaking and carbon neutrality goals, China's energy and power industry, as the main source of carbon emissions, is facing enormous pressure for low-carbon transformation (Kim et al., 2022). Due to the high proportion of installed thermal power capacity in China's power generation industry, a large amount of coal resources is consumed every year (Qi et al., 2016), resulting in high carbon emissions (Chen et al., 2021). To reduce carbon emissions, the energy consumption structure must be fundamentally changed (Sun et al., 2020), such as replacing the coal consumption of generator sets with clean energy (Yang et al., 2022). To change the energy consumption structure of the power generation industry, some market-oriented economic measures are needed (Liu et al., 2020).

Among the current popular economic means, generation rights trading (GRT) is an important measure to adapt to the current China's power reform (Banaei et al., 2019). GRT refers to the exchange of power generation rights allocated by the government between trading parties of power generators, aiming to replace the use of low-efficiency and high-polluting energy in power generation with renewable energy or clean energy. The GRT market is a platform with trading rules that power generation companies must comply with. China's GRT is similar to financial derivatives markets such as power swaps and options in the United Kingdom, New Zealand, and the United States, but there are certain differences in transaction purposes (Frestad, 2008; Benth and Koekebakker, 2008; Poletti, 2021). One of these differences is whether the transactions are conducted under the control of the government. The GRT market is designed to alleviate China's severe renewable energy curtailment problem and is therefore more subject to government influence. Compared with GRT, the power swap in the United States shows more financial characteristics and is more conducive to promoting market competition.

The GRT market has been developing for more than ten years, from the initial stage to entering an important development stage. In 2006, several pilot markets of GRT in China began to be established. Among them, the GRT pilot market in Jiangsu Province achieved a trading volume of 6.248 billion kWh, saving a total of 300,000 tons of standard coal and reducing emissions by nearly 6,000 tons. In 2009, the trading volume of China's first inter-provincial GRT in Northeast was 1.376 billion kWh. In 2017, the total trading volume of China's nationwide GRT was 152.77 billion kWh. At present, GRT is mainly concentrated in areas with large energy demand such as electricity, and is limited by the lack of renewable energy transmission facilities (Tang et al., 2018; Li et al., 2019a). Most importantly, the development of renewable energy in the power generation system will help achieve the emission reduction targets set by the United Nations (Miah et al., 2012; van Ackooij et al., 2018). Governments around the world have taken various measures to prioritize renewable energy over fossil energy in the power generation market (Zhang et al., 2016; Bahramian et al., 2021). The National Energy Administration (NEA) in China issued the notice on further developing GRT. The government encourages generation enterprises to actively participate in GRT market, thus replacing thermal power generation units with clean energy generation units. In recent years, GRT has become popular in the context of China's electricity marketization reform, accompanied by a sharp rise in transaction volume and activity in the market (Dong et al., 2021). The traditional GRT uses a centralized allocation method to make unified resource optimization decisions, which has many drawbacks. At the same time, it relies too much on the central processing system or third-party institutions to establish and maintain transaction information, resulting in high additional costs in the transaction process (Jiang et al., 2017; Luo et al., 2019; Wang et al., 2021).

The existing literature still has two shortcomings in the design of the GRT model, although a large number of related studies (Cartea et al., 2019; Shang et al., 2019; Zhao et al., 2021) have been carried out. First, as a key goal to promote energy conservation and emission reduction in China's power industry, GRT market needs to introduce a new trading mechanism that is more in line with the goal of "dual carbon". Traditional GRT model often does not fully consider the impact of carbon market on model optimization, but separates the electricity market from the carbon market. However, ignoring this factor makes the traditional GRT model unsuitable for the scenario after the operation of China's carbon market in recent years. This will not help China accelerate its goal of peaking carbon neutrality. It is necessary to introduce a GRT model that conforms to the current development of electricity-carbon market linkage. Second, electricity market reforms and government incentives have led to a surge in trading data. The peer-to-peer GRT on the centralized trading platform exposes many drawbacks when faced with big data transactions. This is because the centralized transaction relies too much on the transaction center, which makes it vulnerable to external attacks, low security and privacy factor, and long computing delay of the central node (Carvalho, 2020). Therefore, GRT market urgently needs to introduce new trading mechanisms to alleviate a series of problems caused by the surge in data. The research gaps in the existing literature on the GRT model are the problems mentioned above, so this becomes our research motivation.

To bridge the knowledge gap of big data analysis in the GRT market and develop an optimized GRT model, we intend to conduct research from the following two aspects. (1) From the perspective of carbon emissions, we develop a multi-objective optimized GRT model that combines China's GRT market with the carbon market to achieve the goal of decarbonization of the power industry. (2) We introduce blockchain technology and smart contracts into the GRT model to make the transaction process safer and more efficient, reduce the operation and maintenance costs of third-party management agencies, and further stimulate the activity of the GRT market in the power industry.

The contributions of this study are mainly as follows. (1) The carbon emission factor is introduced into the model, which considers the optimal GRT in the electricity-carbon linkage scenario. The organic combination of electricity market and carbon market can better stimulate the emission reduction capacity of GRT. The proposed GRT model achieves the optimal emission reduction target on the basis of taking into account economic benefits and coal saving. Through quantitative comparison of emission reduction, it is superior to other trading strategies in the existing literature. (2) A weakly centralized GRT thought is proposed by using the smart contract in blockchain technology. The two sides of the transaction use smart contract technology to sign an electronic contract to automatically complete the transaction. The issue of trust between two parties to a transaction is solved through the immutability of smart contracts and blockchain. In addition, there is no need for a third-party trading center to participate in the settlement process, improving the efficiency and security of the GRT process. Through the modification of the traditional trading mechanism, the central authority is only responsible for congestion management of trading transactions. This has greatly promoted data sharing, reduced operating costs, improved participants' trust in market-based trading of power generation rights, and promoted power market reform.

The significance of this research is manifested in two aspects in theoretical innovation and practical application. (1) Through such model optimization, it is not only in line with the current realization of the goal of "carbon peaking and carbon neutrality" in power industry, but also provides a new idea for the combination of the GRT market and the carbon emission trading market. (2) The proposed mechanism of embedding blockchain smart contracts in GRT can solve the shortcomings of high maintenance cost, high risk of data tampering, and low user privacy security. The application of blockchain and smart contract technology in the GRT model has improved participants' trust in the market-based transaction of power generation rights and promoted the reform of the electricity market.

In the context of the ongoing advancement of market-oriented reforms in the power industry, GRT is closely related to carbon trading. The introduction of carbon emission rights into the GRT model is of great significance to the formulation of policies such as carbon quota allocation and caps in the power industry. Reasonable allocation of carbon emission allowances can greatly promote the GRT efficiency of power generation enterprises, thereby achieving carbon emission reduction to a greater extent. Moreover, the promulgation of the new policy should also fully consider the connection with the existing policy, and the implementation of the new policy in stages and steps will eventually gradually promote the linkage between the electricity market and the carbon market.

The remainder of the study is organized as follows. Section 2 introduces the concept of GRT and blockchain in energy industry. The methodology and empirical analysis are given in Sections 3 and 4, respectively. The conclusions and policy implications are summarized in Section 5.

2. Literature Review

2.1 The definition of GRT

The power GRT is a financial transaction behavior referring to the trading rules of the primary and secondary markets of common commodities (Zhang et al., 2018; Banaei et al., 2019). Different from other types of electricity contracts, GRT is a unique type of electricity transaction in China intending to replace inefficient and polluting units with generators of renewable energy or clean energy (Marí et al., 2017; Cartea et al., 2019; Khan, 2019). In the primary market, the annual initial generation rights of various units are determined according to certain rules formulated by the NEA. This generally comes from the annual plans for various types of generator sets formulated by the government (Zhao et al., 2021). In addition, there is a possibility that it comes from short-term bilateral/multilateral transaction contracts signed between power plants.

In the secondary market, enterprises transfer or purchase generation rights through centralized transaction matching or bilateral/multilateral negotiated transactions. That is, the generator set of the power plant (as GRT seller) transfers the power generation right to the high-efficiency, energy-saving, and environmental protection unit (as GRT buyer) with surplus power generation capacity.

The two-level structure of China's electricity market reform adopts the form of national - regional. In line with the "unified market, two-level operations" electricity market framework, the reform can facilitate the wide allocation of energy resources. "Unified market" means that in the primary market, the state should focus on optimizing the allocation of energy resources nationwide, give full play to the decisive role of the market in resource allocation, and avoid artificial barriers affecting the efficiency of resource allocation. "Two-level operations" is to ensure the electricity supply through the coordinated operation of the secondary market (common market) in the regional power market, including the inter-regional and inter-provincial power markets and the provincial power market. The inter-regional and inter-provincial markets is mainly the inter-provincial electricity energy market, supplemented by the inter-provincial auxiliary service market and GRT market, etc., to implement the national energy strategy and promote the optimization of energy and resources allocation in a large range. The provincial market is based on the provincial electricity energy market, supplemented by the development of the provincial auxiliary service market, provincial capacity market, etc., to promote market competition, ensure the balance of supply and demand in the province, and, as far as possible, absorb clean energy. The coordinated operation of the two-level markets can be realized by means of coordination of trading timing, overall optimization and information sharing.

2.2 Model design and optimization

Existing literature on GRT is not abundantly published in international academic journals, although there are some in Chinese academic databases (Zhao et al., 2021). This is due to the fact that GRT has a typical uniqueness in China, which is significantly different from electricity contract transactions in other countries. Li et al. (2019a) introduced the development history of GRT, and analyzed three relative cases, including GRT between hydropower and thermal in Sichuan Province of China, GRT between wind power and thermal in Northeast China, and GRT between renewable units and captive generation units in Gansu Province, Northwest China. Shang et al. (2019) argued that power generation enterprises should determine the optimal GRT scheme according to risk appetite, and therefore proposed a power portfolio optimization method considering spot market bidding behavior, independent system operator (ISO) centralized dispatch, and cross-regional GRT. Zhao et al. (2021) analyzed the main differences between China's GRT and the electricity transactions in the United States, Australia, and other countries based on some actual trading cases, and provided a reference for researchers concerned about China's main solution to reduce renewable energy cuts.

Because of the grid structure, congestion management and security constraints need to be considered when trading electricity. But the secondary market often ignores this problem when they are designed in reality. At present, some scholars have shown that it is necessary to take congestion management into account in the secondary electricity market. Eicke and Schittekate (2022) showed that congestion management can counter the views of those who oppose the implementation of node electricity market (secondary market) in Europe. Graf et al. (2021) said that ignoring system congestion management and generator set operation constraints in the secondary market would give power producers opportunities to speculate and profit. Hirth and Schlecht (2020) also proved that in the process of trading in the secondary market, the aggravation of grid congestion would make manufacturers gain huge profits by using graphic games. Therefore, congestion management needs to be considered in the secondary market to prevent the emergence of improper investment incentives. As a type of transaction in secondary electricity market, GRT also needs to consider congestion management in the trading process.

2.3 Optimization of trading mechanism

Recently, the topic of existing literature has gradually shifted from model optimization to transaction mechanism in GRT market (Xiao et al., 2011; Wang et al., 2019), including the selection of transaction parties, the design of GRT unit access conditions, the transaction time period, the distribution of additional network loss fees and transmission fees after GRT, and income distribution methods. Xiao et al. (2011) studied the coordination between the bilateral negotiation transaction mode and the centralized bidding transaction mode of power generation rights under the hybrid mode. The advantage of this study is that the scheduling problem of GRT in different modes is considered when the system is blocked, and the model optimizes the blocking scheduling mechanism of GRT. Wang et al. (2019) established a cross-provincial transaction strategy optimization model to promote the completion of the "West-to-East Power Transmission" project, thereby reducing the cost and environmental pressure of power generation companies in Guangdong Province and helping Yunnan Province build a national-level hydropower base in China.

2.4 The application of blockchain in electricity trading

Most of the above literatures only study the design of the transaction mechanism, and pay less attention to the security of the transaction mechanism. They ignored that the big data trading platform may face information leakage and lack of trust between the transaction parties (Shao et al., 2022). Some studies have shown that blockchain technology can be considered as an alternative solution to eliminate the drawbacks of the traditional operating mechanism of the GRT market (van Leeuwen, 2020; Teng et al., 2021). These scholars show that the openness, transparency, traceability, non-tampering, decentralization and other characteristics of blockchain technology are in line with the concept of energy and power trading, and become the most promising solution to the problems of big data trading (Pereira et al., 2019; Sadawi et al., 2021). In recent years, some scholars have gradually begun to explore the application of blockchain in the field of energy and electricity sectors.

In the energy-blockchain field, Li et al. (2019b) proposed a set of blockchains embedded with self-enforcing smart contracts to manage the flow of energy and funds between transactional microgrids in a trusted manner. van Leeuwen et al. (2020) proposed a blockchain-based integrated energy management platform. The platform optimizes the flow of energy in the microgrid while implementing a bilateral transaction mechanism. Gourisetti et al. (2021) proposed a reference framework for interactive energy markets based on distributed ledger technologies such as blockchain. Muzumdar (2022) proposed a blockchain-enabled smart contract mechanism to protect the privacy of consumer energy consumption data through energy consumption contracts.

In the electricity-blockchain field, the current research mainly focuses on theoretical explanations (Hou et al., 2020; Wang and Su, 2020; Teng et al., 2021; Oprea and Bâra, 2021; Wu et al., 2022) and technical modes (Li et al., 2019b; van Leeuwen et al., 2020; Gourisetti et al., 2021; Muzumdar et al., 2022). Hou et al. (2020) analyzed the joint development model of "blockchain technology" and "distributed energy" on the basis of summarizing the development status of distributed energy and blockchain technology in China. This reveals the feasibility of applying blockchain technology to distributed energy systems. Wang and Su (2020) discussed the current status of energy and power applications based on blockchain from 2014 to 2020, and predicted the future development trend of energy blockchain. More and more scholars have expounded the development of blockchain in the field of energy and power from the perspectives of academic research, enterprise deployment, and government policies (Teng et al., 2021). The research shows that the energy blockchain is an effective and innovative technology to accelerate the transformation of the global energy structure. The development of blockchain depends on many factors. Transnational cooperation and government leadership are the basis for the large-scale deployment of energy blockchain, and the improvement of regulatory standards is the key to the commercial application of energy blockchain. Oprea and Bâra (2021) came up with a blockchain mechanism to simulate electricity trading, proving that it brings excellent benefits to the transaction. Wu et al. (2022) explored how microgrids and blockchains work individually or together. This enables potential solutions for electrification of transport, building, and industrial sectors through the energy community as an "enabling framework". Scholars have discussed the application of blockchain in the field of energy and electricity (Wang and Su, 2020). The characteristics and mechanism of blockchain make it feasible in all aspects of energy operations. Based on these theories, we can design the application model of blockchain technology in different scenarios.

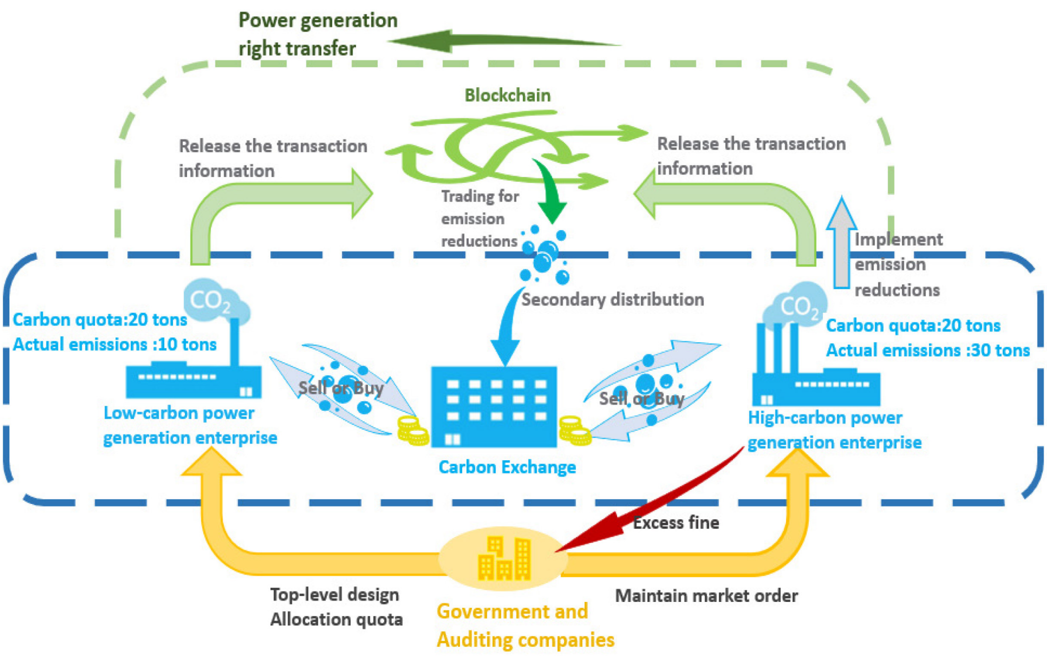

Fig. 1. Framework of GRT mechanism under carbon-electricity linkage

Based on the literature on GRT model, trading mechanism, and transaction security, we found that there are still two areas to be enriched in the GRT market.

(1) Existing literatures on GRT model only consider a single power trading market,

ignoring the impact of carbon market on power generation enterprises. Carbon neutrality factor is the most important theme of sustainable development in today's world. In the context of carbon peaking and carbon neutral sustainable development, GRT market, as a key object of energy conservation and emission reduction in the power industry, needs to integrate carbon trading mechanism to further tap the carbon emission reduction potential of generating units.

Therefore, this paper firstly establishes an optimal GRT model for carbon emissions from the perspective of carbon emissions. The carbon dioxide emission reduction obtained in the transaction will flow into the carbon market again in the form of carbon quotas for secondary trading. It can improve the income of power generators participating in the transaction, realize the cyclic linkage of electricity and carbon market, and promote the reform of electricity market. From Figure 1, government allocates carbon quotas to power generators. The initial carbon quota granted to high-carbon emitters is not enough to support them to complete their power generation plans. They need to take action to reduce emissions, namely GRT. Carbon emissions can be introduced into GRT model through trading in carbon market. The model is based on the carbon emissions of each power generation unit, and the two units with the largest difference in carbon emissions are preferentially traded to obtain the largest emission reduction.

(2) The existing literature on the application of blockchain in the power field is mainly from the perspective of the whole power industry, using blockchain to build the power ecosystem or improve the power trading model and mechanism. As a sub-field

in the electricity market, the current literature is still blank on how to apply blockchain to the GRT market.

Therefore, the problems of low safety factor, high maintenance cost, and low trust among transaction entities caused by the adoption of centralized management model are considered in the current traditional GRT market. Taking the above problems as the breakthrough point, this paper uses blockchain technology to propose a weakly centralized GRT model, which provides an idea to improve the security and efficiency of GRT market.

2.5 Comparisons with the existing research

To illustrate the novelty of this study, we have compared it with existing research on the GRT market in Table 1.

Table 1. Comparison with existing research

Study	Method	Results and findings
Wu et al. (2016)	CVaR-PA model	The CVaR-PA model takes into account both the transferee's risk avoidance needs and the transferee's willingness to participate and can achieve an optimal balance between transaction income and risk avoidance.
He et al. (2017)	Cooperative game theory	The GRT model can alleviate wind and photovoltaic curtailment and provide some practical foundations for renewable energy accommodation.
Li et al. (2019a)	Qualitative analysis	GRT has enhanced power system flexibility and improved renewable energy integration.
Shang et al. (2019)	Bi-level optimal portfolio model	The impact of GRT on generators' revenues is significant, and it is necessary to consider random happenstance in portfolio decisions.
Hou et al. (2019)	Michael Porter five forces model	The joint development mode of "blockchain technology" and "distributed energy" is feasible in China.

Yang et al. (2020)	The cost–benefit analysis method	Under the diversified business model, thermal power generation enterprises can more effectively avoid the risks when the external environment changes and significantly improve their economic benefits.
van Leeuwen et al. (2020)	The alternating direction method of multipliers	An integrated energy management platform based on blockchain can optimize energy flow in microgrids while enabling bilateral trading mechanisms.
Zhao et al. (2021)	Qualitative analysis	GRT can improve the operating profits for renewable energy power plants and reduce renewable energy curtailment.
Oprea and Bâra (2021)	Auctions with pricing mechanisms	Electricity trading based on blockchain mechanism can bring great benefits.
This study	GRT model based on the optimal carbon emission	Carbon emission factor is introduced into the model, and the power market is organically combined with the carbon market to better stimulate the emission reduction ability of GRT. The idea of introducing blockchain smart contract technology into GRT is proposed to improve transaction security.

Based on the analysis of the trading mode and policy system of GRT market, Li et al. (2019a) and Zhao et al. (2021) have showed that GRT can improve the operating profit of renewable energy power plants and promote the consumption of renewable energy. In addition, He et al. (2017) designed conventional and new energy GRT using cooperative game theory. The numerical examples show that the GRT model can alleviate the severe wind and light abandonment phenomenon in northwest China and promote energy consumption. Shang et al. (2019) have proposed a new method of optimal power mix for generators using the Bi-level model from the perspective of generator investment. Through the empirical study, it is found that under normal conditions, about 77% of the spot power for GRT is a preferred option, which can increase the total revenue by 266.21%. Under emergency conditions, the optimal GRT ratio is 70-80%, and the corresponding revenue growth is almost twice that of pure spot trading. This also shows the important position of GRT in the power market. Based on the cost-benefit analysis method, Yang et al. (2020) proposed a benefit analysis and decision model for diversified operation of thermal power generation enterprises. The empirical analysis by using scenario analysis and sensitivity analysis shows that, under the diversified business model (including electricity sales, GRT, etc.), thermal power generation enterprises can more effectively avoid the risks when the external environment changes, and significantly improve economic benefits. Wu et al. (2016) included the external environmental costs of fire and electric units into the power generation costs. Aiming at the transaction risk caused by the random change of external environment cost, the wind-fire GRT model is constructed to minimize the transaction risk.

Existing literature has analyzed that GRT can solve the consumption problem of renewable energy, and established relevant GRT models, including from the perspective of investment risk of power generators, profit maximization of trading, energy saving and consumption reduction. However, in the current context of carbon peaking and carbon neutrality, GRT markets need to introduce trading models that are more consistent with the lower carbon emission objective. The existing literature ignores this point. To make up for this shortcoming, this paper introduces carbon emission factor into the model from the perspective of carbon emission. Different from previous studies, we innovatively propose a GRT model based on optimal carbon emissions, and consider the problem comprehensively by organically combining the electricity market and the carbon market. Through the empirical study, we can see that this model has the best emission reduction effect and can better stimulate the emission reduction capacity of the generator sets.

In addition, given the security of traditional electricity trading mechanisms, existing literature has introduced blockchain technology into energy systems. Hou et al. (2019) analyzed the feasibility of applying the joint development model of "blockchain technology" and "distributed energy" to China's energy power system. Oprea and Bâra (2021) used blockchain to design a trading mechanism for joint price adjustment in the electricity market, and demonstrated through simulation that this mechanism can bring huge benefits. van Leeuwen et al. (2020) proposed an integrated blockchain-based energy management platform that can optimize the flow of energy in the grid and reduce transaction costs while conducting transactions.

Based on the above analysis, we found that the existing literature on the application of blockchain in the field of electricity is mainly from the perspective of the entire power industry, using blockchain to build a power ecosystem or improve power trading models and mechanisms. There is still a research gap in the literature on the application of blockchain in the electricity field, that is, GRT-blockchain market as a special scenario. To make up for this gap, we came up with the idea of bringing smart contract of blockchain to GRT. Using this technology, a weakly centralized GRT platform can be built to facilitate data sharing, reduce operating costs, and accelerate the pace of power reform.

3. Methodology

By reviewing the existing literature, it is found that the carbon emission reduction generated by trading in the process of GRT has not reached the optimum level, and the connection between the GRT and the carbon emission market has not been fully explored. We introduce a carbon emission factor into the model to organically link the electricity carbon market through the carbon emissions of power generation companies. In addition, the rise of blockchain provides us with new ideas to solve various problems in the traditional GRT market. Based on this, we propose a GRT model for the optimization of blockchain digital smart contracts for power generation enterprises.

3.1 The optimized GRT model

For the GRT model formed under the matching transaction mode, it is not comprehensive enough to construct the objective function solely based on the maximum social benefit or the minimum total coal consumption. By comprehensively considering various influencing factors, we have added emission reduction, economic benefits, and coal consumption into the transaction process, and established a relatively complete GRT model.

3.1.1 Assumptions

Some assumptions need to be made before constructing the GRT model.

(1) In order to facilitate the comparison of transportation costs, the coal resources used by the selected power plants are standard coal, which means that they are not only transported from the same area, but also use the same means of transportation.

(2) The GRT transferee needs to have certain carbon emission rights for

subsequent needs. If the transferee's remaining carbon emissions are not sufficient to support the agreed emission reductions in power generation to complete the transaction, it will be purchased in the carbon market by default.

(3) The calculation of the carbon emission of each power generation unit only considers the coal consumption of the unit, but does not consider the impact of other factors such as equipment and environment on the carbon dioxide emission.

3.1.2 Model correction factor

For cross-provincial GRT modeling problems, it is necessary to consider the differences in power generation costs between provinces. For example, some provinces that are geographically close to the coal center have relatively low transportation costs because of their abundant coal resources, while some provinces have to pay higher transportation costs because they are far from the coal center. In the GRT primary market, relevant government departments determine the annual initial power generation rights of power generation enterprises in accordance with certain rules. In the secondary market, power generation enterprises transfer or purchase power generation rights through GRT to realize transactions among power generation enterprises. By quantifying the inter-regional transportation cost into the modified coal consumption, the factors affecting the power generation cost of power generation enterprises are considered more comprehensively. The cost of generating electricity will also affect the price of GRT. The quantization of transportation cost can be included into the objective function, which can make the trading achieve more economic benefits and less coal consumption loss as far as possible on the premise of meeting the optimal carbon emission. When modeling, it is necessary to include the transportation fee into the thermal coal cost according to a specific conversion factor. Therefore, the coal consumption for power supply after considering the thermal coal transportation cost is $\bar{f} = f + \mu$, where f is the coal consumption for power supply without considering the transportation cost, and μ is the coal consumption converted from the transportation cost of unit coal (including transportation loss), that is, the corrected coal consumption for power supply is the sum of the original coal consumption for power supply and the coal consumption caused by transportation loss. The coal consumption converted from the transportation cost per unit coal (including transportation loss) is derived as follows:

$$\bar{f} = f \cdot \eta = f \cdot (1 + \gamma) = f \cdot \left(1 + \frac{C}{P}\right) \tag{1}$$

where C is the transportation cost per ton of coal to the power plant, and P is the price per ton of coal. The amount of thermal coal that can be purchased with the currency equivalent of the transportation cost per ton of coal is γ, where $\gamma = C/P$. Then the coal consumption correction factor is $\eta = 1 + C/P$.

3.1.3 Model specification

In view of the defect that the existing literature can only construct the objective function according to the maximum economic benefit or the minimum total coal saving amount, this paper constructs the optimal carbon emission GRT model considering economic benefits and coal saving under the environment of electricity-carbon linkage. The improved model considers the introduction of carbon emission factors in the context of the current "carbon peak" and "carbon neutrality" goals, which not only has a more intuitive understanding of the emission reductions brought by GRT, but also enriches the literature on GRT market under the electricity-carbon linkage scenario.

Given m transferors and n transferees of GRT market, this paper proposes an optimal GRT model considering factors of carbon emissions and economic benefits. This model adopts the hierarchical sequence method. First, it requires to achieve the maximum carbon emission reduction in trading, for which the objective function is given as follows:

$$F_C = \alpha\left(\sum_{i=1}^{m} C_i\, Q_i - \sum_{j=1}^{n} C_j\, Q_j\right) \quad (2)$$

where C_i and C_j are the carbon dioxide emissions of the transferor and the transferee when generating unit electricity, respectively; Q_i and Q_j are the actual transaction quantity of the transferor and the transferee, respectively; and α represents the penalty factor, which means that in the objective function, F_C maximization must be satisfied first and on this basis F_B can be satisfied. Thus, we achieve the minimum comprehensive coal consumption of the first sub-objective (the maximum comprehensive thermal coal saved by the transaction), and the other sub-objective function for the economic benefit is as follows:

$$F_B = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\bar{f_i} - \bar{f_j}\right) Q_{ij} \quad (3)$$

where Q_{ij} is the trading electricity for both the transferor and the transferee, $\bar{f_i}$ and $\bar{f_j}$are the corrected coal consumption of the transferor and the transferee's generator set, respectively.

Therefore, the GRT model based on the optimal carbon emission can be defined as follows:

$$max\{F_C, F_B\}$$

$$s.t.\begin{cases} Q_i \leq Q_{Bi}, Q_i \leq Q_{Bj}, Q_{ij} \leq min\{Q_i, Q_j\} \\ \sum_{i=1}^{m} Q_i = \sum_{j=1}^{n} Q_j \\ P_i \geq P_j \\ C_i \geq C_j, C_i Q_i \leq C_{Ri}, C_j Q_j \leq C_{Rj} \end{cases} \tag{4}$$

where C_{R_i} and C_{R_j} are the remaining carbon emission rights of the transferor and the transferee, respectively; Q_{B_i} and Q_{B_j} are the quoted electricity quantity of the transferor and the transferee stipulated in the contract, respectively; P_i and P_j are the quoted prices of the transferor and transferee, respectively. Note that the model is simplified and does not take into account the effect of transmission capacity on GRT. This is because once the two parties have signed the transaction contract, it is not necessary to transmit all the transaction power at once, as long as the transferee can complete the power transfer within the specified time.

The maximum value to be achieved by the objective function in Eq. (2) is F_c, that is, the maximum emission reduction after GRT. However, in the actual solving process, the emission reduction of multiple pairs of enterprises will be the same after transaction. At this time, when choosing the transaction priority, we consider that we can choose the suboptimal target, that is, use F_B to reduce the comprehensive coal consumption as much as possible on the basis of ensuring the maximum carbon emission reduction of the matching transaction.

We explain the relationship between quotation and generation cost from the perspective of transferor and transferee, so that we can further understand the quotation of power generation in Eq. (2).

Transferor: If the transaction price is less than the cost of power generation, the profit of power generation right transaction is higher than that of its own power generation. Because the transaction price of GRT is $P_{ij} = \frac{P_i+P_j}{2}(P_i \geq P_j)$, so $P_i \geq P_{ij}$. The transferor hopes that the lower the transaction price is, the better. Therefore, the transferor hopes that the lower the declared price of the transferee dealing with itself, the better.

We consider the worst case, that is, when $P_i = P_j$, the transaction price is equal to the declared price. At this time, as long as the declared price of the transferor is less than the generation cost, the transferor will still choose to trade the generation right.

Transferee: if the transaction price is higher than the cost of power generation, the transaction of power generation rights can improve the profits of the enterprise. The same as the above analysis, we can see from the transaction price formula of power generation right: $P_{ij} \geq P_j$. The transferee hopes that the higher the transaction price, the better. Therefore, the transferee hopes that the higher the declared price of the transferor who deals with itself, the better.

The worst case is still considered. The price quoted by the transferor for the transaction is lower, which is exactly the same as the price quoted by the transferee, that is, when $P_i = P_j$, the transferee will choose to conduct the generation right transaction as long as the reported price of the transferee is more than the generation cost.

Carbon emissions will have a negative effect on society, so we further analyze the social benefits impact of power generation rights trading. Here, we refer to the practice of Yang et al. (2019), and the positive effect of emission reduction generated through trading is as follows:

$$G = \eta \times ER^2 = \eta \times \left(\sum_{i=1}^{m} C_i Q_i - \sum_{j=1}^{n} C_j Q_j\right)^2 \tag{5}$$

Therefore, the social benefits function is given as:

$$SW = EB + G = EB + \eta \times ER^2 \tag{6}$$

where ER is the total emission reduction after the transaction, η is the environmental concern, and EB is the economic benefit.

3.2 Blockchain embedded in GRT model

A smart contract mechanism is designed according to the characteristics of GRT, and embeds the mechanism into the blockchain to establish a weakly centralized GRT platform. Through this model, the value transfer between power generation enterprises and between power generation enterprises and power suppliers can be automatically realized.

3.2.1 Theoretical framework

The traditional GRT market faces the problem of high operation and maintenance costs caused by big data trading and frequent collation with third-party financial institutions (Jiang et al., 2017; Luo et al., 2019). In addition, information asymmetry caused by centralized management is also one of the existing problems to be solved (Hayes et al., 2020). When the central authority is attacked, there is a risk of leakage of transaction information (Wang et al., 2021; Oprea and Bâra, 2021). In order to solve the problems of data leakage and transaction information asymmetry, we consider adopting a smart contract design mechanism based on blockchain technology to achieve peer-to-peer secure transactions between both parties shown in Figure 2.

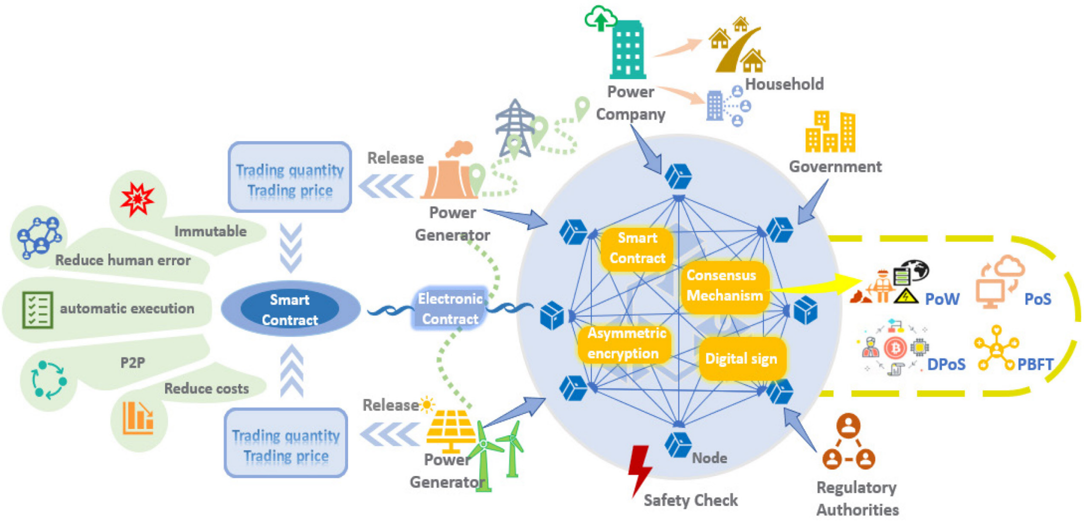

Fig. 2. The framework of market-oriented GRT model based on blockchain

The business framework includes the four steps as follows.

(1) The power plants participating in the transaction broadcast the transaction information to the entire network through the node server.

(2) A carbon emission-optimized GRT model is used for centralized matching.

(3) The electronic agreement is generated using smart contracts, and point-to-point transactions are automatically completed at the appointed time. This process does not require the participation of a central institution without including security verification and congestion management, but can fully realize decentralized GRT transactions.

(4) The enterprises related to the power industry can also link to the blockchain through their own node servers to achieve real-time data sharing and high trust.

Figure 2 shows a complete distributed power system based on blockchain technology, including the entire social level (including power generation enterprises, power supply companies, relevant government departments, power consumers, etc.).

In the left half, power generation enterprises use the features of blockchain smart contract technology such as tamper-proof, automatic execution, and point-to-point transaction to conduct GRT. The right half shows several main features of blockchain technology: smart contract, asymmetric encryption, digital signature, and consensus mechanism.

The main role of consensus mechanism in blockchain technology is to ensure the authenticity, reliability, and tamper ability of the blockchain. Different blockchains adopt different consensus mechanisms, including Proof of Work (PoW), Practical Byzantine Fault Tolerance (PBFT), Proof of Stack (PoS), and Delegated Proof of Stack (DPoS). The advantages and disadvantages of different consensus mechanisms are different, but no matter which consensus mechanism can constrain each decentralized node in the decentralized network, maintain the operation order and fairness of the system, and enable each independent node to verify and confirm the data in the network, thereby generating trust and reaching consensus.

In the next section, this paper expounds the principle of blockchain technology to prevent information tampering, and analyzes how smart contracts can realize high-trust mechanism transactions. Based on the in-depth interpretation, we propose a useful management framework for embedding the blockchain into the GRT model.

3.2.2 Blockchain principle

The essence of blockchain is a distributed storage ledger, which records various types of information (such as transactions, events, etc.) and sets corresponding rules for them. The blockchain is composed of a series of data blocks, and each block records the transaction information within a certain period of time and the hash value of the previous block connected to the blockchain. The length of the blockchain is determined by adding the hash value to the previous block, as shown in Figure 3. The hash value is obtained by a cryptographic hash function based on the content of the file in the block. In general, a cryptographic hash function can ideally generate the hash value of any input, but it is very difficult to reverse the input data using the hash value. Therefore, the use of cryptographic hash values can guarantee tamper-proof data, because if the information of a block is tampered with, the information of all subsequent blocks must also be changed.

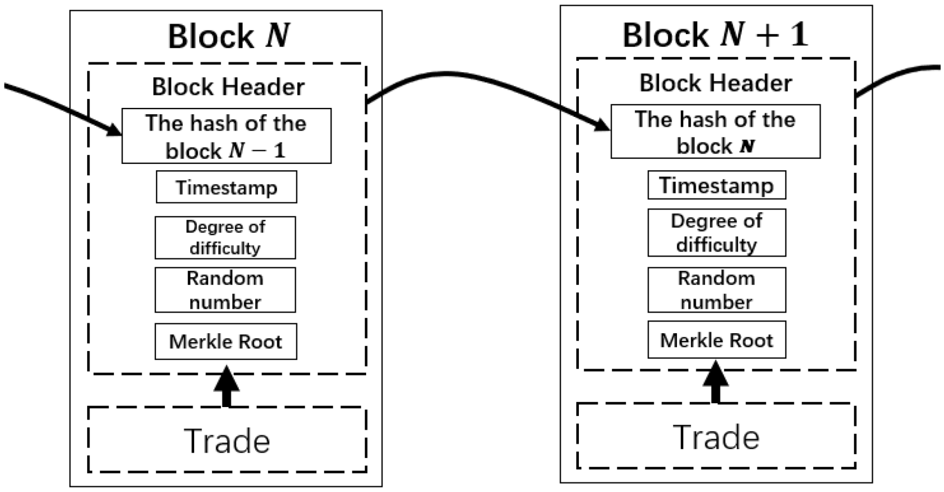

Fig. 3. The links of blocks constitute a blockchain

In addition, each node broadcasts to the blockchain through the entire network after the smart contract writes to a specific block. When the transaction consensus time is reached, the node will package all contracts received in a transaction cycle into a set and store it in a block in a specific form. This specific form is the Merkle root in Figure 4. The Merkle tree is a binary tree whose leaf nodes record transaction information and the hash value generated according to the transaction information, and the hash value of each child node is stored on its parent node. The parent node also records the sum of the hash values corresponding to all its child nodes. All transaction records will generate a unique Merkle root through the hashing process of the Merkle tree and record it in the block header. Therefore, the corresponding leaf node information also changes when a certain transaction information is tampered with. At this time, the hash value generated according to the transaction and the hash value of the parent node corresponding to the node will be changed. This in turn causes the hash value of the root node to be changed. When other nodes receive the node through broadcast, they only need to verify the hash value corresponding to the root node of the Merkle tree. From this, it can be known that the transaction information has been tampered with, so that the transaction information is not accepted, and the tampered block will not be linked to the normal transaction blockchain.

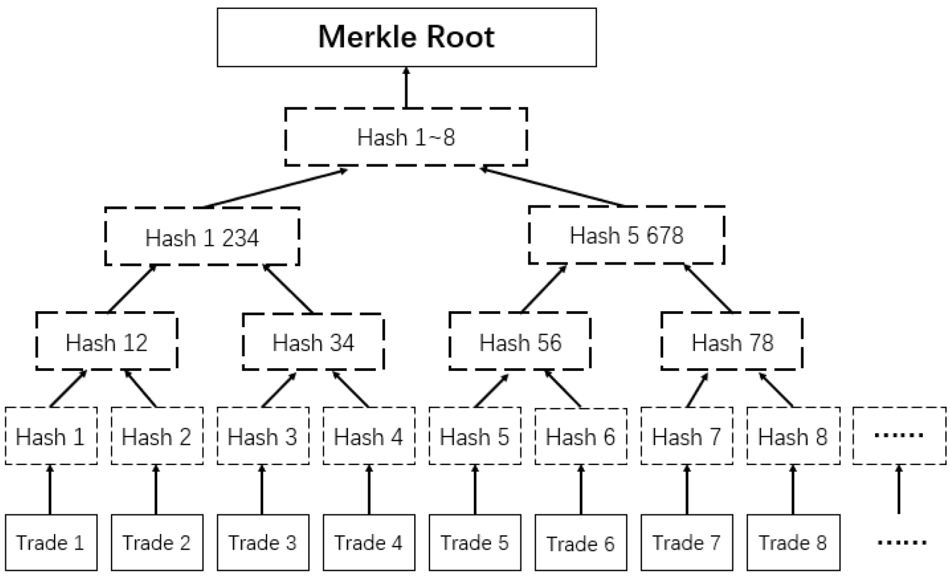

Fig. 4. Schematic diagram of the Merkle Root structure

For further example analysis, a new transaction is created as follows. The creator *A* uses the private key to sign a digital signature on the previous transaction and the next owner B, and attaches the transaction to the end to make a transaction list. Through peer-to-peer network broadcast, other nodes verify the legitimacy of the transaction by solving a specific Hash value. When a node finds a solution, the entire network broadcasts all time-stamped transactions recorded in the node's block, which are verified by the entire network. After the whole network node verifies the accuracy of the block accounting, the block is linked to the local ledger and updated as shown in Figure 5.

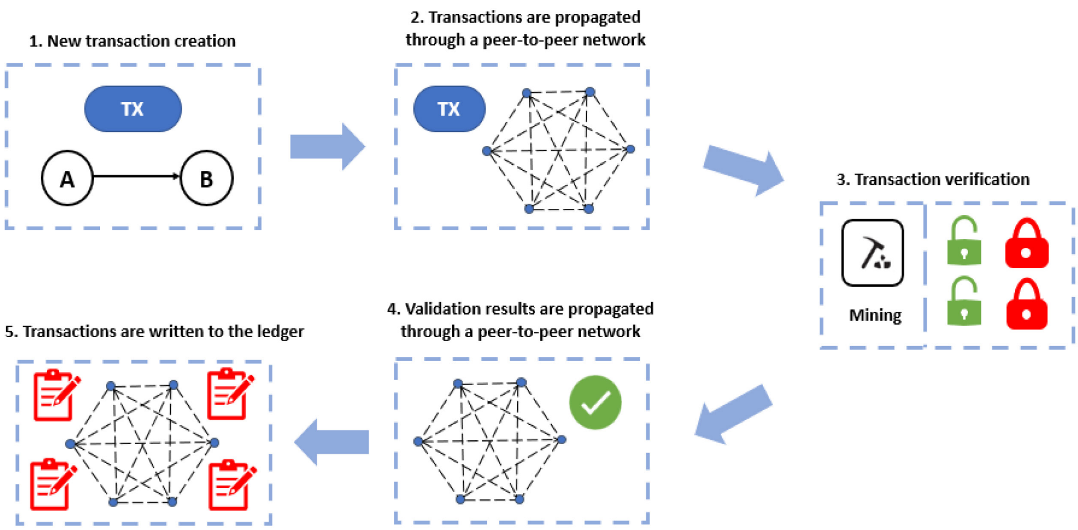

Fig. 5. The flowchart of Blockchain and Distributed Ledger Technology

3.2.3 Smart contracts embedded in GRT model

Smart contract is the most important concept in Ethereum, which adds the function of smart contract on the basis of the original blockchain technology. It can provide developers with a decentralized application platform. A smart contract is a set of commitments defined in digital form, which is essentially a computer protocol to facilitate, verify, or enforce the negotiation or execution of a contract in a digital form. After the transaction center determines that the transaction result meets the grid security constraints, it will be recorded in the blockchain in the form of a smart contract. Smart contracts include predefined states, transition rules, conditions that trigger contract execution, and response actions in specific situations (Carvalho, 2021). As shown in Figure 6, the blockchain can grasp the state of the smart contract in real time and determine whether the trigger conditions are met by checking external data. If the preset trigger conditions are met, the system will automatically execute the contract.

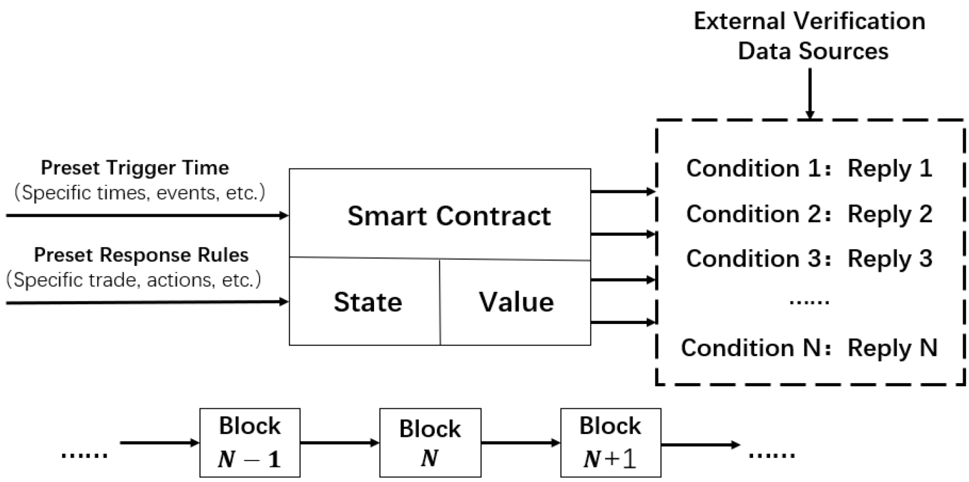

Fig. 6. The diagram of the operation mechanism of smart contracts

In the actual GRT process, the information stored by the smart contract includes trading volume, trading price, trading preset time, and default fees. Among them, the trading preset time refers to the automatic execution time of the smart contract for the electricity trading after negotiation between two parties. The power generation information of each power plant is tracked and recorded through the smart meter. When the scheduled trading time arrives, the smart contract judges whether the trading parties have completed the corresponding plan according to the information recorded by the meter. In this process, if the transferee fails to complete the generation plan, the smart contract will deduct the pre-agreed liquidated damages from the transferee's account.

Conversely, if the transferee completes the generation plan, the smart contract will first settle between the transferee and the transferor, and then settle between the transferor and the power supplier. The advantage of this application is that the immutability of smart contracts and electrical information solves the problem of trust between both trading parties. Moreover, no third-party trading center is required to participate in the settlement process, which improves the efficiency and security of GRT process.

3.2.4 GRT model based on blockchain

The status of all nodes in the blockchain is equal, there is no fully centralized node, and the normal operation is maintained jointly through the consensus mechanism. Under the blockchain architecture, the nodes negotiate to reach the transaction priority scheme, which improves the fairness and effectiveness of real-time transactions. Therefore, the GRT and regulatory model under the blockchain architecture is shown in Figure 7.

The GRT for A and B power generation companies is supported by blockchain technology, forming a GRT and supervision model under the blockchain architecture including BC1 (dispatching chain), BC2 (transaction chain), and BC3 (government supervision chain). BC1 is a scheduling chain that is morphologically private. After the transaction chain has reached a preliminary transaction plan, the scheduling chain is responsible for checking the enforceability of the plan. BC2 is a transaction chain, which is a public chain in form. EP_A and EP_B (electric power enterprises) are parallel nodes. Each node interacts with the trading volumes and price information on the decentralized platform, matches, and forms a preliminary trading plan for the corresponding period, and submits it to the scheduling chain for verification. BC3 is an independently formed data chain of custody, which belongs to the alliance chain in form. Various regulatory authorities participate as nodes in the entire blockchain transaction management. Such nodes only retain the hash summary information generated by each transaction block in the transaction chain, and generate the summary directory tree for real-time recording and post-monitoring the transaction information in the transaction chain.

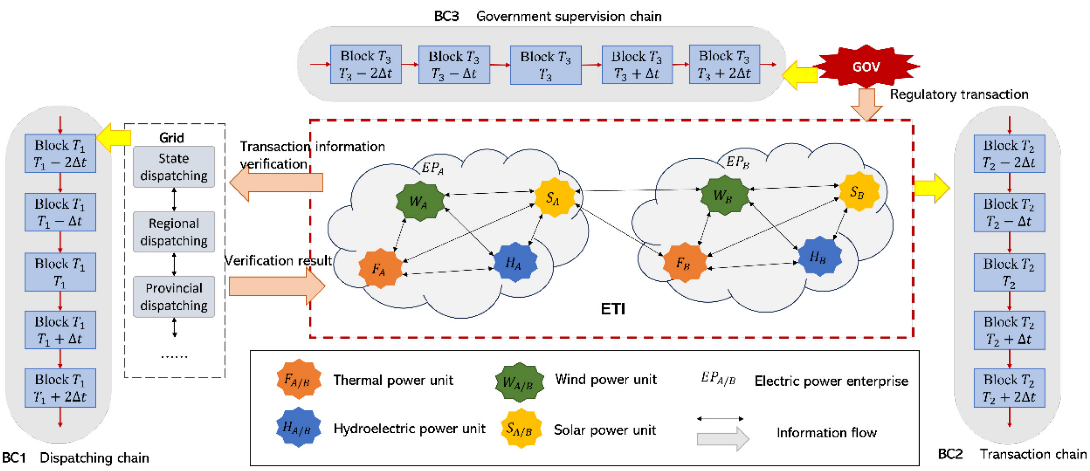

Fig. 7. The application of blockchain technology in the physical model

The operation of GRT based on blockchain mainly depends on the coordination operation mechanism of BC1 and BC2. It is necessary to analyze the constraint conditions such as the price of BC2 and the logical control relationship between them under the clear physical constraint conditions of BC1. According to the mechanism of reaching consensus and generating block with a fixed duration (10min) of the blockchain, combined with the data processing load characteristics of the dispatching center, each node of the dispatching chain BC1 takes a fixed duration (the time required for reaching consensus is $\Delta t = 1h$). Take $T \sim T + \Delta t$ as an example:

(1) BC1 calculates the quota value based on the line load planning of the target period (effective time $T_{te} > T + 3\Delta t$) and the target area. The target period starts from the effective time. At the same time, BC1 provides relevant information of each EP node in the area and broadcasts the above information to each EP node at $T + \Delta t$.

(2) All EP nodes update the information received at $T + \Delta t$ time synchronously.

(3) Based on the GRT matching transaction mechanism, each node negotiates the optimal transaction scheme.

(4) Before $T + 2\Delta t$, the transaction negotiation result data is generated into the transaction information block in the transaction chain. Peer-to-peer smart contracts are reached and broadcast across the network to reach consensus. Then integrate the actual transaction information of the previous period to form a block.

(5) The expected transaction information generated by $T + 2\Delta t$ is reported to the scheduling chain, and the scheduling chain checks the reported expected transaction information. The content of the check includes whether the transaction volume and regional information between nodes meet the advance conditions, and whether there is a 51% attack on the blockchain consensus.

(6) The dispatch chain broadcasts the verification results to the trading market and issues trading permits to approved trading schemes. The transaction that is not approved by the scheduling chain is rejected, its application permission in this period is closed, and the transaction is declared invalid. This can ensure the rationality and real-time of transactions, and prevent the potential distributed denial of service attack caused by several unapproved transaction applications submitted repeatedly in a short period of

time. And then promote the transaction chain to carry out transaction negotiation in strict accordance with the quota information.

3.2.5 The process of weakly centralized GRT model

In the GRT model based on blockchain technology, electronic contracts are automatically formed through smart contracts to complete the process of transaction and value transfer, which can be realized without a centralized management agency. However, this may not comply with the constraints of the network being traded entirely in accordance with the ordinary market, as the right to generate electricity needs to be checked as a special commodity for safety and congestion. Currently, each node in the network can use a distributed algorithm for security checks without a central organization, while the congestion solutions in the existing literature all require mastering the transaction information of the actual network. In the absence of a centralized organization, it is difficult for each node to proceed spontaneously. Therefore, this paper proposes to establish a central authority to manage the congestion of transactions, as shown in Figure 8.

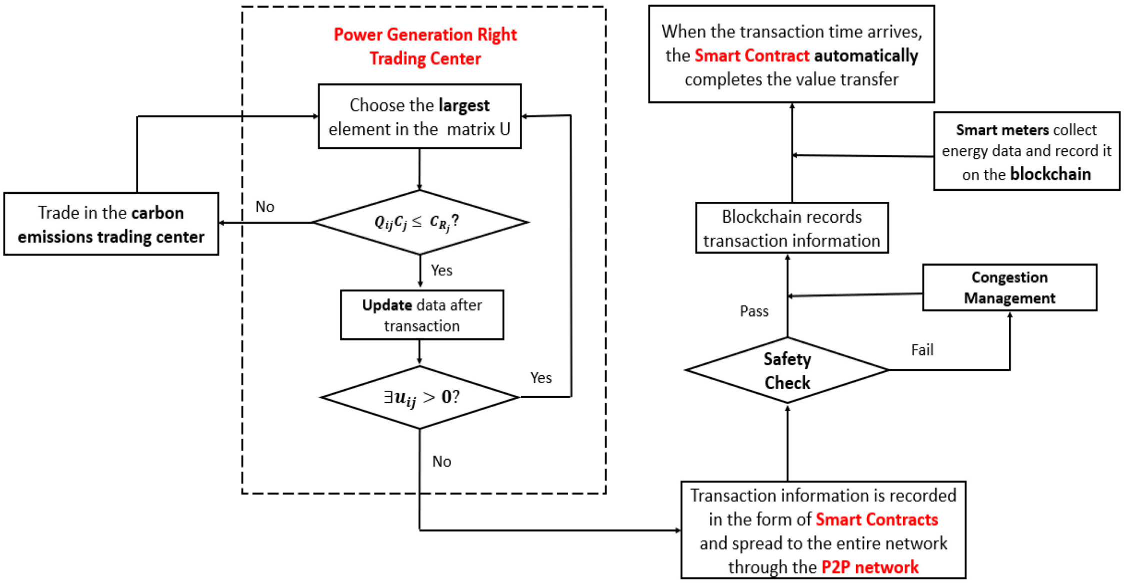

Fig. 8. The general flowchart of GRT-Blockchain process

(1) The power generation right traders conduct centralized matching based on the carbon emission optimized power generation right model to reach a transaction.

(2) The transaction process is recorded in the form of smart contracts and spread to each node of the entire network through the P2P network.

(3) All nodes of the whole network reach a consensus through communication to reach a transaction.

(4) The transaction goes through a security check when all nodes agree to the latest set of contracts. If the security check passes, the contract set will be recorded in the blockchain. Conversely, if the security check fails, the central authority will block the transaction until a new set of transactions that satisfy the security check is generated.

(5) When the agreed time is reached, the smart contract will automatically execute the value conversion of both parties according to the prior agreement.

(6) Through the above steps, the GRT process management with weak centralization and high trust mechanism is realized. In the weak centralization mode,

the central organization only manages the congestion, so it only needs to know the line over-limit information in the process of setting the congestion price, but does not need to know the specific transaction information.

4. Empirical Analysis

4.1 Data

In the selection of sample data, this paper refers to the simulation data of the existing literature (Shi et al., 2017). It takes different provinces and different types of generator sets in China as transaction objects, which can not only ensure the applicability and accuracy of the calculation examples, but also make the model general. The geographic locations of the sample data are located in four central China provinces: Henan, Hubei, Hunan, and Sichuan. This choice is based on the following two aspects. On the one hand, the generator set in Sichuan Province is selected because of its rich hydropower resources, and the corresponding generator set has great advantages in controlling carbon emissions, and its coal consumption is zero. On the other hand, the distances from the four provinces to the center of the coal mines are increasing in turn, with obvious regularity and persuasiveness. Here, the coal mining center we chose is the China Coal Trading Center in Shanxi Province. Shanxi Province is an important coal energy province, which has been providing important guarantee for domestic energy consumption for a long time. China Coal Trading Center in Shanxi Province is centered on national coal production area trading. Therefore, we uniformly assume that all thermal power generation companies purchase thermal coal from coal trading centers in Shanxi Province. According to the coal price and transportation cost of each province, the correction coefficients of coal consumption in Henan, Hubei, Hunan and Sichuan are calculated as: 1.36, 1.43, 1.69 and 1.68 respectively. Table 2 shows the simulation data of each generator set selected in this paper.

Table 2. The power generation data quoted in the contract between each generator set

Code name	Attribute	Province	Quoted volume (MW·h)	Quoted price (RMB/MW·h)	Coal consumption (g/MW·h)
A	Transferor	Hunan	700	305	323
B	Transferor	Hubei	500	315	330
C	Transferor	Hunan	600	291	315
D	Transferor	Hunan	300	282	309
E	Transferor	Hubei	300	273	280
F	Transferee	Henan	600	276	275
G	Transferee	Sichuan	900	270	272
H	Transferee	Henan	800	286	268
I	Transferee	Sichuan	700	259	0

4.2 Model solving process

In this paper, it is assumed that the generator set uses standard coal and only the coal consumption of the generator set is considered when calculating carbon emissions. For the carbon dioxide emission value per unit of standard coal, the reference value of standard coal carbon emission given by *Japan Institute of Energy Economics* is 0.68*tC/tce*, and the reference value given by *U.S. Energy Information Administration* is 0.69*tC/tce*.

According to *China Electric Power Statistical Yearbook in 2021*, the average coal consumption of thermal power units of major power generation enterprises in China is

282.9 *g/kWh*, and the carbon emission value per unit standard coal is 0.69 *tC/tce*. The amount of carbon dioxide emitted per 1 *kg* of standard coal is completely burned. 2.54 *kg*, then after conversion, the carbon dioxide emission per unit of power generation of the generator set is about 718.6 *kg/MWh*. Assuming that a GRT process occurs between a generator set with a coal consumption of 300 *g/kWh* and a generator set with a coal consumption of 275 *g/kWh*, the total amount of electricity traded is 10 *MWh*. When other losses are ignored, the amount of carbon dioxide reduced through trading is 635 *kg*. Therefore, this reduction in carbon emissions through GRT market can be quantified by the difference in coal consumption between the generators on both sides of the transaction amount and the transaction volume.

From the geometric meaning of the matching transaction schematic diagram shown in Figure 9, we can see that the maximum benefit can be achieved by maximizing the area of the shaded part. The shaded area is the difference between the area under the demand curve and the area under the supply curve, which depends on the quotation level and actual volume, regardless of the transaction object. As a welfare maximization problem, the solution to the optimal carbon emission problem only depends on the carbon emission level and the actual transaction volume of buyers and sellers, and has nothing to do with the transaction objects.

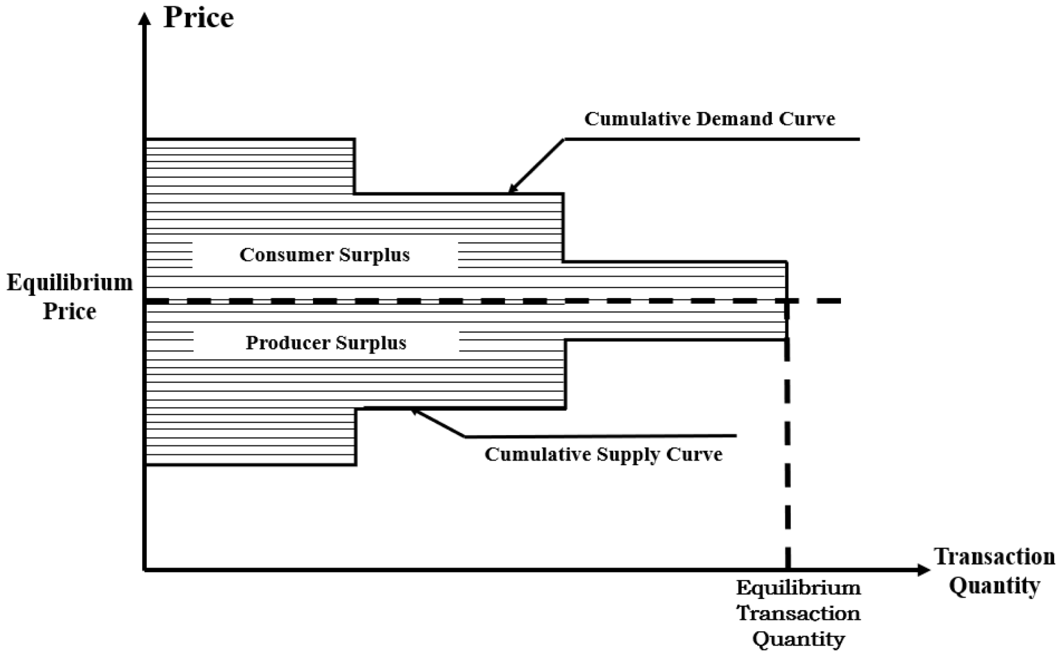

Fig. 9. The trading schematic diagram of matching transaction mode

The GRT model based on optimal carbon emissions needs to take into account the emission reductions and economic benefits of trading. The model is solved by taking the actual total transaction volume of traders as the decision variable, and the transaction price is determined by matching different transaction objects. The primary objective function is achieved based on the determination of the transaction volume, while the optimization of the secondary objective can be further achieved. Our model is solved using a hierarchical heuristic method. The hierarchical sequence method is to reorder the goals in order of importance, putting the most important goals first. Then optimize the first objective and find the set of all optimal solutions, denoted by R_1. Then the optimal solution of the second objective is found in the range of set R_1, and the optimal solution set is represented by R_2. And so on until the optimal solution for the m-th object is found. There are only two objectives in this paper, so we first solve the transaction pairs with the maximum emission reduction after the transaction, which are the optimal solution set of the target F_C. On this basis, we find the optimal solution of the target F_B. The steps in the model solving process are explained as follows.

(1) Form a matrix of coal consumption difference U between the transferor and the transferee, where $f_{ij} = f_i - f_j$.

(2) Select the largest element $\{f_{ij}\}$ in the matrix U to carry out transaction matching for the transaction volume $Q_{ij} = \min\{Q_i, \ Q_j\}$.

(3) Calculate whether $Q_{ij}C_j \leq \ C_{R_j}$ is satisfied. If it is not satisfied, the transferee of power generation rights needs to purchase a certain amount of carbon emission rights in the carbon market before trading.

(4) Updated two types of data after the transaction is completed. One is the remaining transaction volume of the transferor. The other is the transferee's remaining trading volume and remaining carbon emissions. In the end, the transferor and transferee with no remaining trading volume are eliminated from the trading platform.

(5) Repeat step (2) until there is no element greater than zero in the coal consumption difference matrix U.

(6) Check the transaction results for security, if not, adjust the transaction volume of the transaction pair related to blocking until the security constraints are met.

4.3 Comparative analysis

This paper uses the sample data to calculate the target of the benchmark model based on the optimal economic benefit, the improved model 1 based on the optimal comprehensive coal consumption under corrected coal consumption, and the improved model 2 based on the optimal carbon emission. The performance results of the three models in terms of economic benefits, coal saving and carbon emission reduction are shown in Table 3. The first row of the table shows that the variable abbreviations are Transferor (*TO*), Transferee (*TE*), Quoted price difference (*QPD*, RMB/MW·h), Quoted Volume (*QV*, MW·h), Coal consumption (*CC*, g/MW·h), Carbon emissions difference (*CE*, kg/MW·h), Corrected coal consumption difference (*CD*, g/MW·h), Coal saving (*CS*, t), and Emission reduction (*ER*, tCO_2/tce). By comparing the results of these transactions, the advantages of a carbon-optimized GRT model are highlighted.

Table 3. The results of benchmark and improved GRT models

Column (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Models	*Trading Order*	*TO*	*TE*	*QPD* (RMB/MW·h)	*QV* (MW·h)	*CC/CE* (g/MW·h)	*CD* (g/MW·h)	*CS* (t)	*ER* (tCO2/tce)
Benchmark model	1	B	I	56	500	330.00	-	165.00	419.10
	2	A	I	46	200	323.00	-	64.60	164.08
	3	A	G	35	500	51.00	-	25.50	64.77
	4	C	G	21	400	43.00	-	17.20	43.69
	5	C	F	15	200	40.00	-	8.00	20.32
	6	D	F	6	300	34.00	-	10.20	25.91
	7	E	F	-3	100	5.00	-	0.50	1.27
Improved model 1	1	A	I	46	700	323.00	516.80	226.10	574.29
	2	C	H	5	600	47.00	139.52	83.71	71.63
	3	D	H	-4	200	41.00	129.92	25.98	20.83
	4	D	F	6	100	34.00	120.40	12.04	8.64
	5	B	F	39	500	55.00	97.90	48.95	69.85
	6	E	G	3	300	8.00	-56.56	-16.97	6.10
Improved model 2	1	B	I	56	500	838.20	471.90	165.00	419.10
	2	A	I	46	200	820.42	516.80	64.60	164.08
	3	A	H	19	500	139.70	152.32	76.16	69.85
	4	C	H	5	300	119.38	139.52	41.86	35.81

5	C	G	21	300	109.22	47.04	14.11	32.77
6	D	G	12	300	93.98	37.44	11.23	28.19
7	E	G	3	300	20.32	-56.56	-16.97	6.10

Note: The numbers of column (2) such as 1, 2, 3, … are the trading orders. The numbers of column (7) refer to "Coal consumption (*CC*, g/MW·h) " in Benchmark model and Improved model 1, but refer to "Carbon emissions difference (*CE*, kg/MW·h)" in Improved model 2. The "-" in the column (8) means that there is no data here, because the benchmark model does not use the correction factor "Corrected coal consumption difference (*CD*, g/MW·h) ", but the other two models include this correction factor.

For the benchmark model, the GRT model with the traditional economic benefits is matched according to the price difference of each power plant. The seller and transferee with the largest price difference can trade first, and this matching process continues until there is no positive price difference between the parties. The transaction process is shown in rows 2 to 8 in Table 3, which contain 7 rounds of transaction records. The value in line 8 indicates the 7th transaction between the two sides that was stopped because the price difference was negative.

For the improved model 1, the GRT model with the optimal integrated coal consumption calculates the coal loss during transportation into the coal consumption for power generation. Transactions are carried out in sequence according to the corrected coal consumption difference of each power plant. The two sides stop trading until there is no positive corrected coal consumption difference. In Table 3, although the price difference was negative in the third transaction, the revised coal consumption difference between the transferor and transferee was 129.92 g/kWh. The transaction can save 25.98 t of thermal coal and reduce carbon dioxide emissions. It has a good energy saving and emission reduction effect. In the 6th transaction, there was a situation where the corrected coal consumption difference was negative and the coal consumption difference of the generator set was positive. According to the transaction mechanism of the comprehensive coal consumption optimal model, the sixth transaction will not be carried out, so that the carbon dioxide emissions cannot be further reduced.

For the improved model 2, the GRT model of the optimal target of carbon emission calculates the carbon emission difference according to the difference in coal consumption and the emission of carbon dioxide per unit of standard coal. The transactions are matched in order according to the difference in carbon emissions between the transferor and the transferee. In the 7th transaction of Table 3, although the corrected coal consumption difference is negative, the carbon emission difference is positive, so trading can further reduce carbon dioxide emissions. In addition, the price difference between the two sides of the transaction is positive, and economic benefits can also be increased through the transaction.

4.4 Discussion

To sum up, it can be seen from the above transaction results that models with different targets have different trading orders and volumes between the trading parties. This makes a difference in the economic benefits, coal savings, and reduced carbon emissions. In the previous literature, economic benefits and coal savings are usually used as indicators for evaluating GRT models (Wang and Cheng, 2010; Wang et al., 2012). However, the above indicators are no longer in line with the current international community's requirements for climate governance. In the context of "carbon peaking" and "carbon neutrality", this paper uses the reduction of carbon dioxide emissions as a new model evaluation indicator. The final economic benefits, coal savings, total carbon dioxide emissions reductions and social welfare ($\eta = 0.2$) obtained through trading for each model are shown in Table 4.

It can be seen from Table 4 that the total economic benefit of the traditional economic benefit optimal model is 67900 yuan (RMB). However, the transaction only considers the coal consumption of the power generation unit itself and does not consider the loss of coal in the process of trans-provincial transportation, the coal saving effect obtained through the transaction is poor, and the coal saving amount is only 290.5 tons. The improved model 1 based on the optimal comprehensive coal consumption has introduced a coal consumption correction factor, which more truly reflects the coal consumption difference of each power plant, which greatly improves the total coal saving achieved through the transaction. The total coal saving is 396.786 tons, which is 106.286 tons more than the traditional economic benefit optimal model. However, the coal consumption correction factor is easily affected by the distance between the power plant and the mine center, the sixth transaction in Table 4 sometimes occurs during the transaction process, which makes the carbon emission reduction less than optimal model. The GRT model based on the carbon emission optimization proposed in this paper can not only solve the above problems, but also further reduce the carbon dioxide emissions. The total emission reduction reached 755.904 tons, 43.942 tons more than that of the benchmark model, and 10.668 tons more than that of the improved model 1. This is only the emission reduction generated by the trading volume of 2400 MW · h. If the trading volume increases, the emission reduction effect will be more obvious. In addition, the model can give good consideration to economic benefits and coal saving.

It is more suitable for the current GRT market. In addition, the multi-objective model proposed in this paper takes into account the economic benefits on the basis of achieving the optimal emission reduction. As mentioned above, in the 7th transaction in Table 3, if the matching mechanism of the improved model 1 is used for the transaction, the transaction is terminated because the corrected coal consumption difference is negative. But our model can continue to be traded to further reduce carbon emissions and increase economic benefits. This is also the reason why the economic benefit of the GRT model based on the optimal carbon emission is superior to that of the improved model 1 in the result.

Table 4. The comparison between the baseline model and the improved model

Transaction mode	Economic benefit (RMB)	Coal saving (t)	Emission reduction (MW·h)	Social benefits (RMB)
Benchmark model	67900	290.500	711.962	169277.978
Improved model 1	54500	396.786	745.236	165575.339
Improved model 2	59000	355.992	755.904	173278.171

The social benefits generated by trading consists of two parts: economic benefits and emission reduction effectiveness, which is affected by the public's environmental concern η. Therefore, in order to better illustrate how social benefits changes with η, we calculated the changes of social benefits under different environmental concern η values, as shown in Figure 10. We can see that when the η is small, the social utility of carbon emissions reduced by trading is small. At this time, the benchmark model makes the overall social benefits higher than the optimal carbon emission reduction model because of its high economic benefits. However, as people pay more attention to the environment, the carbon emission reduction generated by trading will have higher utility, so that the total social benefits generated by improved model 1 is higher than the benchmark model.

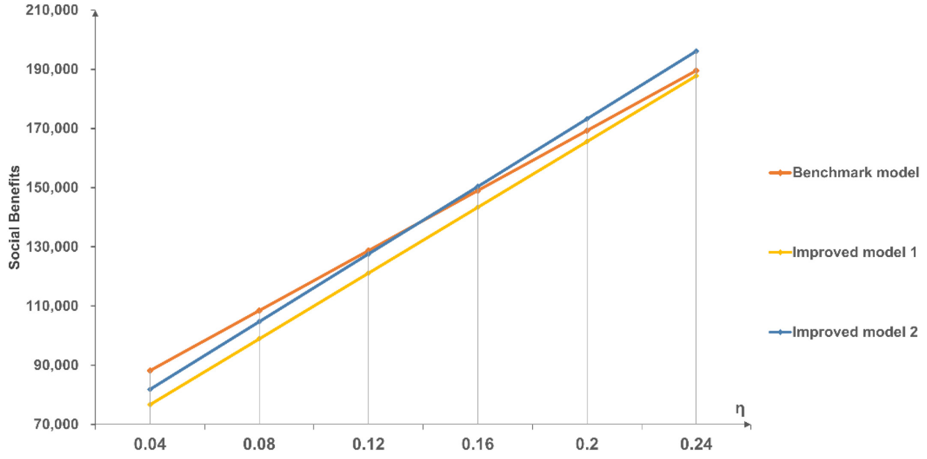

Fig. 10. Sensitive analysis of η on social benefits

4.5 Application of smart contract in blockchain

In 2021, the Ministry of Industry and Information Technology of China proposed to accelerate the application of blockchain technology and industrial development. China's National Energy Administration has made it clear that China will intensify innovation in energy system digitization and intelligent technology, and promote the deep integration of traditional industries and artificial intelligence technology during the "14th Five-Year Plan" period. The government guides the reform of China's power trading market and the application of blockchain technology from the administrative level, so GRT based on blockchain technology is an application worth trying in the market. The application of the model is further explained by taking the carbon emission optimal model transaction as an example. After the transferor and transferee are matched in the trading center, all transaction information is recorded in the node by smart contracts. It is then propagated through the network to the entire blockchain. In the following, we assume that all seven rounds of transactions have passed security checks and block management, and empirically analyze the application effect of blockchain and smart contracts in this model.

Taking the first transaction as an example, the information to be recorded in the smart contract includes: the addresses of Transferor *B* and Transferee *I*, the transaction volume of 500 *MW·h*, the transaction price (the average value of the quotation applied by both trading parties) of 287 *RMB/MW·h*, and the transaction time after negotiation between both trading parties. When the consensus time is reached, the smart contract is automatically executed to complete the value transfer. As the on-grid electricity prices in Henan, Hubei, Hunan and Sichuan are 0.3779, 0.4161, 0.45 and 0.4012, the amount paid by the electricity supply enterprise to the transferor is 200,600 *yuan*, which can be calculated using the on-grid electricity price of 0.4012 *yuan* and transaction volume of 500 *yuan* in Sichuan Province. In the same way of calculation, the amount paid by transferor *B* to transferee *I* is 143,500 *yuan*, and the difference between these two transactions is 57,100 *yuan*, i.e., the settlement price of transferor *B*. It can be seen that when all transaction entities complete their tasks on time, the smart contract will automatically transfer value when the agreed time arrives. The final changes in the financial accounts of each market entity are shown in Table 5.

Table 5. Financial account changes of trading parties (in RMB)

Trading Order	Power Plant A	Power Plant B	Power plant C	Power Plant D	Power Plant E	Power plant F	Power plant G	Power plant H	Power Plant I
1	-	57100	-	-	-	-	-	-	143500

2	23840	-	-	-	-	-	-	-	56400
3	41200	-	-	-	-	-	-	147750	-
4	-	-	26820	-	-	-	-	86550	-
5	-	-	36210	-	-	-	84150	-	-
6	-	-	-	37560	-	-	82800	-	-
7	-	-	-	-	38910	-	81450		
Total	65040	57100	63030	37560	38910	0	248400	234300	199900

Note: The "-" in the table means that the corresponding generator did not participate in this power generation right transaction. The row 8 in the table represents the total change in the account funds of power generation enterprise after all power generation rights transactions are completed.

5. Conclusions and Policy Implications

5.1 Conclusions

The GRT modeling problem has received widespread attention in recent years. Through the GRT process, the power generation plans of different units can be exchanged flexibly. On the one hand, GRT provides more space for power generation and online power generation for low-energy-consuming units and renewable energy units. This makes full use of social resources and improves the overall resource utilization efficiency of the system. On the other hand, GRT reduces the emission of pollutants from high-energy-consuming units. This will help promote the implementation of China's energy conservation and emission reduction policies. In addition, compared with other methods such as improving emission reduction technology, energy saving and emission reduction through GRT means have the advantages of lower cost and strong emission reduction enthusiasm (Zhang et al., 2014). This is bound to occupy an increasingly important position in the future development of the industry.

The way to achieve emission reduction in carbon emission trading is to set carbon quotas for each market entity participating, and the annual carbon emissions of enterprises cannot exceed this quota. Under this rule, firms in the market face three choices. 1) Increase R&D investment and carry out technological innovation, so as to reduce carbon emissions of enterprises. If the actual carbon emissions are lower than the carbon quotas, the remaining carbon emission rights will be sold in the market. 2) Carbon emissions exceed the carbon quotas. Companies buy carbon quotas from other companies at market prices to offset excess carbon emissions. 3) No R&D investment and no purchase of carbon emission rights. Fines are imposed if emissions exceed the carbon quotas. The penalty is usually set by the government and is much higher than the cost of investing in research and development or buying carbon permits. Therefore, in order to obtain more profits, considering that the trading price of carbon emission rights is uncertain, and the volatility risk is large, enterprises will be inclined to carry out emission reduction projects, that is, GRT. So, the transaction motivation of the transferor and the transferee is to save costs, gain more benefits, and finally achieve emission reduction targets.

Due to the instability of carbon quota price, when the carbon quota price is high, high-carbon thermal power generation enterprises will be the transferor for GRT. When the price of carbon quota is low, clean energy and other low-carbon power generation enterprises do not earn much profit from selling the remaining carbon quota. At this time, they will be the transferee for GRT. Different enterprises will adjust their power generation strategies due to different power generation costs, different unit carbon emissions, unstable carbon quota price, and other factors. By integrating the GRT market with the carbon trading market, the state can promote the GRT by regulating the initial carbon quota of different enterprises and carbon quota price, so as to promote the emission reduction activities of enterprises. Enterprises can also choose the trading market more flexibly according to their own conditions, so as to maximize their own interests.

This paper proposes an improved GRT model based on carbon emission optimization to analyze China's current basic national conditions and the decarbonization of the power industry. From the perspective of "carbon peaking" and "carbon neutrality", the remaining carbon emission rights of each generator set are dynamically updated during the transaction process, so that generator sets without carbon emission rights can trade in a timely manner. The model combines the power generation right market with the carbon market to promote emission reduction capabilities. The results show that the total emission reduction of the improved model we proposed is 755.904 tons in 2400 MW·h transaction volumes, which is 43.942 tons more than that of the benchmark model and 10.668 tons more than that of the improved model 1. If the trading volumes increases, the emission reduction effect of trading based on the optimal carbon emission GRT model will be more obvious. Through the emission reduction generated by GRT, enterprises can also use the form of carbon quotas to make it flow into the carbon market again. This can not only realize the secondary allocation of carbon emission rights, but also internalize the carbon assets of power generation enterprises, so as to make up for the profit loss of power generation enterprises in the process of carbon emission reduction, effectively enhance power generation efficiency and accelerate the reform process of the power industry.

The model proposed in this paper helps to solve the problems of information leakage and lack of trust between transaction parties in traditional GRT institutions by establishing a weakly centralized GRT management model with a high trust mechanism. In this mode, the transaction process only needs a central agency to manage the congestion of GRT. The central agency does not involve the release and storage of transaction information, but uses blockchain and smart contract technology to allow nodes in the entire network to independently conduct transaction information. Maintenance and management and automatic transfer of funds. This not only reduces transaction management costs, but also increases participants' trust in GRT and ultimately further power market reform.

5.2 Policy implications

Based on the above research conclusions, we propose some policy implications and future work ideas based on the limitations of this paper as follows.

On the one hand, it is suggested that when setting the initial carbon quota, the government should consider the willingness of power generators to invest in reducing carbon emissions, and also consider the maximum expected profit of power generators. In this way, the optimal allocation of resources can be achieved and eventually it will play a certain role in China's carbon neutralization goal. The government can comprehensively analyze the conclusions of this paper, formulate carbon constraints reasonably, and guide power generators to consider the impact of carbon emission trading prices on corporate benefits in the GRT market, thereby promoting the maximization of social welfare.

On the other hand, it is recommended that relevant departments introduce blockchain technology into the GRT market and support relevant legal and regulatory systems to ensure that emerging technologies are beneficial to the market. In view of the challenges faced by the application of blockchain in the GRT market, it is suggested that the management authorities should quickly strengthen the combination of blockchain technology and transactions. In short, the application of blockchain technology in the GRT market still needs to be continuously explored.

As a preliminary study, this paper inevitably has some limitations. As China's power GRT market is still in the process of further development and improvement, the price of power generation rights in actual transactions is mainly based on bilateral negotiations. Therefore, this paper does not consider the impact of power GRT price changes on power plant trading strategies. With the further standardization and improvement of the market, the impact of the transaction price of power generation rights can be further considered in the analysis of power plant transaction strategies in the future. In addition, smart contracts, as a core technology of blockchain, are still in the initial stage of development. Supporting tools, mature frameworks, and third-party packages are few and far between. Security vulnerabilities can easily occur when writing smart contracts for complex business scenarios. Therefore, in the design process, how to reduce the potential risks of smart contract technology and apply it to the electricity-carbon coupling market, as well as how government regulation can respond to emergencies through blockchain smart contract, are also our future work. Finally, the solution of the heuristic used to solve the optimization problem may not coincide with the global optimal solution. Therefore, future research could explore the development and evaluation of mixed integer programming (MIP) formulations with optimality guarantees as potentially more effective methods for solving hierarchical models.

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