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Article

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Research paper

A gas-on-gas competition trading mechanism based on cooperative game models in China's gas market

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ABSTRACT

A growing number of major natural gas markets in the world have adopted the gas-on-gas competition, or are in the phase of transition to this price formation mechanism. In this situation, China has also started to reform the pricing mechanism by establishing gas trading centers in Shanghai and Chongqing, providing platforms for sellers and buyers to complete the competition-based transactions, marking a transition from oil index pricing to gas-on-gas competition pricing. In order to carry out research on China's gas market based on gas-on-gas competition trading mechanism, this paper builds a natural gas trading model based on cooperative game theory, discusses the key parameter in the models, taking into account of the representative issues of China's gas market in transformation. Also, this paper designs scenarios based on Jiangsu Province, a relatively well-established gas trading market in China, and explores the impact of each issue on the market by using the comparative analysis and sensitivity analysis. This study concludes that establishing the gas-on-gas competition model corresponds to the current gas market development in China. In addition, the market participants need to optimize the contract modes of gas supply, reduce gas supply cost and improve the price affordability, in order to maximize the cooperation benefits in gas market, increase the trading volume, promotes the development and maturation of China's gas market.

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1. Introduction

Two main competing price mechanisms — oil indexation and gas-on-gas competition (GOG, spot or hub-based pricing) are contributors shaping the global gas market (Zhang et al., 2018a,b), which can be divided into three major regional markets: the North American, the European and the East Asian market, with each using different price formation mechanism (IEA, 2013). North America is home to the most mature natural gas market, where gas prices are determined by the interplay of supply and demand — gas-on-gas competition (Grandi, 2014). The gas market there has become a single highly integrated one (Park et al., 2008) and is decoupled from the oil market (Perifanis and Dagoumas, 2018) as the impact of oil price on natural gas price has reduced after the 2008 global financial crisis (Ji et al., 2018). It is found that the economic conditions, total energy demand, US dollar exchange rate and gas consumption are the major factors affecting gas price formation in the market (Li et al., 2017). The European market uses both gas-on-gas competition and oil

indexation, and is now transiting from oil indexation to gas-on-gas competition (Shi, 2016). During the transition, National Balance Point (NBP), Title Transfer Facility (TTF) and Net Connect Germany (NCG) have played the vital roles in the reform of European gas markets (Heather, 2012; Hulshof et al., 2016), and GOG reforms have been proved to be effective (Miriello and Polo, 2015). The East Asian market is essentially linked to oil pricing (Grandi, 2014), and there have been rising calls for establishing a price formation mechanism based on gas-on-gas competition. Major countries in Asia, including China, Japan and Singapore, are making vigorous efforts to set up their own gas hubs (Shi et al., 2019; Shi and Variam, 2016, 2017, 2018; Stern, 2014; Zhang et al., 2018a,b). As a key gas market in East Asia, though the gas prices in China have been regulated by the government for a long time, it has gradually linked to alternative energy of crude oil, LPG and fuel oil only in recent years. The country has also started pricing mechanism reform based on gas-on-gas competition by establishing gas hubs in Shanghai and Chongqing. Hu et al. (2011) and Hu (2014) envisioned a gas hub based on gas-on-gas competition taking into account actual and development trend of China's natural gas market. Tong et al. (2014) systematically explored the necessity, feasibility and phased strategic approaches of building a gas hub in China, and provides decision support for promoting the establishment of China's gas hubs. Shi (2017)

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made suggestions with regards to the formation of benchmark prices for China's natural gas by analyzing the fundamental conditions necessary to set up gas-on-gas competition mechanism and reviewing current situation contributing to benchmark price formation. Though assumptions and suggestions on how to build gas-on-gas competition-based gas market in China proposed by scholars are not uncommon, there have been few discussions on trading behaviors in China's gas market based on gas-on-gas competition.

A growing number of major natural gas markets in the world have adopted gas-on-gas competition, or have been migrating to this mechanism. As a part of its growing efforts in this regard, China has established gas hubs in Shanghai and Chongqing. Though their trading volume accounts for only a small portion of the country's total volume right now due to the relatively short history of such hubs, market prices of natural gas formed through gas-on-gas competition will be a reliable guide as an increasing number of entities trade through hubs.

There is a game between players in market-based gas transactions. Such a game can be either a cooperative game or a non-cooperative game depending on whether a binding agreement can be reached in transactions. Though both games emphasize rational decision making, a cooperative game highlights collective rationality, pays attention to equal distribution of benefits in decision-making, focuses on characteristics of collective behavior, while a non-cooperative game emphasizes individual rationality, gives priority to individual interests in decision-making, and focuses on individual behavioral characteristics. Compared with other gas markets, China's gas market has its own characteristics, as government pays more attention to properly handling the relationship between the enterprises, markets and government in supervision, in order to achieve the unification of national interests, corporate interests and social interests (The State Council, 2017). The theoretical basis of cooperative game theory is to increase interests of all parties without harming any participants, if not, increase interests of at least one party. In the case of China's gas market, though players compete with each other, mutual cooperation also lies in each participants. For instance, China's gas supply is dominated by a few state-owned oil companies, which are essentially extensions of the government and responsible for multi-task objectives, as a consequence of powerful government supervision (Xin et al., 2019). While pursuing profitability, those stated-owned oil companies also need to consider the national demand to ensure energy security, as well as the overall fairness and orderliness of the market. Therefore, they need to cooperate with other players to maximize the overall benefits of the gas market. Normally, for both groups of gas suppliers and buyers, one player's gain is another one's loss under a non-cooperative game. However, China's natural gas market tends to keep the benefits of both parties or even to increase, thus the formation of a strategic coalition between suppliers and buyers will be facilitated and a cooperative game will be formed (Jiang et al., 2016). When facing the strong suppliers, disadvantaged gas buyers can provide a joint offer while competing with them (Paola and Marco, 2005). There is both cooperation and competition between players, creating a unified grand coalition. In this case, cooperative game theory is more suitable for China's gas market.

This paper intends to carry out the research on the hub-based Chinese gas market based on gas-on-gas competition, by exploring four representative issues in the transformation of the market, i.e., contract model selection on supply side, the reform on pipeline transmission pricing mechanism, gas price affordability change on demand side and the reform of the gas pricing mechanism. In addition, the paper examines cooperative benefits allocation options for different players in each scenario with an objective of maximizing cooperative benefits in the gas market,

studies the impact of each issue on the Chinese gas market by comparing market equilibrium prices, cooperative benefits allocation and total market transaction volumes of players in each scenario.

The paper is organized as follows: Section 2 builds natural gas trading model based on cooperative games, and discusses key parameters in the models through taking four representative issues in the transformation of the China's gas market into account. Section 3 presents scenarios based on a target market in Jiangsu Province, home to China's most well-established natural gas market. Section 4 computes cooperative benefits allocation among players in each case with the model and performs sensitivity analysis. Results are also reviewed. Finally, Section 5 provides a summary and concluding remarks.

2. Modeling and analysis

2.1. Modeling

Cooperative game is a mathematical model effectively addressing coordination problems of multiple stakeholders. As Lozano et al. (2013) indicated that the essence of cooperative game is to find a beneficial distribution method promoting cooperation among primary participants, and to reach a fair and just agreement by collective rationality, thus the overall efficiency will be improved. By introducing cooperative game theory into the Chinese gas trading market based on gas-on-gas competition, we could explore how players on supply and demand side allocate benefits upon cooperation, and gain insight on market trading behaviors.

Therefore, the paper builds natural gas trading model based on cooperative game theory. Given it is feasible to maximize the joint payoffs through the model, the paper allocates the joint payoffs among players, figures out market equilibrium prices and explores market-based trading mechanisms. In view that this process is implemented in three steps, the model is divided into three sub models, and each step is performed by a sub model. Model I – Benefit optimization model, a total benefits function for a gas market, which is created through mutual dealings by players in the market. With the goal of gaining the maximum cooperative benefits by a grand coalition, the function calculates transaction volume of each player in mutual transactions subject to relevant constraints, and then figure out benefits for each transaction. Model II – Shapley value allocation model, allocates cooperative benefits using Shapely value method among players in each coalition in the gas market. Cooperative benefits mean collective payoffs generated through market transactions between players in the market. Model III – Trading price model identifies trading prices and market equilibrium prices between players based on definite cooperative benefits distribution plans for the maximum cooperative benefits of the grand coalition.

2.1.1. Benefit optimization model

Assume there are a total of z players in a gas market, including m gas suppliers and n gas buyers ($z = m + n$), forming a grand coalition $Z = \{A_1, A_2, \dots, A_m, B_1, B_2, \dots, B_n\}$ with transferable utility. If any subset S of Z corresponds to a real-valued function $v(S)$, satisfying $v(\emptyset) = 0$, $v(S_1 \cup S_2) \geq v(S_1) + v(S_2)$ and $\forall S_1, S_2 \subseteq Z, S_1 \cap S_2 = \emptyset$, we say that $[Z, v]$ is a cooperative game consisting of a set of players z , and a characteristic function v .

When Gas supplier A_i ($i \in m$) deals with Gas buyer B_j ($j \in n$), the supplier's quotation is P_{Ai} , while the buyer's quotation is P_{Bj} , the trading volume is Q_{ij} , and the payoffs generated through the transaction is π_{ij} , which is calculated by the equation $\pi_{ij} = (P_{Bj} - P_{Ai}) Q_{ij}$. In the equation, P_{Bj} should be less than affordable price W_{Bj} , i.e., the buyer's willingness to pay, while the supplier's

quotation P_{Ai} should be higher than its supply cost C_{Ai} , and the trading volume Q_{ij} should be less than supplier's maximum supply available Q_{Ai} and the buyer's maximum demand Q_{Bj} , as in Eq. (2.1):

$$\pi_{ij} = (P_{Bj} - P_{Ai}) Q_{ij} \tag{2.1}$$

s.t. $P_{Ai} \geq C_{Ai}$, $P_{Bj} \leq W_{Bj}$, $Q_{Ai} \geq Q_{ij}$, $Q_{Bj} \geq Q_{ij}$

Further, when there are l gas suppliers and k buyers in the market forming a coalition S , the payoffs generated through the cooperation between players within the coalition is denoted by characteristic function $v(S)$, then:

$$v(S) = \sum_{i=1}^l \sum_{j=1}^k (P_{Bj} - P_{Ai}) Q_{ij}, \quad \forall l \in m, \quad k \in n \tag{2.2}$$

s.t. $P_{Ai} \geq C_{Ai}$, $P_{Bj} \leq W_{Bj}$, $Q_{Ai} \geq \sum_{j=1}^k Q_{ij}$, $Q_{Bj} \geq \sum_{i=1}^l Q_{ij}$

Benefit optimization model aims at maximizing total payoffs of a grand coalition in a gas market, i.e.:

$$\max v(Z) = \sum_{i=1}^m \sum_{j=1}^n (P_{Bj} - P_{Ai}) Q_{ij} \tag{2.3}$$

s.t. $P_{Ai} \geq C_{Ai}$, $P_{Bj} \leq W_{Bj}$, $Q_{Ai} \geq \sum_{j=1}^n Q_{ij}$, $Q_{Bj} \geq \sum_{i=1}^m Q_{ij}$

2.1.2. Shapley value allocation model

Many cooperative game calculation methods are available and the most representative one is the Shapley value method (Shapley, 1953). The Shapley value is determined by characteristic function v , and denoted by $X = (X_1, X_2, \dots, X_z)$, for any $t \in Z$, X_t is defined as:

$$X_t(v) = \sum_{S \subseteq Z} \frac{(|S| - 1)! (z - |S|)!}{z!} [v(S) - v(S - \{t\})] \quad \forall t \in Z \tag{2.4}$$

where, $X_t(v)$ represents payoffs allocation for Player t , $|S|$ is the number of players in a coalition S , $v(S)$ denotes the collective payoffs for players including Player t , $v(S - \{t\})$ is the collective payoffs for players excluding Player t .

With the premise of maximizing cooperative benefits in the gas market, we allocate the total benefits among players with the Shapley value method, and players who quote in big difference or have large trading volume will enjoy larger allocation.

2.1.3. Equilibrium prices model

When addressing the problem of cooperative payoffs distribution among players in a gas market, it is important to compute trading prices, trading volumes and market equilibrium prices between players, in order to study trading behaviors in the gas market under cooperative game conditions.

The trading price P_{ij} of Gas supplier A_i and Gas buyer B_j can be derived from the following equation:

$$\begin{cases} X_i(v) = \sum_{j=1}^n (P_{ij} - P_{Ai}) Q_{ij} \\ X_j(v) = \sum_{i=1}^m (P_{Bj} - P_{ij}) Q_{ij} \end{cases} \tag{2.5}$$

where, $X_i(v)$ and $X_j(v)$ are payoffs allocations for Gas supplier A_i and Gas buyer B_j respectively (calculated from Eq. (2.4)). As the supply price P_{Ai} of Gas supplier A_i , the purchase price P_{Bj} of Gas buyer B_j and total volume Q_{ij} are known, the trading price

P_{ij} for both supplier and buyer can be calculated with equations and applied to the following equation:

$$\bar{P} = \left(\sum_{i=1}^m \sum_{j=1}^n P_{ij} Q_{ij} \right) / \left(\sum_{i=1}^m \sum_{j=1}^n Q_{ij} \right) \tag{2.6}$$

Eq. (2.6) is designed to determine market equilibrium prices \bar{P} for a grand coalition by calculating a weighted average for trading prices P_{ij} of all participating gas suppliers and buyers at the time of the transaction. It is not the actual trading prices in the coalition, but virtual price indexes reflecting total trading price level of the grand coalition.

2.2. Discussion of related issues

In order to gain a better insight into trading behaviors of China's gas market based on gas-on-gas competition, the paper reviews the characteristics of China's gas market and the key areas of reform in the country's gas industry chain, and explores issues in the market using the natural gas trading model.

2.2.1. Selection of trading contract modes

When making a transaction in China, a gas supplier will sign with a buyer a gas supply contract, which will stipulate the gas source. In China, where gas prices are controlled by the government, it is common not to define certain gas source in gas supply contract and settlement owing to various factors, enabling some costly gas sources to participate in related transactions, making major suppliers suffer from huge cost pressure. However, with the introduction of more market-oriented pricing mechanism, whether a gas source is defined becomes a key factor directly affecting supply cost (by affecting values of the constraint C_{Ai} in Model 1) and benefits distribution among players in a coalition.

Regarding C_{Ai} in Eq. (2.3), a gas supplier may provide a buyer with gas from different sources if the source is not defined in the related contract. Assuming there are h gas sources for Supplier A_i , we can compute the gas supply cost C_{Ai} as follows:

$$C_{Ai} = \left(\sum_{\alpha=1}^h C_{Ai\alpha} Q_{Ai\alpha} \right) / \sum_{\alpha=1}^h Q_{Ai\alpha} \quad \forall \alpha \in h \tag{2.7}$$

If the gas source is clearly labeled, and defined as α ($\forall \alpha \in h$), the supplier provides the buyer with the gas α at a supply cost $C_{Ai\alpha}$.

2.2.2. Reform of pipeline pricing mechanism

In October, 2016, the National Development and Reform Commission (NDRC) announced new administrative measures on pipeline transmission pricing (NDRC, 2016), marking the start of substantial reform on natural gas transmission price forming in China. The measures have strengthened regulation on the price of the natural gas pipeline transmission, preventing pipeline enterprises from gaining excessive benefits from excess supply or monopoly. Soon afterward, The NDRC published the pipeline transmission prices based on the new mechanism for 13 inter-provincial pipeline enterprises around the country (NDRC, 2017a), which were 15% less on average compared with prices before the adjustment (NDRC, 2017b). The reform on the gas pipeline pricing mechanism not only has made major impact on the gas pipeline transmission, but also will affect the collective payoffs distribution in the gas market.

In Eq. (2.3), assume that the unit gas supply cost of Supplier A_i under the current pipeline transmission pricing mechanism is C_{Ai} , known that the original supply cost under preceding pricing mechanism C_{Ai}^* , and the price change caused by the reform on the pipeline transmission pricing mechanism is ΔC_{Ai} , then $C_{Ai} = C_{Ai}^* + \Delta C_{Ai}$.

2.2.3. Gas price affordability change

Gas price affordability reflects a gas user's ability to withstand the gas price, and its price form can be expressed as affordable gas price, which is affected by policies, economic and environment conditions, etc. It tends to change in response to external factors (Wang et al., 2014), resulting in changes in the constraint W_{Bj} in Model I, which in turn affects the payoffs distribution among players in a coalition. For example, in 2017, China took strong measures to replace coal with natural gas, improving price affordability of residential and industrial users, which stimulated the rapid growth of gas demand as well as the development of gas market (Yang, 2018).

In order to investigate the impact of the change in the affordable gas price on the distribution of payoffs, it is assumed that the affordable gas price of Buyer B_j is W_{Bj} , and changes to W_{Bj}^* after affected by external factors, the difference is ΔW_{Bj} , then $W_{Bj}^* = W_{Bj} + \Delta W_{Bj}$.

2.2.4. Gas prices regulated by the government

China's gas market is moving from the controlled pricing mechanism toward a market-oriented one. Since the gas prices have been controlled by the government over decades, and the market-oriented mechanism is still not sophisticated, gas suppliers have been conditioned to managing production and operation costs, developing gas supply plans and sales pricing programs, and buyers are also used to haggling over prices with suppliers and defining gas purchasing programs, in accordance with prices guided by the government. In the meantime, given the small scale and insufficiency of competitive price transactions in the gas hubs in China, more work needs to be done to formulate market prices reflecting the interaction of supply and demand through the hubs. Many transactions are made based on provincial gate benchmark prices set by the governments of different provinces.

The trading price P_{ij} for Gas supplier A_i and Gas buyer B_j is not formed through a cooperative game, but a price controlled by the government-controlled price P^* , based on which payoffs is distributed while the equilibrium trading price \bar{P} for the grand coalition is government-controlled price P^* .

3. Case study

In 2017, China's gas consumption totaled 237.3 bcm, of which 23 bcm or 9.69% went to Jiangsu Province, making the province the biggest, most dynamic and representative gas consumer in the country. Therefore, the paper selects the province for the case study.

Jiangsu's gas market is dominated by CNPC and Sinopec, with gas resources consisting of domestic gas, gas imported from Central Asian countries and imported LNG. The domestic gas and Central Asia-imported gas are transmitted through inter-provincial pipelines (the First and Second West–East Gas Pipelines, the Sichuan to East China Natural Gas Pipeline) and the imported LNG is also sold directly to users through provincial pipeline networks after gasification. The market enjoys a huge user base which is geographically dispersed, and gas is mainly used in four areas: gas power generation, industrial fuel, chemical gas, and urban gas, and each of them can be subdivided depending on uses.

Considering the actual gas industry landscape in Jiangsu Province and its huge but geographically dispersed users, we select a certain county instead of the whole province as the target market for the case study. Assume the market adopts gas-to-gas competition mechanism, whereby both suppliers and buyers trade on the Shanghai Gas Exchange, distribute payoffs among players with the aim of maximizing total payoffs of a grand coalition and forming a market equilibrium price through the game. In addition, we assume that there are two large gas suppliers, A_1

and A_2 , and three buyers, i.e., a petrochemical company B_1 , a gas power plant B_2 and a chemical company B_3 in the target market, and there are three pipeline companies, i.e., D_1 , D_2 and D_3 .

The data of the model is derived according to the following principles: (1) the provincial gate price and pipeline transmission price are set based on the actual prices published by NDRC; (2) the inter-provincial pipeline transmission distance, purchase prices for gas imported from Central Asia and imported LNG (taking into account VAT credit) are defined with reference to actual data of each company; (3) affordable gas prices of users are calculated with the corresponding evaluation method (Li et al., 2012, 2011); (4) gas supply volume of each gas supplier in the target market is reasonably assumed with reference to their market share, and demand of each buyer is reasonably assumed according to the research data.

3.1. Data sources

Assume there are two gas sources available for Gas supplier A_1 . Gas source a is domestic gas from Xinjiang Province with a supply amount of $1.66 \times 10^8 \text{ m}^3$, the gate benchmark price in Xinjiang is the purchase price, i.e. RMB $1.03/\text{m}^3$ (NDRC, 2019a). The inter-provincial pipeline transmission cost totals at RMB $0.568/\text{m}^3$ and includes three parts – the unit transmission price is RMB $0.1416/10^3 \text{ m}^3 \text{ km}$ charged by the inter-provincial pipeline company D_1 (NDRC, 2019b), covering a transportation distance of 2177 km, the unit transmission price is RMB $0.1202/10^3 \text{ m}^3 \text{ km}$ charged by the inter-provincial pipeline company D_2 (NDRC, 2019b), covering a transportation distance of 2163 km, and the Jiangsu provincial pipeline network transmission fee is RMB $0.205/\text{m}^3$, of which RMB $4.463/10^3 \text{ m}^3 \text{ km}$ is charged by the provincial pipeline network company D_3 as the provincial pipeline transmission fee (Rui et al., 2018), covering a transmission distance of 46 km. Gas source b is the imported LNG with a supply amount of $0.34 \times 10^8 \text{ m}^3$. The purchase price is set by reference to CIF Northeast Asia prices (duty paid), i.e. RMB $2.87/\text{m}^3$ in this case, and the gasification fee refers to the actual price at a LNG terminal in Jiangsu Province, i.e., RMB $0.345/\text{m}^3$ in this case, and the provincial pipeline transmission fee is RMB $0.205/\text{m}^3$. Gas supplier A_2 supplies gas from a single source, i.e. domestic gas from Sichuan Province, with a supply amount of $1.50 \times 10^8 \text{ m}^3$, the gate benchmark price in Sichuan Province as the purchase price, i.e. RMB $1.53/\text{m}^3$ (NDRC, 2019a). The inter-provincial pipeline transmission fee totals at RMB $0.650/\text{m}^3$, of which RMB $0.3824/10^3 \text{ m}^3 \text{ km}$ is charged by inter-provincial pipeline company D_3 as the inter-provincial pipeline transmission fee (NDRC, 2019b), covering a transmission distance of 1700 km. The supplier provides natural gas directly to users without using pipeline transmission service from provincial pipeline companies.

As noted earlier, affordable price reflects gas price bearing ability of buyers, and is the highest price buyers are willing to pay. Li et al. (2012) and Li et al. (2011) proposed a set of evaluation methods, including “Net back method”, “Alternative value method” and “Statistical analyze method”, to assess the price affordability of gas buyers. Assume that Gas buyer B_1 is a petrochemical enterprise, with a gas demand of $1.20 \times 10^8 \text{ m}^3$, Gas buyer B_2 is a gas plant, with a gas demand of $1.50 \times 10^8 \text{ m}^3$, and Gas buyer B_3 is a chemical company, with a gas demand of $0.50 \times 10^8 \text{ m}^3$. According to the above methods, the affordable prices for three buyers are RMB $3.55/\text{m}^3$, RMB $2.25/\text{m}^3$ and RMB $0.85/\text{m}^3$ respectively. The relevant parameters used are summarized in Table 1.

Table 1
Relevant parameters in the target market.

S/N	Item	Unit	Gas supplier		
			A ₁		A ₂
			Gas source a	Gas source b	Gas source c
1	Gas supply amount	10 ⁸ m ³	1.660	0.340	1.500
2	Supply cost	RMB/m ³	1.803	3.077	2.180
2.1	Purchase price	RMB/m ³	1.030	2.870	1.530
2.2	Inter-provincial pipeline transmission fee	RMB/m ³	0.568	/	0.650
2.3	Gasification fee	RMB/m ³	/	0.345	/
2.4	Provincial pipeline transmission fee	RMB/m ³		0.205	/
S/N	Item	Unit	Gas buyer		
			B ₁	B ₂	B ₃
1	Gas demand	10 ⁸ m ³	1.200	1.500	0.500
2	Affordable price	RMB/m ³	3.550	2.250	0.850

3.2. Scenario design

Five scenarios are designed based on the case.

Scenario 1: Gas supplier A₁ does not specify the gas source in contracts with the buyers, and supplies gas at the comprehensive gas supply cost C_{A1} , which is calculated as RMB 2.020/m³ with Eq. (2.7).

Scenario 2: Gas supplier A₁ specifies the gas source in contracts with the buyers, and supplies them with the gas at a cost based on the designated gas source. The supply cost of gas source *a* is RMB 1.803/m³ referred as C_{A1a} , and that of gas source *b* is RMB 3.077/m³ referred as C_{A1b} .

Scenario 3: Based on Scenario 1, each pipeline company charges based on preceding transmission pricing mechanism, which has increased by 15% compared with current pipeline price. As the pipeline transportation cost changes, the gas supply cost C_{A1}^* is RMB 2.139/m³, C_{A2}^* RMB 2.295/m³, and the pipeline transmission fee change ΔC_{A1a} is RMB 0.136/m³, ΔC_{A1b} RMB 0.036/m³, ΔC_{A2c} RMB 0.012/m³.

Scenario 4: Based on Scenario 1, assume gas buyer B₃ uses gas as a replacement of coal and its affordable price rises from RMB 0.850/m³ to RMB 2.770/m³, an increase of RMB 1.920/m³, after considering the environment benefits (Wang et al., 2014).

Scenario 5: Based on Scenario 1, assume the gas price is regulated by the government. Both parties make a deal based on the benchmark price for the time being in force in Jiangsu Province issued by the NDRC in 2019, i.e., P^* is RMB 2.030/m³.

In order to further analyze issues in Section 2.2, we compare results from Scenarios 2–5 with Scenario 1 as a benchmark scenario, and each comparison result corresponds to detailed analysis of the issues mentioned above, respectively, as shown in Fig. 1.

4. Results and discussion

4.1. Results

Applying the scenario specific parameters to Natural gas trading model, we got the results of Scenario 1 to 5, as shown in the Table 2.

In Scenario 1, Gas supplier A₁ enjoys the same supply cost at a weighted average supply cost of RMB 2.02/m³ in every transaction by cost sharing, lower than that of Gas supplier A₂, i.e. RMB 2.18/m³. Gas supplier A₁ gains the competitive pricing advantage, enabling buyers to receive more profit allocations through cooperation. As a rational participant in the market, all buyers would give priority to working with Gas supplier A₁, thus, all 200 million m³ gas would be sold and gas supplier A would reap a profit of 101 million RMB. Then the buyers continue to trade with Gas supplier A₂ to cover the remaining achievable

transaction, and Gas supplier A₂ gains a profit of 2 million RMB. Gas buyer B₁ can buy gas at an affordable price of RMB 3.550/m³, the highest among all suppliers, which could make suppliers gain more profit allocation through cooperation. Being rational players, all suppliers would give priority to working with Gas buyer B₁, the demand of buyer B₁ could be met at 120 million m³ gas, and gets a profit allocation of 92 million RMB. Then, the suppliers continue to trade with Gas buyer B₂ for the remaining achievable transactions, and sell the buyer 150 million m³ gas, and the buyer gains a profit allocation of 12 million RMB. In this case, the achievable trades in the market reaches 270 million m³ gas, creating the total benefits of 207 million RMB. The market equilibrium price is RMB 2.44/m³.

In Scenario 2, Gas supplier A₁ enjoys the lowest supply cost (RMB 1.803/m³) with gas source *a*. It preferentially participates in market transactions and sells all 166 million m³ gas it can supply, generating a profit allocation of 115 million RMB. After the trade is made, gas supplier A₂ with the second lowest supply cost (RMB 2.18/m³) under source *c* comes to participate in the market. After Gas supplier A₂ sells 104 million m³ gas, all the achievable transactions are completed and transactions stop. It gets a profit allocation of 4 million RMB. Since Gas supplier A₁'s gas source *b* is the most expensive (RMB 3.08/m³), it is unable to participate in trading even when the achievable transactions are all realized in the market. Each buyer participates in market transactions in the order of highest to lowest affordable price, until all achievable transactions have been completed. Gas buyer B₁ purchases 120 million m³ of natural gas, generating a profit allocation of 105 million RMB, and Gas buyer B₂ 150 million m³, totals at 14 million RMB. The available trades in the market reaches 270 million m³ gas, creating total benefits of 237 million RMB. The market equilibrium price is RMB 2.39/m³.

In Scenario 3, the pipeline transmission price determined by the preceding pricing mechanism is 15% higher than the current one, which increases supply cost of each gas supplier. Gas supplier A₁ enjoys the lowest supply cost (RMB 2.14/m³), and takes priority to selling all 200 million m³ gas it can supply with a profit allocation of 89 million RMB. With the supply cost increasing to RMB 2.295/m³, higher than affordable price of buyers in the remaining achievable transactions, Gas supplier A₂ cannot complete the transactions and transactions halt. Gas buyer B₁ offers the highest affordable price and preferentially participates in market transactions, its demand for 120 million m³ of natural gas is fully satisfied, generating a profit allocation of 85 million RMB. Constrained by the supply capacity of a single gas supplier A₁ in the market, Gas buyer B₂ can only buy 80 million m³ gas, which is far short that what it demands, i.e. 150 million m³, generating a profit allocation of 4 million RMB. The available trades in the market reaches 200 million m³ gas, creating total benefits of 178 million RMB. The market equilibrium price is RMB 2.58/m³.

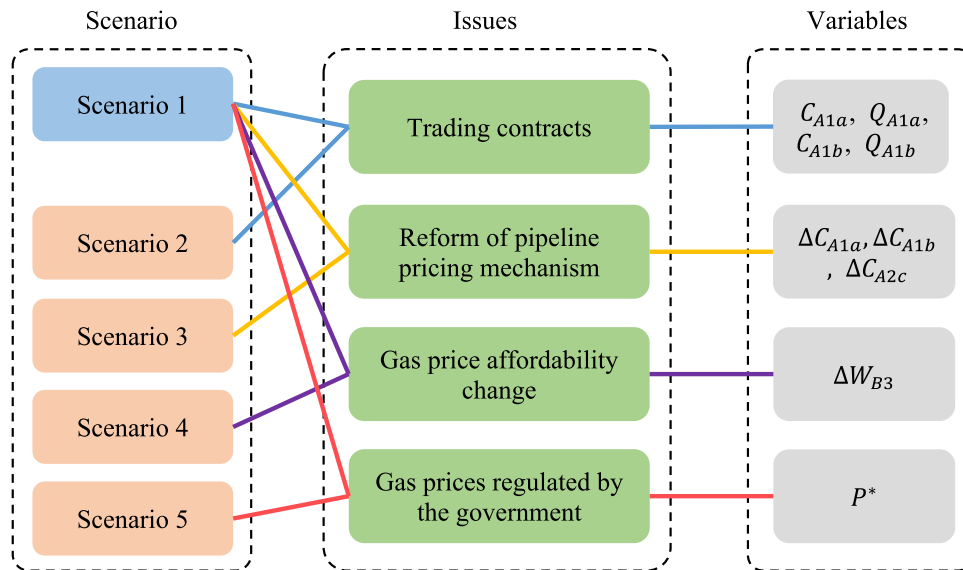


Fig. 1. Schematic diagram of research method.

Table 2
Results in different scenarios.

			Scenario 1			Scenario 2			Scenario 3			Scenario 4			Scenario 5		
			$X(v)$	Q_{ij}	P_{ij}	$X(v)$	Q_{ij}	P_{ij}	$X(v)$	Q_{ij}	P_{ij}	$X(v)$	Q_{ij}	P_{ij}	$X(v)$	Q_{ij}	P_{ij}
Gas supplier	A_1	Gas source a	1.01	2.00	2.52	1.15	1.66	2.50	0.89	2.00	2.58	1.14	2.00	2.59	0.02	2.00	2.03
		Gas source b				-	-	-									
	A_2	Gas source c	0.02	0.70	2.22	0.04	1.04	2.22	-	-	-	0.04	1.20	2.22	-	-	-
Total			1.03	2.70	-	1.19	2.70	-	0.89	2.00	-	1.18	3.20	-	0.02	2.00	-
Gas buyer	B_1		0.92	1.20	2.78	1.05	1.20	2.68	0.85	1.20	2.84	0.92	1.20	2.78	1.82	1.20	2.03
	B_2		0.12	1.50	2.17	0.14	1.50	2.16	0.04	0.80	2.19	0.08	1.50	2.20	0.18	0.80	2.03
	B_3		-	-	-	-	-	-	-	-	-	0.19	0.50	2.39	-	-	-
	Total			1.03	2.70	-	1.19	2.70	-	0.89	2.00	-	1.18	3.20	-	2.00	2.00
\bar{P}			2.44			2.39			2.58			2.45			2.03		
$v(Z)$			2.07			2.37			1.78			2.36			2.02		

In Scenario 4, Gas supplier A_1 enjoys the lowest supply cost (RMB 2.02/m³). It preferentially participates in market transactions and sells all 200 million m³ gas, generating a profit allocation of 114 million RMB. To complete the remaining achievable transactions, buyers continue to deal with Gas supplier A_2 , which sells 120 million m³ natural gas, generating a profit allocation of 4 million RMB. Gas buyer B_1 offers the highest affordable price and preferentially participates in market transactions. Its demand for 120 million m³ of natural gas is fully satisfied, generating a profit allocation of 92 million RMB. Considering the environment benefits, the affordable price Gas buyer B_3 can accept increases from RMB 0.85/m³ to RMB 2.77/m³, and will preferentially participate in the market. Its demand for 50 million m³ of natural gas is fully satisfied, generating a profit allocation of 19 million RMB. Since Gas buyer B_2 's affordable price is higher than the supply cost of the remaining gas suppliers, it can proceed the transaction and satisfy its total demand of 150 million m³ natural gas, generating a profit allocation of 8 million RMB. The available trades in the market reaches 320 million m³ gas, creating total benefits of 236 million RMB. The market equilibrium price is RMB 2.45/m³.

In Scenario 5, the gas prices are regulated by the government. Both suppliers and buyers have to apply the price (RMB 2.03/m³) guided by the government as the trading price. Only Gas supplier A_1 enjoys supply cost lower than the trading price, enabling it to sell all 200 million m³ gas, generating a profit allocation of 2 million RMB. Gas supplier A_2 cannot participate in the market transactions, which will decrease the total supply amount in the

market, resulting in short supply of natural gas. Gas buyer B_1 offers the highest affordable price and preferentially participates in market transactions. Its demand for 120 million m³ of natural gas is fully satisfied, creating a profit allocation of 182 million RMB. Constrained by the supply capacity of a single gas supplier A_1 in the market, Gas buyer B_2 can only buy 80 million m³ natural gas, which is much less than what it demands, i.e. 150 million m³, generating a profit allocation of 18 million RMB. The available trades in the market reaches 200 million m³ gas, creating total benefits of 202 million RMB. The market equilibrium price is RMB 2.03/m³.

4.2. Sensitivity analysis

Setting scenario 1 as the benchmark, the research made the comparison among market equilibrium prices \bar{P} , collective pay-offs v , transaction volume Q in Scenario 2–5. To ensure the effectiveness and stability of the result, the paper performs sensitivity analyses of key variables affecting the comparison results for each issue, as shown in Fig. 1.

4.2.1. Trading contract modes

The difference between Scenario 1 and Scenario 2 is whether gas source is specified by Gas supplier A_1 . In Scenario 1, Supplier A_1 does not specify the gas source, but use the unified weighted gas supply cost, while in Scenario 2, Supplier A_1 specifies the gas source, offers a price based on the cost of each gas source.

Therefore, variables affecting the results are gas supply cost C_{A1a} and gas supply volume Q_{A1a} of gas source a , and gas supply cost C_{A1b} and gas supply volume Q_{A1b} of gas source b .

Single factor sensitivity analyses are performed for each variable. Variation ranges from -50% to $+50\%$, and we take 10% as the final variation. Market equilibrium prices \bar{P} , collective payoffs v , and transaction volume Q for each single factor change in two scenarios are shown in Figs. 2–5.

The sensitivity analysis shows that within the range of -50% to $+50\%$ of each variable, the equilibrium price in the target market under Scenario 2 is not higher than Scenario 1, while the collective payoffs are not lower than Scenario 1, indicating that gas suppliers can lower the equilibrium price in the natural gas market and increase the collective payoffs when transactions are made through the gas supply mode in Scenario 2.

4.2.2. Reform of pipeline transmission pricing mechanism

The difference between Scenario 1 and Scenario 3 is that in Scenario 1, inter-provincial pipeline transmission fee is set by the new mechanism, while it is determined by the original mechanism in Scenario 3. Therefore, the variable affecting the results is the difference ΔC_{Ai} between the transmission prices caused by the reform of the pricing mechanism.

Single factor sensitivity analyses are performed on ΔC_{A1a} , ΔC_{A1b} , and ΔC_{A2c} . Considering that the goal of pricing mechanism reform is to reduce pipeline transmission fee, the actual new pipeline transmission fee is lower than the original pipeline price, that is, $\Delta C_{Ai} \geq 0$. Variation of each factor ranges from 0% to $+50\%$, and we take 10% as the final variation.

As shown in Figs. 6–8, within the range of 0% – 50% of each variable, the equilibrium price in the target market under Scenario 3 is higher than Scenario 1, while the collective payoffs and total trading volume are not higher than Scenario 1, indicating that the reform of the pipeline transmission pricing mechanism (Scenario 1) effectively lowers the market trading price, while helping improve the collective payoffs and market trading.

4.2.3. Gas price affordability change

The difference between Scenario 1 and Scenario 4 is that the environmental benefits of Gas buyer B_3 in Scenario 1 who uses gas as a replacement to coal is not included, whereas in Scenario 4, the affordable price of Gas buyer B_3 comprises of the environmental benefits and it is much higher. Therefore, the variable that affects the result is the affordable price change ΔW_{B3} .

Considering that natural gas is cleaner and more environmentally friendly than coal, replacing coal with natural gas can create environmental benefits, $\Delta W_{B3} \geq 0$, the range of price change is RMB $0/m^3$ to RMB $3.84/m^3$, and we take RMB $0.38/m^3$ as the final change.

As shown in Fig. 9, with the increase in the affordable price change ΔW_{B3} , Gas buyer B_3 in Scenario 4 is able to participate in market transactions gradually, the market equilibrium price is affected by new players, the collective payoffs and trading volume increase, illustrating that enhancing gas price affordability will help improve collective payoffs and gas market transactions.

4.2.4. Gas prices are regulated by the government

Scenario 1 differs from Scenario 5 in that the equilibrium price in Scenario 1 is determined by the market, whereas it is government-controlled in Scenario 5. The variable affecting the results is the government-controlled price P^* .

The current government-controlled price P^* is RMB $2.03/m^3$. With reference to historical gas benchmark prices in Jiangsu Province, the range of change is from -20% to 20% , and we take 5% as the final change.

As shown in Fig. 10, when the government-controlled price P^* is RMB $2.03/m^3$, the equilibrium price in Scenario 5 \bar{P} is lower compared with Scenario 1, while the collective payoffs and trading volume in Scenario 5 are also lower than in Scenario 1. When the government-controlled price P^* is lower than supply cost of each player, the collective payoffs and trading volume in Scenario 5 reduce to 0, and the suppliers refuse to participate in the market. When the government-controlled price P^* rises, the collective payoffs and trading volume in Scenario 5 will increase and reach its maximum when the government-controlled price is at a certain value (optimal government-controlled price, e.g. RMB $2.23/m^3$), and then it will gradually drop as the government-controlled price P^* continues to rise. It can be found that within the range of government-controlled price change, the collective payoffs and trading volume in Scenario 5 are consistently not greater than those in Scenario 1, suggesting that government price controls are not conducive to improving collective payoffs and gas market development.

4.3. Discussions

Comparing scenario 1 with scenario 2, the result suggests that the suppliers with comprehensive cost advantage will benefit from the contract which does not specify the gas sources. They are able to increase sales volume of gas, expand the market share, and dominate the market through cost advantage, but the benefits will not improve along with the increasing sales, which means it is not conducive to maximizing benefits. When a contract specifies certain gas source, part of costly gas sources will not be able to participate in market, the market equilibrium prices will be pushed down and the cooperative payoffs of the overall coalition will increase. Also, the profit allocations of all participants will increase. Apparently, when grand coalition set the maximum profits as the goal, specifying the certain gas source in the contract meets all participants' interests in the gas-on-gas competition-based market.

Comparing Scenario 1 and Scenario 3, the result suggests that the benefits generated from the price cut in transmission will be transferred to the downstream trading markets, after the reform on pipeline transmission pricing mechanism. The benefits of all participants will be re-distributed by the cooperative game between suppliers and buyers, and the profit allocations of all parties will increase, same for the trading volume and total proceeds, while the market equilibrium price will decrease. Obviously, if Chinese government strengthens the supervision on pipelines characterized by natural monopoly and reduces the pipeline transmission fees, in order to prevent the pipeline enterprises obtaining excess returns and lower the downstream gas cost, the gas-on-gas competition-based gas market will grow and the trading market will be promoted.

Comparing Scenario 1 with Scenario 4, the benefits generated of reduced by external factors will be passed to related buyers, then entire market, resulting in changes in market transaction volume and total benefits which will be re-distributed among all participants. Thus the gas trading market will be effected. Recent years, in order to promote the development of gas market, Chinese government has proposed a number of policies, intended to encourage the users to abandon alternative energy and switch to natural gas instead. For instance, local government offer allowance to families using centralized heating service (Shijiazhuang Municipal People's Government, 2017), ensure the purchase price of electricity generated by natural gas does not exceed RMB $0.35/kWh$ benchmark price of coal-derived power plants (NDRC, 2014). The subsidy policies have significantly enhanced price affordability of users consuming natural gas, which is undoubtedly conducive to increasing total proceeds of the

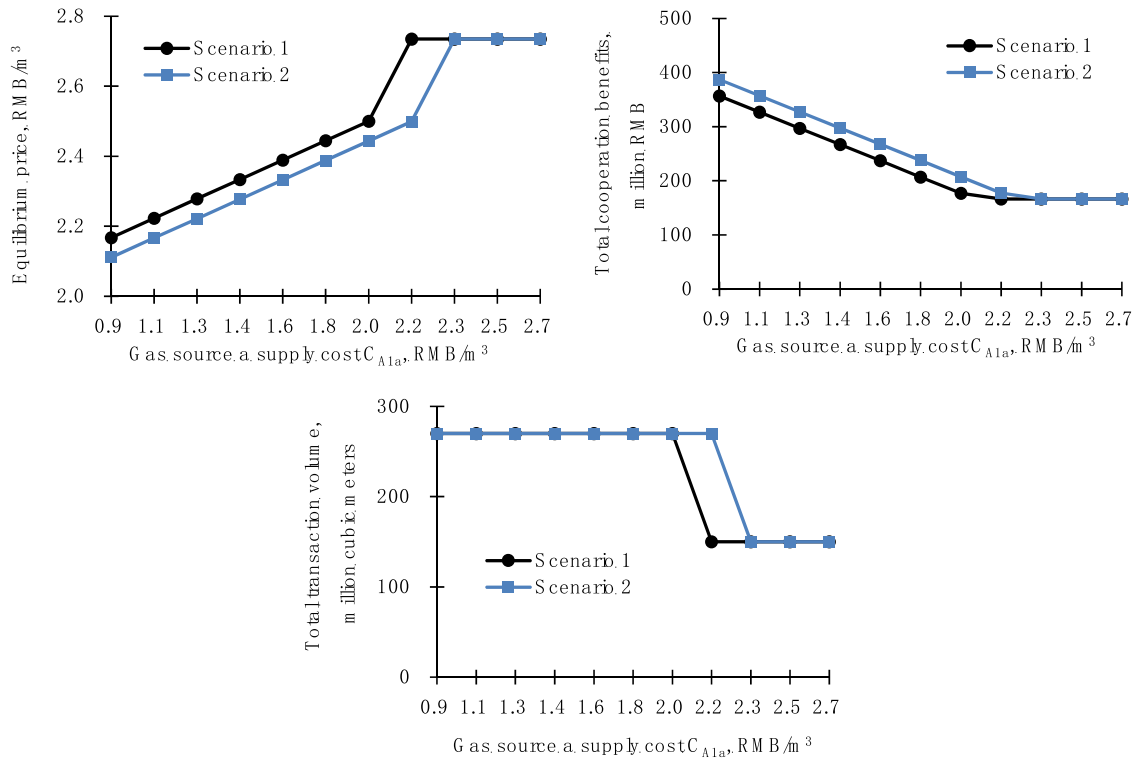


Fig. 2. Sensitivity analysis of gas supply cost C_{A1a} .

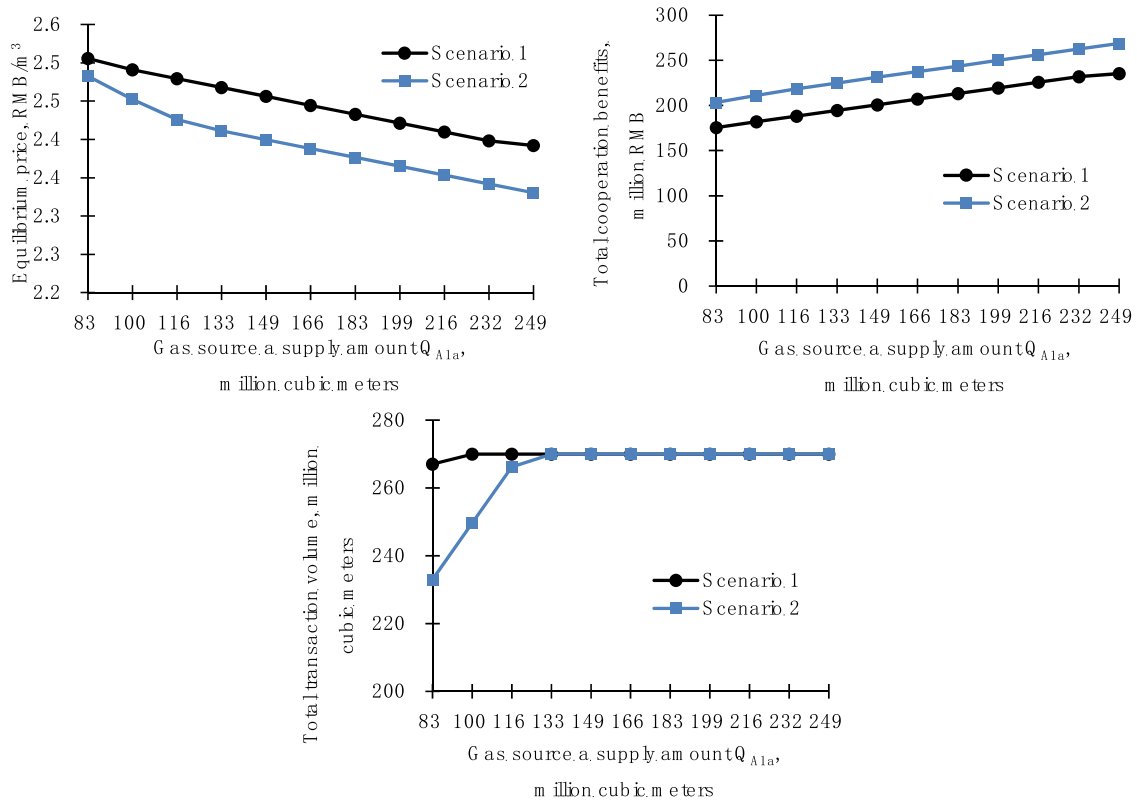


Fig. 3. Sensitivity analysis of gas supply volume Q_{A1a} .

gas market, promoting gas trading and expanding China's gas consumption market.

Comparing scenario 1 with scenario 5, the research shows that the gas suppliers share a less portion of profit than the gas

buyers, which has severely suppressed the suppliers' enthusiasm for production, while stimulates the demand of buyers, resulting a shorten-supplied gas market. In addition, the cooperation pay-offs and total transaction volume in the price-controlled market

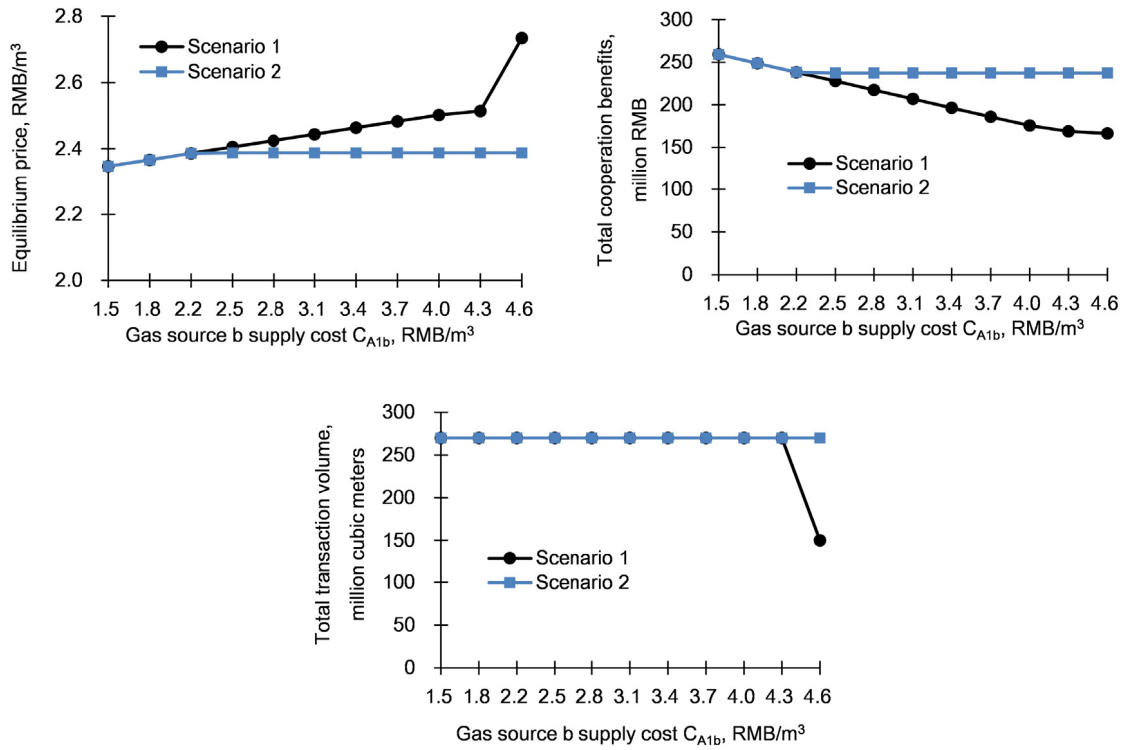


Fig. 4. Sensitivity analysis of gas supply cost C_{A1b} .

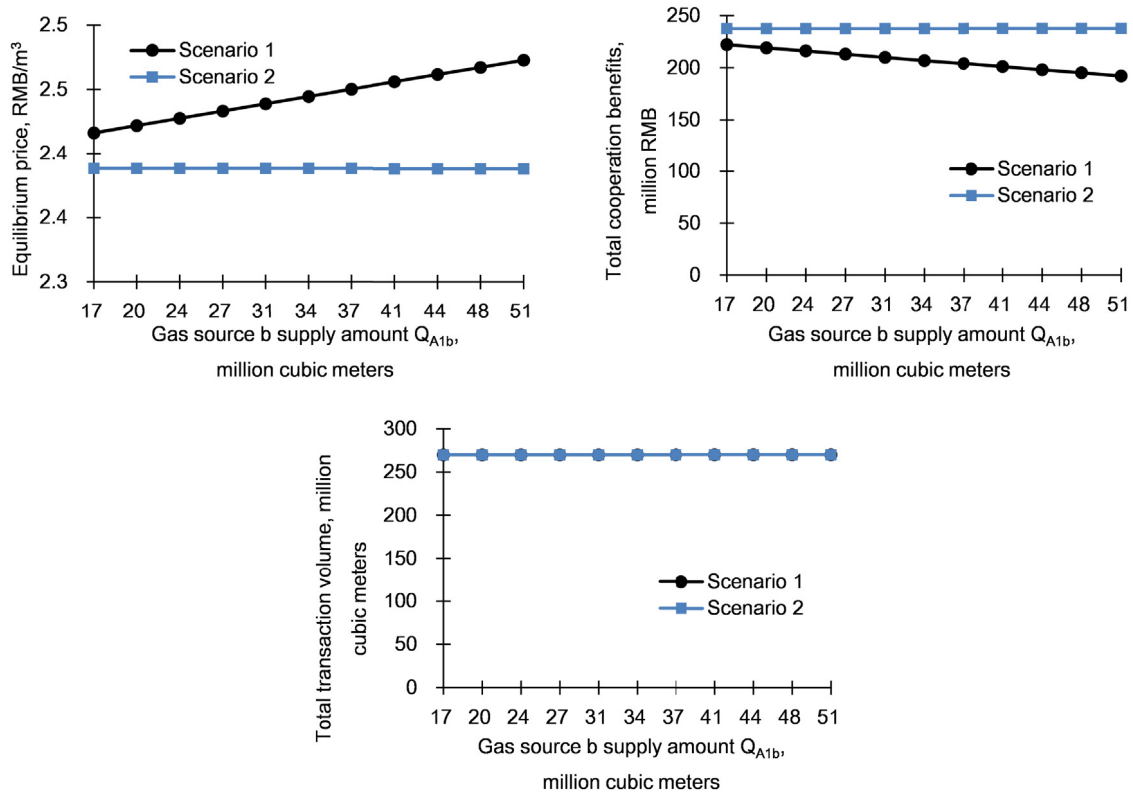


Fig. 5. Sensitivity analysis of gas supply volume Q_{A1b} .

are relatively low, indicating that the development of the gas market has been suppressed. Reviewing the history of China's gas market, natural gas was over-supplied in the early stage of market development, and its low price set by the government had tremendously stimulated the market demand and promoted

the development of gas industry (Yang, 2018). As the market expanded, to meet the demand, gas suppliers need to supply their gas sources with the higher supply cost, leading the supply cost to keep increase, even reached the top limit of gate prices guided by the local government, which were either too low or not

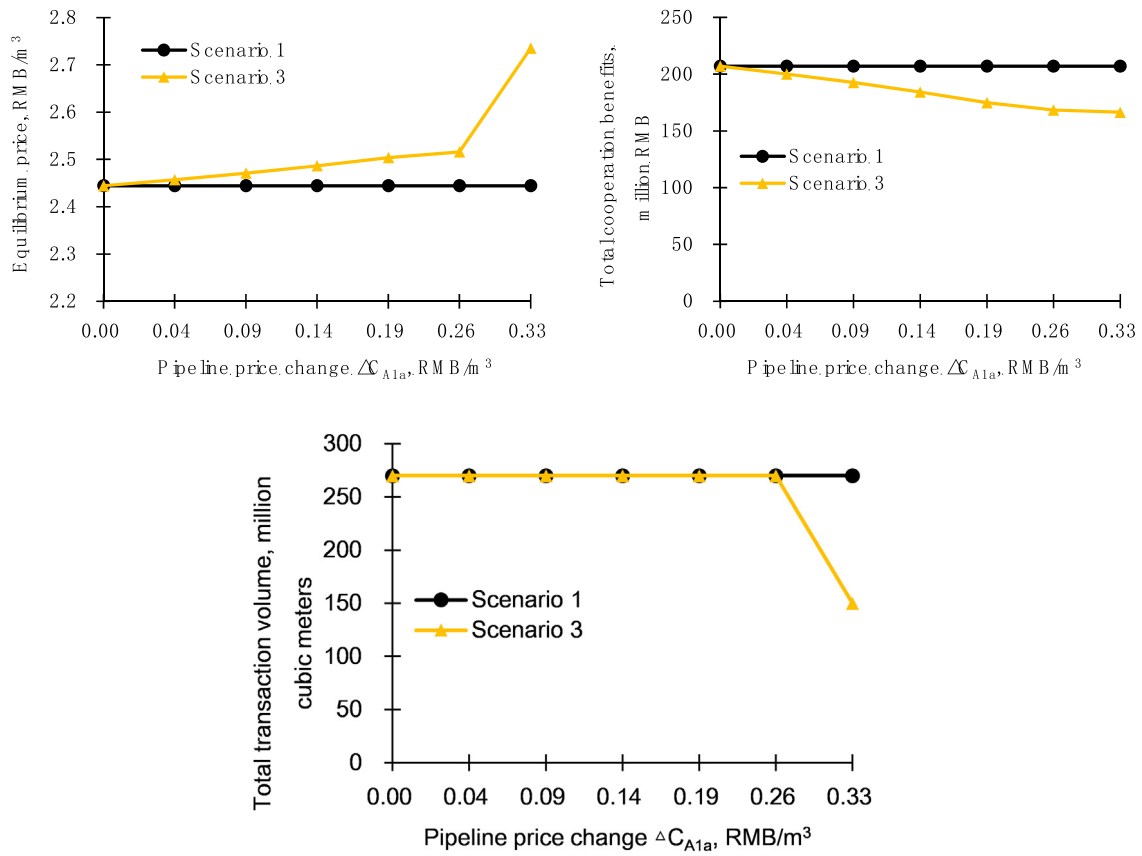


Fig. 6. Sensitivity analysis of changes in pipeline transmission price ΔC_{A1a} .

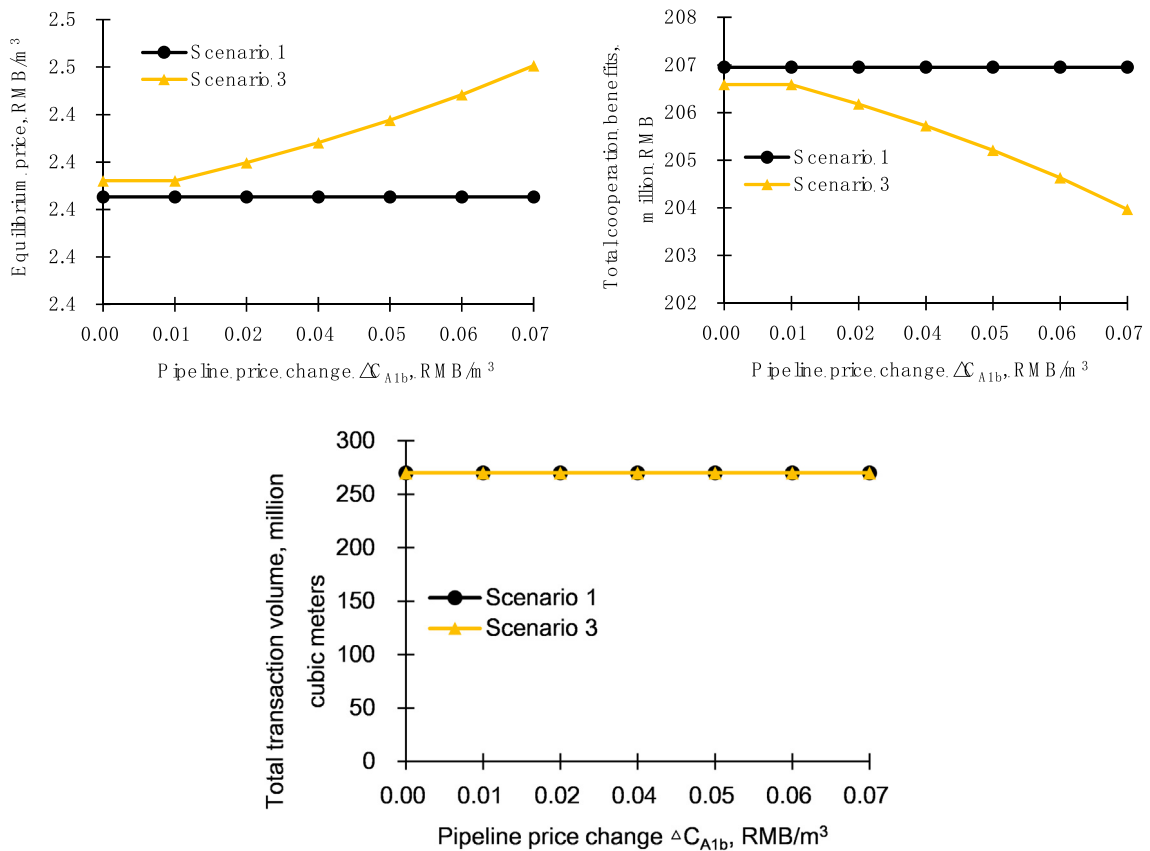


Fig. 7. Sensitivity analysis of changes in pipeline transmission price ΔC_{A1b} .

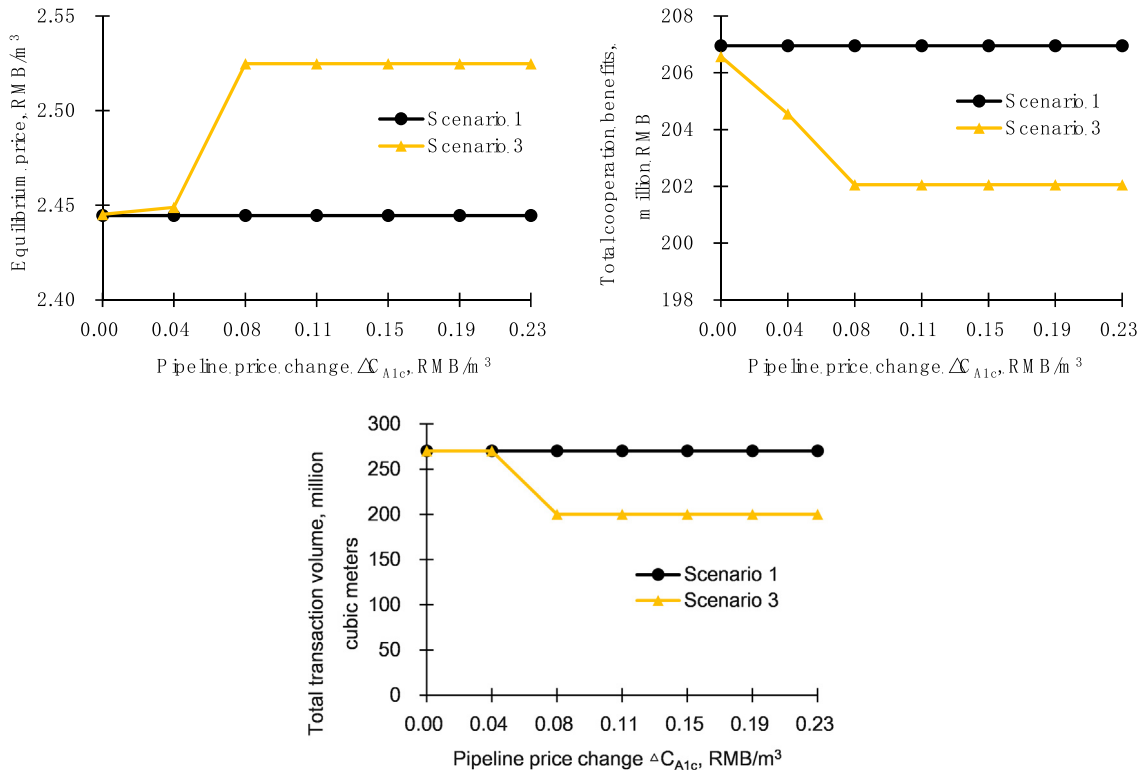


Fig. 8. Sensitivity analysis of changes in pipeline transmission price ΔC_{A2c} .

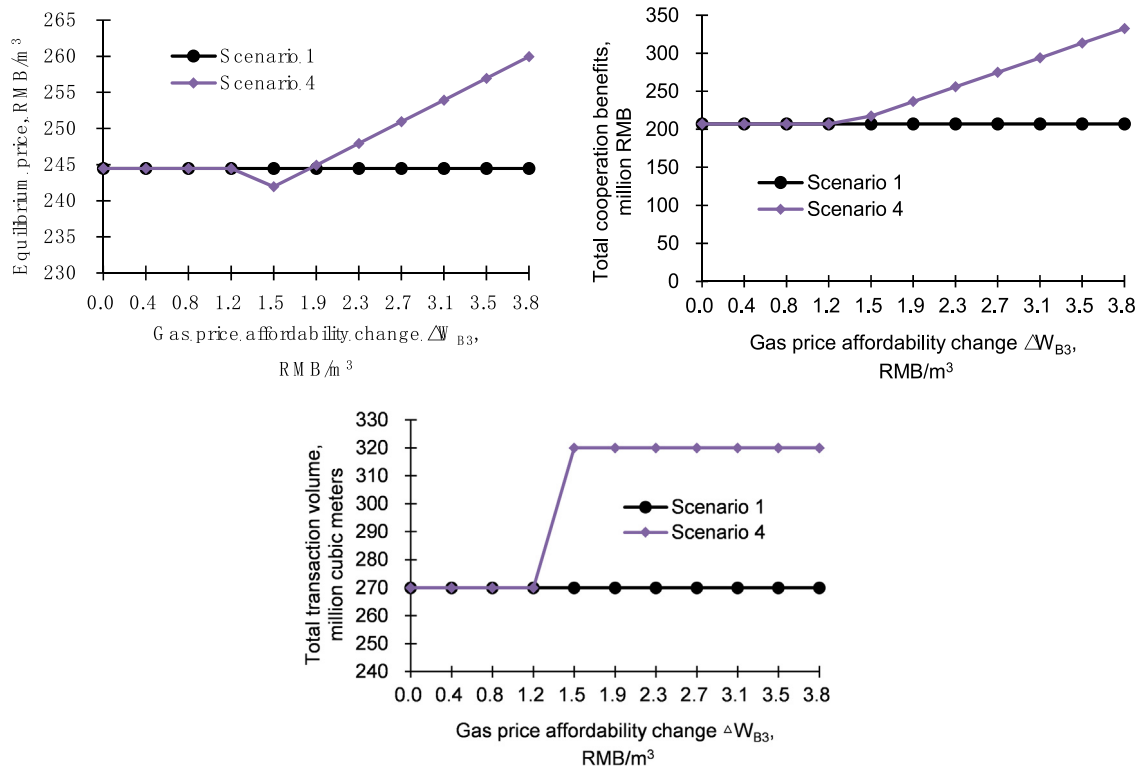


Fig. 9. Sensitivity analysis of gas price affordability change ΔW_{B3} .

adjusted in time. Gas suppliers were reluctant to supply natural gas, which seriously constrained the trading volume and resulted

in the bottleneck of the market development. Clearly, relaxing the price controls on gas and realizing the gas-on-gas competition is

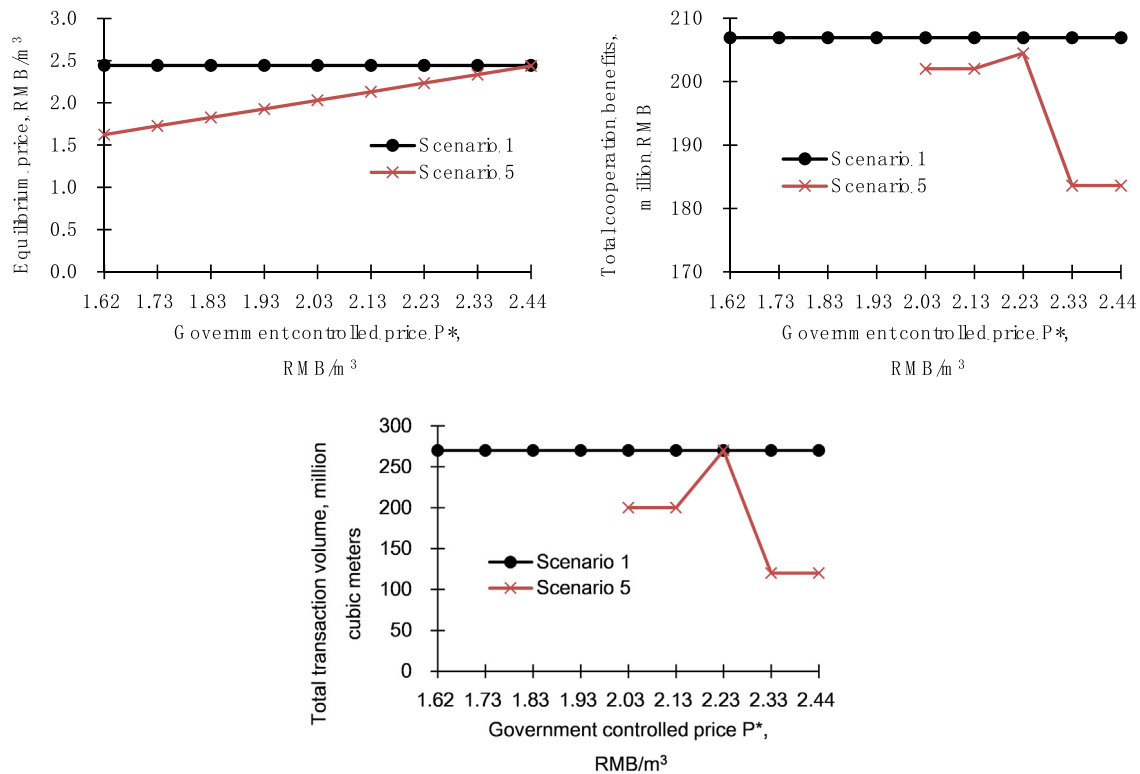


Fig. 10. Sensitivity analysis of government-controlled prices P^* .

the right tool to address the issue mentioned above. Also, Chinese government has been implementing a series of reform initiatives to build a gas pricing system based on gas-on-gas competition.

5. Conclusions

In order to carry out the research on Chinese gas market based on gas-on-gas competition oriented by gas hubs, this paper builds a gas trading model based on cooperative game theory, discusses the representative issues in the phase of market transformation, and performs multi-scenarios and sensitivity analyses with reference to different cases. The study suggests that it has become increasingly difficult for the traditional gas pricing mechanism to meet the needs of the rapid development of the country's gas market, resulting in rigid benefits distribution system. The mechanism has seriously constrained the trading volume and became the bottleneck of market development. It is imperative to establish a gas pricing system based on gas-on-gas competition, optimize benefits distribution and expand market trading volume. The study concludes that China should proceed with gas market reform, speed up the establishment of a gas-on-gas competition trading mechanism, and take measures to optimize contract modes of gas supply, reduce gas supply cost and improve price affordability, in order to maximize cooperative benefits in the gas market, expand market transaction volume and promote the development and maturation of its gas market.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Xutao Rui: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Lianyong Feng:** Conceptualization, Methodology, Validation, Supervision, Project administration. **Jingxuan Feng:** Formal analysis, Resources, Data curation.

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