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Assessing the congestion cost of gas pipeline between China and Russia

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ABSTRACT

Determining transportation routes is of great importance for advancing China-Russian gas cooperation, which has been hanging in the balance. This paper employs a general equilibrium model to assess the congestion cost of diversified gas transmission schemes between China and Russia on domestic long-distance pipelines, which addresses the inherent limitations of exclusively considering transport impacts in the decision-making process. Findings reveal a notable decrease in pipeline congestion incidents for the route integrated with the Shaan-Jing system, thus lending empirical credence to the feasibility of the proposed scenario involving Mongolia. In addition, key routes are defined in this paper based on congestion costs, which emphasize the challenges posed by bilateral gas cooperation to China's long-distance natural gas pipeline network, necessitating a strategic focus on critical pipelines as the top priority of pipeline optimization efforts in the future. This paper provides valuable insights into planning the second China-Russia gas pipeline and the decision-making process for the future development of long-distance pipeline infrastructure.

1. Introduction

While the completion of the first China-Russia gas pipeline occurred relatively recently, discussions regarding the construction of a second pipeline have been ongoing. The China-Russia East-Route Natural Gas Pipeline (CRER) was completed in December 2019, marking the culmination of a 30-year-long negotiation process between China and Russia [1]. A significant milestone was achieved in 2022 with the official commissioning of the southern section of the pipeline, extending from Taian to Taixing, thereby completing the entire pipeline network. The transported gas volume through this pipeline is projected to reach 38 billion cubic meters (bcm) annually by 2024, constituting 8 % of China's total gas consumption and 20 % of its gas imports. Despite the recent completion and the significant amount, both countries considered the first pipeline not large enough [2].

Over the past decade, there has been ongoing deliberation between China and Russia regarding establishing a second gas pipeline with a combined annual capacity of 50 bcm [3]. However, a definitive decision regarding the selection of one among the three proposed routes has yet to be reached. The choice of route alternatives holds significant importance in bilateral cooperation decision-making, notwithstanding the extensive discourse surrounding gas trading prices and volumes [4]. China prefers the eastern route when selecting natural gas cooperation routes, primarily driven by the concentration of natural gas consumption areas in the east region. Conversely, Russia's inclination leans towards the narrower western route, considering the geographic distribution of gas fields. Consequently, it is imperative to systematically address the pivotal factors that warrant consideration in the decision-making process and to establish a robust methodology for the judicious selection of gas transmission routes between China and Russia in the context of their prospective collaboration within the natural gas sector.

An additional 50 bcm in bilateral gas trading and the construction of new pipelines are expected to significantly impact China's domestic long-distance gas pipeline network, which will influence China's decision-making on the routing of Russian-Chinese gas pipelines. As China's domestic gas pipeline network becomes more interconnected, offshore pipelines will indirectly affect other pipelines through their directly connected pipelines. Thus, the present exposition embarks upon a comprehensive inquiry into the manifold impacts arising from diverse options for the transportation of China-Russian gas upon China's extant long-distance gas conduit framework. The central objective of this

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inquiry is to identify the optimal strategy that minimizes disruptions to China's extensive natural gas pipeline network. Furthermore, this research delves into the potential consequences of different transportation routes on the configuration of the market's supply structure and related aspects.

In this study, we examine the issue of route selection from the perspective of congestion costs. It emphasizes the limitation of relying solely on transportation distance and gas prices when determining the optimal route for the Russian-Chinese natural gas transmission program. Congestion costs, which encompass the economic and efficiency-related expenses arising from the overutilization or saturation of a transportation or communication system, are employed to elucidate the impact of the Russia-China natural gas transmission program on the natural gas pipelines within the region. Firstly, we devise scenarios based on three distinct gas transmission routes derived from the historical context of China-Russia gas cooperation negotiations. Secondly, we utilize a market equilibrium model to quantify the congestion costs associated with the long-distance natural gas pipeline network under various scenarios and to compare the congestion costs incurred in the context of the three scenarios. In addition to examining congestion costs, we also analyze capacity allocation within the pipeline network and the involvement of third-party traders in the market. These additional factors contribute to the overall decision-making process.

This paper endeavors to supplement the decision-making framework for the China-Russia gas transmission route with the congestion cost, which is ignored despite its importance. Firstly, geopolitics, gas price, and transportation distance are the main factors affecting China-Russian cooperation [5,6], for which China, as the demand side of China-Russian natural gas, ignores the impact on the domestic long-distance pipeline network natural gas. Nevertheless, the domestic long-distance pipeline network plays a pivotal role in China's natural gas market, directly influencing the implementation of China's foreign natural gas cooperation decisions. Secondly, this paper employs congestion costs as a critical parameter for evaluating the ramifications of route selection on domestic pipeline networks. While extant literature predominantly focuses on transportation distance's impact on gas costs during decision-making processes, it disregards the congestion costs stemming from diverse routes, constituting a significant aspect of overall gas expenses [7]. By integrating congestion costs into the assessment of pipeline alternatives, this paper offers a more comprehensive framework for decision-makers, thus furnishing stakeholders with invaluable insights conducive to well-informed choices regarding the prospective second China-Russia pipeline. Consequently, the findings of this research furnish stakeholders with a holistic perspective, enriching the decision-making process concerning China-Russia gas cooperation.

The cooperation in natural gas between China and Russia holds profound implications for the two nations involved and the broader global energy landscape. This partnership in the China-Russia gas trade diversifies energy sources and bolsters China's energy independence. According to PipeChina, the completion of the CRER is expected to alleviate gas-supply bottlenecks in the Yangtze River Delta, a region of paramount economic importance in China. Simultaneously, this collaboration allows Russia to expand its gas export capacity and gain entry into China's rapidly growing energy market, thereby substantially contributing to Russia's economic progress and broadening its export portfolio. Positioned as a prominent global supplier of natural gas and oil, the collaborative venture between China and Russia in the natural gas sector has the potential to reshape global patterns of natural gas supply and demand [8]. Consequently, research endeavors to facilitate and enhance China-Russian natural gas cooperation have ascended to paramount importance. More importantly, determining the optimal route for gas pipelines is a primary research priority. As governments and energy companies decide the optimal route for the proposed gas pipelines, it is imperative to comprehend the implications for China's foundational natural gas infrastructure system.

In the next section, a brief literature review will be introduced. Then, we will propose the natural gas market model and four scenarios. Subsequently, the main findings will be discussed. Finally, conclusions and some policy implications will be proposed.

2. Literature review

2.1. China-Russia natural gas cooperation

As early as November 2014, China National Petroleum Corporation (CNPC) and Gazprom executed a framework agreement delineating cooperative measures for the China-Russian West route. This collaborative arrangement outlines Russia's intention to furnish an annual supply of 30 bcm of natural gas through the China-Russia west route, with a stipulated gas supply duration of 30 years. Subsequently, in May 2015, CNPC and Gazprom formalized an accord encompassing the fundamental terms governing the China-Russian western pipeline's provisioning of gas to China. Gazprom designated this conduit as Power of Siberia II, formerly recognized as the Altai pipeline. The collaborative efforts culminated in June 2018 when the heads of state of China, Russia, and Mongolia convened to deliberate upon the blueprint for constructing the Russia-Mongolia-China natural gas pipeline, which evolved into the China-Russia Middle Line, constituting the second phase of the China-Russia West Line initiative. The adjustment also increased the annual gas supply from 30 bcm to 50 bcm.

The China-Russia natural gas cooperation has aroused much interest among politicians and academics. Some studies proposed that China-Russia natural gas cooperation increasingly impacts global energy markets and geopolitical security among countries [6,9]. For example, Orlov has analyzed the long-term influence of Russia and China's second natural gas agreement on the European gas market. After disrupting Russian gas transportation via Ukraine, Europe will face potential gas supply risks [9]. Europe is struggling to find alternatives to gas imports while failing to commit to diversification despite Russian dominance, even though the US will be a potential rival for Russia [10]. In the present global environment, Russia is progressively reorienting its focus on natural gas cooperation towards exporting to China. Thus, several studies focus on promoting China-Russian natural gas cooperation, as certain aspects of future collaboration are still being negotiated.

Geopolitical, natural gas pricing dynamics, energy transition objectives, and the international environment collectively influence the China-Russian natural gas trade [11]. For instance, Henderson attempted to synthesize China and Russia's business and political considerations while predicting future energy cooperation [7]. Shadrina assessed the possibility of China-Russian natural gas cooperation by analyzing the development trends of China's natural gas market [12]. As these papers make clear, the volume of Russia's exports depends mainly on developing the gas market in China. Therefore, it is imperative to analyze the promotion of bilateral gas cooperation from the Chinese perspective. Additionally, Koch-Wesers comprehensively examined the historical context of China-Russia negotiations on natural gas cooperation, encompassing geopolitical, pricing, and routing factors [13]. Henderson delved into the history of China-Russian natural gas price negotiations, offering insights into potential influencing factors to facilitate progress in the negotiations [14,15]. These studies have comprehensively analyzed the main factors affecting China-Russia natural gas cooperation, in which infrastructure such as pipelines is an

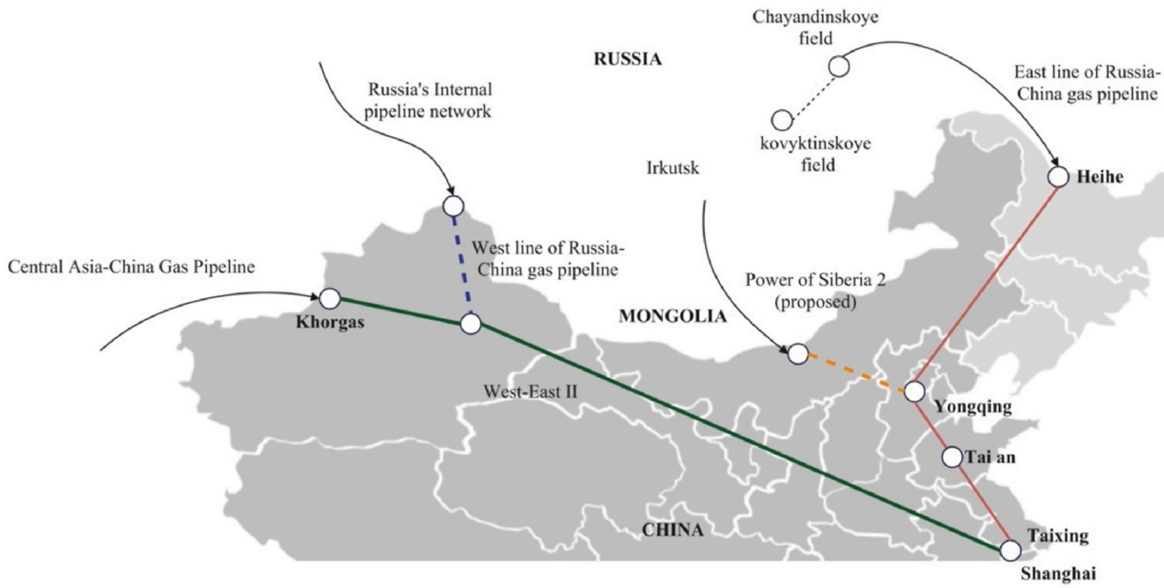


Fig. 1. Potential gas pipeline routes from Russia to China (adapted from Ref. [2]; [34]).

essential factor affecting cooperation. Still, none of these papers have studied them more precisely.

2.2. Difference interests in the proposed second Russia-China gas pipeline

As early as September 2022, Gazprom said it wanted to speed up the construction of the China-Russia Western Route gas pipeline project [16]. Russia and China have proposed different plans for pipeline routes under national circumstances. Considering the construction and transportation cost of the pipeline, Russia prefers the gas pipeline to enter China in northern Xinjiang and to connect to the long-distance pipeline network upstream of the West-East II, which was the plan of the initial cooperation between China and Russia. Indeed, the fundamental reason why Gazprom lobbied hard for the Altai pipeline was that it would enable Gazprom to transport its surplus gas from Europe to China, enhancing its ability to use gas as a political bargaining tool [17]. This plan means that China's natural gas will bear more domestic transportation costs, as natural gas consumption in China is mainly centered in the eastern region.

Conversely, to reduce domestic gas transportation costs, China would prefer a gas pipeline, the China-Mongolia-Russia pipeline, to pass through Mongolia, enter China from Inner Mongolia, connect to the Shaanxi-Beijing system, and then head south to Shanghai [18]. This option is the most bilaterally recognized pipeline route under active negotiation. It is the successor to the Gazprom-operated Power of Siberia 1 pipeline, which runs from eastern Siberia to northern China [19]. This route would directly and effectively alleviate gas tensions in the Beijing-Tianjin-Hebei region and reduce domestic transport costs by shortening transport distances. In addition, adding the transportation capacity of the China-Russian eastern route, which is almost fully operational, could be considered a third alternative. Increasing the transportation capacity of existing pipelines is more economical than building new ones, to some extent.

Currently, the selection of routes is mainly based on the location of the gas source, the transportation distance, and the price of natural gas. However, when considering this issue from a Chinese perspective, it is necessary to assess the impact of different options on pipeline congestion within the country, which has been neglected in many studies.

2.3. The system-wide impact of the new pipeline

From the beginning of the China-Russian natural gas trade negotiations, the routes of natural gas pipelines have been one of the most concerning and contentious issues between the two sides [20,21]. Many specialists have mentioned in their research the importance of pipelines for the energy cooperation of both sides [2,22]. For example, the layout of pipelines will influence the distribution of gas storage, affecting other decisions in the natural gas market [23]. Some studies will touch on pipelines in analyzing the energy strategy [24,25].

Moreover, the route choice mainly considers the transportation price, which is primarily affected by the distance, which is why the change from the Altai route to the Power of Siberia-I route [7]. By promoting the China-favored route, gas trade cooperation seems to be more smoothly accomplished [26]. However, it is imperative to consider that insufficient capacity in existing pipelines can result in congestion, leading to the imposition of congestion fees and subsequently escalating transportation costs. Hence, when making decisions about pipeline layout while factoring in transportation costs, it becomes crucial to account for the potential impact of new pipelines on the arrangement of existing lines and the potential crowding costs arising from increased volumes of natural gas. However, most studies mainly focus on optimizing domestic long-distance pipeline networks, such as pipeline network optimization studies considering natural gas flow configuration, and pay little attention to the potential impact of overseas natural gas routes.

3. Methodology

The analysis aims to shed light on the potential implications of these alternative routes, emphasizing their impact on congestion costs within China's natural gas network. By addressing the gap in existing assessment efforts that often overlook the comprehensive effects on domestic infrastructure systems, this study offers essential insights to inform decision-makers involved in the pipeline route selection process.

The critical aspect of this analysis lies in its concentration on congestion costs. This factor plays a pivotal role in determining the efficiency and operational stability of a gas transportation network.

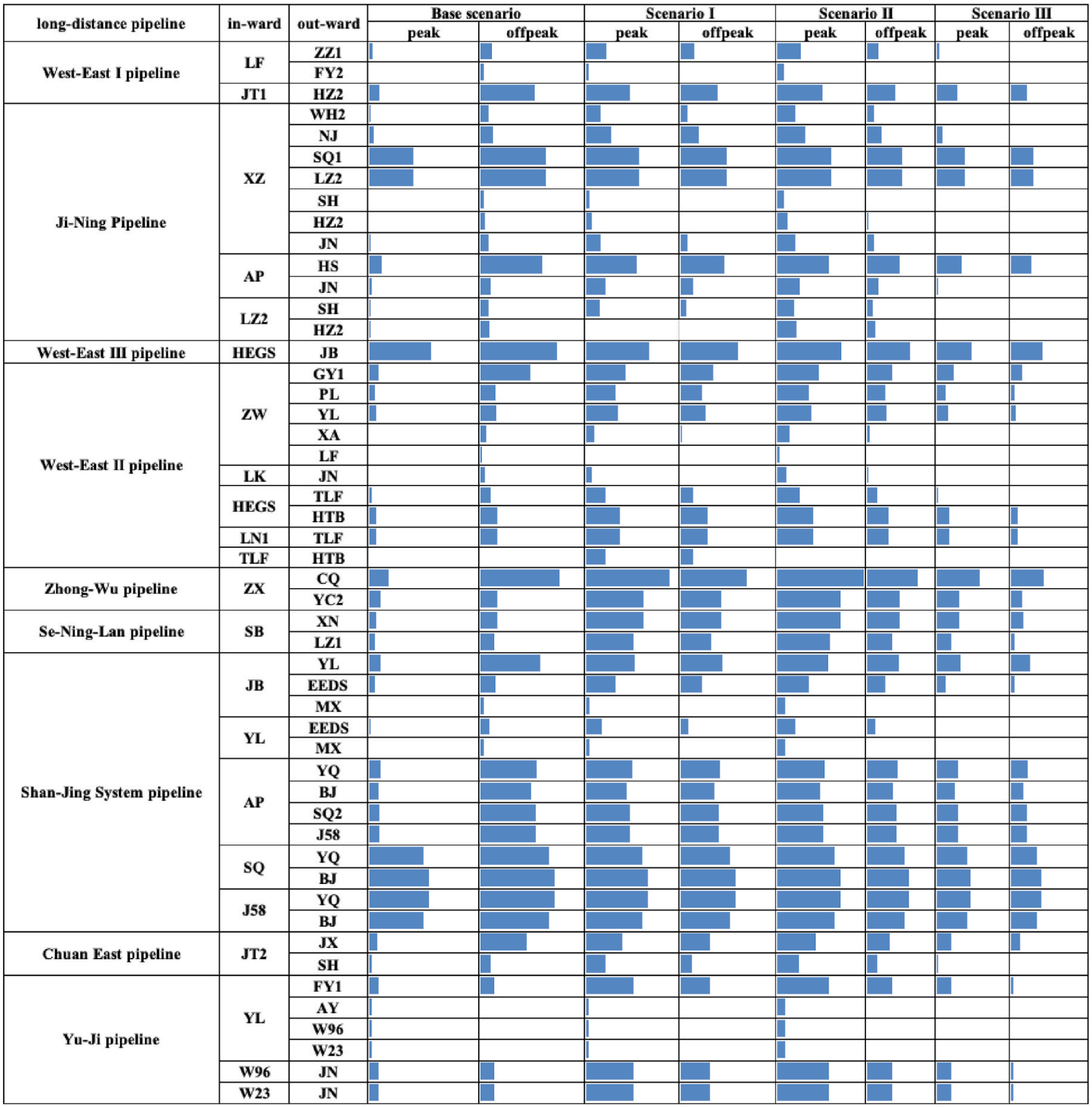


Fig. 2. The comparison of congestion costs between four scenarios.

Congestion costs arise from the potential bottlenecks, capacity limitations, and system imbalances that can emerge due to changes in pipeline routes. Neglecting these costs could result in suboptimal resource allocation, compromised energy security, and economic inefficiencies.

3.1. China natural gas market equilibrium model

The natural gas market is a supply chain system that includes upstream producers, midstream storage and transportation operators, traders, and downstream consumers, where the decisions of each of these agents affect the changes and development of the natural gas system. The natural gas equilibrium model is well matched to this characteristic. In line with this rationale, we have employed the natural gas equilibrium model formulated by Wei [27] and simplified the marketing behaviors of storage operators based on the conclusion.

In the natural gas market, producers produce and sell natural gas to end consumers and third-party agents while assuming the costs associated with extracting and transporting natural gas. Producers must carefully determine the optimal volume of natural gas to allocate to each marketing behavior, adhering to their production capacity constraints to maximize their profits. Producers aim to maximize their discounted profits over time while considering the various costs and revenues associated with each marketing behavior.

The producers, including the domestic gas producers and the importers, maximize the net profit by selling the gas and controlling the production cost.

$$\max_{\substack{T_{wct}\\T_{wpt}\\T^{'}_{wpt_2}\\T_{wst_2}\\FLOW^{W}_{mnt}}} \left\{ \sum_{w\in W}\sum_{t\in T} d_t\left(\pi^{C}_{t}T_{wct} + \pi^{W\to P}_{t}T_{wpt}\right) + d_{t_2}\sum_{w\in W}\left(\pi^{S\leftarrow W}_{t_2}T_{wst_2} + \pi^{W\to P}_{t}T^{'}_{wpt_2}\right) - \sum_{w\in W}\sum_{t\in T} d_t cf^{W}_{t}\left(T_{wct}+T_{wpt}+T_{wst_2}+T^{'}_{wpt_2}\right) - \sum_{t\in T}\sum_{m\in M}\sum_{n\in N} d_t\left(\tau^{A}_{mnt}+\pi^{Areg}_{mnt}\right)FLOW^{W}_{mnt} \right\} \quad (1)$$

Due to engineering and economic factors, the sales volume is

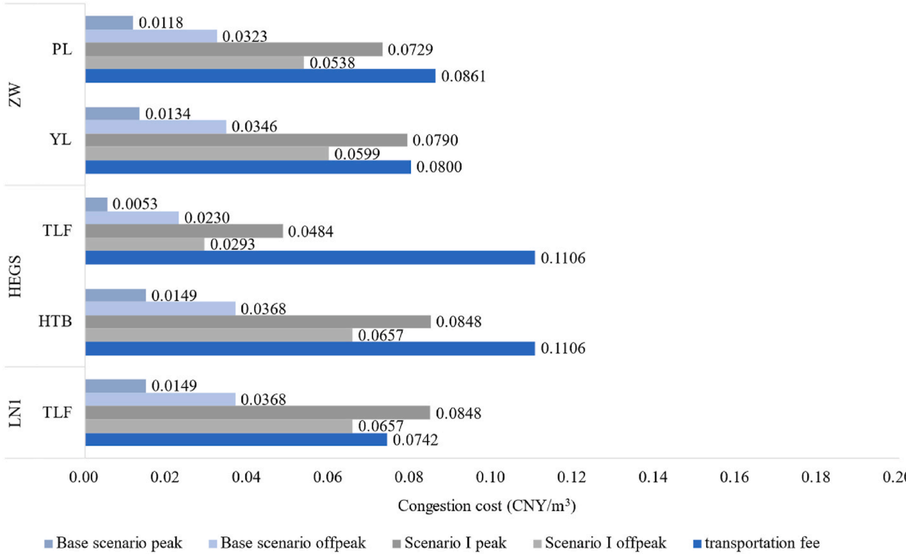


Fig. 3. The congested fee of West-East Pipeline II in Scenario I.

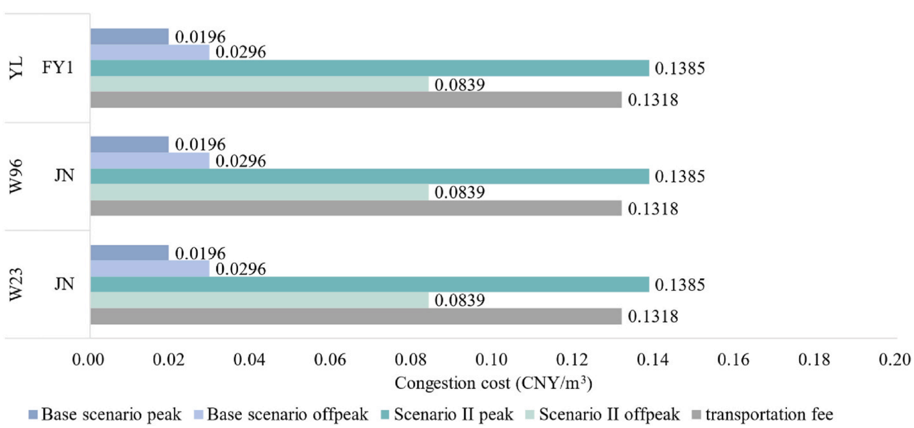


Fig. 4. The congested fee of the Yu-Ji pipeline in Scenario II.

restricted by the daily production $\overline{PR_t}^W$ and the yearly sales volume $\overline{PROD}^W$.

$$s.t.\ \sum\nolimits_{c\in C} T_{wct} + \sum\nolimits_{p\in P}\left(T_{wpt} + T^{'}_{wpt_2}\right) + \sum\nolimits_{s\in S} T_{wst_2} \leq \overline{PR_t}^W \quad \forall w,t \ \left(\alpha^W_{wt}\right) \tag{2}$$

$$\sum\nolimits_{c\in C}\sum\nolimits_{t\in T} d_t T_{wct} + \sum\nolimits_{p\in P}\sum\nolimits_{t\in T} d_t T_{wpt} + d_{t_2}\left(\sum\nolimits_{s\in S} T_{wst_2} + \sum\nolimits_{p\in P} T^{'}_{wpt_2}\right) \leq \overline{PROD}^W \quad \forall w \ \left(\beta^W_w\right) \tag{3}$$

The portion of the natural gas volume for which the producer is required to bear the cost of the pipeline capacity cannot exceed the capacity it purchased. Additionally, all decision variables are guaranteed to be non-negative.

$$\sum_{w\in W}\sum\nolimits_{c\in C} T_{wct} \leq \sum_{m\in M}\sum_{n\in N} FLOW^W_{mnt} \quad \forall m,n,t,w \ \left(\eta^W_t\right) \tag{4}$$

$$T_{wct} \geq 0 \quad \forall w,c,t \tag{5}$$

$$T_{wpt} \geq 0 \quad \forall w,p,t \tag{6}$$

$$T_{wst_2} \geq 0 \quad \forall w,s,t_2 \tag{7}$$

$$T^{'}_{wpt_2} \geq 0 \quad \forall w,p,t_2 \tag{8}$$

$$FLOW^W_{nmt} \geq 0 \quad \forall w,n,m,t \tag{9}$$

Storage operators are responsible for providing storage services to all parties without discrimination. In addition, certain seasonal arbitrage behaviors may be considered when conducting market operations, along with the associated transportation costs. Storage operators must determine the optimal storage service capacity to maximize profits while identifying the most profitable volume for seasonal arbitrage within the storage reservoir's physical limitations. Thus, this involves considering the costs and benefits associated with each storage service and arbitrage strategy.

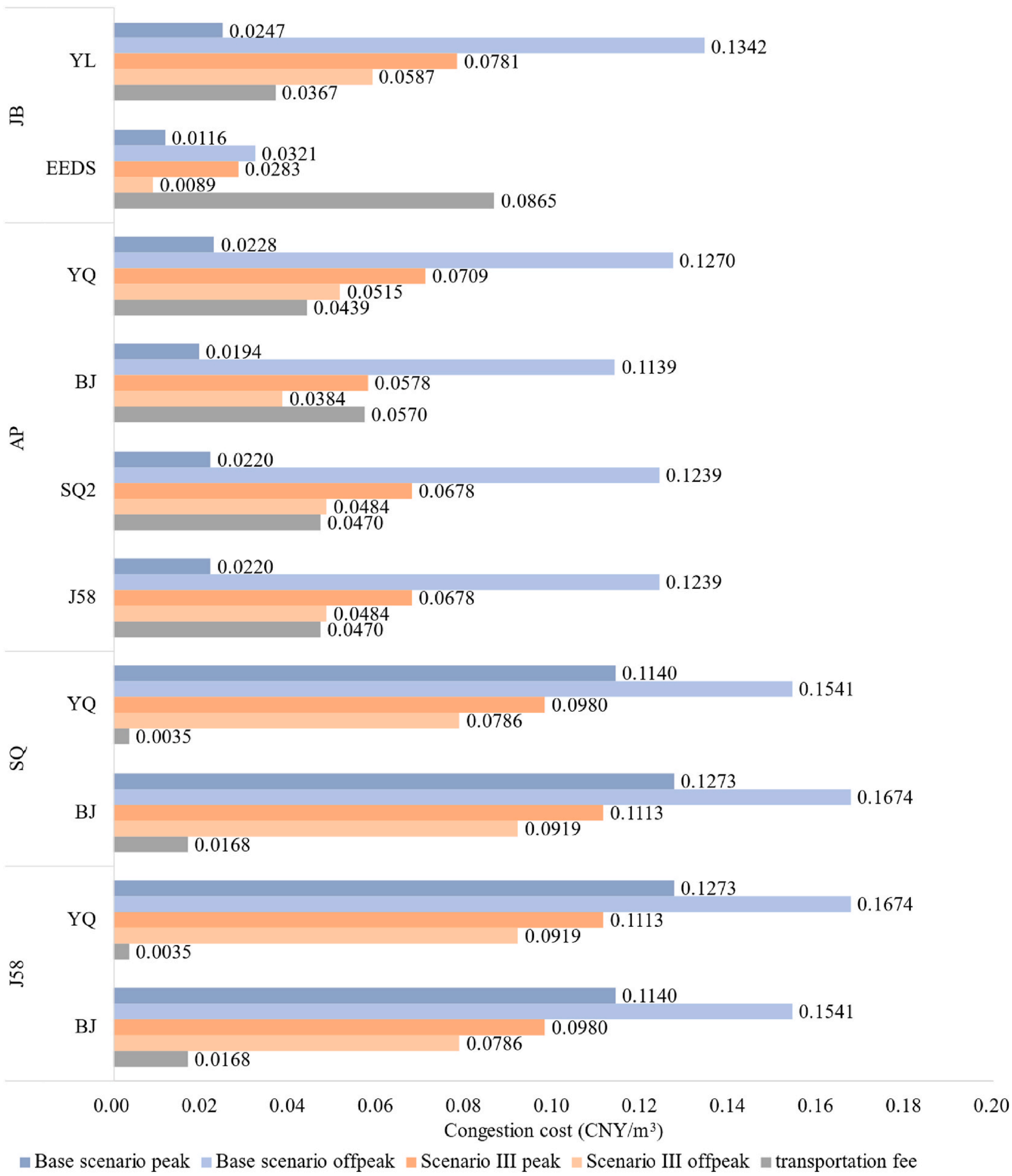


Fig. 5. The congested fee of the Shan-Jing system in Scenario III.

The gas storage site is essential to address seasonal and daily gas shortages.

$$\max_{\substack{PUR_{wst_2}\\ EXT_{sct_1}\\ EXT_{spt_1}\\ STO_{spt_2}\\ FLOW^S_{nmt}}} \left\{ d_{t_1}\sum_{s\in S}\left(\pi_t^C EXT_{sct_1} + \pi_{t_1}^{S\to P} EXT_{spt_1}\right) + d_{t_2}\left[\sum_{s\in S}\left(\pi_{t_2}^S STO_{spt_2} - \pi_{t_2}^{S\leftarrow W} PUR_{wst_2} - sc_t^S\left(PUR_{wst_2} + STO_{spt_2}\right)\right)\right] - \sum_{t\in T}\sum_{n\in N}\sum_{m\in M}\left[d_t\left(\tau^A_{nmt} + \pi^{Areg}_{nmt}\right)FLOW^S_{mnt}\right]\right\} \tag{10}$$

Due to reserve limitations, the reservoir capacity can be restricted by the aggregate storage capacity CAP^S.

$$\text{s.t.} \sum\nolimits_{w\in W} PUR_{wst_2} + \sum\nolimits_{p\in P} STO_{spt_2} \le CAP^S \forall w, s, t\left(\mu^S_{st_2}\right) \tag{11}$$

The mass balance constraint ensures that the volumes bought from the producer must be enough to meet the total sales for a given loss rate.

$$d_{t_1}\left(\sum\nolimits_{c\in C} EXT_{sct_1} + \sum\nolimits_{p\in P} EXT_{spt_1}\right) \le d_{t_2}\left(1-\gamma^S\right)\sum\nolimits_{w\in W} PUR_{wst_2} \quad \forall s, t\left(\nu^S_s\right) \tag{12}$$

Furthermore, the decision variables must satisfy the pipeline flow rate conservation law. Additionally, all decision variables are guaranteed to be non-negative.

$$\sum_{s\in S}\sum\nolimits_{c\in C} EXT_{sct_1} + \sum\nolimits_{s\in S}\sum\nolimits_{w\in W} PUR_{wst_2} \le \sum_{n\in N}\sum_{m\in M}\left(FLOW^S_{mnt}\right) \forall t \left(\xi^S_t\right) \tag{13}$$

$$PUR_{wst_2} \ge 0 \quad \forall w, s, t_2 \tag{14}$$

$$EXT_{sct_1} \ge 0 \quad \forall w, s, c, t_1 \tag{15}$$

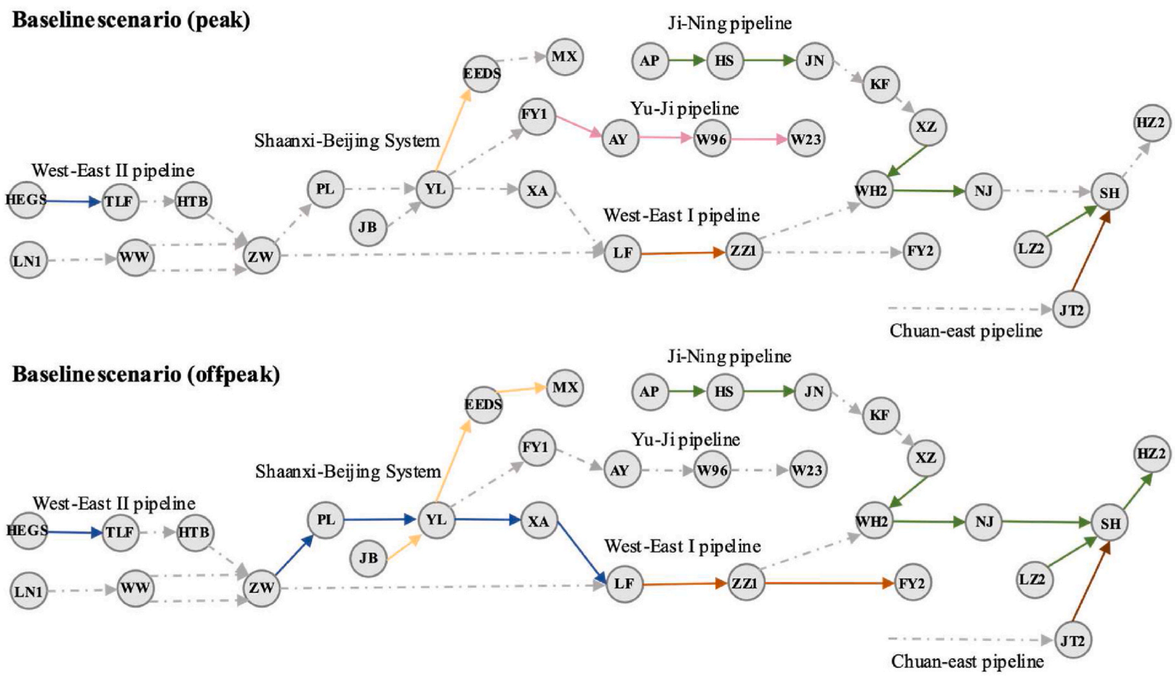


Fig. 6. Partial congested segments in the baseline scenario.

Table 1
Percentage of congestion costs in total costs.

long-distance pipeline	in-ward	out-ward	Base scenario	Scenario I	Scenario II	Scenario III
			peak	peak	peak	peak
West-East I pipeline	JT1	HZ2	16.77 %	50.77 %	53.07 %	38.14 %
Ji-Ning Pipeline	XZ	SQ1	46.68 %	55.66 %	57.54 %	45.66 %
		LZ2	46.68 %	55.66 %	57.54 %	45.66 %
	AP	HS	19.47 %	54.22 %	56.21 %	43.48 %
West-East III pipeline	HEGS	JB	55.07 %	59.85 %	61.39 %	51.82 %
West-East II pipeline	ZW	GY1	14.93 %	48.24 %	50.78 %	34.08 %
Zhong-Wu pipeline	ZX	CQ	27.34 %	66.27 %	68.30 %	56.35 %
		YC2	17.59 %	57.72 %	60.85 %	40.87 %
Se-Ning-Lan pipeline	SB	XN	12.71 %	57.77 %	60.90 %	40.97 %
		LZ1	9.23 %	52.95 %	56.79 %	31.10 %
Shan-Jing System pipeline	JB	YL	18.82 %	53.42 %	55.48 %	42.25 %
	AP	YQ	17.64 %	51.90 %	54.10 %	39.91 %
		BJ	15.39 %	48.89 %	51.36 %	35.13 %
		SQ2	17.11 %	51.22 %	53.48 %	38.84 %
		J58	17.11 %	51.22 %	53.48 %	38.84 %
	SQ	YQ	51.65 %	57.14 %	58.89 %	47.87 %
		BJ	54.40 %	59.31 %	60.90 %	51.05 %
	J58	YQ	54.40 %	59.31 %	60.90 %	51.05 %
		BJ	51.65 %	57.14 %	58.89 %	47.87 %
Yu-Ji pipeline	YL	FY1	15.49 %	52.57 %	56.48 %	30.29 %
	W96	JN	15.49 %	52.57 %	56.48 %	30.29 %
	W23	JN	15.49 %	52.57 %	56.48 %	30.29 %

$$EXT_{spt_1} \geq 0 \quad \forall w, s, p, t_1 \tag{16}$$

$$STO_{spt_2} \geq 0 \quad \forall w, s, p, t_2 \tag{17}$$

$$FLOW^{S}_{nmt} \geq 0 \quad \forall n, m, s, t \tag{18}$$

The third-party is granted equitable access to gas transportation and storage facilities in the natural gas market under Third-Party Access (TPA) regulatory framework. To maximize their discounted profits, third parties need to optimize their trading volumes with producers and end users while determining the optimal storage capacity with storage operators and transportation capacity with pipeline operators, which requires a careful balancing of costs and revenues associated with each market activity, while also taking into account various market and regulatory factors that impact the behavior third-parties in the natural gas market.

In the natural gas market, the trader is considered an independent agent who does not rely on natural gas producers or is authorized to construct and manage natural gas infrastructure, including pipeline networks and storage depots.

$$\max_{\substack{T_{pct}\\PUR_{wpt}\\PUR'_{wpt_2}\\INJ_{spt_2}\\PUR_{spt_1}\\FLOW^P_{nmt}}} \left(\sum_{t\in T}\sum_{p\in P} d_t\left(\pi^C_t T_{pct} - \pi^{W\to P}_t PUR_{wpt}\right) - d_{t_1}\sum_{p\in P}\pi^{S\to P}_{t_1} PUR_{spt_1} - d_{t_2}\sum_{p\in P}\left(\pi^S_{t_2} INJ_{spt_2} + \pi^{W\to P}_t PUR'_{wpt_2}\right) - \sum_{t\in T}\sum_{n\in N}\sum_{m\in M}\left(d_t\left(\tau^A_{nmt} + \pi^{Areg}_{nmt}\right) FLOW^P_{mnt}\right) \right) \tag{19}$$

The following mass balance constraint ensures that the volumes bought from the producer and the storage operator must be enough to meet the total sales.

$$\begin{aligned} s.t.\ & \sum_{t\in T}\sum\nolimits_{c\in C} d_t T_{pct} \le \sum_{t\in T}\sum\nolimits_{w\in W} d_t PUR_{wpt} + d_{t_1}\sum\nolimits_{s\in S} PUR_{spt_1} \\ & + d_{t_2}\sum\nolimits_{s\in S} INJ_{spt_2} \quad \forall p,t \quad \left(\gamma^P_p\right) \end{aligned} \tag{20}$$

The decision variables must satisfy the conservation law of the pipeline flow rate, and all decision variables are guaranteed to be non-negative.

$$\begin{aligned} & \sum_{n\in N}\sum_{m\in M} FLOW^P_{nmt} \ge \sum_{p\in P}\sum\nolimits_{c\in C} T_{pct} + \sum_{p\in P}\sum\nolimits_{s\in S} INJ_{spt_2} + \sum_{p\in P}\sum\nolimits_{w\in W} PUR'_{wpt_2} \\ & + \sum_{p\in P}\sum\nolimits_{w\in W} PUR_{wpt} + \sum_{p\in P}\sum\nolimits_{s\in S} PUR_{spt_1} \quad \forall t \quad \left(\delta^P_t\right) \end{aligned} \tag{21}$$

$$d_{t_2}\sum\nolimits_{s\in S} INJ_{spt_2} \le d_{t_2}\sum\nolimits_{w\in W} PUR'_{wpt_2} \forall p \quad \left(\chi^P_p\right) \tag{22}$$

$$T_{pct} \ge 0, \forall p,c,t \tag{23}$$

$$PUR_{wpt} \ge 0 \quad \forall p,w,t \tag{24}$$

$$PUR'_{wpt_2} \ge 0 \quad \forall p,w,t_2 \tag{25}$$

$$PUR_{spt_1} \ge 0 \quad \forall p,s,t_2 \tag{26}$$

$$INJ_{spt_2} \ge 0 \quad \forall p,s,t_2 \tag{27}$$

$$FLOW^P_{nmt} \ge 0 \quad \forall n,m,p \tag{28}$$

The operation of long-distance pipelines is centralized under the authority of PipeChina, which was established in December 2019. Similar to storage operators, pipeline operators are mandated to provide transportation services to all agents in the natural gas market. Furthermore, the transportation fee is regulated, while congestion fees may be levied when pipeline capacity is constrained and congestion occurs. To maximize their discounted profits, pipeline operators must optimize the allocation of pipeline capacity to other agents in the natural gas market, considering various factors such as costs, revenues, and capacity constraints. π^{Areg}_{nmt} indicates the price to be paid for transportation per unit volume of pipeline flow, and τ^A_{nmt} represents the additional congestion cost per unit volume of pipeline flow when pipeline congestion exists. In addition, the model is built to ensure the integration of the pipeline [28, 29].

$$\max_{FLOW^A_{nmt}} f_A(x) = \max_{FLOW^A_{nmt}} \sum_{t\in T}\sum_{n\in N}\sum_{m\in M} d_t\left(\tau^A_{nmt} + \pi^{Areg}_{nmt}\right) FLOW^A_{nmt} \tag{29}$$

The assigned pipeline capacity $FLOW^A_{nmt}$ must be at most the available pipeline capacity $\overline{FLOW}^A_{nmt}$. And $FLOW^A_{nmt}$ is guaranteed to be non-negative.

$$s.t.\ FLOW^A_{nmt} \le \overline{FLOW}^A_{nmt} \quad \forall n,m,t \quad \left(\sigma^A_{nmt}\right) \tag{30}$$

$$FLOW^A_{nmt} \ge 0 \quad \forall n,m,t \tag{31}$$

Equilibrium models are typical models of energy systems containing multiple agents. In addition to the objective function and constraints for each market player, each market player has KKT conditions to reach the equilibrium outcome, which are the necessary conditions to achieve equilibrium optimization. These conditions will also appear as constraints in the optimization problem [30,31]. All KKT conditions are listed in Appendix B.

In addition, the market-clearing conditions enable the association of more than one separated agent through aggregate conservation, and the prices of economic activities between agents are simultaneously obtained.

$$\begin{aligned} 0 \le & \sum_{n\in N}\sum_{m\in M} - \sum FLOW^A_{nmt} - \sum_{n\in N}\sum_{m\in M} FLOW^S_{nmt} - \sum_{n\in N}\sum_{m\in M} FLOW^W_{nmt} \\ & + \sum_{n\in N}\sum_{m\in M} FLOW^P_{nmt} \forall p,t,s,w,m,n,\tau^A_{nmt}(free) \end{aligned} \tag{32}$$

$$T_{wst_2} \ge PUR_{wst_2} \quad \forall w,s,t,\pi^{W\to S}_{t_2}(free) \tag{33}$$

$$\sum_{t\in T} d_t T_{wpt} + d_{t_2} T'_{wpt_2} \ge \sum_{t\in T} d_t PUR_{wpt} + d_{t_2} PUR'_{wpt_2} \quad \forall w,p,\pi^{W\to P}_t(free) \tag{34}$$

$$EXT_{spt_1} \ge PUR_{spt_1} \quad \forall s,p,\pi^{S\to P}_{t_1}(free) \tag{35}$$

$$STO_{spt_2} \ge INJ_{spt_2} \quad \forall s,p,\pi^S_{t_2}(free) \tag{36}$$

Table 2
Congestion fee of key congested routes in the peak season (unit: CNY/m^3).

Long-distance pipeline	In-ward	Out-ward	Based Scenario	Scenario I	Scenario II	Scenario III
West-East I pipeline	JT1	HZ2	0.0215	0.1100	0.1207	0.0658
Ji-Ning Pipeline	XZ	SQ1	0.0934	0.1339	0.1446	0.0897
		LZ2	0.0934	0.1339	0.1446	0.0897
	AP	HS	0.0258	0.1263	0.1370	0.0821
West-East II pipeline	ZW	GY1	0.0187	0.0994	0.1101	0.0552
		PL	0.0118	0.0729	0.0836	0.0287
		YL	0.0134	0.0790	0.0897	0.0348
	HEGS	HTB	0.0149	0.0848	0.0955	0.0406
	LN1	TLF	0.0149	0.0848	0.0955	0.0406
Zhong-Wu pipeline	ZX	CQ	0.0402	0.2097	0.2299	0.1378
		YC2	0.0228	0.1457	0.1659	0.0738
Se-Ning-Lan pipeline	SB	XN	0.0155	0.1460	0.1662	0.0741
		LZ1	0.0108	0.1201	0.1403	0.0482
Shan-Jing System pipeline	JB	YL	0.0247	0.1223	0.1330	0.0781
		EEDS	0.0116	0.0725	0.0832	0.0283
	AP	YQ	0.0228	0.1151	0.1258	0.0709
		BJ	0.0194	0.1020	0.1127	0.0578
		SQ2	0.0220	0.1120	0.1227	0.0678
		J58	0.0220	0.1120	0.1227	0.0678
	SQ	YQ	0.1140	0.1422	0.1529	0.0980
		BJ	0.1273	0.1555	0.1662	0.1113
	J58	YQ	0.1273	0.1555	0.1662	0.1113
		BJ	0.1140	0.1422	0.1529	0.0980
West-East III pipeline	HEGS	JB	0.1308	0.1590	0.1697	0.1148
Chuan East pipeline	JT2	JX	0.0164	0.0906	0.1013	0.0464
Yu-Ji pipeline	YL	FY1	0.0196	0.1183	0.1385	0.0464
	W96	JN	0.0196	0.1183	0.1385	0.0464
	W23	JN	0.0196	0.1183	0.1385	0.0464

$$\pi_t^c \ge p_0^r \times \left[\left(\sum_{w\in W} T_{wct} + \sum_{s\in S} EXT_{sct_1} + \sum_{p\in P} T_{pct}\right) \Big/ d_0^r\right]^{1/\varepsilon_c} \tag{37}$$

in this paper, consumers are defined as 30 cities in 18 provinces, identified as consumer nodes, with the combined demand derived from three distinct sectors: residential, commercial, and industrial. The total consumption in each node is characterized by an aggregate inverse demand function, which captures the relationship between the quantity demanded and the corresponding price levels.

3.2. Scenarios design

This section describes potential gas flow changes, pipeline capacity expansion plans for the baseline, and three alternative scenarios. All three scenarios are set based on the content of the Sino-Russian gas cooperation negotiations, which are detailed in Section 2.2.

3.2.1. Baseline scenario

In December 2022, the southern section of the CRER in China, extending from Taian to Taixing, was officially commissioned, signifying the completion of the entire China-Russian Eastern Pipeline. This achievement has significantly impacted the gas supply capacity in eastern China. China's natural gas market currently encompasses three major import routes for natural gas pipelines: Central Asia, China-Myanmar, and China-Russia. Consequently, as a comparative benchmark, we propose a scenario assuming that no further pipeline expansions are planned soon. Our investigation aims to explore the potential congestion in the natural gas pipeline network when the market reaches its equilibrium state.

3.2.2. Scenario I

The Altai route was the initial natural gas pipeline project proposed for the China-Russian natural gas cooperation initiative. However, it was eventually replaced by the CRER. Nevertheless, the feasibility of the Altai route is currently being re-evaluated in light of new developments in gas cooperation between the two countries. The Altai route is intended to transport natural gas from Russia's western Siberian gas fields through the Altai Mountains and ultimately to western China. Upon reaching China, the pipeline will link up with the West-East Pipeline II in Xinjiang and deliver natural gas to areas with high gas consumption levels, such as Shanghai.

The advantages of this plan are significant. Primarily, the West-East pipeline system constitutes a crucial component of China's natural gas infrastructure, comprising three main lines and numerous branch lines. It connects to as many other pipelines as possible, such as the northbound connection to the Shaanxi-Beijing long-distance gas transmission system and the southbound connection to the Sichuan-East gas transmission system via the Zhong-Gui pipeline. By extension, the West-East gas transmission system, directly or indirectly, interconnects with most gas-using cities in China. As such, augmenting the transportation capacity of this system would enhance the efficiency of natural gas transmission to a vast majority of cities across the country.

But the disadvantages are also corresponding. The cities with high gas consumption in China are primarily situated in the eastern region. The transportation costs associated with the West-East gas transmission plan are likely to be high, which could ultimately be passed onto the Chinese gas market, rendering the project economically unfeasible in the natural gas decision-making process between Russia and China. Furthermore, the current pipeline capacity limitations of the West-East gas transmission system may lead to increased pipeline congestion costs, which represent a significant risk factor in terms of raising pipeline transmission costs. Although there are plans to expand the capacity of the West-East gas transmission system in the future, more pipeline capacity necessitates further investment in expansion, and the economic feasibility of such an expansion requires additional demonstration.

3.2.3. Scenario II

Another option is increasing the volume of gas delivered by the existing CRER, which provides a more direct and shorter route for gas transportation than the Altai route, effectively lowering overall transportation costs. Utilizing the pre-existing infrastructure along the Eastern Route enables an increase in gas delivery volumes with minimal supplementary investments. However, additional investigation is necessary to ascertain if the pipeline network capacity of CRER can accommodate a 50 bcm augmentation. If the existing capacity is inadequate, augmenting the natural gas supply on CRER would necessitate investing in expanding existing pipelines.

3.2.4. Scenario III

As China and Russia negotiate, a gas pipeline through Mongolia seems more probable [32]. The China-Mongolia-Russia pipeline would start in western Siberia, pass through Mongolia, and connect to China's long-distance natural gas pipeline network in the northern part of Inner Mongolia. In China, there is a high demand for natural gas in the Beijing-Tianjin-Hebei region. The China-Mongolia-Russia pipeline would connect to the Shaan-Jing system in Inner Mongolia, directly alleviating the pressure on the gas supply to the Beijing-Tianjin-Hebei region, which would also connect to the China-Russia East Line via other liaison lines to deliver gas to the Yangtze River Delta region.

Hence, compared to the routes of the other two scenarios, The China-Mongolia-Russia pipeline is a more direct route for gas transportation, which would reduce transportation costs. It also has the potential to provide China with a more stable and reliable gas transportation route, as it will diversify China's gas supply sources and transit countries, reducing dependence on a single pipeline and transit country. However, The China-Mongolia-Russia pipeline also faces several challenges. For example, the project may face geopolitical and environmental issues as it crosses Mongolia and must address complex political and regulatory matters.

3.3. Data

Considering the projected gas delivery volume of 38 bcm for CRER in 2024, this research aims to simulate the natural gas market in 2025 and examine the congestion impact of various pipeline scenarios on China's long-distance natural gas pipeline network. The World and China Energy Outlook (2021), a publication by the China Petroleum Economic and Technological Research Institute, has provided forecasts indicating that China's natural gas production will reach 350 bcm and natural gas consumption will reach 610 bcm by 2035. Thus, for the 2025 scenario, assumptions are made based on the available data for 2020 and the forecasted values for 2035.

Despite the extensive coverage of long-distance pipelines connecting numerous city nodes, this study focuses on a subset of 47 strategically chosen off-take cities as pipeline nodes to facilitate computational simplification. The annual gas consumption of each province is evenly distributed among these selected off-take cities. Previous research has introduced a variation coefficient to account for seasonal variations in consumption. Due to data availability constraints, we mainly decided on domestic gas producers connected to long-distance pipeline trunk lines, such as the Tarim Oilfield Branch, Changqing Oilfield Branch, Puguang Gas Field Branch, Zhongxian Seven Days Branch, and Qinghai Gas Field Branch. The National Development and Reform Commission (NDRC) regulated a marginal profit of 12 % of the wellhead price, from which we can assume that the production cost is 88 % of the wellhead price [33].

4. Results and discussion

This section conducts a comprehensive comparative analysis, examining four distinct scenarios with particular emphasis on congested fees, gas flow patterns, and market shares (see Fig. 1).

4.1. Congested fees for long-distance pipelines

The pressure of existing pipeline transportation systems has significantly intensified with the growing demand for natural gas. In Fig. 2, "in-ward" refers to cities upstream of the pipeline where gas is coming in, and "out-ward" refers to cities downstream of the pipeline where gas is going out. The blue bars indicate the size of the corresponding pipeline congestion costs, with larger bars indicating higher pipeline congestion costs. The baseline scenario analysis reveals that the long-distance pipelines within the Shaanxi-Beijing system will experience the highest congestion levels of all pipelines by 2025. Compared to the baseline scenario, Scenarios I and II are anticipated to increase congestion, particularly during peak seasons. Scenario III is expected to alleviate transmission pressures.

The most congested pipelines among the four scenarios are predominantly located in the middle and downstream segments of the Shaanxi-Beijing system, specifically within the Beijing-Tianjin-Hebei region. However, Scenario III reduces congestion costs for a series of pipelines.

Under Scenario I, natural gas transportation from China and Russia commences through Xinjiang, subsequently integrating into the West-East Gas Pipeline System, facilitating the conveyance of natural gas toward eastern China. In light of congestion costs, this plan yields a discernible influence on the West-East Gas Pipeline system, particularly affecting the upper and middle reaches, which are shown in Fig. 3. Specific segments impacted by this arrangement include the ZW-PL section, ZW-YL section, LN1-TLF section, HEGS-HTB section, HEGS-TLF section of the West-East Gas Pipeline II Line.

As illustrated in Fig. 4, natural gas enters from the China-Russian East Route and goes south to the eastern coastal area of China in Scenario II. Consequently, the Yu-Ji pipeline, the two primary connecting lines from the southern to northern regions, experienced more pronounced effects.

The third alternative exhibits a more pronounced impact on the Shaanxi-Beijing system, as depicted in Fig. 5. Assuming the entry of natural gas into China via Inner Mongolia to link with the Shaanxi-Beijing system, it directly addresses the issue of gas scarcity in the Beijing-Tianjin-Hebei region. In addition, this approach reduces congestion costs associated with the Shaanxi-Beijing pipeline to some extent, particularly at the terminus of the Shaanxi-Beijing system (see Fig. 6).

Table 3
Congestion fee of key congested routes in off-peak season (unit: CNY/m^3).

Long-distance pipeline	In-ward	Out-ward	Based Scenario	Scenario I	Scenario II	Scenario III
West-East I pipeline	JT1	HZ2	0.1219	0.0909	0.0982	0.0464
Ji-Ning Pipeline	XZ	SQ1	0.1458	0.1148	0.1221	0.0703
		LZ2	0.1458	0.1148	0.1221	0.0703
	AP	HS	0.1382	0.1072	0.1145	0.0627
West-East II pipeline	ZW	GY1	0.1113	0.0803	0.0876	0.0358
		PL	0.0323	0.0538	0.0611	0.0093
		YL	0.0346	0.0599	0.0672	0.0154
	HEGS	HTB	0.0368	0.0657	0.0730	0.0212
	LN1	TLF	0.0368	0.0657	0.0730	0.0212
Zhong-Wu pipeline	ZX	CQ	0.1769	0.1637	0.1753	0.0997
		YC2	0.0369	0.0997	0.1113	0.0357
Se-Ning-Lan pipeline	SB	XN	0.0370	0.1000	0.1116	0.0360
		LZ1	0.0300	0.0741	0.0857	0.0101
Shan-Jing System pipeline	JB	YL	0.1342	0.1032	0.1105	0.0587
		EEDS	0.0321	0.0534	0.0607	0.0089
	AP	YQ	0.1270	0.0960	0.1033	0.0515
		BJ	0.1139	0.0829	0.0902	0.0384
		SQ2	0.1239	0.0929	0.1002	0.0484
		J58	0.1239	0.0929	0.1002	0.0484
	SQ	YQ	0.1541	0.1231	0.1304	0.0786
		BJ	0.1674	0.1364	0.1437	0.0919
	J58	YQ	0.1674	0.1364	0.1437	0.0919
		BJ	0.1541	0.1231	0.1304	0.0786
West-East III pipeline	HEGS	JB	0.1709	0.1399	0.1472	0.0954
Chuan East pipeline	JT2	JX	0.1025	0.0715	0.0788	0.0270
Yu-Ji pipeline	YL	FY1	0.0296	0.0723	0.0839	0.0083
	W96	JN	0.0296	0.0723	0.0839	0.0083
	W23	JN	0.0296	0.0723	0.0839	0.0083

Moreover, the study compares congestion costs with total costs, encompassing both congestion and transportation costs. Table 1 delineates pipelines where congestion costs exceed 50 % of total costs across all scenarios. A higher proportion signifies more significant cost pressure attributable to congestion for the respective pipelines. Scenarios I and II of gas transmission exhibit higher congestion costs for several pipelines. Despite Scenario III demonstrating lower congestion costs compared to the former scenarios, it registers higher congestion costs relative to the Base Case, particularly as a percentage of total transportation costs, notably affecting the Ji-Ning Line, the Zhong-Wu Line, and certain pipelines within the Shaanxi-Beijing system.

In conclusion, through a comprehensive analysis of congestion costs across all pipelines in the four scenarios, it becomes evident that the Altai line and CRER exert substantial transportation pressure on China's long-distance natural gas pipeline network. Conversely, implementing the China-Mongolia-Russia pipeline demonstrates a notable alleviation of pipeline pressure. Therefore, the China-Mongolia-Russia line should be the preferred option from the point of view of causing less pressure on pipelines within China.

4.2. *Key congested routes*

The table presented below outlines the pipelines that experience congestion in all four scenarios, encompassing the West-East pipelines, Ji-Ning pipeline, Zhong-Wu pipeline, Se-Ning-Lan pipeline, Shaanxi-Beijing System, Chuan-East pipeline, and a segment of the Yu-Ji pipeline. This paper adopts a seasonal approach to provide an in-depth analysis of congestion costs. The congested costs are represented using conditional formatting, where the color scheme transitions from dark to light red, followed by light blue, and finally, dark blue. This color gradient indicates a linear progression of increasing congestion costs, with dark red indicating the highest congestion cost value, followed by light red, light blue, and dark blue representing the lowest.

Table 2 visually illustrates the distribution of colors, highlighting the highest congestion costs observed on the Zhong-Wu pipeline (con (ZX, CQ, peak) = 0.2299 CNY/m^3) during the peak period of Scenario II. It is evident that congestion costs associated with the West-East III pipeline, Ji-Ning pipeline, and Shaanxi-Beijing system pipelines are generally significant; however, Scenario III exhibits the potential to mitigate congestion issues. A comparative analysis of congestion costs during peak gas consumption across the four scenarios reveals that most of the

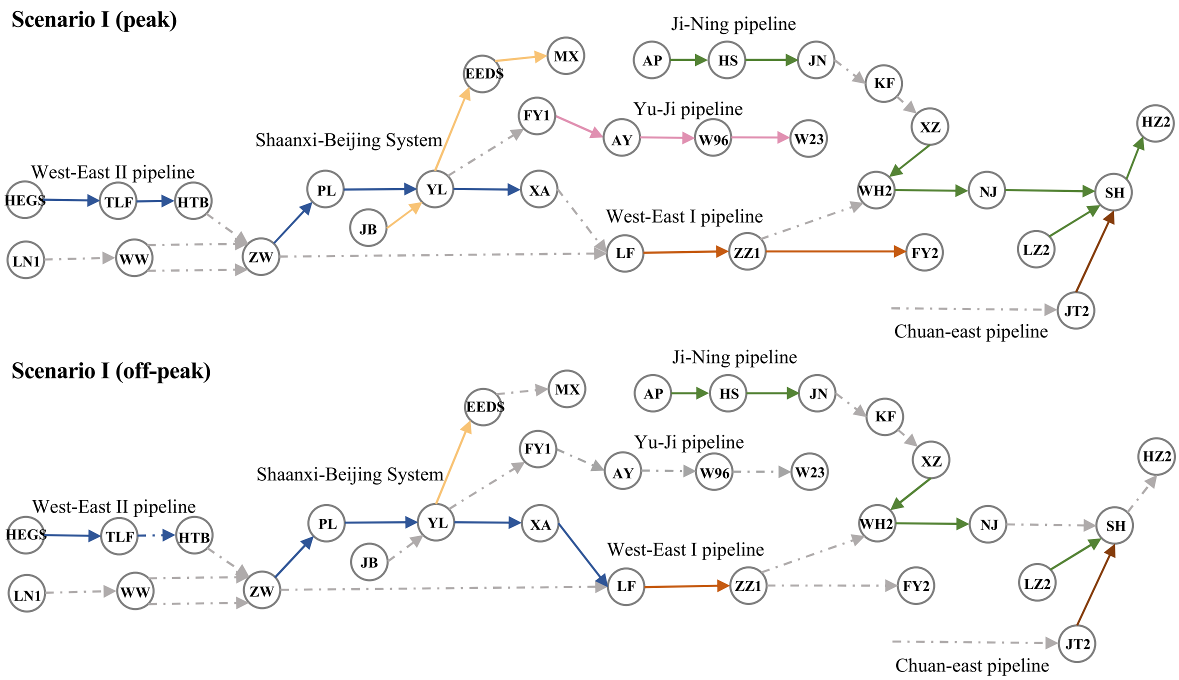


Fig. 7. Partial congested segments in Scenario I.

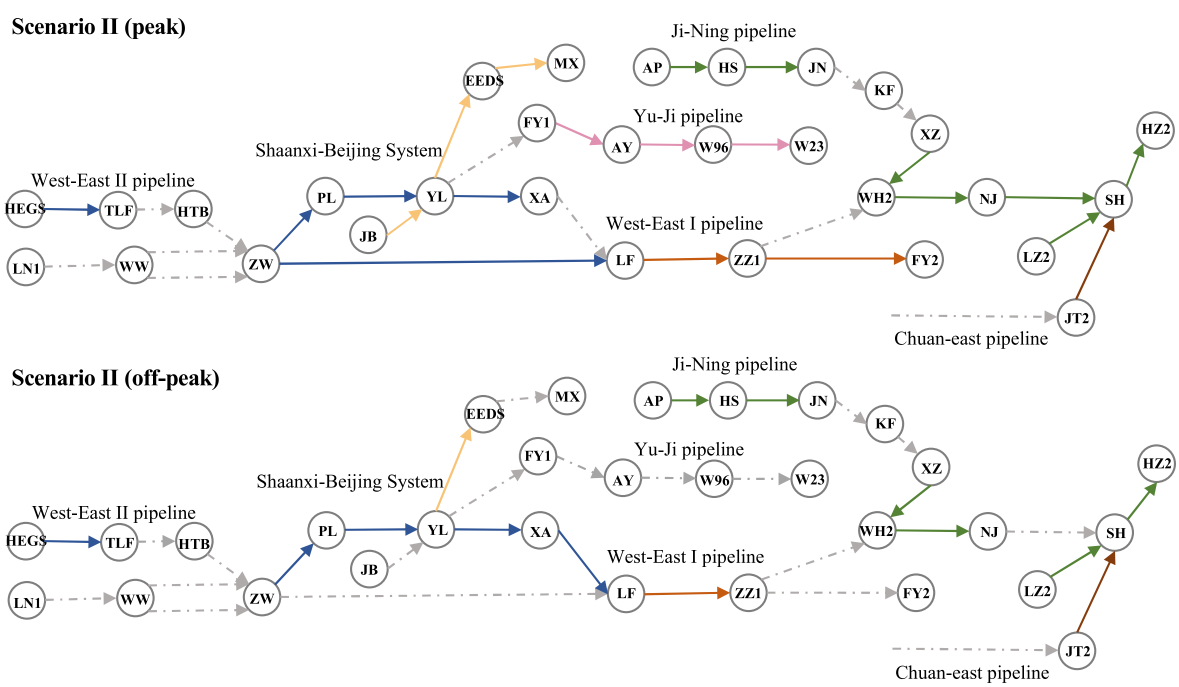


Fig. 8. Partial congested segments in Scenario II.

transmission scenarios result in congestion-related costs for pipeline transportation during peak gas consumption. Scenario III, apart from the SQ and J58 segments of the Shaanxi-Beijing system, incorporates a route where natural gas enters through Inner Mongolia and travels southwards for direct transportation to the Beijing-Tianjin-Hebei region. This alternative route directly alleviates transportation pressures from west to east within the Shaanxi-Beijing system (see Table 3).

Similar to the peak season, the Zhong-Wu line stands out as the most congested pipeline during the off-peak season (con (ZW, CQ, off-peak) = 0.1769 CNY/m^3). Notably, implementing the China-Russian gas transmission project reduces transmission pressures on numerous gas pipelines during periods of low gas consumption. Specifically, the West-East I line, Ji-Ning line, Shan-Jing System, West-East line, and Chuan East line benefit from alleviated transmission pressures. However, it is essential to note that for the West-East II line and the Yu-Ji Line, both the Altai Route and the China-Russia East Route options introduce increased transmission pressures on these pipelines.

However, it is imperative to acknowledge that the practical realization of this strategy necessitates the optimization and modernization of the domestic gas pipeline network. Notably, selecting different transportation routes can significantly adjust allocating capacity within China's extensive long-distance pipeline network. In this context, it is

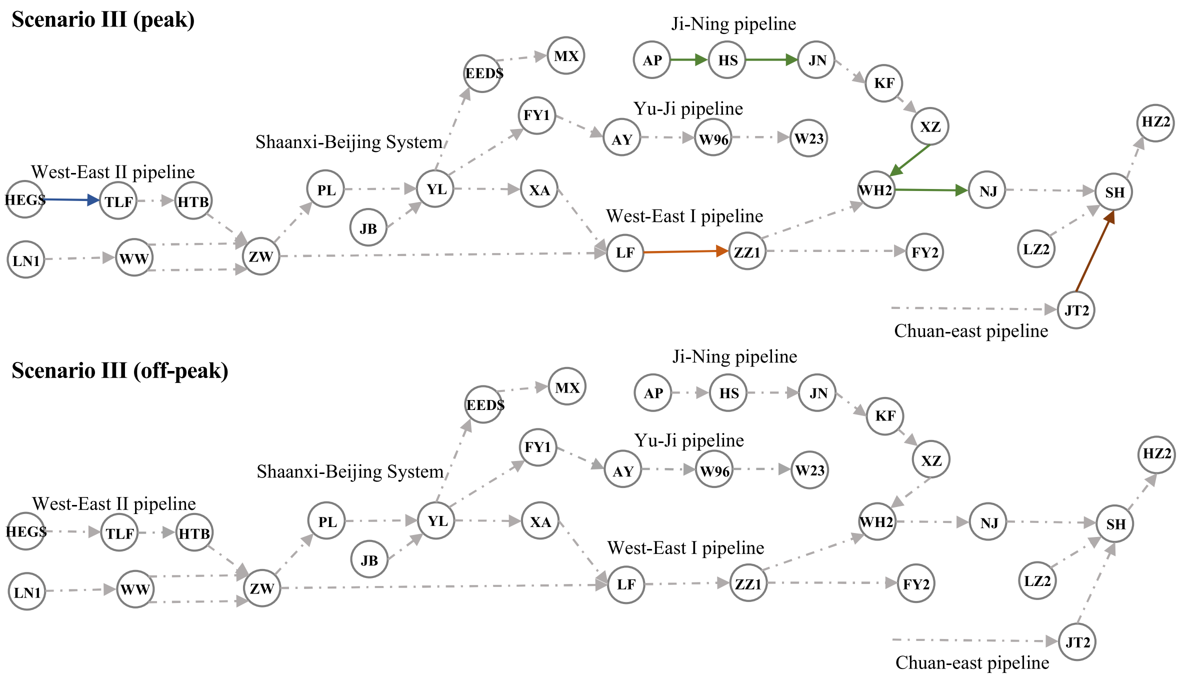


Fig. 9. Partial congested segments in Scenario III.

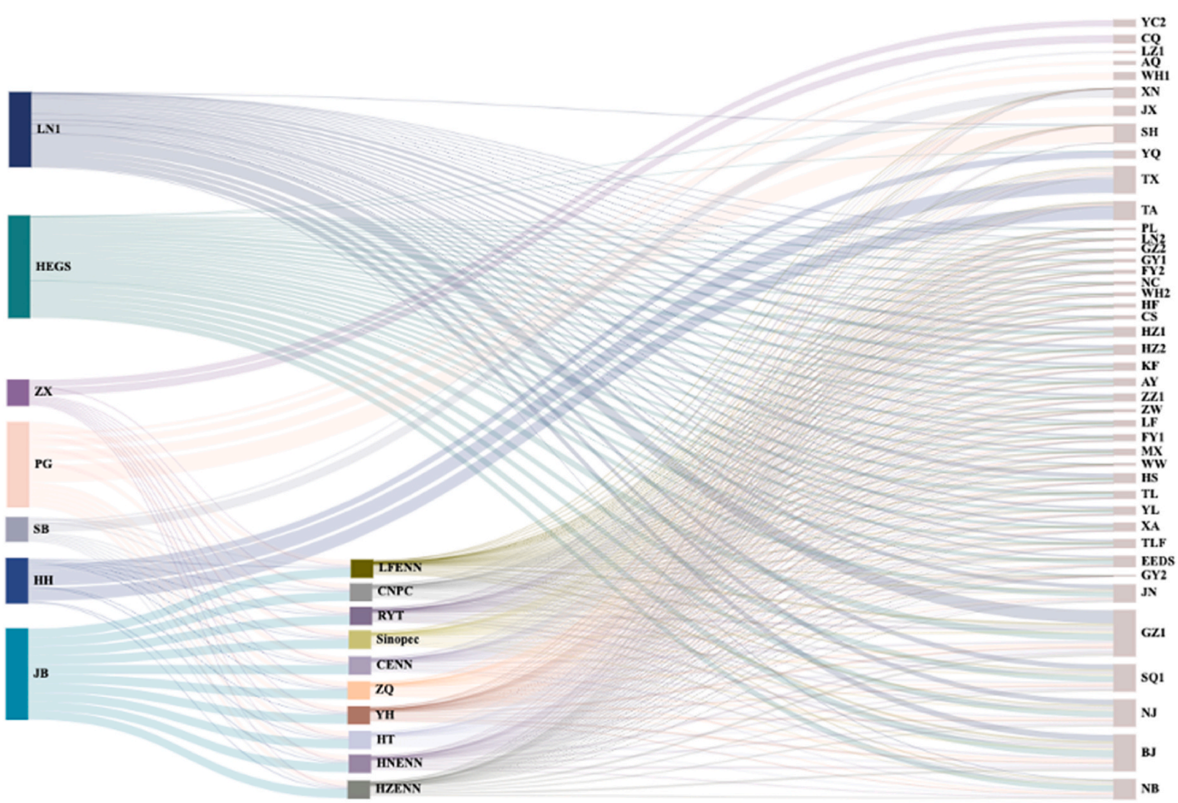


Fig. 10. Natural gas flows for the baseline scenario.

paramount to prioritize the expansion and fortification of critical pipelines that have been identified as pivotal to the success of the chosen plan. These pipelines include the West-East Gas Transmission, the Ji-Ning Line, the Zhong-Wu Line, the Se-Ning-Lan Line, the Shan-Jing System, the Chuan-East Gas Transmission, and the Yu-Ji Line. These initiatives may encompass the augmentation of pipeline capacity, the enhancement of infrastructure resilience, and the adoption of advanced technologies to optimize operational efficiency and mitigate congestion-related challenges.

4.3. Network structure variations in different contexts

Various scenario-specific factors can influence the existence or absence of pipeline congestion, and topology diagrams are utilized as a

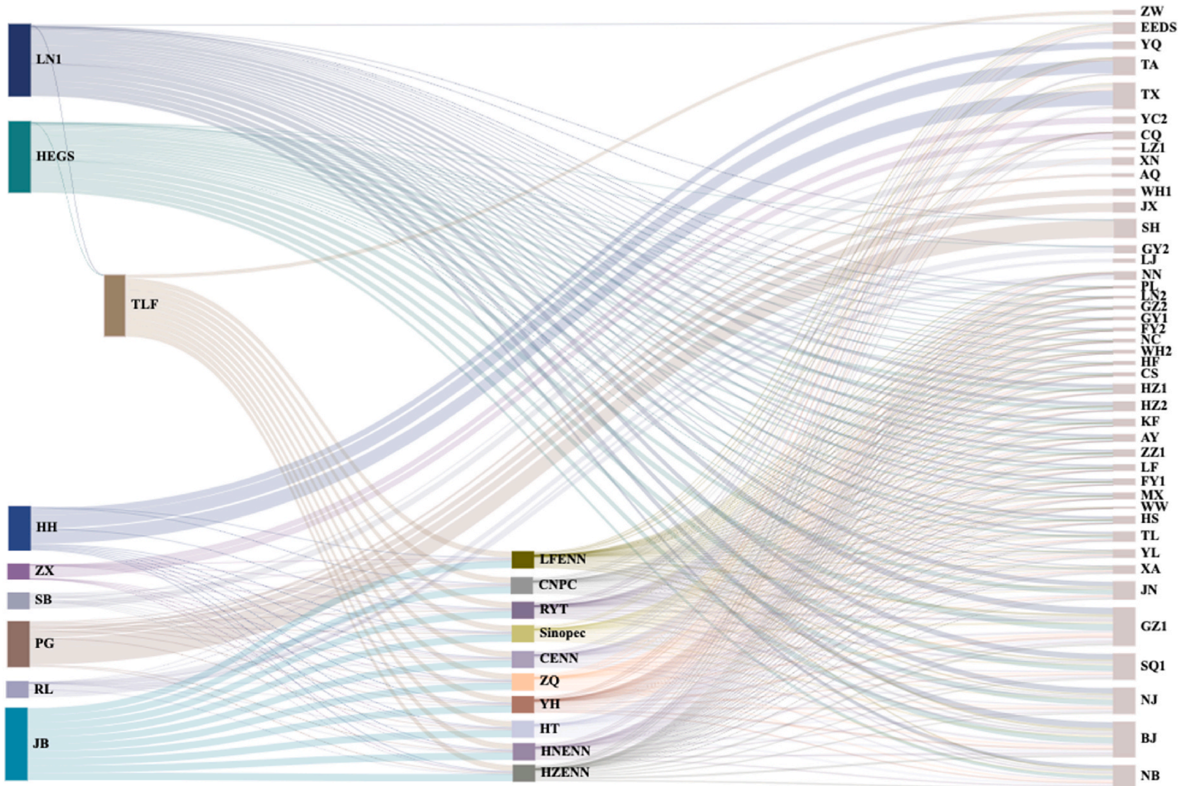


Fig. 11. Natural gas flows in Scenario I.

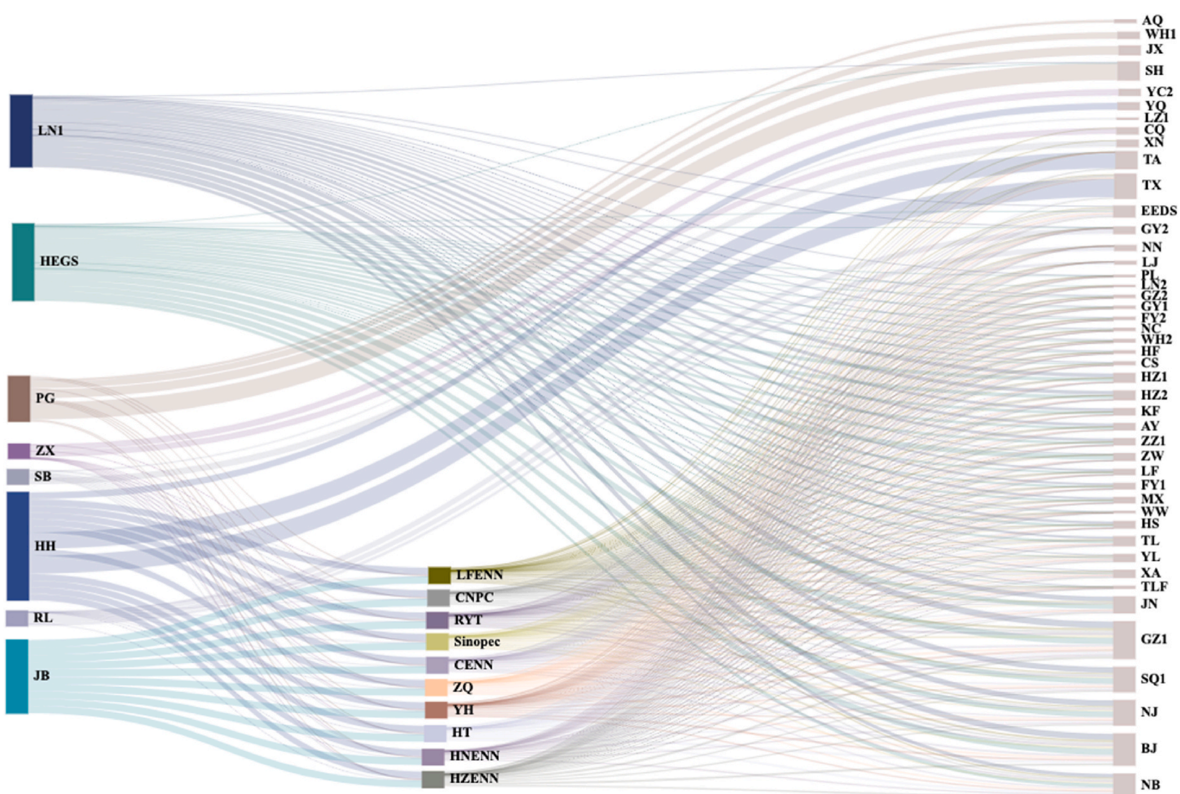


Fig. 12. Natural gas flows in Scenario II.

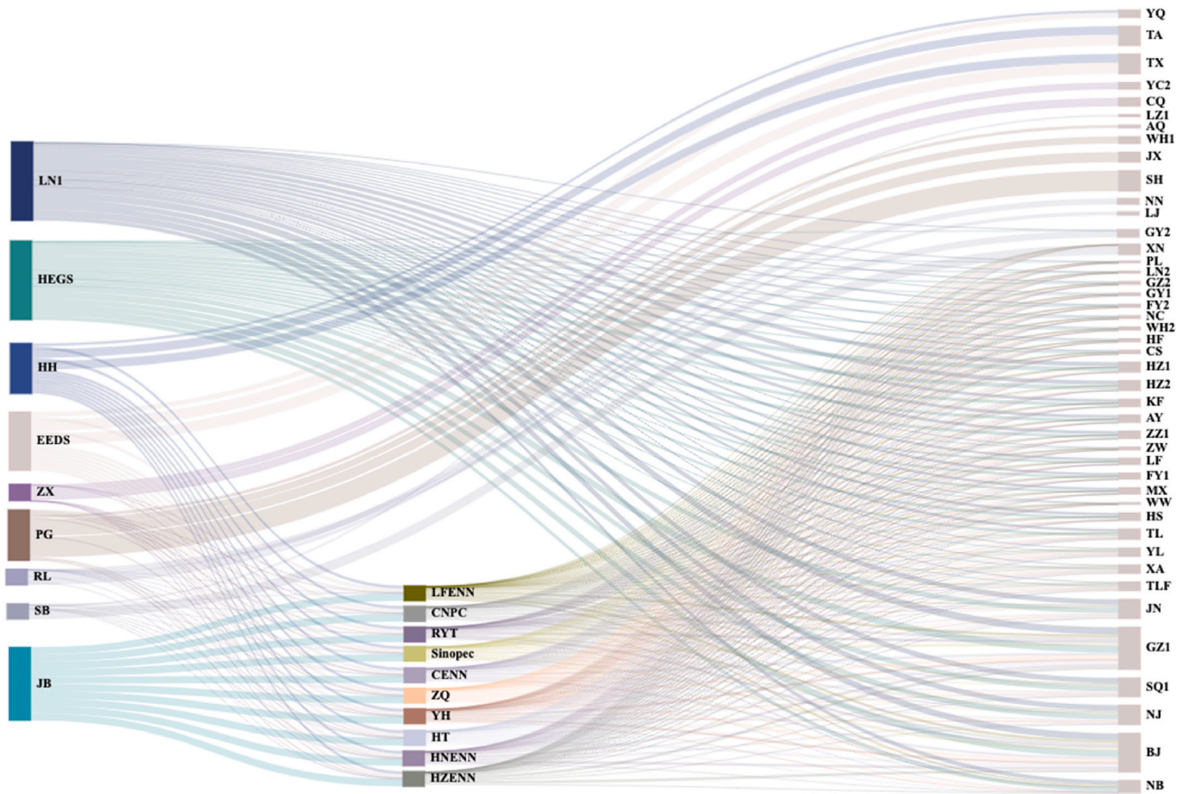


Fig. 13. Natural gas flows in scenario III.

visual representation tool. These diagrams offer a comprehensive and detailed visualization that enhances our understanding of the complex dynamics and interactions within the pipeline network under different scenarios. In the graph below, pipeline nodes are represented by circles accompanied by letters, while arrows indicate the direction of natural gas flow within the pipelines. Dashed lines indicate segments currently unaffected by transportation pressures, while solid lines indicate the existence of congestion costs in those particular segments.

Consistent with previous observations, congestion costs within the Based Scenario tend to be higher during low gas consumption periods than peak gas consumption. The diagram highlights the emergence of new pipeline congestion costs during off-peak periods compared to peak gas consumption periods. Notably, congestion costs arise within the Shaan-Jing system (EEDS-MX) and the West-East II pipeline (ZW-LF) during off-peak periods. However, it is worth noting that the congestion cost on the Yu-Ji pipeline during the peak gas consumption period disappears in the low gas consumption period.

In Scenario I, natural gas is transported through the West-East II pipeline to meet the high demand in the eastern region of China. However, maintaining the transportation capacity of the West-East gas transmission system unchanged in this scenario results in new transportation pressures and congestion costs, such as TLF-HTB and XA-LF in the West-East II pipeline. Compared with the baseline scenario, numerous congested pipelines emerge during the peak season in Scenario I, essentially encompassing all the pipelines that experience congestion in both peak and off-peak periods of the baseline scenario. Conversely, there are instances where pipeline congestion costs disappear during the off-peak period in Scenario I. These include TLF-HTB and XA-LF in the West-East II pipeline, LF-FY2 in the West-East I pipeline, JB-YL and EEDS-MX in the Shaanxi-Beijing system, and NJ-SH and NJ-HZ2 in the Ji-Ning pipeline, as well as the entire section of the Yu-Ji pipeline.

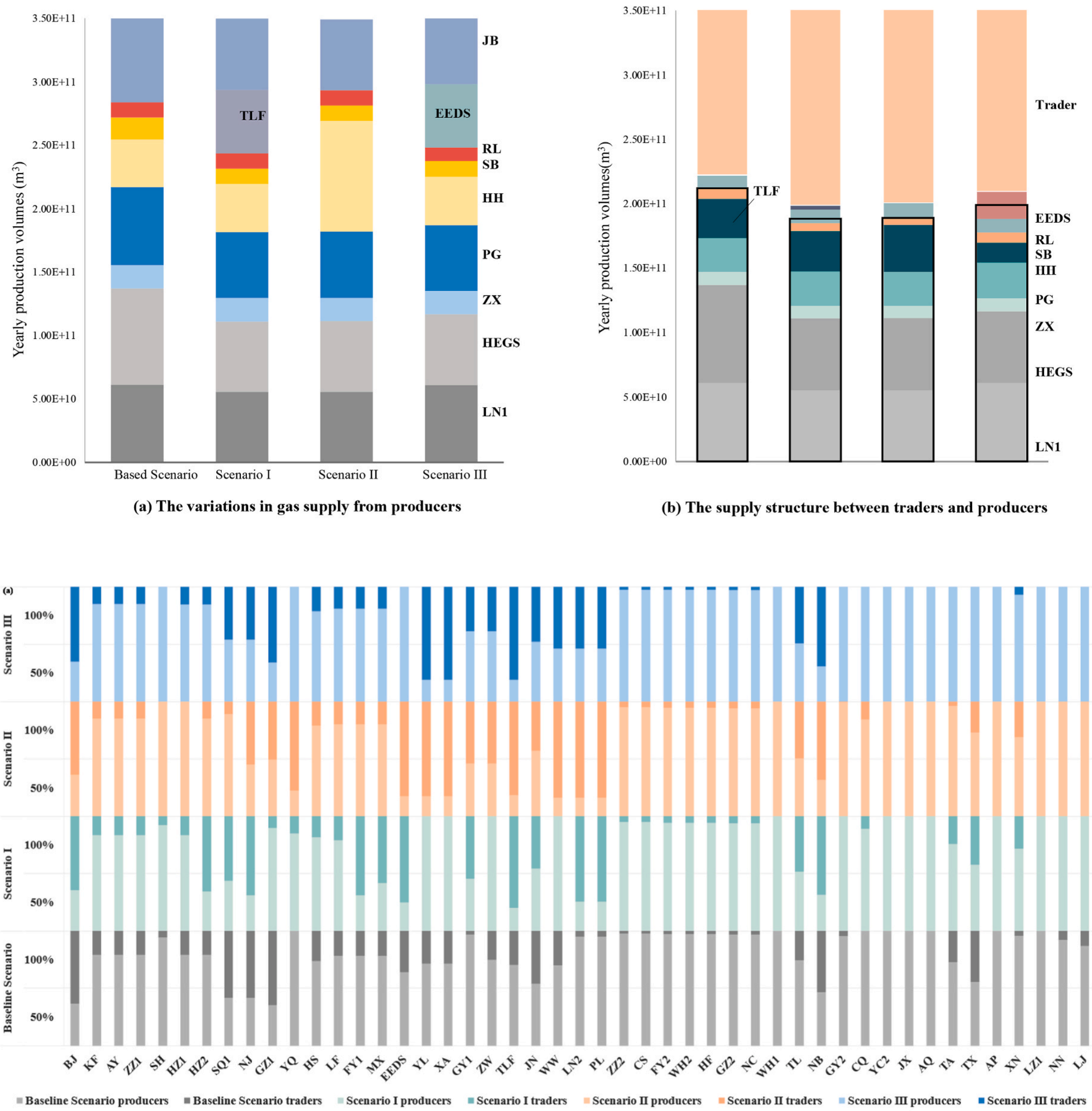
Scenario II involves increasing the transmission volume of the original China-Russian Eastern Pipeline, with the primary objective of reducing the transportation distance of natural gas and meeting the gas demand in the eastern region of China. However, a comparative analysis of pipeline congestion costs reveals that Scenario II also increases congestion costs for several pipelines, particularly during peak periods of gas consumption. Compared to the based scenario, congestion costs escalate for specific pipelines within the Shaanxi-Beijing system, the West-East gas transmission system, and the Ji-Ning pipeline during peak periods. However, similar to Scenario I, the transportation pressure on pipelines during off-peak periods is reduced in Scenario II when compared to the baseline scenario.

Compared to the previous two scenarios, the implementation of Scenario III demonstrates a notable advantage by avoiding new pipeline congestion and mitigating congestion on existing pipelines during peak and off-peak periods. The accompanying figure provides a visual representation supporting this observation. In Scenario III, only a few pipelines within the West-East System (HEGS-TLF and LF-ZZ1) and the Ji-Ning line (AP–HS–JN and XZ-WH2-NJ) experience congestion. Mainly during periods of low gas consumption, pipelines that may encounter congestion in other scenarios exhibit alleviation of congestion in Scenario III.

It is important to note that changes in supply and demand lead to corresponding shifts in the transportation flow within the natural gas pipeline network, impacting the congestion costs associated with different pipeline segments. When influences such as geopolitical and international environments are prioritized, corresponding pipeline optimization solutions need to be made for different route choices.

4.4. *Market sharing analysis: gas transactions between producers, traders, and off-take cities*

This section presents the Sankey diagram, which provides a detailed visualization of the natural gas transactions between producers, traders, and off-take cities in each scenario when the natural gas market achieves equilibrium. The connections depicted by the lines between the entities



(a) The variations in gas supply from producers

(b) The supply structure between traders and producers

(c) The gas supply structure for the selected end -use off-take cities

Fig. 14. Comparison of the changes in gas supply.

symbolize the flow of natural gas transactions. Producers are represented on the left side of the diagram, off-take cities on the right side, and traders in the middle. In all four scenarios, Lunan and Horgos directly supply natural gas solely to end-consuming cities without involving transactions with third-party traders. However, transactions with third-party traders are prevalent within the natural gas market environment for all other fields, particularly the JB producer. In this context, the JB producer exclusively engages with traders rather than directly selling gas to end-consuming cities.

In the baseline scenario, a distinct pattern emerges where only seven off-take cities (YC2, CQ, LZ1, AQ, WH1, JX, YQ) exclusively receive their gas supply directly from producers. In contrast, the remaining cities engage with traders in the gas market. On the producer side, LN1 and HEGS opt for a direct supply approach, selling their gas exclusively to the end-offtake cities. Conversely, JB chooses to conduct transactions with third-party Traders rather than a gas of sale directly to the end-consuming cities. Other producers, such as HH, predominantly supply gas to the end-use off-take cities, with a small portion of their production allocated for sale to Traders.

In Scenario I, implementing the China-Russian gas transmission program entails utilizing TLF as the starting point for the program, with the gas volume sold by TLF serving as the designated volume for the transmission program. The figure illustrates that the gas supply volume from the HEGS producer undergoes a significant reduction following the introduction of the Russian-Chinese gas transmission program (as visually represented by the last bar), while the volume of gas sold to the end-user cities remains unchanged. Similar trends are observed for LN1, with a decrease in supply volume. Additionally, the supply pattern of off-take cities changes this scenario. Notably, off-take cities such as ZW, YQ, YC2, LZ, XN, AQ, WH1, JX, LJ, and SH now require gas from the producer to meet their demand.

In Scenario II, an obvious observation is a substantial increase in gas supply from the HH producer. This surge in supply corresponds to the second China-Russian transmission plan, which aims to enhance the volume of gas delivered through the existing China-Russian Eastern Route. Consequently, the volume of gas supplied by HH to third-party traders also experiences a significant increase. Consistent with the findings of Scenario I, LN1 and HEGS continue to sell gas to the end-user cities directly. However, HEGS and PG producers exhibit reduced gas supply compared to the baseline scenario. Furthermore, the gas supply pattern of several off-take cities changes this scenario, as AQ, WH1, JX, SH, YC2, YQ, and LZ now receive direct supply from the producer.

In Scenario III, implementing the China-Russian gas transmission plan involves a route that passes through Mongolia, entering China directly from Inner Mongolia and supplying gas to the Beijing-Tianjin-Hebei region. For this plan, we consider EEDS to be the designated producer. As depicted in the figure below, the increased gas supply from EEDS leads to notable changes in the gas supply from other producers. Comparatively, the gas supply from HEGS and PG fields experiences a decrease in this scenario when compared to the baseline scenario. Moreover, the gas supply mix at the HH field changes, with an increase in the volume of gas sold to third-party traders, constituting approximately 50 % of the total gas sold by HH. Notably, the gas supply pattern of several off-take cities, including YQ, TA, TX, YC2, CQ, LZ1, AQ, WH1, JX, SH, NN, and LJ, depend exclusively on supply from a single producer.

To comprehensively compare the changes in gas supply among producers and end-use cities in each scenario, we have generated 3 bar charts, as depicted in Fig. 14. Fig. 14(a) illustrates the variations in gas supply from producers across different scenarios. The implementation of the China-Russian gas transmission plans has a significant impact on the HEGS, PG, and JB fields. Consequently, the gas supply from these three fields decreases by an amount equivalent to the planned transmission volume. Fig. 14(b) further dissects the supply structure by differentiating between third-party traders and producers. All three China-Russian gas transmission plans facilitate the entry of third-party traders into the gas market. It becomes apparent that in Scenario I, most of TLF's gas supply is directed toward third-party traders. Lastly, Fig. 14(c) focuses on the gas supply structure for the selected end-use off-take cities, clearly identifying changes in the supply framework across different scenarios (see Fig. 8) (see Fig. 9) (see Fig. 10) (see Fig. 11) (see Fig. 12) (see Fig. 13) (see Fig. 7).

5. Conclusion

To facilitate informed decision-making within China, this study employs the concept of congestion costs to assess and analyze the implications of Russia-China natural gas transmission plans on the domestic long-distance pipeline network. The research aims to establish a foundational framework for assessing gas transportation routes between China and Russia, with a specific emphasis on considering congestion costs. By employing this approach, a comprehensive evaluation of the impacts of the transmission plans on the pipeline network can be systematically conducted.

A comprehensive analysis of congestion costs across all pipelines in the four scenarios shows that the Altai line and CRER exert substantial transportation pressure on China's long-distance natural gas pipeline network. Conversely, implementing the China-Mongolia-Russia pipeline demonstrates a notable alleviation of pipeline pressure. Scenario III, which entails the route through Mongolia, emerges as the most favorable decision among the scenarios considered. Taking the Yu-Ji pipeline as an example, the congestion cost of the pipeline from YL to FY1 is 0.1183 CNY/m^3 and 0.1385 CNY/m^3, respectively, in Scenario I and Scenario II, compared to \$0.0464/m3 in Scenario III. The research findings underscore the manifold advantages of adopting this route, specifically focusing on its efficacy in mitigating congestion-related challenges within the domestic long-distance pipeline network and ameliorating gas supply constraints in the Beijing-Tianjin-Hebei region. Additionally, implementing this plan yields the supplementary advantage of alleviating transportation pressures within the Shaanxi-Beijing system. For example, the congestion charge for SQ-YQ in the Shaanjing system in Scenario III is 0.0160 CNY/m^3 lower than the baseline scenario. Furthermore, it is imperative to recognize that within the framework of Scenario III, the market share of gas traders exhibits a comparatively diminished presence when contrasted with the two alternative scenarios. Consequently, a compelling need arises for government intervention in the form of policy measures aimed at nurturing an open and transparent market milieu. Such a regulatory approach is essential to guarantee equitable market entry opportunities for emerging stakeholders and to stimulate healthy competition amongst critical participants, including gas producers, traders, and off-take municipalities. The advocacy of competition and the refinement of gas allocation mechanisms through these prescribed measures can, in turn, yield enhancements in the overall operational efficiency and efficacy of the natural gas market.

Future research endeavors should adopt a comprehensive approach, encompassing variables such as transportation distance, gas trading prices, and pipeline congestion costs, to propose a more rational and reasonable choice of natural gas routes. Such an approach can further enhance the collaboration in natural gas between China and Russia.

CRediT authorship contribution statement

Qi Wei: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Peng Zhou:** Writing – review & editing, Supervision, Project administration. **Xunpeng Shi:** Conceptualization, Writing – review & editing, Supervision, Project administration.

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.

Data availability

Data will be made available on request.

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Appendix A. China's Natural Gas Model Formulation

Table A.1
Sets

Symbol	Description
n,m	Nodes of the pipeline ($n \in N, m \in M$)
A	Set of pipeline arcs (n,m)
W	Set of producers w
P	Set of the traders p
S	Set of storage operators s
C	Set of consumers c
T	Set of seasons t
d_t	Days of season t
d_{t_1}	Days of peak season t_1 ($t_1 = 151$)
d_{t_2}	Days of off-peak season t_2 ($t_2 = 214$)

Table A.2
Decision Variables (unit: m^3)

Symbol	Description
T_{wct}	Amount of gas sold by producers w to consumers c in season t
T_{wpt}	Amount of gas sold by producers w to the traders p in season t
T_{pct}	Amount of gas sold by the traders p to consumers c in season t
T'_{wpt_2} *	Amount of gas sold by producers w to the traders p in season t_2
$FLOW^{W}_{nmt}$	The flow allocation of producers w over arc (m,n)
$FLOW^{A}_{nmt}$	The flow allocation of pipeline operators A over arc (m,n)
$FLOW^{P}_{nmt}$	The flow allocation of the traders p over arc (m,n)
$PUR^{P\leftarrow W}_{wpt}$	Amount of gas brought by the traders p from producers w in season t
$PUR^{P\leftarrow S}_{spt_2}$	Amount of gas brought by the traders p from storage operators s in season t_1
EXT_{sct_1}	Amount of gas sold by storage operators s to consumers c in season t_1
EXT_{spt_1}	Amount of gas sold by storage operators s to the traders p in season t_1
STO_{spt_2}	Storage capacity provided by storage operators s to the traders p in season t_2
INJ_{spt_2}	Amount of gas stored by the traders from storage operators s in season t_2

* T'_{wpt_2} is the extra amount of gas brought by the traders for storage in season t_2.

Table A.3
Parameters

Symbol	Description
π^{C}_{t}	Price of gas sold by producers w to consumers c in season t
$\pi^{S}_{t_2}$	Price of gas storage by the traders p from storage operators s in season t_2
$\pi^{W\rightarrow P}_{t}$	Price of gas sold by producers w to the traders p in season t
$\pi^{S\leftarrow W}_{t_2}$	Price of gas sold by storage operators s to producers w in season t_2
$\pi^{S\rightarrow P}_{t_1}$	Price of gas sold by storage operators s to the traders p in season t_1
$cf^{W}_{t}(\cdot)$	The cost function of producers
τ^{A}_{nmt}	The congestion fee
π^{Areg}_{nmt}	The transportation fee
sc^{S}_{t}	Storage cost
$\overline{PR_t}^{W}$	Daily maximum capacity of producers w, in m^3
$\overline{PROD}^{W}$	Annual maximum capacity of producers w, in m^3
CAP_s	Maximum storage capacity of storage operators s, in m^3
γ^{S}	The loss rate of storage operators s (%)
$\overline{FLOW}^{A}_{nmt}$	Maximum flow of the pipeline, in m^3
p^{r}_{0}	Price of consumers (city-gate price)
d^{r}_{0}	The demand of consumers (2019), in m^3

All prices, costs, and fees are in CNY.

Table A.4
Dual Variables

Symbol	Description
α^{W}_{wt}	The dual variable of maximum daily capacity
β^{W}_{wt}	The dual variable of annual maximum capacity
η^{W}_{wt}	The dual variable of pipeline capacity limitation
σ^{A}_{mnt}	The dual variable of pipeline flow limitation for pipeline operators

(continued on next page)

Table A.4 (*continued*)

Symbol	Description
μ_{st}^S	The dual variable of storage capacity limitation
ν_{st}^S	The dual variable of storage balance limitation
ξ_{st}^S	The dual variable of pipeline flow limitation for storage operators
γ_{pt}^P	The dual variable of total volume balance for the traders
δ_{pt}^P	The dual variable of total storage volume balance for the traders
χ_p^P	The dual variable of pipeline flow limitation for the traders

Table A.5
The acronyms of cities

City	Acronym	City	Acronym	City	Acronym
Beijing	BJ	Hefei	HF	Nanjing	NN
Kaifeng	KF	Yulin	YL	Guangzhou	GZ1
Anyang	AY	Xi'an	XA	Erdos	EEDS
Zhengzhou	ZZ1	Changqing	CQ	Lijiang	LJ
Taixing	TA	Ganzhou	GZ2	Hangzhou	HZ1
Suqian	SQ1	Nanchang	NC	Huzhou	HZ2
Nanjing	NJ	Guyuan	GY1	Jiaxing	JX
Anqing	AQ	Zhongwei	ZW	Yongqing	YQ
Fuyang	FY2	Wuhan	WH1	Hengshui	HS
Wuhu	WH2	Yichang	YC2	anping	AP
Xining	XN	Nanbu	NB	Shanghai	SH
Guiyang	GY2	Wuwei	WW	Lanzhou	LZ1
Longnan	LN2	Linfen	LF	Mengxian	MX
Pingliang	PL	Fenyang	FY1	Zhuzhou	ZZ2
Changsha	CS	Tanan	TA	Jinan	JN

Appendix B. Karush-Kuhn-Tucker conditions

In this paper, the Lagrange multipliers are applied to solve the optimization problem for each subject. The Karush-Kuhn-Tucker (KKT) condition acts as a necessary and sufficient criterion for subjects to maximize their objectives in situations involving convex optimization problems.

(1) KKT conditions for producers' problem

$$0 \le -d_t\pi_t^C + d_t cf_t^W + \alpha_{wt}^W + d_t\beta_w^W + \eta_t^W \perp T_{wct} \ge 0 \ \ \forall w,t \tag{B.1}$$

$$0 \le -d_t\pi_t^{W\to P} + d_t cf_t^W + \alpha_{wt}^W + d_t\beta_w^W \perp T_{wpt} \ge 0 \ \ \forall w,t \tag{B.2}$$

$$0 \le -d_{t_2}\pi_t^{W\to S} + d_t cf_t^W + \alpha_{wt}^W + d_t\beta_w^W \perp T_{wst_2} \ge 0 \ \ \forall w,t \tag{B.3}$$

$$0 \le -d_{t_2}\pi_t^{W\to P} + d_t cf_t^W + \alpha_{wt}^W + d_t\beta_w^W \perp T'_{wpt_2} \ge 0 \ \ \forall w,t \tag{B.4}$$

$$0 \le d_t\left(\tau_{mnt}^A + \pi_{mnt}^{Areg}\right) - \eta_t^W \perp FLOW_{mnt}^W \ge 0 \quad \forall t \tag{B.5}$$

$$0 \le \overline{PR}_t^W - \sum_{c\in C} T_{wct} - \sum_{p\in P} T_{wpt} - \sum_{p\in P} T'_{wpt_2} - \sum_{s\in S} T_{wst_2} \perp \alpha_{wt}^W \ge 0 \tag{B.6}$$

$$0 \le \overline{PROD}^W - \sum_{c\in C}\sum_{t\in T} d_t T_{wct} - \sum_{p\in P}\sum_{t\in T} d_t T_{wpt} - d_{t_2}\left(\sum_{s\in S} T_{wst_2} + \sum_{p\in P} T'_{wpt_2}\right) \perp \beta_w^W \ge 0 \tag{B.7}$$

$$0 \le \sum_{m\in M}\sum_{n\in N} FLOW_{mnt}^W - \sum_{w\in W}\sum_{c\in C} T_{wct} \perp \eta_t^W \ge 0 \tag{B.8}$$

(2) KKT conditions for storage operators' problem

$$0 \le d_{t_2}\left(sc_t^S + \pi_{t_2}^{S\leftarrow W}\right) + \mu_{st_2}^S - d_{t_2}\nu_s^S\left(1-\gamma^S\right) + \xi_t^S \perp PUR_{wst_2} \ge 0 \tag{B.9}$$

$$0 \le -d_{t_1}\pi_t^C + d_{t_1}\nu_s^S + \xi_t^S \perp EXT_{sct_1} \ge 0 \tag{B.10}$$

$$0 \le -d_{t_1}\pi_{t_1}^{S\to P} + d_{t_1}\nu_s^S \perp EXT_{spt_1} \ge 0 \tag{B.11}$$

$$0 \le -d_{t_2}\left(\pi_{t_2}^S - sc_t^S\right) + \mu_{st_2}^S \perp STO_{spt_2} \ge 0 \tag{B.12}$$

$$0 \le d_t\left(\tau^A_{nmt} + \pi^{Areg}_{nmt}\right) - \xi^S_t \perp FLOW^S_{nmt} \ge 0 \tag{B.13}$$

$$0 \le CAP^S - \sum_{w\in W} PUR_{wst_2} - \sum_{s\in S} STO_{spt_2} \perp \mu^S_{st_2} \ge 0 \tag{B.14}$$

$$0 \le d_{t_2}\sum_{w\in W}(1-\gamma^S)PUR_{wst_2} - d_{t_1}\left(\sum_{c\in C} EXT_{sct_1} + \sum_{p\in P} EXT_{spt_1}\right) \perp \nu^S_s \ge 0 \tag{B.15}$$

$$0 \le \sum_{n\in N}\sum_{m\in M}\left(FLOW^S_{mnt}\right) - \sum_{s\in S}\sum_{c\in C} EXT_{sct_1} - \sum_{w\in W}\sum_{s\in S} PUR_{wst_2} \perp \xi^S_t \ge 0 \tag{B.16}$$

(3) KKT conditions for traders' problem

$$0 \le -d_t\pi^C_t + d_t\gamma^P_p + \delta^P_t \perp T_{pct} \ge 0 \tag{B.17}$$

$$0 \le d_t\pi^{W\to P}_t - d_t\gamma^P_p + \delta^P_t \perp PUR_{wpt} \ge 0 \tag{B.18}$$

$$0 \le d_{t_2}\pi^{W\to P}_t + \delta^P_t - d_{t_2}\chi^P_p \perp PUR^{'}_{wpt_2} \ge 0 \tag{B.19}$$

$$0 \le d_{t_2}\pi^S_{t_2} - d_{t_2}\gamma^P_p + \delta^P_t + d_{t_2}\chi^P_p \perp INJ_{spt_2} \ge 0 \tag{B.20}$$

$$0 \le d_{t_1}\pi^{S\to P}_{t_1} - d_{t_1}\gamma^P_p + \delta^P_t \perp PUR_{spt_1} \ge 0 \tag{B.21}$$

$$0 \le d_t\left(\tau^A_{nmt} + \pi^{Areg}_{nmt}\right) - \delta^P_t \perp FLOW^P_{nmt} \ge 0 \tag{B.22}$$

$$0 \le \sum_{t\in T}\sum_{w\in W} d_t PUR_{wpt} + d_{t_1}\sum_{s\in S} PUR_{spt_1} + d_{t_2}\sum_{s\in S} INJ_{spt_2} - \sum_{t\in T}\sum_{c\in C} d_t T_{pct} \perp \gamma^P_p \ge 0 \tag{B.23}$$

$$0 \le \sum_{n\in N}\sum_{m\in M} FLOW^P_{nmt} - \sum_{p\in P}\sum_{c\in C} T_{pct} - \sum_{p\in P}\sum_{s\in S} INJ_{spt_2} - \sum_{p\in P}\sum_{w\in W} PUR^{'}_{wpt_2} - \sum_{p\in P}\sum_{w\in W} PUR_{wpt} - \sum_{p\in P}\sum_{s\in S} PUR_{spt_1} \perp \delta^P_t \ge 0 \tag{B.24}$$

$$0 \le d_{t_2}\sum_{w\in W} PUR^{'}_{wpt_2} - d_{t_2}\sum_{s\in S} INJ_{spt_2} \perp \chi^P_p \ge 0 \tag{B.25}$$

(4) KKT conditions for pipeline operators' problem

$$0 \le -\left(\tau^A_{nmt} + \pi^{Areg}_{nmt}\right) + \sigma^A_{nmt} \perp FLOW^A_{nmt} \ge 0 \tag{B.26}$$

$$0 \le \overline{FLOW}^A_{nmt} - FLOW^A_{nmt} \perp \sigma^A_{nmt} \ge 0 \tag{B.27}$$

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