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# Evaluating natural gas supply security in China: An exhaustible resource market equilibrium model

Xiaolin Wang [a,b], Yangyang Qiu [a], Jun Chen [c,**], Xiangping Hu [d,*]

[a] School of Economics and Management, China University of Geosciences (Wuhan), Hubei, Wuhan, 430074, China
[b] China University of Geosciences (Wuhan) Resource & Environment Center, Hubei, Wuhan, 430074, China
[c] School of Marxism, China University of Geosciences (Wuhan), Hubei, Wuhan, 430074, China
[d] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, N-7491 Trondheim, Norway

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ABSTRACT

The continuous growth of natural gas demand in China has brought about supply security from the insufficient supply of domestic resources and ever-increasing dependency on natural gas imports. A multi-agent game framework for supply security is proposed to investigate availability, accessibility, and affordability along natural gas industry and supply chain. In this framework, an exhaustible resource market equilibrium model based on mixed complementary programming (MCP) is developed, taking into account the dynamic depletion of the remaining recoverable reserves, to evaluate the gas supply security in China. The results indicate the supply security of China's natural gas is far from optimistic from 2020 to 2049, and the newly-increased recoverable reserves of 200 bcm/a are required to meet the expanding scale of the natural gas market. However, it will face supply risks with lower Reserve-Production ratios after 2030 and higher dependencies after 2040. Therefore, the equilibrium model is used to simulate for seeking feasible solutions to ensure the natural gas supply security from three aspects: market structure, discount rate, and resources tax. Several combinational strategies suitable for China's natural gas supply security are suggested according to the market structure, natural gas import, discount rate, and resources tax for building a more diversification system of natural gas supply, establishing an efficient allocation system of the natural gas market and setting up an effective strategic stockpile system of natural gas resources.

## 1. Introduction

Chinese government has been committed to the development and utilization of natural gas resources in the latest decade, aiming at ensuring the security of energy transition and achieving the goal of carbon emission reduction (Qin et al., 2018; Xu and Lin, 2019; NDRC, 2017). China's natural gas consumption has rapidly increased from 24.7 billion cubic meters (bcm) in 2000 to 306.3 bcm in 2019 (BP, 2020). It is expected to continue with growing and will reach 533 bcm in 2030 and 655 bcm in 2040 (IEA, 2020; State Council, 2018). Therefore, China's natural gas supply security is emerging because the domestic gas production could not meet the demand, resulting in the ever-increasing dependency of imported natural gas from 5% in 2007 to 45% in 2019. The dependence is expected to exceed 62% by 2030 (Shaikh and Ji, 2016), which is close to the 70% red line of energy security (Zou et al., 2020). Meanwhile the maximum capacity of domestic gas production is optimistically estimated to reach 320 bcm/a in 2030 (Lin and Wang, 2012; Zou et al., 2018). They have caused the Chinese government's double concerns about the security of natural gas supply in the coming decades. To address these two issues, Chinese government has put forward two strategies: diversity of gas import to resist natural gas supply risks (Vivoda, 2014; Hafezi et al., 2020) , and investment augmentation for increasing proven gas reserves and expanding production capacities. The strategies aim to reach sufficient availability of 250 bcm/a by 2025 (State Council, 2018).Nevertheless, natural gas supply crisis occurred by the sudden cut of imported gas from Turkmenistan at the end of 2017 (Liu, 2018), highlighting the rigid supply of domestic production could not hedge the gas imported risk. Meanwhile, there is not enough strategic stockpile to make up for the huge natural gas shortage in short term. Therefore, three conflicts have been existing in the progress of

* Corresponding author.
** Corresponding author.
*E-mail addresses:* wangxiaolin_cug@163.com (X. Wang), qiuyangyang@cug.edu.cn (Y. Qiu), cj-2010@139.com (J. Chen), Xiangping.Hu@ntnu.no (X. Hu).

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market-oriented reform. First, higher amount of cheap imported gas would crowd out domestic natural gas with high production costs, thereby domestic producers will not be willing to produce more natural gas. Second, ever-increasing scarcity rent will push up the market price with the gradually decline of remaining recoverable reserves of natural gas resources in China, leading to loss of consumer welfare (Fan, 2018) Third, producers tend to over-develop or withhold natural gas resources to arbitrage during the depletion period of non-renewable resources for maximizing profits. Intertemporal arbitrage would trigger the shrinkage and even interruption of natural gas supply chain (Rioux et al., 2019). Therefore, these three conflicts would be the challenges faced by China, and need to be solved urgently.

Energy security evaluation is very important for any country to formulate its energy strategy. In general, energy supply security evaluation mainly focuses on affordability, availability, accessibility and acceptability (Harker and Lutz, 1990; IEA, 2007; Ang et al., 2015 ; APERC, 2018). Generally, Since every country has its own unique energy consumption structure, resource endowment and governance system, it is very difficult to objectively evaluate the supply security according to the goal of each country's energy security. The comprehensive evaluation methods were commonly employed to identify the key factors of supply security, including, e.g., principal component analysis (PCA), analytic hierarchy process (AHP), and Technique for Order Preference by Similarity to Ideal Solution(TOPSIS). . The PCA and AHP were introduced to analyze the interruption within the gas supply chain in Serbia and Turkey, respectively (Madarevi et al., 2018; Berk et al., 2018; Pavlović et al., 2018). These authors argued that high risk of import dependency would reduce the availability and accessibility along natural gas supply chain. Moreover, the supply security in regional natural gas market was also a big concern. Chloé and Paltseva (2009) used PCA to evaluate the EU's anti-risk ability and appointed out that the EU energy security map should be expanded to the Mediterranean Sea and the United States. Certainly, the energy security of Asian countries was also investigated. Vivoda (2010, 2019) and Geng et al. (2014) assessed the natural gas supply security of China, Japan, and Korea by TOPSIS. They concluded that the competition among these countries to obtain more natural gas would lead to import risk resonance, and the accessibility within this area should be expected to rely on the construction of energy import alliances among them. However, the evaluations mentioned earlier are usually criticized for the subjective, static, and even rigid judgment on supply security without considering the relationship of availability, accessibility, and affordability in the natural gas industry. Additionally, these evaluation methods evade a critical question in which supply security is shaped by the gambling behaviors among the participants in the natural gas market.

The mixed complementarity programming (MCP) provides a general mathematical framework for the equilibrium modelling of electricity, crude oil and natural gas markets (Golombek et al., 1995; Gaberial et al., 2005a; Huppmann and Holz, 2014; Berk and Ediger, 2018). Moreover, the MCP framework was extended to wind power (Weigt, 2009) and energy transition risk (Guo and Hawkes, 2018; Ansari and Holz, 2020). In the framework, each market participant solves an optimization problem by implementing the MCP model through the Karush-Kuhn-Tucker (KKT) conditions and market clearing. To our knowledge, the researches on natural gas supply security have focused on the liberalization of European and America natural gas market. Golombek et al. (1995) established a multi-agent model based on MCP to investigate the long-term impact of the third-party access policy on natural gas supply security in Western Europe. In this model, producers act as strategic behaviors while traders, end customers and arbitrageurs act as price-takers. Inspired by their work, a large-scale linear complementary programming (LCP) and MCP were used to analyze the restructuring natural gas market in North America after Order No.636 issued in 1985 (Gaberial et al., 2005b; 2005c). Liberalization of North American and European markets shifted market structure from monopoly to perfect competition, leading to more accessibility in the restructured market. Consequently, the social welfare was increased while the growth of gas production was provoked.

Compared with North American natural gas market, supply security in Europe has been more concerned, due to the ever-decreasing natural gas reserves of European continent and the heavier dependency on imported gas outside European Union (EU). Another MCP model GASTALE is the first attempt to apply successive oligopoly structure to natural gas production and wholesale (Boots et al., 2004). Both producers and wholesalers in this model tended to exert market powers by reducing the amount of natural gas to obtain more excessive profits. Subsequently, GASTALE was further developed into a series of typical MCP models, such as multi-period equilibrium models (Egging et al., 2008; Egging and Gabriel, 2006), GASMOD (Holz, 2008) and WGM (Gabriel et al., 2012; Egging et al., 2010), with more details regarding the demand seasonality, a storage sector, gas pipeline capacities and infrastructure expansions (Lise and Hobbs, 2008). Of these models, conjectural variables (*cv*) are used as a graceful way to model the market powers in imperfect market. The reactions of strategic rival are captured by setting the parameters *cv*. Therefore, these more complicated models could help us to identify accessibility barriers better than the comprehensive evaluation methods.

One of advantages in MCP models is that a logarithmic cost function, proposed by Golombek et al. (1995), is adopted to be helpful for capturing the specific characteristics of gas production: sharply increasing costs when producing close to full capacity. However, a major drawback in the function was that the production capacity was given exogenously in future periods, without counting for the production capacity limited to the remaining recoverable reserves. What's Furthermore, the reserves was were dynamically decreasing in each period. In order toTo overcome this shortcoming, Abada et al. (2013) replaced the capacity with the remaining recoverable reserve in GaMMES model, taking into account the exhaustibility of the resource. Moreover, Huppmann et al. (2013) put forward another approach, and theoretically proved that the production capacity was determined by the investment in gas production. The purpose of these two approaches is to reduce the scarcity rent of exhaustible resources through relaxing the constraints of natural gas production capacity. Ever-reducing scarcity rent will extend the supply curve of natural gas resources, thereby improving the sustainable availability of the exhaustible resources.

Nevertheless, such two approaches were only devoted to the impact of production cost change in one period on decision-making of output (Abada et al., 2013; Huppmann et al., 2013). In particular, limited to scarce natural gas resources, producers pay more attention to making reasonable strategic arrangements for the sustainable exploration and development over time, to obtain more lasting profits through inter-temporal arbitrage (Pindyck, 1978; Lin and He, 2008). In basic Hotelling model (Hotelling, 1931), the dynamic depletion of exhaustible resources is more detailed than that of MCP models. The remaining recoverable reserves in Hotelling model is a state variable, which will increase with exploration while exhausted with natural gas extraction. The continuous production of natural resources is a process of dynamically recovering the value of remaining recoverable reserves. The process is normally affected by market price, technological progress, investment and tax policy(Knapp, 1996; Ge and Zhou, 2007; Bommier et al., 2017). Unfortunately, marginal production cost was usually treated as a constant among the literatures on Hotelling models (Slade, 2009; Nguyen and Nguyen-Van, 2016; Atewamba and Nkuiya, 2015).

Therefore, an exhaustible resource market equilibrium model based on MCP (abbreviated as ERMEM) was advanced in this paper, combing the Hotelling model with the logarithmic cost function in MCP framework. In ERMEM model, the remaining recoverable reserves acts as a critical decision variable for producers, and differential equations of the reserves in adjacent periods are used to express the dynamic natural gas production over time. Moreover, discount rate reflects the economic expectations of producers on natural resource market (Dasgupta et al., 1994), so the rate is put into ERMEM model to take producer's decision preference into account. For instances, the financial crisis, drastic price fluctuations and large-scale utilization of renewable energies will have an important impact on the discount rate (Howarth and Norgaard, 1993; Nguyen and Nguyen-Van,2016). Besides, resource tax is also considered, as a macro-control instrument of the government, to regulate the speed of natural resources depletion (Lin and He, 2008; Shogren and Smulders, 2020). Generally speaking, resource tax is regarded as a very important parameter in academic research. It can be used to express the concern of policy makers about intergenerational equity of natural resource utilization and sustainable development, such as international resource trade disputes (Hillman and Ngo, 1983), environmental pollution (Cairns and Robert, 2014), market failure (Lin and He, 2008) and supply security (Zhong et al., 2016). Therefore, our model is more suitable for simulating the intervention of policies on the development of exhaustible resources.

We summarize our main contributions as follows. (i)A multi-agent game framework for supply security is proposed to analyze the supply security of the Chinese natural gas industry and supply chain based on availability, accessibility, and affordability. In this framework, supply security is dynamically evaluated using a novel multi-year market equilibrium model of exhaustible resources based on MCP. (ii) Considering the remaining recoverable reserves as the endogenous variable, we establish a differential relationship between the successive production of natural gas and the dynamic depletion of the remaining recoverable reserves. It builds a bridge between the dynamic development of natural gas resources and the market allocation and theoretically supports the construction of an integrated energy supply security management system of enterprise-market-government. (iii) Market structure, discount rate and resource tax are used as tools for supply security management to reveal the temporal and spatial evolution of producers and importers' adaptive supply strategies. We believe that our work provides a starting point for policy making to improve the incentive-compatible mechanism for fair, efficient, and sustainable natural gas allocation.

## 2. Methodologies

### 2.1. An analysis framework of natural gas supply security

China's natural gas market-oriented reform has been driven by policies and began with net-back pricing in 2013 (NDRC, 2013). Subsequently, a series of reform policies were gradually implemented, such as resource tax (MOF, 2014), regulatory review of pipeline transmission fees (NDRC, 2016), price regulation of inter-provincial pipeline transportation (NDRC, 2017), competitive transfer of mining rights (MNR, 2019) and open and fair access of infrastructure (NDRC, 2019). Until now, the reform has made great progress, including price deregulation, Third Party Access(TPA) and ongoing spilt of vertical-integrated market structure. The goal of the reform is to encourage more participants to enter the market, so as to obtain the more effective allocation and supply guarantee of natural gas resources. Therefore, we developed a market equilibrium analysis framework of exhaustible resources centered on the objectives of enterprises, markets and government (see Fig. 1). The goal is to describe the profit distribution and coordination among the upstream, midstream and downstream market players.

***Upstream market.*** The upstream market is mainly dominated by domestic producers, pipeline natural gas (PNG) and LNG importers. Producers are engaged in natural gas exploration, development and production while selling gas production $q_{gm}$ to wholesalers at wellhead prices$p_g$, so as to recover the marginal production cost $mac_g$ and user cost $\lambda_g$. PNG importers purchase foreign PNG at the border and LNG importers buy foreign LNG. Under the Take-or-pay clause, the import amount are constrained by the imported total quantity regarded as exhaustible resources, and then the scarcity rents $\lambda_f$ need to be recovered through the wholesale prices$p_f$. At present, China's natural gas production and import are mainly monopolized by three major state-owned companies, namely CNPC, Sinopec and CNOOC, and then the activities of production and wholesale are integrated (Xu et al., 2017). However, the liberalization of natural resource mining rights and the open access of infrastructure has facilitated more private enterprises to enter the upstream market. Therefore, the upstream market participants will fully compete, and then the integrated activities of production and wholesale

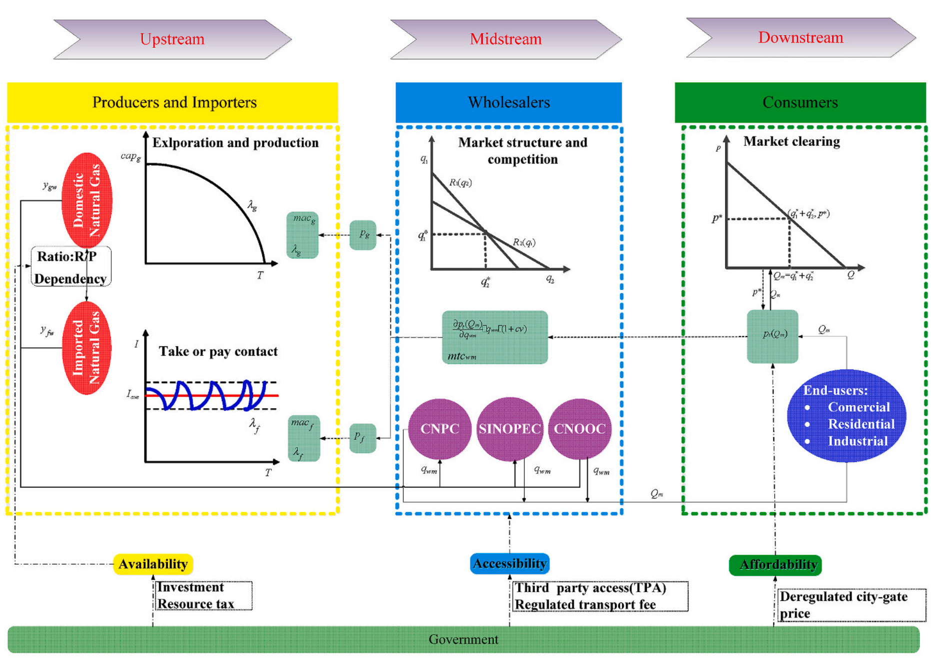



**Fig. 1. An analysis framework of natural gas supply security in China.** The solid line denotes the mass flow from the upstream to downstream market and the dotted line represents the cash flow reversely. The dot dash line indirectly denotes the intervention of policies made by the Government.

will be split up in the future.

***Midstream market.*** Wholesalers and transmission system operator (TSO) are the major participants in midstream market. Wholesalers purchase natural gas $q_{wm}$ competitively from upstream market, sign consignment agreements with TSO to transport the natural gas $Qm$ to downstream market, and then sell it to end users at city-gate price $p(Qm)$. At present, the major wholesalers are three wholesale companies owned by CNPC, Sinopec and CNOOC respectively. They act as strategic players and tend to exert market power to acquire much more make-up $\partial p_t(Q_m)/\partial q_{wm} \cdot q_{wm} \cdot (1+cv)$ while recovering gas purchased cost $p_g$ (or $p_f$) and transportation cost $mtcwm$. TSO will be obliged to deliver natural gas $Qm$ from the wellhead to the city gate on the premise of ensuring the safe operation of pipeline network, and eventually obtain the regulated transportation fee. In 2019, the National Pipeline Company was established. This event indicates that infrastructure, such as natural gas pipelines, large LNG terminals and gas storages, will be stripped from the three major oil gas companies and then opened to the market. It can be expected that more participants will enter the wholesale market and retail market. Eventually, market structure will evolve from monopoly to perfect competition.

***Downstream market.*** The market reaction of power generation, commerce and resident could be characterized by price-demand elasticity. In China, the elasticity of power generation is higher than that of commerce followed by that of resident. Wholesalers sell natural gas $Qm$ to distributors at city gate and then the latter distributes it to end users at different prices for arbitrage. Moreover, there are great spatial differences among the elasticity of end users. However, focusing on study the long-term supply security, we temporarily ignore the differences of end users' elasticity, as well as the spatial differences of the elasticity. Therefore, the downstream market is aggregated into a market or end user. The aggregated market is like the power pool, that is, all natural gas $qwm$ is injected into a "bathtub". Market clearing price $p^*$ is the source of profit and recovery of cost for all participants. Certainly, higher price will reduce the affordability of end users. In addition, Supply security acts as a public product for the well-running of natural gas industry and supply chain, and Chinese government should be responsible for ensuring the availability, accessibility, affordability. To achieve these targets, policy makers tend to intervene in upstream, midstream and downstream markets. Concretely, the government drives upstream market competition by adjusting resource tax, opening mining rights and increasing investment of state-owned producers, with the aim of increasing the availability of natural gas resources. Meanwhile, the government attaches great importance to midstream market, focusing on the allocation efficiency and the accessibility of natural gas resources. In the future, the barriers to entry are mainly broken through the TPA so as toto facilitate more participants to enter the market. Moreover, transmission charge, LNG degasified fee and gas storage price will be regulated, so as toto prevent the National Natural Gas Pipeline Company from making extra profits by exerting market power. The government deregulated the city-gate prices, aiming at allowing more gas sources to compete in downstream market, so that the cheaper price will be cheaper obtained and the affordability of end users will be also improved.

### 2.2. An exhaustible resources market equilibrium model

The ERMEM model based on MCP is established to simulate the successive multi-year production, import, wholesale and consumption in China's natural gas industry. Producers, importers and wholesalers are modeled as linear or nonlinear programming. The reaction of end user to natural gas supply is expressed by an inverse demand function. Additionally, we believe that TSO will expand the infrastructure capacity to meet the transportation requirements and the delivery of natural gas could not be limited to infrastructure. Therefore, TSO is not considered for in our coarse granularity model.

#### 2.2.1. Producers

Each producer $g$ seeks to maximize the net present value profit of natural gas exploration, development and production. The profit is expressed as sales income minus production cost in Eq. (1) where the gas production $y_{gwt}$ is the volume sold to the wholesalers $w$ at the period $t$. The sum of $y_{gwt}$ could not exceed the existing remaining recoverable reserve$cap_{gt}$ (Eq. (2)) and equals to the $\dot{c}\,ap_{gt}$ which is the derivative of the $cap_{gt}$ as showed in Eq. (3). Namely, the $\dot{c}\,ap_{gt}$ depends on the previous reserve$cap_{g,t-1}$, current newly increased reserve $\bar{c}\,ap_{gt}$ and the remaining reserve $cap_{gt}$. In upstream market, the producer trades with wholesalers as the wellhead at a market clearing price $\varphi_{wt}$ in Eq. (4), and the volume $q_{wmt}$ purchased by wholesalers is equal to the total of volumes sold by the producers and importers. Moreover, resource tax $k$ is adopted by government to decease the net profits of the producers, aiming to regulate the depletion speed of natural gas resources. The discount rate $r$ indirectly reflects the confidence or expectation of producers on market development. $\varphi_{gt}$ is the shadow price or use cost of natural gas reserves and $\lambda_{gt}$ is the scarce rent of the natural gas production.

$$MaxU_g = \int_0^\infty \sum_w \left[(1-k)\mathrm{P}_{gwt}y_{gwt} - \mathrm{mac}_{gt}\left(y_{gwt}\right)y_{gwt}\right] \quad \times e^{-rt}dt, \quad \forall g, w, t \tag{1}$$

$$s.t. 0 \le \sum_w y_{gwt} \le cap_{gt}, \quad \lambda_{gt} \ge 0 \quad \forall g, t \tag{2}$$

$$\sum_w y_{gwt} = \dot{c}\,ap_{gt} = cap_{g,t-1} + \bar{c}\,ap_{gt} - cap_{gt} \quad \varphi_{gt} \ge 0, \quad \forall g, t \tag{3}$$

$$\sum_g y_{gwt} + \sum_f y_{fwt} - q_{wmt} = 0 \quad \varphi_{wt}, free \quad \forall w, t \tag{4}$$

The gross cost of natural gas production for each gas field is not constant. When the accumulated gas production $\sum_t\sum_w y_{gwt}$ approaches the remaining recoverable reserves, the cost will rise sharply (Abada et al., 2013). It can be expressed as a nonlinear function of cumulative production and remaining recoverable reserves, as shown in Eq. (5). Deriving this nonlinear function, we can obtain the marginal production cost function $mac_{gt}$ in Eq. (6) where $a_g, b_g, c_g$ are the production cost coefficients of each gas field, and $res_g$ is the total of resources owned by the producer.

$$\begin{aligned} PC_{gt}\left(\sum_t\sum_w y_{gwt}, cap_{gt}\right) &= a_g\sum_t\sum_w y_{gwt} + b_g\frac{\left(\sum_t\sum_w y_{gwt}\right)^2}{2} \\ &- res_g c_g\left(\frac{cap_{gt}}{res_g}\ln\left(\frac{cap_{gt}}{res_g}\right) + \frac{\sum_t\sum_w y_{gwt}}{res_g}\right) \end{aligned} \tag{5}$$

$$mac_{gt} = \frac{dPC_{gt}}{d\sum_t\sum_w y_{gwt}} = a_g + b_g\sum_t\sum_w y_{gwt} + c_g \ln\left(\frac{cap_{gt}}{res_g}\right) \tag{6}$$

here, the present value Hamiltonian function(as shwon in Eq. (7)) is introduced (Xu and Liu, 2011) to dynamically describe the optimal gas production and depletion of natural gas resources. And then the KKT conditions are obtained by solving the first order condition of the variables $y_{gwt}$, $\lambda_{gt}$, $cap_{gt}$ and$\varphi_{gt}$.respectively as below Eqs. (8)–(11).

$$H\left(\lambda_{gt}, y_{gwt}, cap_{gt}\right) = \sum_{w}((1-k)p_{gwt}y_{gwt} - mac_{gt}(y_{gwt}, cap_{gt})y_{gwt}) - \varphi_{gt}\left(cap_{gt} - \sum_{w}y_{gwt}\right)$$
$$- \lambda_{gt}\left(\dot{c}\,ap_{gt} - cap_{g,t-1} - \bar{c}\,ap_{gt} + cap_{gt}\right) - \varphi_{wt}\left(\sum_{g}y_{gwt} + \sum_{f}y_{fwt} - q_{wmt}\right) \tag{7}$$

KKT conditions:

$$\frac{\partial H}{\partial y_{gwt}} = -(1-\mathrm{k})p_{gwt} + \frac{\partial \mathrm{mac}_{gt}}{\partial y_{gwt}} + \lambda_{gt} + \varphi_{wt} \geq 0, \quad \perp y_{gw} \geq 0 \quad \forall g, w, t \tag{8}$$

$$\frac{\partial H}{\partial \lambda_{gt}} = -\sum_{w}y_{gwt} = \dot{-}\,cap_{gt} = cap_{gt} - \bar{c}\,ap_{gt} - cap_{g,t-1} \quad \perp \lambda_{gt} \geq 0 \quad \forall g, t \tag{9}$$

$$\frac{\partial H}{\partial cap_{gt}} = r^{*}\lambda_{gt} - \dot{\lambda}_{gt} - \varphi_{gt} = \frac{\partial mac_{gt}}{\partial cap_{gt}}, \quad \perp cap_{gt} \geq 0, \quad \forall g, t \tag{10}$$

$$\frac{\partial H}{\partial \varphi_{gt}} = cap_{gt} - \sum_{w}y_{gwt} \geq 0, \quad \perp \varphi_{gt} \geq 0, \quad \forall g, t \tag{11}$$

### 2.2.2. Importers

Importers $f$ are modeled as maximizing the net present value profit (Eq. (12)), and the profit comes from the sales revenue minus the purchase cost of PNG or LNG. Limited to Take-or-pay clause, the cumulative imported natural gas $\sum_{t}\sum_{w}y_{fwt}$ shall not exceed the total amount $cap_f$ stipulated in the clause (Eq. (13)). Annual import gas may fluctuate within 20% of the annual average import volume $cap_f/T$ (Eq. (14)). Solving the first order condition of this function about the imported volumes $y_{fwt}$ and the scarcity rents of imported natural gas $\varphi_{ft}$ $\lambda'_{ft}$, and $\lambda''_{ft}$, the following KKT conditions are obtained as shown in Eq. (15)–(17).

$$\underset{y_{fwt}}{MaxU_f} = \int_{0}^{\infty}\sum_{w}\left[(p_{fwt} - mac_f)y_{fwt}\right]e^{-rt}dt \tag{12}$$

$$s.t.\sum_{t}\sum_{w}y_{fwt} \leq cap_f, \quad \varphi_{ft} \geq 0 \quad \forall f, t \tag{13}$$

$$\frac{cap_f}{T}(1-20\%) \leq \sum_{w}y_{fwt} \leq \frac{cap_f}{T}(1+20\%), \quad \perp cap_{gt} \geq 0, \quad \forall f, t \tag{14}$$

KKT conditions

$$0 \leq -p_{fwt} + \mathrm{c}_f + \lambda'_{ft} - \lambda''_{ft} + \varphi_{ft}, \quad \perp y_{fwt} \geq 0, \quad \forall f, w, t \tag{15}$$

$$s.t.\sum_{t}\sum_{w}y_{fwt} \leq cap_f, \quad \perp \lambda_{gt} \geq 0, \quad \forall f, t \tag{16}$$

$$\frac{cap_f}{T}(1-20\%) \leq \sum_{w}y_{fwt} \leq \frac{cap_f}{T}(1+20\%), \quad \perp \lambda'_{ft}, \lambda''_{ft} \geq 0, \quad \forall f, t \tag{17}$$

### 2.2.3. Wholesalers

Each wholesaler $w$ tries to gain the maximum profit in the market competition. Wholesalers make the total income by selling natural gas to end users at the gate price $p_t(Q_{mt})$. So, its net profit is equal to the income minus the cost of gas purchase and transportation (Eq. (18)). The market clearing condition is that the total supply of wholesalers $\sum_{w}\mathrm{q}_{\mathrm{wmt}}$ equals the total consumption demand $Q_{mt}$ (Eq. (19)). In ERMEM model, the market structure is described with the conjecture variable $cv$, and the value of is set within the range of $[-1, 0]$. When $cv$ is equal to 0, the market structure is monopoly. When $cv$ is equal to $-1$, the market structure is perfect. For other values of $cv$, the market structure will be between monopoly and perfect competition. Similar to producers and importers, a present value Hamiltonian function of wholesaler is constructed, and KKT conditions are obtained from this function, as shown in Eqs. (20) and (21).

$$\underset{q_{wmt}}{MaxU_w} = \int_{0}^{\infty}\left[(p_t(Q_{mt}) - mtc_{wmt})q_{wmt} - \sum_{f}p_{fwt}y_{fwt} - \sum_{g}p_{gwt}y_{gwt}\right]{}^{*}e^{-rt}dt \tag{18}$$

$$st.\sum_{w}\mathrm{q}_{\mathrm{wmt}} - Q_{mt} = 0, \quad \varphi_{wm}, free, \quad \forall w, t \tag{19}$$

KKT conditions

$$0 \leq p_t(Q_{mt}) - -\frac{\partial p_t(Q_{mt})}{\partial \mathrm{q}_{wmt}}\cdot q_{wmt}(1+cv) + mtc_{wmt} + \varphi_{wm}, \quad \perp q_{wmt} \geq 0 \quad \forall w, t \tag{20}$$

$$\sum_{w}\mathrm{q}_{\mathrm{wmt}} - Q_{mt} = 0, \quad \perp \varphi_{wm}, free, \quad \forall w, t \tag{21}$$

### 2.2.4. Consumption

The inverse demand function is used to measure the consumer behavior (Eq. (22)). The intercept in this function represents the maximum market demand $A_t$ when the price is zero, and the slope $B_t$ represents the end user's reaction to the market price. In general, the slope depends on the long-term demand elasticity $\varepsilon$ (Eq. (23)) (Holz et al., 2008; Xu et al., 2017). In addition, the slope and intercept are calculated according to the reference price $P^{ref}$ and consumption $Q_m{}^{\mathrm{ref}}$ (Eqs. (24) and (25)). Moreover, the market-clearing condition in the downstream market is given in Eq. (26).

$$P_t(Q_m) = A_t - B_t\cdot Q_{mt} \tag{22}$$

$$Q_{mt} = -\frac{A_t}{B_t} + \frac{1}{B_t}P_t(Q_{mt}), \varepsilon = \frac{\partial Q_{mt}}{\partial P_t(Q_{mt})} = \frac{1}{B_t}\frac{P_t}{Q_{mt}} \tag{23}$$

$$A_t = P^{ref} - B_t\cdot Q_m{}^{\mathrm{ref}} = P^{ref} - \frac{P^{ref}}{\mathrm{Q_m}{}^{\mathrm{ref}}}\cdot\frac{1}{\varepsilon}\cdot Q_m{}^{\mathrm{ref}} \tag{24}$$

$$B_t = \frac{P_t}{Q_{mt}}\cdot\frac{1}{\varepsilon} = \frac{P^{ref}}{Q_m{}^{\mathrm{ref}}}\cdot\frac{1}{\varepsilon} \tag{25}$$

$$Q_m = \sum_{w}q_{wmt} \tag{26}$$

## 2.3. Data

The exogenous variables in the model are remaining recoverable reserves, newly-increased recoverable reserves and marginal gas exploitation cost, marginal transportation cost, demand elasticity, discount rate and resource tax.

***Economical recoverable reserves.*** SEC standard is adopted to calculate the existing natural gas reserves in China. The geological reserves are converted into technically recoverable reserves with an average of 40%, while the technically recoverable reserves are further converted into economical recoverable reserves at an average of 75% (Li et al., 2017; Zhao et al., 2018). Geological reserve data mainly come from the MLR, China Statistical Yearbook, the websites of PetroChina, Sinopec and CNOOC. The annul newly-increased recoverable reserves of each gas field are distributed according to the percentage of the annual production of each gas field in 2015, as shown in Table C1-3 of Appendix C.

***Marginal exploitation cost:*** The marginal exploitation cost is business secrets owned by the enterprise and is difficult to obtain directly. To solve this issue, To solve this issue, an econometric model was introduced to extract the marginal production cost function of each gas fields in China according to Eq. (6). The required data of mining cost, resources and production comes from. SINOPEC's annual reports from 2004 to 2017. The estimated coefficients of $a_f = 0.45, b_f = 0.002, c_f = -0.37$ passed the statistical confidence test of 90% and it showed these three coefficients are in good agreement with gas fields. The estimated production for each gas field has been listed in Appendix C.4 and the original data comes from China Economic Net Database, SINOPEC Yearbook and CNPC Yearbook.

***Inverse demand function.*** The long-term price elasticity $\varepsilon$ of gas market in China's gas market was $-0.496$ from 2000 to 2007 (Cheng et al., 2014), Therefore, the elasticity of $-0.496$ is accepted in this paper and then the coefficients $A_t$ and $B_t$ in the period $t$ is calculated according to Eq.(22)–(24). Subsequently, Gompertz model was then used to simulate and predict the two coefficients from 2000 to 2060 based on the series of $A_t$ and $B_t$ from 2000 to 2017 (Lin and Wang, 2012).as shown in Appendix E. The data are from the China Statistical Yearbook from 2000 to 2017 and the reports of BP and IEA from 2011 to 2018.

***Marginal transportation cost.*** This cost is determined by the unit transportation cost and the delivery distance. The unit cost is regulated by NDRC (2017). The trajectory of gas consumption center in China was determined by gravity model (Li et al., 2017), and then the distance from the location of each gas field to the consumption center is calculated by longitude and latitude.

***Resource tax and discount rate***: In 2014, the State Administration of Taxation (SAT, 2014) issued the Notice on Adjusting the Relevant Policies of Crude Oil and Natural Gas Resource Tax. The benchmark tax rate of resource tax is adjusted to 6% with the reference of the Notice. The discount rate is mainly used to analyze the ex-ante behavior of enterprises and can be adjusted periodically according to the long-term market interest rate. Additionally, the rate in developing countries is generally higher than 5% (Neumayer, 2004; Lin and He, 2008).

### 2.4. Calibration

This model is calibrated by setting the $cv = 0$, and the real and simulated results from 2015 to 2020 are shown in Fig. 2. Mean Absolute Percentage Error (MAPE) is used to calculate the errors between the real and simulated natural gas supply volume. The errors from 2015 to 2020 are 2.5%, 2.6%, 3.2%, 3.9%, 2.8% and 3.0% respectively. All of the errors are far less than 10%, indicating our model is reliable and credible as well as the parameters set reasonably. An unexpected result from the simulation results clearly confirms that the current market is still monopoly.

The simulated dependencies in 2015 and 2016 were close to the real ones. However, the simulated dependencies in 2017 and 2018 were lower than the real ones. It can be explained that the sharply reduction of PNG from Turkmenistan could not be made up by domestic natural gas production in a short term. This incident triggered the Chinese government's concern about the supply security of natural gas in the aftermath of 2018. Therefore, Chinese government was devoted to diversifying natural gas imports and increasing the exploration and development of domestic natural gas resources (zhou, 2020). As a result, the simulated dependencies were higher in 2019 and 2020.

These two counterfactual results clearly show that policy intervention on domestic natural gas production will lead to the growth of supply in a short time, hedge the risk of imported natural gas. In our model, this kind of policy intervention has been expressed by adding the newly-increased recoverable reserves. However, the policy-driven increase of domestic reserves was not considered in the simulation. This leads to a big gap between the dependency of simulation and reality, which is not the defect of our model itself. Therefore, our model is applicable to scenario simulation of China's natural gas supply security and policy making of supply security.

## 3. Evaluating supply security of natural gas

The existing proven geological reserves are close to 50 trillion cubic meters (tcm), which exhibits the potential availability of natural gas resources in China (Ministry of Land and Resources (MLR), 2020). Moreover, it was reported that the annual proven geological reserve of natural gas in China from 2012 to 2018 are between 555 and 1110 bcm ((MLR, 2018), and they can be only transferred into technological and economical recoverable reserves of 160–330 bcm/a by 30% (see

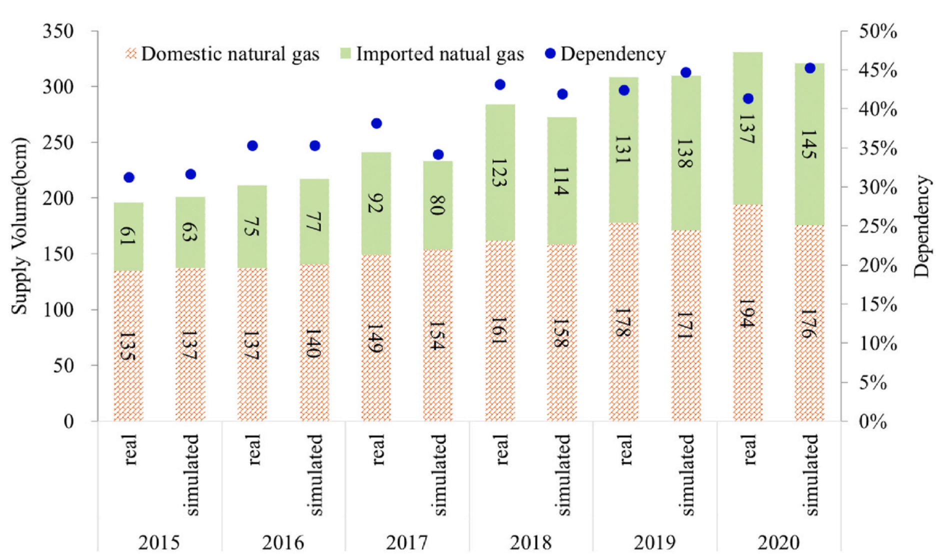
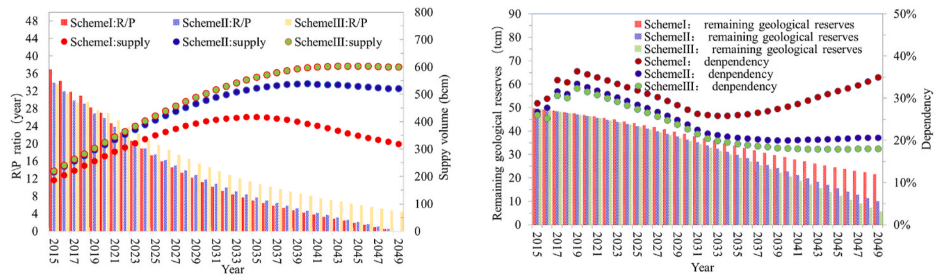



**Fig. 2.** Real and simulated results of domestic and imported natural gas.




a. ratio of R/P and supply volume

b. remaining geological reserves and dependency

**Fig. 3.** The availability of natural gas resources, natural gas supply volume and dependency.

Table C3 in Appendix C). It is necessary to take factors such as technology, cost and market demand etc. into account in the development of natural gas for producers to make supply strategies prudently.

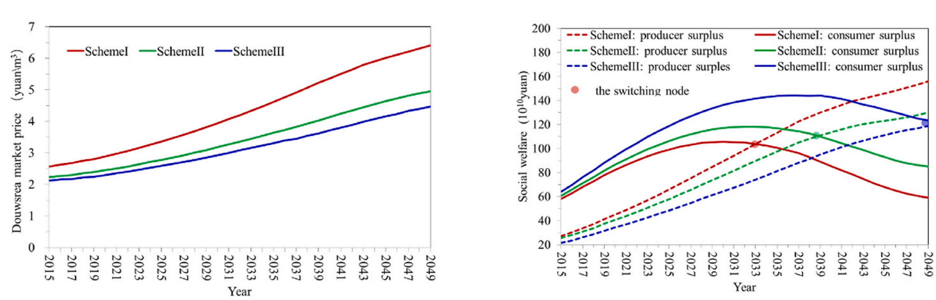
Three development schemes of natural gas resources are assumed in this paper to be Schemes I, II, and III. In scheme I, the recoverable reserve will be only increased by 100 bcm/a, constrained by high development cost; In scheme II, the recoverable reserve be increased by 200 bcm/a, motivated by technical progress of exploration and development and the annual growth rate 10% of market demand; In scheme III, the recoverable reserves will be more increased by 300bcm/a, concerning about the strong natural gas demand and high import risk in the future. In addition, it is also assumed that the newly-increased recoverable reserves are distributed to the 27 existing domestic gas fields in terms of gas production ratio of each field, as shown in Appendix B. On the prerequisite that the existing natural gas import is 170bcm/a, The ERMEM model is used to evaluate the supply security of China's natural gas market by 2050 from three aspects of availability, accessibility, and affordability.

More newly increased recoverable reserves could support the rapid expansion of the natural gas market among these three schemes (in Fig. 3a) and decrease the dependency on import gas (in Fig. 3b). However, the successive rapid expansion will, in turn, reduce the remaining recoverable reserves, bringing about a decrease in the availability of natural gas resources in the coming decades. Compared with Scheme I, Schemes II and III could provide the natural gas market with 500–600 bcm/a after 2040 while hindering the ever-declining trend of natural gas supply after 2030 in Scheme I. That is to say that there are not enough remaining recoverable reserves in Scheme I to meet with natural gas demand after 2030(in Fig. 3a), eventually leading to the ascending dependency, and reaching about 35% in 2049(in Fig. 3b). The trend could be interpreted that more geological reserves in Scheme I withhold than those in Schemes II and III, as shown in Fig. 3b. Moreover, the declines of ratio R/P in Schemes I and II rapidly reduce to 4 years by 2040, and faster than that in Scheme III. Whereas the ratio R/P in Scheme III could be maintained for more than 10 years, prolonging the buffer time for energy transition security in China. Therefore, the decrease of R/P will inevitably lead to the availability decline of natural gas resources. Once Schemes III are implemented, the accumulated recoverable reserves of 10.8 tcm will be exploited by 2049. Namely, this scheme will exhaust geological reserves exceeding 40 tcm close to the upper limit of 50 tcm. Therefore, Schemes III will lead to a huge supply risk without potential available natural gas resources after 2050.

Declining reserves and expanding market scale together will drive the price to rise from 2015 to 2049, as shown in Figs. 3 and 4 (a). Obviously, the rising price will eventually reduce the affordability of end-users. In addition, the price in Scheme I will start to rise rapidly after 2025, reaching about 6.5 yuan/m$^3$ in 2049. The reason is that the remaining recoverable reserves in Scheme I cannot be fully made up for by the newly increased recoverable reserves, so that producer tend to withhold resources and exert market power for more price markup. On the contrary, there are much more newly increased recoverable reserves every year in Schemes II and III, so producers are willing to increase gas production and gain more profits by expanding the market scale. As a result, Schemes II and III prices rose slowly from about 2.3 to 5.6 yuan/m$^3$ in 2015–2049. Therefore, Schemes II and III could provide end users with more affordable natural gas.

Moreover, more newly-increased recoverable reserves will reduce producers' market power and increase the accessibility of natural gas. It is helpful to delay the switching time node between consumer and producer surplus (see Fig. 4b) and extend the supply curve of natural gas (see Fig. 3). In Scheme I, the switching node is located in about 2030. Before the time node, the consumers' surplus is higher than the producers', and the natural gas market scale will expand rapidly. After the node, producers will gain more benefits than consumers, shrinking the consumer market and even the natural gas industry chain. Whereas, in Schemes II and III, the switching nodes are located around 2040 and 2049. It means that the two schemes will alleviate the contradiction between natural gas supply and demand and strive for more buffer time for China's market-oriented reform from monopoly to perfect competition.

In the next 30 years, the three schemes will face conflict among natural gas availability, accessibility, and affordability. Therefore, to




a. downstream market price

b. producer and consumer surplus

**Fig. 4.** The gas price and the surplus of producers and consumers under three schemes.

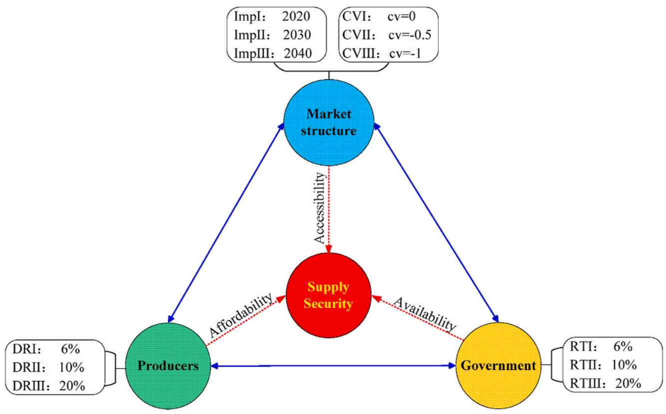



**Fig. 5.** The integrated management system of market-enterprise-government in China.

improve the efficiency of resource allocation, it is necessary to carefully balance between the depletion of natural gas resources and the expansion of market scale and coordinate the interests of producers and consumers. The supply guarantee of China's natural gas market will be far from optimistic. If Scheme II is accepted, there are more than remaining geological reserves of 10 tcm to be exploited for supporting market scale of 550 bcm. It will benefit the price rising at a low speed after 2049. Therefore, the newly-increased recoverable reserves of 200 bcm/a will be the cornerstone of making natural gas supply security strategy in China.

## 4. Scenario simulation

In this section, our model is used to analyze the safety of China's gas market from three aspects of market, enterprise and government (See Fig. 5), assuming that the newly-increased recoverable reserves are 200 bcm/a. Its purpose is to seek supply security strategies and measures suitable for China's natural gas market.

### 4.1. Scenario settings

In this section, the ERMEM model is used to analyze the supply security from three aspects: market, producers and government, to seek supply security strategies suitable for China's natural gas market. The presupposition is the newly-increased recoverable reserves of 200 bcm/a.

***Market structure.*** TPA policy has been implemented in 2020, and there will be more market players entering the natural gas market. It will lead to more accessibility of natural gas resources and even the driving force of market structure from monopoly to perfect competition. The market structure is described by schemes in this paper: monopoly competition (CV I: $cv = 0$), weak monopoly competition (CV II: $cv = 0.5$) and perfect competition (CV III: $cv = 1$). In addition, more imported natural gas is permitted to enter China's natural gas market, and it is an important measure for the security supply around 2030 and 2040. Therefore, three gas import schemes are assumed: Imp I: from 2020 to 2049, and the existing import volume will be increased by 30 bcm/a based on 170 bcm/a; Imp II: based on Imp I, 20 bcm/a will be added after 2030; Imp III: based on Imp II, 30 bcm/a will be increased after 2040.

***Producers behavior***. Producers often decide how much natural gas to produce by adjusting the discount rate according to their expectations on the futures market, thus controlling the payback period of investment (KAPSARC, 2020). Tracing backward along with the cash flow within the analysis framework in Fig. 1, it can be found that the price paid by end-users consists of marginal production cost, user cost(or scarcity rent of exhaustible resources), monopoly rent and transportation cost. In a perfect market, if production costs and transportation costs are not considered, the growth rate of scarcity rent and market price will rise with a discount rate (Slade and Thille, 2009). There is no doubt that the discount rate will affect the affordability of end-users. In China, the discount rate is generally set from 6% to 10% (Gao and Zhao, 2014). However, the depletion speed of exhaustible resources needs to be controlled to ensure the safety of China's energy transition. So the discount rate will be raised to 20% (Wang et al., 2020). Therefore, three discount schemes are adopted: 6% (discount rate(DR) I), 10% (DR II), and 20% (DR III). ***Government regulation.*** The government should try its best to use economic means to solve the externality of resource depletion. A practical resource tax act is an essential economic means usually used by the government. Therefore, policymaker prevents producers from excessively exploiting resources to maximize short-term profits by levying higher resource tax. Higher resource tax will help increase the availability of natural gas resources to realize sustainable utilization of resources. Generally speaking, if the resource tax is less than 20%, it will not have a relatively small negative impact on the national macroeconomy (Lin and He, 2008). Therefore, three tax schemes were adopted from the reference schemes: resource tax(RT) I: $tax = 6\%$, RT II: $tax = 10\%$, and RT III: $tax = 20\%$.

As mentioned above, we designed a progressive simulation route of three scenarios: about Chinese natural gas market's accessibility, affordability, and availability (Fig. 6). Firstly, Scenario I is composed of alternative combinations of natural gas imports and market structures and is used to simulate the accessibility of China's natural gas market. Secondly, the feasible schemes in Scenario I are selected into Scenario II and further combined with the discount rate schemes to simulate the affordability of natural gas. Finally, the feasible schemes in Scenario II enter Scenario III, which are related to the resource tax schemes to affect the availability of natural gas .

### 4.2. Market structure

In Scenario I, three aspects are analyzed from dependency, market price, and social welfare to refine feasible strategies of accessibility in China's natural gas market. Overall, the natural gas supply exhibits an inverted U-shaped curve(the dotted line shown in Fig. 7), which grows rapidly in the early stage (2020–2030), keep stable in the middle stage (2030–2040) and declines in the later stage (2040–2049). Specifically, Imp I will reduce the dependency on gas import from 45% in 2020 to 35% in 2049.However, after 2040, there will be no more natural gas resources entering the market, and the market scale will shrink. On the contrary, Imp II and III can continuously provide natural gas resources for the growth of market demand after 2030 and 2040, which not only alleviate the pressure of domestic resource supply, but also promote the expansion of market scale. Although the dependencies from the two import schemes are higher than that from Imp I, they are lower than 45%,and it is at an acceptable level of gas supply security for China's natural gas market.

Compared with monopoly and weak monopoly competition, perfect competition eliminates the market power exerted by domestic producers to manipulate natural gas prices and enables the suppliers to enter the market fairly and openly. Consequently, the total amount of natural gas supply increases gradually in schemes cvIII + ImpI, cvIII + ImpII, and cvIII + ImpIII (Fig. 7). In other words, perfect market improves the accessibility of the natural gas market. However, in the scheme cvIII + ImpI, the imported gas is gradually constrained by the Take-or-Pay clause in the middle and late periods, and it undoubtedly increases the vulnerability and risk of the natural gas supply chain. Furthermore, it suppose the total amount of natural gas import reaches 200bcm/a and 270bcm/a respectively in the middle and later period, as shown in combination schemes cvIII + ImpII and cvIII + ImpIII in Fig. 7. In that case, imported gas could maintain the dynamic balance between the stable market scale and the domestic resource depletion. This result indicates that more natural gas resources will enter the market and

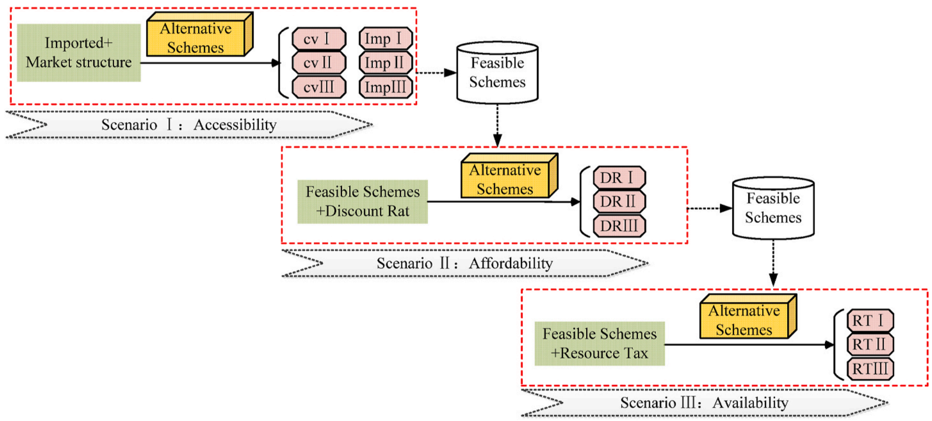



**Fig. 6.** Scenarios and feasible solutions of schemes.

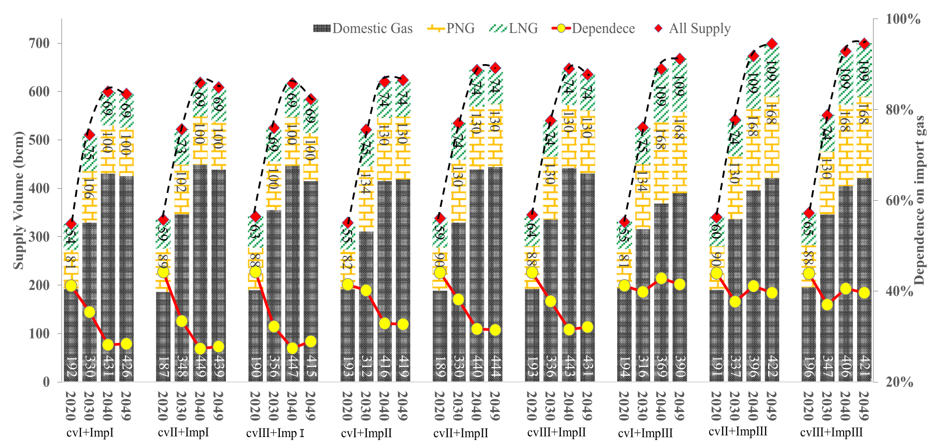



**Fig. 7.** Market structure, domestic and foreign resources' supply and dependence.

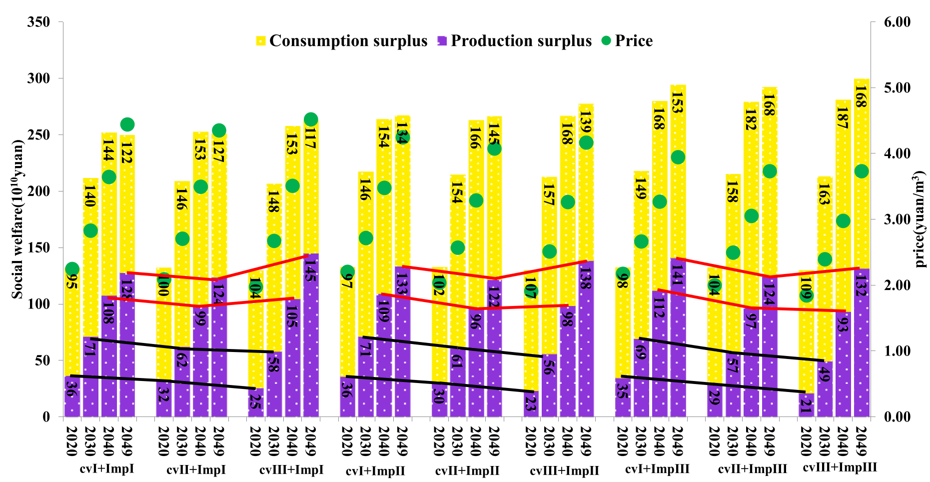



**Fig. 8.** Market structures' social welfares and gas prices.

provide resources guarantee for market-oriented reform in China's natural gas market.

Changes in social welfare provide an observable window tostudy the impacts of market structure on the distribution of benefits between producers and consumers. Compared with monopoly and weak monopoly competition, perfect competition increases the total social welfare, as the shaded histogram in Fig. 8. During the evolution of market structure from monopoly to perfect competition, the distribution of total social welfare is inclined to consumers in 2020–2030. The inclines illustrate that the surplus of producers decreases while the surplus of consumers increases, as the downward inclined straight line in Fig. 8. However, after 2030, social welfare will be transferred to producers first and then to consumers, showing a "V" -shaped broken line. These two kinds of lines indicate that radical structural reform of the natural gas market will be restricted by the supply of natural gas resources. Therefore, the rigid constraint of resources supply would push up the market price, resulting in the same loss of consumer surplus under perfect competition and monopoly competition. Contrary to these two market structures, when cv = −0.5, weak monopoly competition could keep a prudent balance between the interests of producers and consumers after 2030.

To sum up, the market-oriented reform of natural gas market in China should be based on the accessibility of natural gas resources. Monopoly competition will produce invisible barriers for foreign natural gas resources to enter the market, while perfect competition will lead to no more domestic resources to supply the market in the middle and late period. It is impossible for China's natural gas market to transform from monopoly to perfect competition in a short term. Therefore, the combinations of cvII + ImpII and cvII + ImpIII under weak monopoly competition could support feasible accessibility for China's natural gas market. These two combined schemes would play the ballast role stone in natural gas supply security dominated by large state-owned oil and gas companies such as CNPC, SINOPEC, and CNOOC, while encouraging private companies to participate in market competition.

### 4.3. Discount rate

The two feasible combination schemes in Scenario I are combined with three discount rates, consisting of the six combination schemes in Scenario II. The six schemes are used to examine the impacts of discount rates on the decision-making of producers. The cumulative supplies of producers and importers from 2015 to 2049 are simulated respectively by the first two schemes among the six schemes. These two cumulative supplies in the above six schemes are used as benchmarks. Furthermore, the differences between the cumulative supplies of the third and fourth schemes and that of the first scheme are depicted in Fig.9a and c. In addition, the differences are also simulated between the cumulative supplies of the fifth and sixth schemes and that of the second scheme, as shown in Fig. 9b and d.

Once the discount rate is increased from 6% to 10% and 20%, the suppliers will decide to speed up the development of the remaining recoverable reserves before 2040, as the green bar in Fig. 9a and c. Moreover, gas production will increase with the rise of discount rate. The decision-making will be helpful for suppliers to recover their investments ahead of time, thus avoiding the risk of asset stranding. However, the negative externality brought about by the decision-making is that the remaining recoverable reserves will be greatly depleted before 2040, and there will be no more sufficient resources for the successive development. Thereby, suppliers have to decide to withhold natural gas resources, which will lead to a rapid decline in the amount of natural gas supply, as the blue bar charts in Fig. 9 a and c.

If imported natural gas fails to fill the market demand gap in time, higher rent from scarce resources will increase the market price after 2040. Meanwhile, although suppliers reduce gas production, they tend to decrease gas production to exert market power, obtaining more monopoly rent to make up for the profit's loss. Therefore, scarcity rent and monopoly rent together raise the market price, and it will inevitably reduce the affordability of the natural gas market.

Furthermore, if scheme cvII+ ImpIII is adopted, there will be more import natural gas in the later period to meet market demand, compared with scheme cvII+ImpII. Under the discount rate of 10% and 20%, the willingness of producers to speed up the development of natural gas resources will be suppressed, as well as the motivation to exert market power. In this way, sufficient imported natural gas controls the trend of excessive price increase, as depicted in Fig. 9f, and smoothies the supply curve, as shown in Fig. 9b and d. What's more, The change of discount rate does not cause the price to fluctuate greatly, as shown in Fig. 9e and f. The price fluctuates within 1 yuan/m$^3$, and the range gradually narrows with the increase of more imported gas, such as scheme ImpIII. . It can be concluded that the discount rate only changes the temporal redistribution of the depletion rate of remaining recoverable reserves in time, while more imported natural gas can affect the decision-making of producers on natural gas production.

Six representative gas fields of CNPC and SINOPEC , such as Tarim, Changqing, Huabei, Zhongyuan, North-East and North-West, are selected to analyze the specific impacts of discount rate on gas

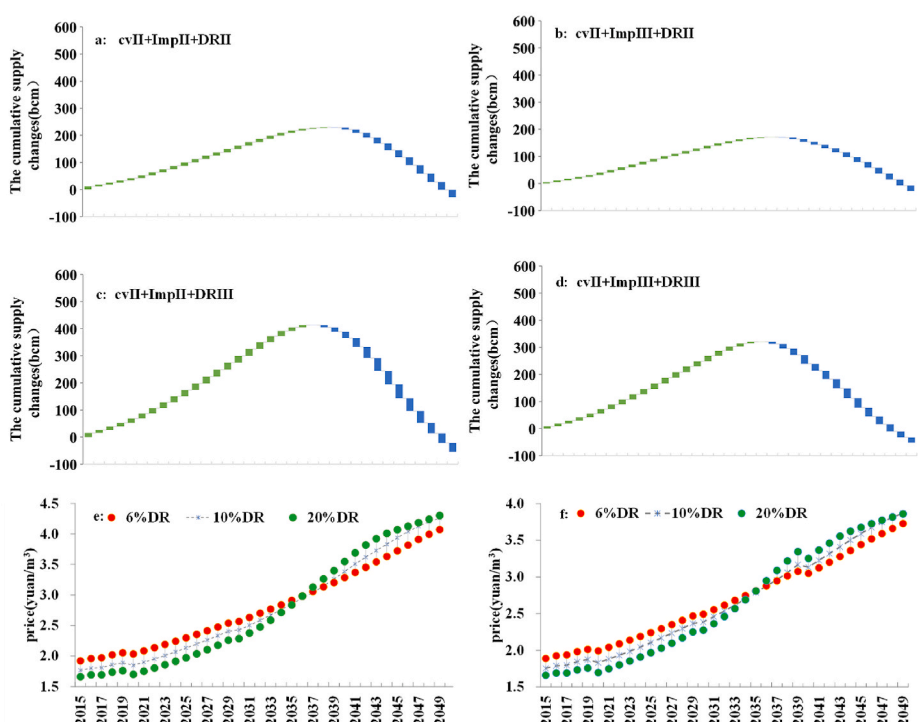



**Fig. 9.** Discount rates and cumulative changes of supply volume and prices.

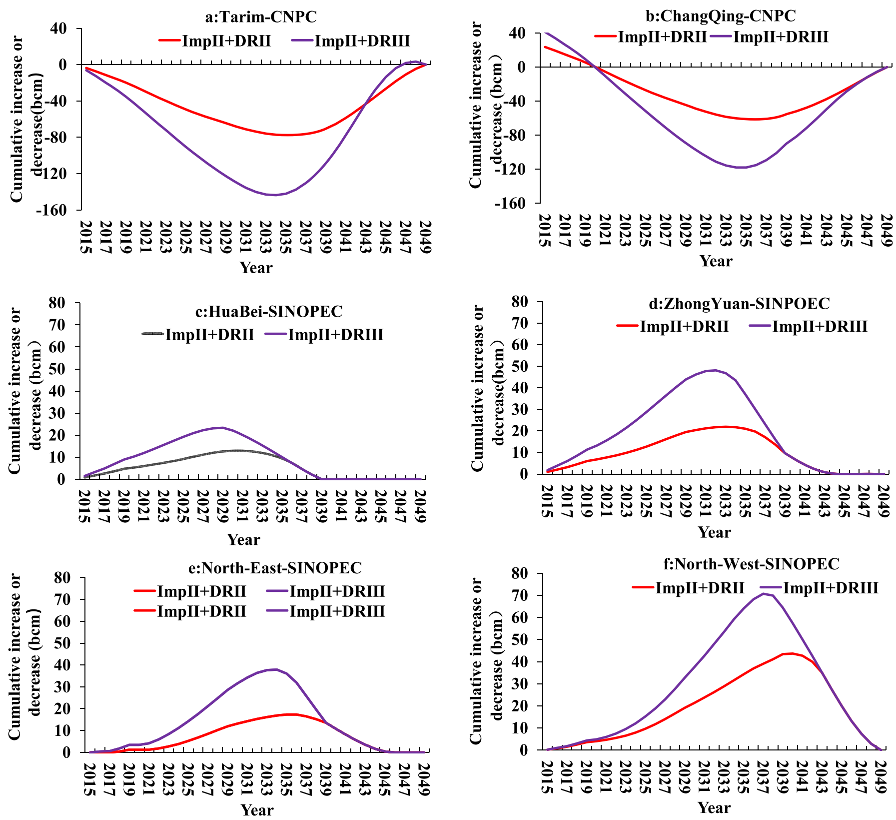



**Fig. 10. Discount rate and cumulative supply changes.** The red solid line is depicted as the cumulative amount of the difference between gas production in scheme DR II(10%) and that in scheme DR I(6%). The solid blue line represents the cumulative amount of the difference between the gas production of DR III (20%) and DR I(6%).

production decision under the scheme cvII+ImpII, and the results are shown in Fig. 10. The red solid line is depicted as the cumulative amount of the difference between gas production in scheme DR II(10%)and that in scheme DR I(6%).

The discount rate does differentiate gas production decision-making of producers, as shown in Fig. 10. Increasing the discount rate will force smaller producers to increase the production, as shown in Fig. 10c and d. However, the time node for increasing production depends on the scale of remaining recoverable reserves of the gas fields, as shown in Fig. 10f and g. Meanwhile, there is a counterfactual among the simulation results. The output of Tarim and Changqing gas fields does not increase with the rise of the discount rate but decreases, as shown in Fig. 9a and b.

The potential reason is that these two gas fields are rich in remaining reserves, and their output can cover more than 50% of the market share. Therefore, the producers of these two gas fields can use the output decision to dominate the market price and then withhold the remaining recoverable reserves to obtain more profits as expected. However, producers with small-scale remaining recoverable reserves cannot influence the market price because of their output. Therefore, they can only act as

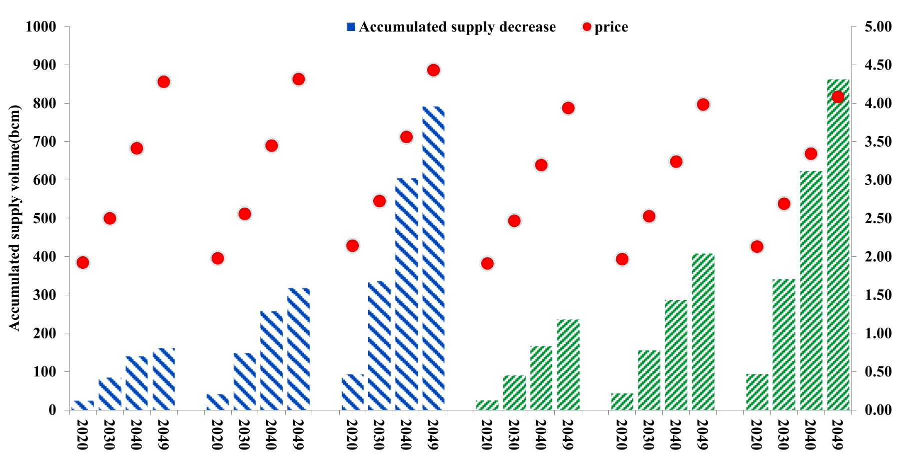



**Fig. 11.** Resource tax and cumulative supply volumes.

price followers and speed up the exploitation of remaining recoverable reserves to recover investment and guard against market price risks.

To summarize, the discount rates promote the differentiation and self-adaptive adjustment of producer's decision-making. Large-scale producers provide ballast stone for stabilizing natural gas supply in China. Small-scale natural gas producers, as price-takers, diversify the suppliers and stabilize the prices. In the long run, the rise of gas production and price under the discount rate of 10% are gentler than that under the rate 20%. Thereby, the scheme DRII can avoid the decline of the availability of China's natural gas market after 2040, and contribute to the smooth transition from monopoly to monopoly competition. Therefore, the combination of CVII+ImpII+DRII and cvII+ImpIII+DRII can be accepted as feasible schemes for China's natural gas market supply.

### *4.4. Resource tax*

Three resource taxes of 6% (RTI), 10% (RTII), and 20%(RTIII) in Scenario III are selected to investigate the impacts of government macro-control policies on the availability of natural gas resources in China , combined with the two feasible schemes in Scenario II to form six scheme combinations as shown in Fig. 11. Taking the cumulative supplies of natural gas as a benchmark when the resource tax is 0%, we can observe the reduction of cumulative supplies relative to the benchmark under six schemes in Scenario 3. The reduction of accumulated remaining recoverable reserves can be regarded as saving reserves.

The simulation results illuminate that resource tax reduces the exploitation speed of remaining recoverable reserves, and the saving reserves increase accordingly, thus producing a kind of implicit strategic stockpile. For example, under the IMP II + RT I (6%) among the six combination schemes, the saving reserves in 2030, 2040, and 2049 are about 100bcm, 150bcm, and 180bcm respectively. That is to say, the resource tax improves the short-term, medium-term, and long-term emergency stockpile for the security of the national natural gas supply, and the stockpile level will increase with the rise of resource tax. When the resource tax is increased to 10% in the schemes of IMP II + RT I (see Fig. 11), the saving reserves in 2030, 2040, and 2049 are about 160bcm, 240bcm, and 330bcm respectively, which is close to 50% of the total demand in that year. It can support a 180-day emergency guarantee, which greatly improves the risk resistance from the external supply interruption according to the 90-day standard of IEA.

Furthermore, if the resource tax is raised to 20%, the saving reserve will be twice as much as that of 10%, and it will provide the market with an emergency stockpile for about one year in the short, medium and long term, as shown in the combinations of ImpII+RTIII among the six schemes. However, the negative externality of these savings comes at the expense of the shrinking market scale and the ever-rising price. The externality can be offset by the schemes of ImpIII within the six combinations. Under the schemes of ImpIII, the imported gas in 2040 can not only increase the scale of strategic stockpile, but also effectively restrain the excessive price rise.

The increase of strategic stockpile is the result of redistribution of interests between domestic producers and importers, contributed to resources tax. We can notice the changes of scarcity rents of these two types of suppliers, as shown in Fig. 12.

Assume that the import schemes of ImpIII have been adopted among these six combinations. When the resource tax is increased from 6% to 10% and 20%, the scarcity rents of imported natural gas gradually increase by 0.1 yuan/m$^3$, 0.15 yuan/m$^3$ and 0.35 yuan/m$^3$ respectively, as shown in the dotted line in the upper part of Fig. 12. On the contrary, the scarcity rent of domestic resources is reduced by an average of 0.2 yuan/m$^3$, as shown in the solid line in the lower half of Fig. 12. It indicates that the higher resource tax will shift the responsibility of the availability of natural gas resources from domestic supply to imports.

It is worth noting that the scarce rents of Tarim and Changqing gas fields are nearly close to zero, as the solid yellow line in Fig. 12. Zero rent could be attributed to the abundant remaining recoverable reserves of these two gas fields, so the producers of these two dilute the impact of resources tax on their supply costs by expanding the scale of natural gas production. Our results further illustrate that resources tax redistributes the interests between producers and importers according to the supply guarantee responsibilities between them, by means of the economic leverage brought by the scarcity rent of natural gas resources. Therefore, resources tax will be helpful for forming an incentive and compatible mechanism for the development and utilization of natural gas resources with the goal of improving availability.

The domestic gas fields with declining scarcity rent are further analyzed, as the dashed line in the lower half of Fig. 13, we found that most of these fields have small reserves and high production costs as shown in Appendix 3. Therefore, we choose four small and medium-sized oil and gas fields, namely Tuha, East China, Dagang and Northeast, and investigate their production changes with results shown in Fig. 13.

Under the combinations of the import schemes Imp II and III and the tax schemes RT II and III, the outputs of these gas fields are less than 1bcm before 2020, increased to 2-14 bcm/a from 2020 to 2040, and then

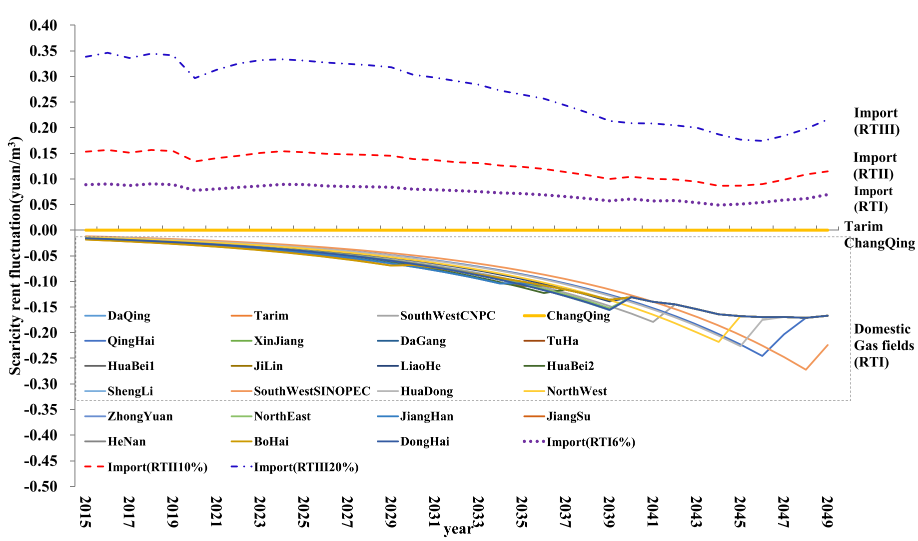



**Fig. 12.** The scarcity rents of domestic and import gas resources.

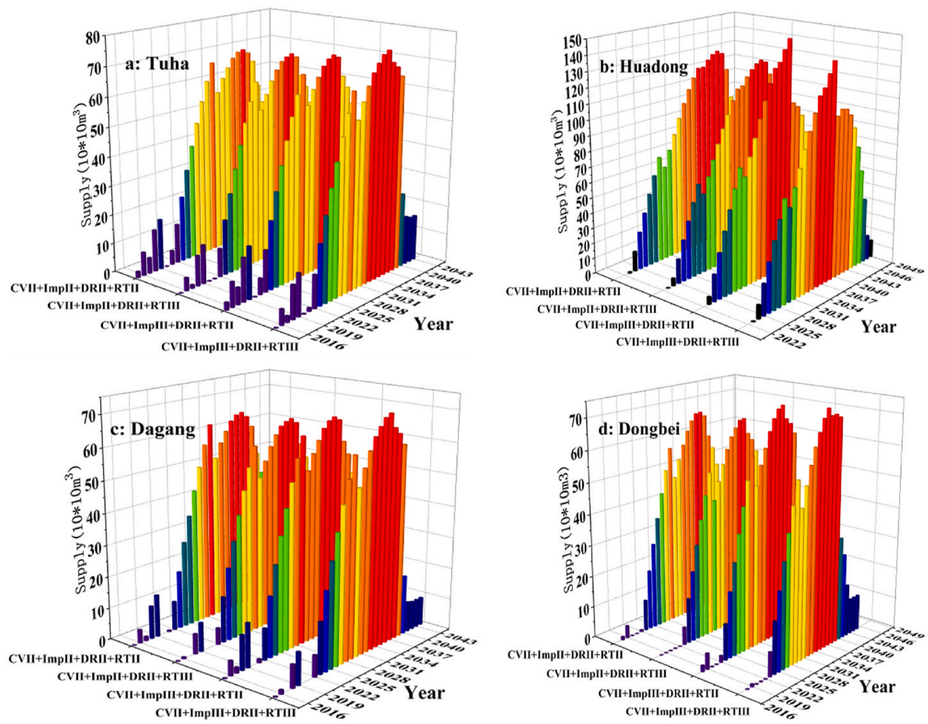



**Fig. 13.** The changes of supply in small and medium-sized natural gas fields.

decreased to about 2 bcm/a after 2040. The trend mainly depends on the change of scarcity rent, that is, it slows down in the early period, drops rapidly in the middle period, and rises gradually in the later period. Therefore, as far as the gas field with high production cost is concerned, the scarcity rent of natural gas resources can delay the producers from exploiting the remaining reserves. Objectively, it leaves a space for resources regulation and control for the expansion of market scale in the later period. These kinds of gas fields are located at Tarim Basin, Songniao Basin and the southeast offshore, seeing in Appendix B. These basins are characterized by low permeability, low pressure and high compactness, so their costs of production are relatively high.

Therefore, considering the supply risks in China's gas market for the next decades, these small and medium-sized gas fields with higher cost can be employed as strategic stockpile. . The remaining recoverable reserves of these gas fields should are developed and utilized sequentially to construct a supply guarantee for the temporal and spatial allocation of natural gas resources in China.

## 5. Conclusions and policy implications

The continuous growth of China's natural gas demand has risen the concerns on the supply security of natural gas. This is mainly due to the shortage of domestic natural gas resources and the ever-increasing dependency on imported natural gas. This paper puts forward a multi-agent analysis framework of supply security with availability, accessibility, and affordability as indicators. Under this framework, the ERMEM model is established to evaluate China's natural gas supply security. Furthermore, the model simulates and analyzes the feasible solutions and strategic choices to ensure supply security from three aspects: market, producers, and government. Based on our findings, the following conclusions are drawn.

(1) EMEM model can identify the influencing factors of the supply security in the natural gas supply chain and explicitly trace the dynamic evolution of output decision-makings of suppliers. Therefore, the model can act as a scientific method for investigating the formation mechanism of supply security along the industry chain and be used as a quantitative evaluation tool for the feasible strategies selection of demand-supply security Moreover, the model embeds the newly-increased recoverable reserves as a key variable into the natural gas industry chain and build a bridge between resource management and market management. With the help of the variable, the model could reveal the intern logic of the conflict between the sustainable development and efficient allocation of natural gas, and it comes from the negative externality that the consumption surplus produced by resources depletion is shifted to the production surplus. This enriches the theoretical understanding of natural gas supply security research.

(2) The supply security of China's natural gas market is not optimistic because the existing domestic resource supply capacity is only 180 bcm/a. It is difficult to guarantee that the market scale will reach 600bcm/a and the dependency will be below 50%. Increasing exploration and development of natural gas resources is the foothold of formulating natural gas supply strategies to build a resources barrier for security. If the scheme of increasing recoverable reserves by 200 cm/a is accepted, the guarantee of natural gas supply can be improved. In this case, China's natural gas market will have a supply capacity of about 400bcm/a, while the natural gas import will only gradually increase from 170bcm/a to 270bcm/a, and the dependency will remain within 45%. Therefore, in the next 20 years, strengthening exploration and development and expanding production capacity will be the basic starting points of making China's natural gas supply security strategies.

(3) Effective management of domestic and imported natural gas resources from three aspects: market, enterprises and government is an entry point of improving supply security. Firstly, weak monopoly competition reduces the entry barriers caused by domestic producers' market powers and would present a feasible market structure choice for the accessibility of natural gas resources. It will help to play the role of supply guarantee for large state-owned oil and gas companies and encourage private companies to participate in market competition. Secondly, discount

rate induces the differentiation of suppliers' supply strategies, and eventually the suppliers will be self-adaptive to arbitrage inter-temporally. Thereby, discount rate increases the supply elasticity of supply chain. In China's natural gas market, the discount rate of 10% is recommend for reducing the impact of production decisions, on the fluctuation of market price and enhance the affordability of the natural gas market. Finally, Resource tax redistributes the interests between producers and importers according to their supply security responsibilities by leveraging the rent of scarce resources. It is beneficial to adjust the exploitation speed of remaining recoverable reserves, construct implicit strategic. stockpile, and improve natural gas resources availability. If resource tax is raised from 6% to 10%, strategic stockpile of 160, 240 and 330 bcm could be built in 2030, 2040 and 2049 respectively. Meanwhile, it would be necessary to increase the import volume by 220–250bcm/a between 2030 and 2040.Therefore, it is necessary to develop high-cost small and medium-sized gas fields in an orderly manner as emergency stockpile to cope with supply risks.

The main policy implications are related to guarantee the mechanism of natural gas supply. They are to establish three systems of diversified natural gas supply efficient market management, and strategic stockpile. Specifically as follows:

(1) Establish a diversified supply system and construct a gas resource security barrier. First, it is necessary to liberalize the mining rights market in China by opening the mining rights market and promoting the open circulation of mining rights in an orderly manner. Therefore, more oil and gas companies will participate in exploring and developing natural gas resources, regardless of whether these companies are state-owned or private. Second, the natural gas reserve basis should be consolidated. Investment in exploration and development of onshore gas-rich basins should be increased. Moreover, much more investments should be encouraged to explore and develop tight gas, coalbed methane, and shale gas. Third, there will be two ways to diversify foreign gas imports. Domestic oil and gas companies should participate in overseas gas field development and invest in natural gas liquefaction projects. Meanwhile, foreign natural gas resources should be encouraged to be introduced back to China in various forms of cooperation.
(2) Construct an efficient market management system and give full play to the market price-oriented regulation of natural gas resources supply. The government should speed up the implementation of the TPA system to realize the separation of production, sales and transportation in the natural gas industry chain as soon as possible for establishing a fully competitive natural gas market and realizing the efficient allocation of resources. The mechanism of the natural gas trading center should be further improved to enhance the function of price signal discovery to accelerate the flexibility of natural gas.
(3) (3) Set up a strategic stockpile system of gas resources, and expand the space for regulation and control of natural gas supply guarantee. The national natural gas stockpile regime should be established to coordinate the construction of large-scale underground gas storage groups across regions. In particular, it is necessary to improve the natural gas stockpile mechanism. The nation and company's stockpile are organically combined and complemented to enhance the emergency peak shaving capability. In addition, the government should play a macro-control role in the production and consumption of natural gas resources and deepen the reform of resource tax and drives the economic and intensive utilization of natural gas and promotes the establishment of gas fields as a strategic stockpile system.

## 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.

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## Appendix A. Nomenclature

**Table A.1**
Nomenclature: sets, variables and parameters.

| Sets | |
|---|---|
| $g$ | Set of domestic gas fields or suppliers, $g \in G$ |
| $f$ | Sets of foreign importer, $f \in F$ |
| $w$ | Set of wholesalers, $w \in W$ |
| $m$ | Set of consumer central |
| $t$ | Set of times, $t \in T$ |
| Primal Variables | |
| $y_{gwt}$ | Amounts of domestic suppliers sold to wholesalers |
| $cap_{gt}$ | Economically recoverable reserves in any year |
| $y_{fwt}$ | Amounts of importer sold to wholesalers |
| $p_{gwt}$ | The price between domestic suppliers and wholesalers |
| $mac_{gt}$ | The marginal cost of domestic production |
| $p_{fwt}$ | The price between imported suppliers and wholesalers |
| $q_{wmt}$ | Amounts of wholesalers sold to consumer central |
| $Q_{mt}$ | Amounts of all consumers in china |
| $p_t(Q_m)$ | Market-clearing price between wholesalers and consumers |
| Dual variables | |
| $\lambda_{gt}$ | Dual variable of the annua domestic fields rate constraint |
| $\lambda_{ft}$ | Dual variable of the annua imported rate constraint |
| $\varphi_{wt}, free$ | Free variable of the balance between suppliers and wholesalers |
| $\varphi_{wmt}, free$ | Free variable of the balance between wholesalers and consumers |
| Parameters | |

(continued on next page)

**Table A.1** (*continued*)

| Sets | |
|---|---|
| $cap_{g0}$ | Economically recoverable reserves in 2015 |
| $\overline{cap}_{gt}$ | New economically recoverable reserves in any year |
| $cap_f$ | Total import contract |
| $r$ | Discount rate |
| $k$ | Resource tax |
| $c_f$ | The marginal cost of imported |
| $mtc_{wmt}$ | Marginal transportation cost |
| $cv$ | Speculation variation |
| $\varepsilon$ | Price elasticity demand |
| $Q_m{}^{ref}$ | Initial demand in 2015 |
| $p^{ref}$ | Initial price in 2015 |
| $a_g, b_g, c_g$ | Coefficient of marginal production cost function |

## Appendix B. Natural Gas Supply deployment in China

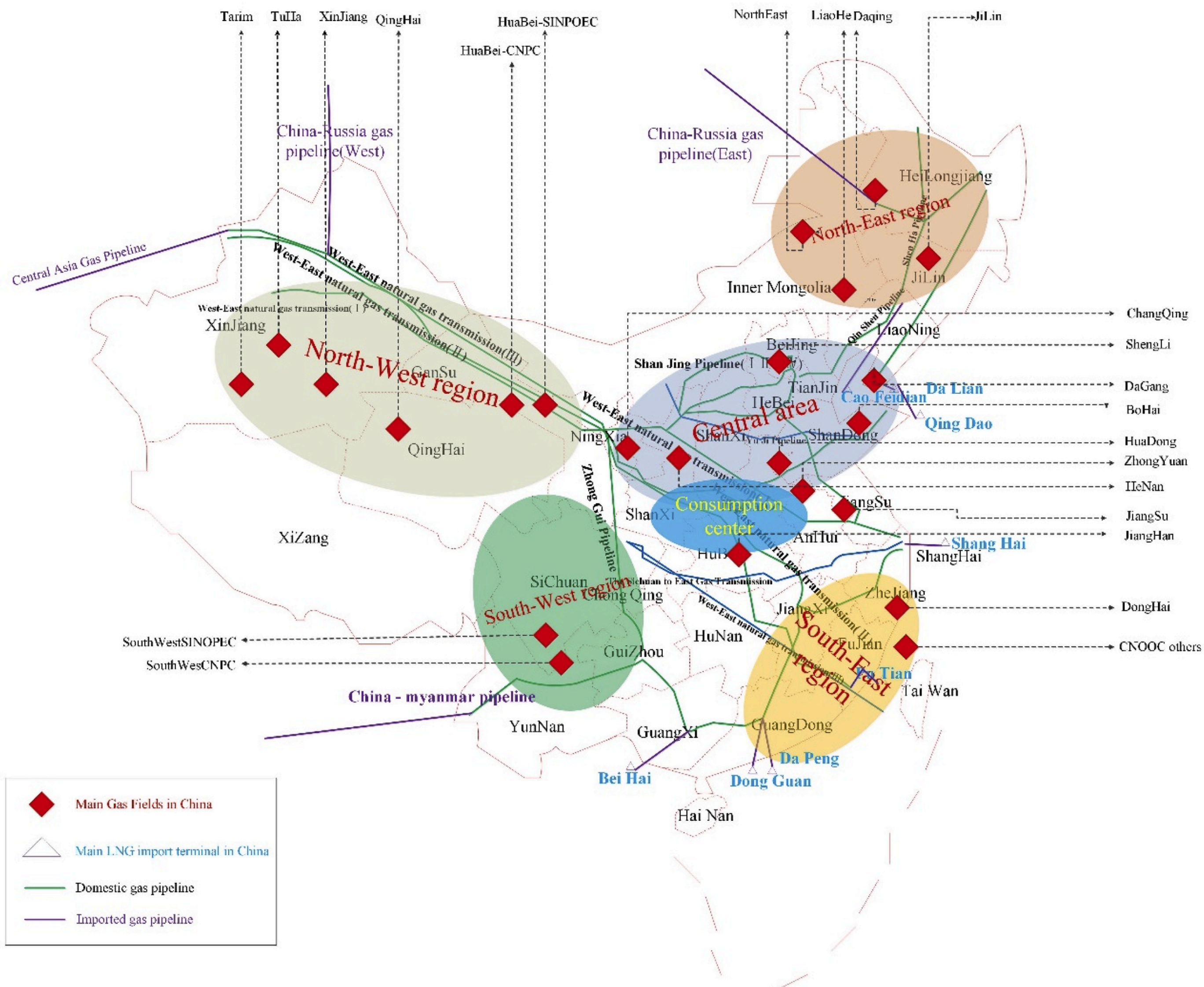


**Fig. B.** Natural Gas Supply deployment in China.

## Appendix C. Proven reserves

**Table C.1**
Initial economical recoverable reserves of natural gas producers in 2015

| CNPC | $cap_{gi}$ (bcm) | SINOPEC | $cap_{gi}$ (bcm) | CNOOC | $cap_{gi}$ (bcm) | Import | $cap_{gi}$ (bcm) |
|---|---|---|---|---|---|---|---|
| DaQing | 548.2 | HuaBeiSINOPEC | 273.65 | BoHai | 15 | ZhongYaPNG | 350.00 |
| Tarim | 18500.00 | ShengLi | 215.30 | DongHai | 700 | ZhongMianPNG | 120.00 |
| SouthWestCNPC | 2949.00 | SouthWestSINOPEC | 2949.00 | | | ZhongEPNG | 300.00 |
| ChangQing | 15700.00 | HuaDong | 1900.50 | | | ZhongDongLNG | 54.00 |
| QingHai | 2200.00 | NorthWest | 1497.41 | | | AustralianLNG | 54.00 |
| XinJiang | 736.62 | ZhongYuan | 929.44 | | | LndonesiaLNG | 38.00 |
| DaGang | 734.77 | NorthEast | 654.00 | | | MalaysiaLNG | 45.00 |
| TuHa | 669.00 | JiangHan | 159.91 | | | others | 30.00 |
| HuaBeiCNPC | 273.65 | JiangSu | 81.83 | | | | |
| JiLin | 176.00 | HeNan | 1.01 | | | | |
| LiaoHe | 5.32 | | | | | | |

**Table C.2**
Actual production of natural gas producers and proportion in 2015

| Gas-Field | Production (bcm) | Share | Gas-Field | Production (bcm) | Share | Gas-Field | Production (bcm) | Share |
|---|---|---|---|---|---|---|---|---|
| DaQing | 3.53 | 3.07% | TuHa | 0.91 | 0.79% | HuaDong | 0.11 | 0.10% |
| Tarim | 23.55 | 20.49% | HuaBeiCNPC | 1.09 | 0.95% | NorthWest | 1.60 | 1.39% |
| SouthWestCNPC | 15.48 | 13.47% | JiLin | 1.32 | 1.15% | ZhongYuan | 5.85 | 5.09% |
| ChangQing | 37.46 | 32.59% | LiaoHe | 0.58 | 0.50% | NorthEast | 0.65 | 0.57% |
| QingHai | 6.14 | 5.34% | HuaBeiSINOPEC | 3.33 | 2.90% | JiangHan | 3.31 | 2.88% |
| XinJiang | 3.00 | 2.61% | ShengLi | 0.46 | 0.40% | JiangSu | 0.04 | 0.03% |
| DaGang | 0.51 | 0.44% | SouthWestSINOPEC | 4.82 | 4.19% | HeNan | 0.05 | 0.04% |
| BoHai | 0.25 | 0.22% | DongHai | 0.90 | 0.78% | | | |

**Table C.3**
New proven reserves of natural gas in China from 2011 to 2018

| Year | New-increased proven geological reserves(bcm) | New-increased technological recoverable reserves(bcm) | New-increased economical recoverable reserves (bcm) |
|---|---|---|---|
| 2011 | 765.95 | 306.38 | 229.78 |
| 2012 | 961.22 | 384.48 | 288.36 |
| 2013 | 616.43 | 246.57 | 184.93 |
| 2014 | 1110.71 | 444.28 | 333.21 |
| 2015 | 677.22 | 270.88 | 203.16 |
| 2016 | 726.56 | 290.62 | 217.96 |
| 2017 | 555.38 | 222.15 | 166.61 |
| 2018 | 831.15 | 332.46 | 249.35 |

## Appendix D. Exploit marginal costs of domestic gas fields in 2015

| CNPC | $c_{i0}$ (¥/m$^3$) | SINOPEC | $c_{i0}$ (¥ ¥/m$^3$) | CNOOC | $c_{i0}$ (¥/m$^3$) | Import | $c_{i0}$ (¥/m$^3$) |
|---|---|---|---|---|---|---|---|
| DaQing | 1.324 | HuaBeiSINOPEC | 1.290 | BoHai | 1.271 | ZhongYaPNG | 1.555 |
| Tarim | 0.977 | ShengLi | 1.462 | DongHai | 1.042 | ZhongMianPNG | 1.043 |
| SouthWestCNPC | 0.585 | SouthWestSINOPEC | 1.509 | | | ZhongEPNG | 1.945 |
| ChangQing | 0.923 | HuaDong | 1.681 | | | ZhongDongLNG | 1.820 |
| QingHai | 1.324 | NorthWest | 1.462 | | | AustralianLNG | 1.750 |
| XinJiang | 1.242 | ZhongYuan | 1.254 | | | LndonesiaLNG | 1.820 |
| DaGang | 1.546 | NorthEast | 1.539 | | | MalaysiaLNG | 1.692 |
| TuHa | 1.455 | JiangHan | 1.214 | | | others | 1.830 |
| HuaBeiCNPC | 1.383 | JiangSu | 1.385 | | | | |
| JiLin | 1.331 | HeNan | 1.045 | | | | |
| LiaoHe | 1.304 | | | | | | |

## Appendix E. intercept $A_t$& slope $B_t$

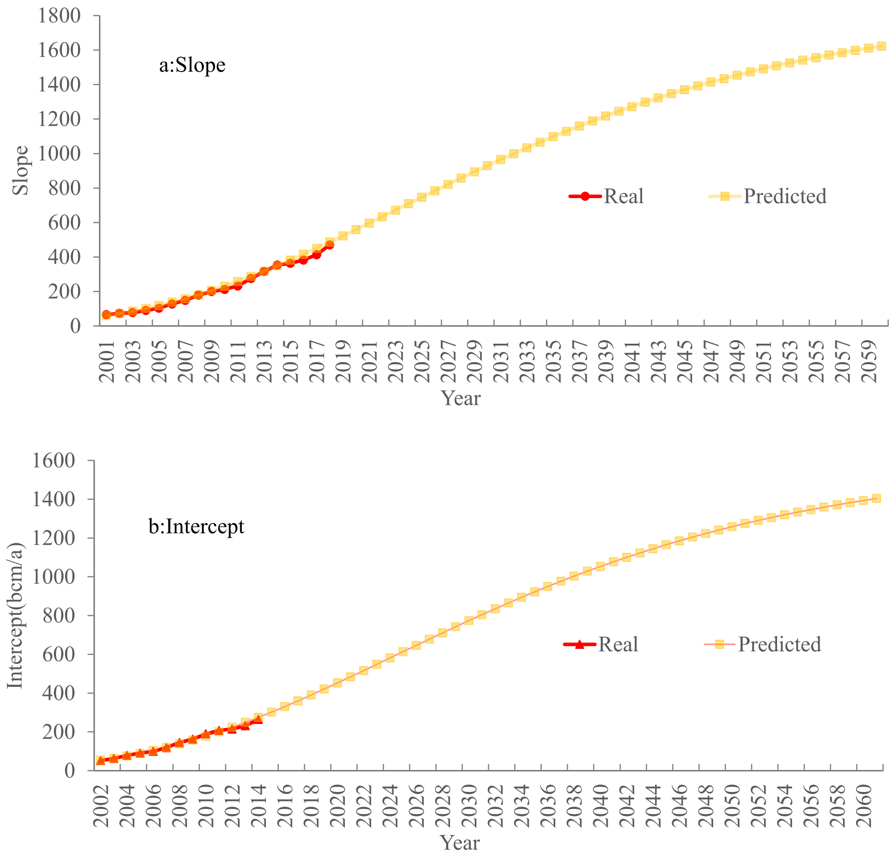


**Fig. E.** Real and simulated of slope and intercept.

## Appendix F. Gas Field Cost and reserves distribution in China

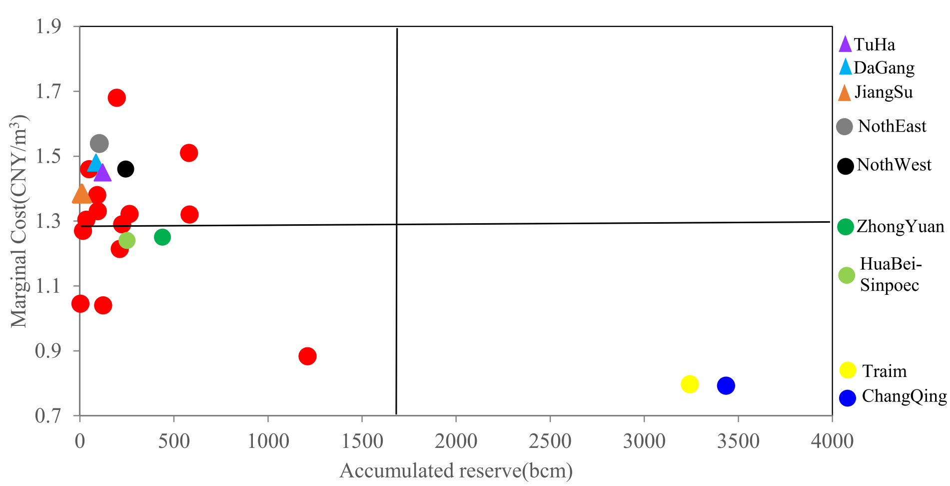


**Fig. F.** Gas Field Cost and reserves distribution in China.

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