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Article

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Research paper

What are the key barriers for the further development of shale gas in China? A grey-DEMATEL approach

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ABSTRACT

The evaluation and analysis of barriers that restrict the large-scale development of shale gas are beneficial to the selection of a scientific and reasonable development model. The objective of our study was to reveal the key barriers to the large-scale development of shale gas in China. Sixteen barriers were identified by adopting literature reviews and expert interviews, and the grey-based Decision-Making Trial and Evaluation Laboratory (grey-DEMATEL) approach was adopted to analyze the barriers based on the sample data obtained from a questionnaire of senior experts in China's shale gas industry. The results showed that high development costs, lack of experience, lack of technology transfer between enterprises, risk of environmental pollution, lack of key technologies, and lack of capability in investment and risk resistance are the key barriers to the further development of shale gas in China. We put forward some policy suggestions based on these results.

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1. Introduction

As the country with the most abundant shale gas resources, China has made long-term and ambitious plans to safeguard national energy security and reduce the country's overdependence on coal resources (Chang et al., 2014); however, the development of shale gas in China is still not as smooth as expected. Most companies with shale gas exploration rights in China have not made substantial progress in exploration, nor have they invested the expected amount (Hu and Xu, 2013). The Chinese government, moreover, has gradually become more conservative in its planning target for shale gas development. For instance, the government has changed the planned shale gas output of 2020 from 60–100 billion cubic meters (bcm) to 30 bcm (NEA, 2016).

What is hindering the further scale development of shale gas in China? This is the question plaguing China's decision-makers. Previous studies have identified barriers to the development of shale gas in China from different theoretical perspectives (Wan et al., 2014; Deemer and Song, 2014; Li et al., 2016; Yang, 2015; Wang et al., 2014b). However, the main barriers may have changed to some extent with the development of shale gas, and most previous studies focused only on the general identification of barriers, but lacked the evaluation and analysis of the key and most emergent barriers and neglected to research the relationship between different barriers. Therefore, we sought to analyze

the key barriers restricting further scale development of shale gas in China. Based on literature reviews and expert interviews, barriers were identified. The grey-based Decision-Making Trial and Evaluation Laboratory (grey-DEMATEL) approach was adopted in the study to analyze the prioritization and interrelationships among the barriers. Subsequently, some policy suggestions were put forward.

2. Barrier identification

2.1. Resource base

The geological conditions of China are more complex than those of North America (Tian et al., 2014). Most of China's shale basins are also tectonically complex, featuring extensive folding and faulting that present a big challenge for shale gas development (EIA, 2013). Moreover, Sichuan Basin, the most promising shale gas player in China (Krupnick et al., 2014), is confronted with not only geological challenges, such as numerous faults, steep dips, and high tectonic stress, but also problems such as rough terrain, deeply buried formations, and a shortage of water resources (World Resources Institute, 2014). The aforementioned challenges led us to arrive at two barriers to the large-scale development of shale gas in China: poor resource endowments (B1) and poor resource development conditions (B2).

2.2. Internal capability

China's shale gas development has heavily imitated and absorbed technology and experience from the United States (Wang

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et al., 2014b; Ren et al., 2015). Considering the less favorable geology of shale gas resources in China (Tian et al., 2014), technologies employed in the United States such as horizontal well-drilling, and multi-stage hydraulic fracturing (Li et al., 2016) may not be suitable for China, as more advanced technologies are needed (Pi et al., 2015a). Also, there are great differences in mineral rights and the industrial environment between China and the United States, which means that the development mode of shale gas in the United States may not be suitable for China.

There is a great geographical distance between shale gas resource-rich areas and the main shale gas consumption centers. What is worse, China's oil and gas trunk pipeline network is still poor, which means that the existing infrastructure has difficulty meeting the actual development needs (Wang et al., 2014b). Moreover, the influence of complex geological conditions has increased the cost and uncertainty of shale gas development in China. However, most shale gas enterprises lack effective financing channels and risk transfer mechanisms, which is why it remains a challenge for enterprises to invest in shale gas development and take the investment risk.

An effective market relationship has not been established between oil companies and oil service enterprises, which has restricted the improvement of shale gas development through market competition (Liu et al., 2013). Even if they did establish a relationship, the oil service companies owned by state-owned petroleum companies would limit technology transfer as a result of the competitive relationship with each other (Pi et al., 2015b). Therefore, it is difficult for enterprises to achieve the effective transfer of technology with market cooperation. The aforementioned challenges led us to develop six additional barriers to the large-scale development of shale gas in China: the lack of key technologies (B3), the lack of experience (B4), the lack of infrastructure (B5), the lack of capability of investment and risk resistance (B6), low management efficiency (B7), and the lack of technology transfer between enterprises (B8).

2.3. Market and economic

To promote the development of shale gas, the NEA released the “Shale Gas Industry Policy”, (2013), which stated that the price of shale gas should be determined by the market. However, the policy has not been implemented (Wu et al., 2015). Furthermore, although the price of natural gas has indeed increased in the past few years, it is still insufficient to offset the cost of shale gas development, as it has a much higher exploration and development cost than conventional gas does (Wang et al., 2016). Moreover, China's shale gas development cost is still much higher than those of other developed countries, and the high development cost has become a major problem that has restricted the development of shale gas (Li et al., 2016; Zhao and Yang, 2015; Dong et al., 2016). Inevitably, the high cost of shale gas has put it at a disadvantage in competing with other kinds of gas sources, which has led to a lack of market demand. For example, the investment return rate of China National Petroleum Corporation (CNPC) for shale gas is rarely higher than 8%, whereas that for conventional gas is generally above 12% (Wan et al., 2014). Therefore, the high costs and low prices of shale gas have undoubtedly led to low economic benefits and even short-term losses. These challenges led us to develop four additional barriers to the further development of shale gas in China: low prices (B9), high development costs (B10), the lack of market demand (B11), and low economic benefits (B12).

Table 1
List of respondents.

No.	Organization	Title	Working experience
1	Shale Gas R&D Institution	Professor of engineering	More than 31 years
2	Shale Gas R&D Institution	Senior engineer	More than 26 years
3	Shale Gas Development Enterprises	Senior engineer	More than 15 years
4	Shale Gas Development Enterprises	Senior engineer	More than 10 years

2.4. Social–political

As the current subsidy policy is affected by low gas prices and high development costs, it cannot effectively promote enthusiasm among enterprises for shale gas development (Zhao and Yang, 2015). What is more, it remains a great challenge for shale gas enterprises to establish and maintain a harmonious relationship with local communities and their residents in China (Hu and Xu, 2013), even though these communities and their residents share the benefits and bear the environmental risks of shale gas development, such as water contamination, CO₂ and methane emissions, seismicity, surface ecological damage, and noise (Olmstead et al., 2013; Wang et al., 2014a). With the enhancement of environmental awareness in the government and the public, the relationship between enterprises and local communities and environmental risks pose great challenges in shale gas development.

There remains a lack of precise and detailed policies and regulations for shale gas (Deemer and Song, 2014). The government of China has recognized shale gas as the 172th mineral, which means that related policies and regulations of oil and gas resources cannot be fully applied to shale gas. A robust set of policies, regulations, and standards of shale gas industry is urgently needed. These challenges led us to develop four additional barriers to the further development of shale gas in China: low governmental support (B13), uncertainty of industry–community relationship (B14), risk of environmental pollution (B15) and imperfection of policies and regulations (B16).

3. Methodology

DEMATEL is a systematic method used to build and analyze the structure of complicated causal relations between a set of factors with matrices or digraphs. It is widely used to identify the key barriers in various systems (Wang et al., 2017). However, uncertainty and a lack of information are often unavoidable in real-life scenarios, which is why that the normal DEMATEL method does not work well in such conditions (Ren et al., 2017; Xia et al., 2015). Compared with related methods, the grey-based DEMATEL method allows for broader discrimination of measures, whereas the analytical hierarchy process (AHP) has only a unidirectional relationship, and interpretative structural modeling (ISM) has only 0–1 levels and multi-directional relationships (Shao et al., 2016). In addition, compared with other improved DEMATEL methods, the grey-based DEMATEL method is better at dealing with uncertainties caused by small samples and inaccurate and incomplete information (Shao et al., 2016; Wang et al., 2017). It should also be noted that the grey-DEMATEL method, similar to related methods, requires qualitative evaluation by experts as data input, which may lead to inaccurate evaluation results when there is a substantial deviation between experts' cognition and reality. Because we could get only some imprecise and incomplete information about barriers to the further development of shale gas in China, we adopted the grey-DEMATEL approach for this study.

Table 2
The prominence and net effect of the barriers.

Barriers	R_i	C_j	Prominence		Net effect	
			$R_i + C_j$	Ranking	$R_i - C_j$	Ranking
Poor resource endowments (B1)	1.881	1.616	3.497	16	0.265	3
Poor resource development conditions (B2)	2.389	1.787	4.176	12	0.603	1
The lack of key technologies (B3)	2.666	2.716	5.382	6	-0.051	11
The lack of experience (B4)	2.727	2.556	5.283	7	0.171	5
The lack of infrastructure (B5)	2.029	2.300	4.329	11	-0.272	13
The lack of capability of investment and risk resistance (B6)	2.696	2.718	5.414	5	-0.021	8
Low management efficiency (B7)	1.867	2.290	4.156	13	-0.423	14
The lack of technology transfer between enterprises (B8)	2.634	2.458	5.092	8	0.176	4
Low price (B9)	2.413	2.437	4.850	9	-0.024	10
High development cost (B10)	3.509	3.346	6.855	1	0.164	6
The lack of market demand (B11)	1.979	2.001	3.980	15	-0.022	9
Low economic benefits (B12)	3.034	3.546	6.580	2	-0.512	15
Low governmental support (B13)	2.279	2.344	4.623	10	-0.065	12
Uncertainty of industry–community relationship (B14)	2.429	3.045	5.475	4	-0.616	16
Risk of environmental pollution (B15)	2.955	2.924	5.879	3	0.032	7
Imperfection of policies and regulations (B16)	2.294	1.698	3.993	14	0.596	2

The procedure for the grey-DEMATEL was as follows:

Step 1: Define the grey semantic scale.

A five-level grey semantic scale was used in this study. The scale items were as follows: No influence = [0, 0], Very low influence = [0, 0.25], Low influence = [0.25, 0.5], High influence = [0.5, 0.75], Very high influence = [0.75, 1] (Shao et al., 2016; Xia et al., 2015).

Step 2: Develop the grey direct-relation matrix X .

Four experts with a deep understanding of China's shale gas industry were invited to participate in this study. Table 1 shows the backgrounds of the respondents. The questionnaires, which contained the definitions of the barriers and relevant filling rules, were distributed to the respondents to collect the data needed for our study. Tables A.1–A.4 show the completed direct-relation matrices. The direct-relation matrices were transformed into grey direct-relation matrices based on the grey semantic scale.

Step 3: Compute the overall crisp direct-relationship matrix Z .

By referencing previous studies (Shao et al., 2016; Xia et al., 2015), we obtained the crisp matrix using the modified-CFCS method. Subsequently, we developed the overall crisp direct-relationship matrix Z using Eq. (1):

$$z_{ij} = \frac{1}{k} (z_{ij}^1 + z_{ij}^2 + \dots + z_{ij}^k). \quad (1)$$

Step 4: Compute the normalized direct-relation matrix N .

The normalized direct-relation matrix N was calculated using Eqs. (2) and (3):

$$N = sZ \quad (2)$$

$$s = \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n z_{ij}}. \quad (3)$$

Step 5: Compute the total relation matrix T .

The total relation matrix T was developed using Eq. (4), where I represents the identity matrix:

$$T = N + N^2 + N^3 + \dots = \sum_{i=1}^{\infty} N^i = N(I - N)^{-1}. \quad (4)$$

Step 6: Compute the prominence and net effect of the barriers.

The prominence (P_i) and net effect (E_i) of the barriers were computed using Eqs. (5)–(8), as Table 2 shows.

$$R_i = \sum_{j=1}^n t_{ij}, \forall i \quad (5)$$

$$C_j = \sum_{i=1}^n t_{ij}, \forall j \quad (6)$$

$$P_i = \{R_i + C_j \mid i = j\} \quad (7)$$

$$E_i = \{R_i - C_j \mid i = j\}. \quad (8)$$

Step 7: Plot the prominence–causal diagram.

The prominence ($R_i + C_j$) is represented on the horizontal axis, and the net effect ($R_i - C_j$) is represented on the vertical axis in the prominence–causal diagram (Tsai, 2018), as Fig. 1 shows.

4. Results and discussion

4.1. Results

According to the value of net effect ($R_i - C_j$), the barriers could be divided into the following three categories (Ren et al., 2017):

(1) The “cause” group: poor resource development conditions (B2), the imperfection of policies and regulations (B16), poor resource endowments (B1), the lack of technology transfer between enterprises (B8), the lack of experience (B4), and high development costs (B10). The $R_i - C_j$ value of these barriers was greater than zero, which means that these barriers affected other barriers more significantly than they were affected.

(2) The “linkage” group: the lack of market demand (B11), low governmental support (B13), low prices (B9), the lack of key technologies (B3), the lack of capability of investment and risk resistance (B6), and the risk of environmental pollution (B15). The $R_i - C_j$ value of these barriers was near zero, which means that these barriers had a high chance of transitioning from the “cause” to the “effect” group.

(3) The “effect” group: the lack of infrastructure (B5), low management efficiency (B7), low economic benefits (B12), and uncertainty in the industry–community relationship (B14). The $R_i - C_j$ value of these barriers was less than zero, which means that these barriers were more affected by other barriers.

In addition, a critical line was drawn on the mean value of prominence ($R_i + C_j$), and the barriers were further divided into two groups according to prominence value. Barriers with a prominence value greater than the mean value were considered central barriers, which means that these barriers significantly affected other barriers or were significantly affected by others.

Therefore, the barriers in the “cause” and “linkage” group with a prominence value greater than the mean value were considered critical barriers. These barriers significantly affected other barriers more than they were affected, and they represented the core barriers in the network of barriers. That is to say,

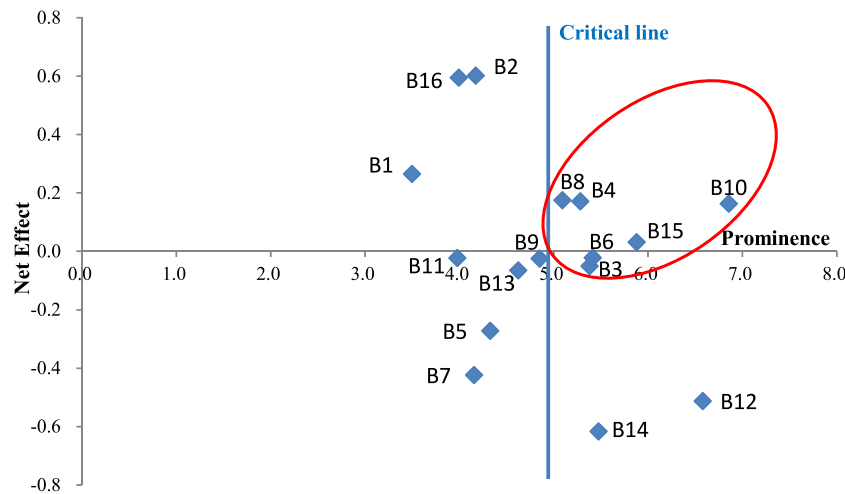


Fig. 1. Overall DEMATEL prominence-causal diagram.

Table 3

Weight assignment for respondents of sensitivity analysis.

	Expert 1	Expert 2	Expert 3	Expert 4
Scenario 1	0.4	0.2	0.2	0.2
Scenario 2	0.2	0.4	0.2	0.2
Scenario 3	0.2	0.2	0.4	0.2
Scenario 4	0.2	0.2	0.2	0.4
Current	0.25	0.25	0.25	0.25

high development costs (B10), the lack of experience (B4), the lack of technology transfer between enterprises (B8), the risk of environmental pollution (B15), the lack of key technologies (B3), and the lack of capability of investment and risk resistance (B6) were found to be the key barriers to the further development of shale gas in China.

4.2. Sensitivity analysis

A sensitivity analysis that aimed to verify the robustness of the results of the study was conducted by assigning the highest weight to each respondent and assigning an equal weight for other respondents (Rajesh and Ravi, 2017). Table 3 shows the weight assignments for respondents. By referencing a previous study (Celik, 2017), we analyzed the ranking differences in different scenarios to verify the robustness of the results, and Figs. 2 and 3 show the results. The rankings of most barriers were not affected by variations in the respondents' weights in different scenarios. Although there were some deviations between different scenarios, the overall relationship maintained relative consistency. Thus, it was our view that there was robustness and relative consistency in our relationship evaluations.

4.3. Discussion

Although previous studies have analyzed barriers to shale gas development in China, the conclusions of previous studies were often different due to the differences in individual experience and the research perspectives of scholars (Hu and Xu, 2013; Wan et al., 2014; Zhao and Yang, 2015; Li et al., 2016). Compared with previous studies, our study revealed which of the 16 barriers were key, as well as the interrelationships among the barriers. Moreover, previous studies generally considered geological factors to be the most important barriers to shale gas development in China (Tian et al., 2014; Wang et al., 2016). The results of this paper indicated that although geological factors are still very important

factors, the relative importance of these factors in the further development of shale gas in China may have declined to some extent in recent years. The reason for this change may be that with the continuous exploration and development of shale gas in recent years, the geological condition of shale gas resource has been well understood, and the technology of shale gas development has increasingly improved. This phenomenon may lead experts to consider the importance of barriers more closely from the perspective of technology, economy, and management than geology, and may even lead them to adopt the view that under existing conditions of shale gas resources, technological progress, experience accumulation, cost control, and risk management are more effective ways to promote the further development of shale gas in China compared with the exploration of shale gas resource blocks with better geological conditions.

Based on the results of our study, we concluded that shale gas development enterprises and relevant government departments should pay more attention to the control of shale gas development costs, accumulation and sharing of development technology, and the experience, management of environmental risk, and capability of investment and risk resistance, which can all give way to a more efficient shale gas development process in China.

Conducting this study supplied us with a fresh perspective on which barriers are the key barriers that require urgent focus and immediate resource investment. The results of our study can be used to improve cognitive barriers to the further development of shale gas in China and to provide a scientific decision-making basis for decision-makers and stakeholders.

5. Conclusions and implications

To identify the key barriers for the further development of shale gas in China, the grey-DEMATEL approach was applied in this study. The results showed that high development costs (B10), the lack of experience (B4), the lack of technology transfer between enterprises (B8), risk of environmental pollution (B15), the lack of key technologies (B3), and the lack of capability of investment and risk resistance (B6) are the key barriers that need to be overcome urgently. This study also deepened our understanding of the barriers that hinder the further development of shale gas in China.

Based on our analysis, efforts should be made to carry out the shale gas development in China through the following four approaches:



Fig. 2. Sensitivity analysis of $R_i + C_j$ values.

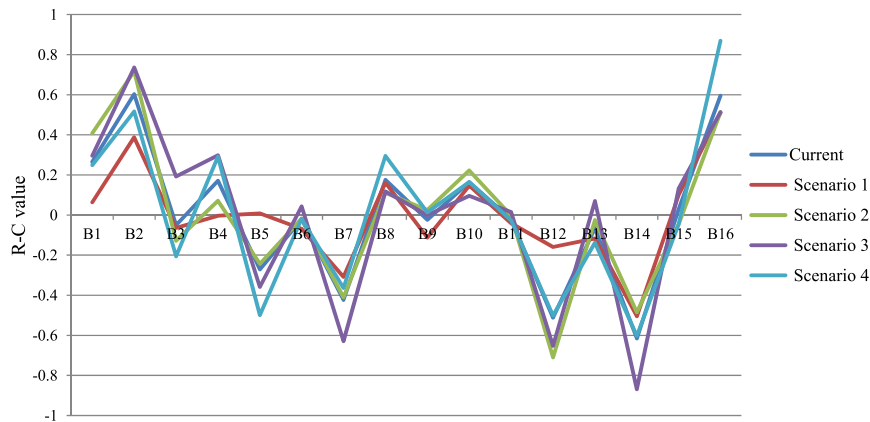


Fig. 3. Sensitivity analysis of $R_i - C_j$ values.

Table A.1
Direct-relation matrix by expert 1.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
B1	0	4	0	0	0	0	0	0	0	0	0	1	1	0	0	0
B2	4	0	4	3	2	0	0	1	1	1	0	0	0	0	1	0
B3	0	4	0	3	0	2	0	3	0	3	1	1	0	0	1	0
B4	2	3	2	0	1	2	2	1	0	4	0	1	0	0	1	0
B5	3	3	0	0	0	2	0	4	2	2	3	3	2	3	2	1
B6	1	1	2	3	1	0	1	1	1	3	3	1	1	2	4	4
B7	0	0	0	0	0	2	0	0	1	1	2	1	2	0	1	1
B8	1	1	1	2	3	1	0	0	4	4	1	4	0	2	3	0
B9	0	1	0	0	1	1	0	3	0	2	4	3	3	0	1	3
B10	2	2	3	4	2	3	0	4	3	0	0	2	0	3	4	0
B11	0	0	1	0	3	2	0	0	4	0	0	3	4	0	1	2
B12	2	2	3	3	3	3	1	3	4	3	3	0	2	2	3	1
B13	0	0	0	0	0	2	1	0	0	3	2	0	0	3	2	0
B14	0	1	0	1	1	3	1	2	0	2	0	3	3	0	3	0
B15	1	1	3	3	1	3	1	3	3	4	2	2	1	3	0	2
B16	0	0	0	0	0	3	0	0	3	0	3	1	2	0	2	0

(1) Strengthen policy support and R&D investment. The Chinese government should further expand the strength and breadth of government incentives on the shale gas industry, such as price subsidy, preferential tax policies, and R&D investment (Ren et al., 2015; Yang et al., 2017), which will help make up for the negative impact of high development costs on the shale gas industry. But it should be noted that state-owned petroleum enterprises, such as CNPC and Sinopec Group, which have absolute advantages in capital, capability of technology innovation, and development experience over the new entrants, should be given more attention and guidance from the Chinese government in order to make a

breakthrough in key technologies for shale gas development and reduce development costs.

(2) Perfect shale gas industry policies, regulations, and the supervision system. We suggest establishing more detailed and scientific industry policies, regulatory standards, and industry guidelines for the shale gas industry, which will provide a basis for regulating the behavior of shale gas enterprises. Moreover, it is our view that a high-efficiency supervision system and professional regulatory agencies urgently need to be established to enhance the regulatory capacity of the shale gas industry in China.

(3) Strengthen the international cooperation of shale gas development. We suggest that the Chinese government actively

Table A.2
Direct-relation matrix by expert 2.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
B1	0	1	4	4	1	2	0	3	3	4	0	4	1	0	2	0
B2	1	0	4	4	2	2	0	3	2	4	1	4	2	4	4	1
B3	1	2	0	4	2	3	2	2	2	3	2	4	2	3	3	1
B4	2	3	3	0	2	3	3	2	3	3	2	4	2	3	3	2
B5	1	1	3	3	0	2	3	2	2	2	2	3	2	3	3	2
B6	1	2	2	3	3	0	4	2	2	3	1	3	3	4	3	2
B7	0	1	2	2	3	3	0	2	2	3	2	3	3	3	2	3
B8	1	2	2	3	3	3	3	0	3	3	1	3	2	3	3	2
B9	3	2	3	3	2	2	2	3	0	3	1	3	2	3	3	2
B10	3	3	4	4	3	3	3	3	0	2	2	4	3	4	4	2
B11	0	0	2	2	3	1	2	2	1	2	0	2	1	2	2	3
B12	3	1	2	2	2	2	2	3	2	3	2	0	3	3	3	2
B13	2	2	2	2	3	2	3	2	2	2	2	3	0	4	3	3
B14	1	2	3	3	3	4	3	3	3	4	2	4	4	0	4	3
B15	1	3	3	3	1	3	3	3	3	3	1	4	3	4	0	3
B16	1	1	3	2	2	3	4	2	1	3	1	3	3	4	3	0

Table A.3
Direct-relation matrix by expert 3.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
B1	0	0	1	1	1	1	1	1	0	1	1	4	0	0	0	1
B2	3	0	2	2	2	1	1	1	0	3	1	4	1	0	1	1
B3	0	3	0	3	3	3	3	3	2	4	2	4	2	3	3	2
B4	1	0	2	0	2	3	3	2	2	3	2	3	2	3	3	2
B5	0	2	2	1	0	1	3	2	2	3	2	3	2	2	2	2
B6	0	0	2	2	2	0	3	2	2	3	2	3	2	2	2	2
B7	0	0	2	2	2	2	0	2	1	3	2	3	2	2	1	2
B8	0	0	3	2	2	2	3	0	1	2	1	2	2	3	3	1
B9	1	1	3	1	2	1	3	1	0	2	1	4	2	2	1	2
B10	0	0	3	3	3	3	3	3	1	0	3	4	2	3	3	2
B11	0	0	2	1	3	1	2	3	2	3	0	4	2	1	1	2
B12	1	0	3	3	3	3	3	3	3	3	2	0	2	3	2	2
B13	0	0	2	1	3	2	2	1	3	3	2	3	0	3	3	3
B14	0	0	0	0	0	0	3	2	1	2	1	3	0	0	2	1
B15	0	0	2	3	2	2	2	2	2	3	2	3	3	3	0	3
B16	0	0	2	1	3	1	3	1	2	3	3	3	2	3	1	0

Table A.4
Direct-relation matrix by expert 4.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
B1	0	4	3	3	1	2	1	3	3	4	3	4	4	3	4	1
B2	2	0	3	3	2	3	1	3	2	4	0	4	3	3	4	1
B3	3	3	0	2	2	2	1	3	3	3	2	2	2	2	3	1
B4	3	4	4	0	2	3	3	1	3	3	2	3	3	3	3	1
B5	3	2	1	1	0	1	1	1	2	1	2	1	1	1	1	1
B6	3	3	4	3	1	0	3	2	3	3	2	3	3	3	2	2
B7	1	2	1	2	2	4	0	1	2	2	2	2	2	3	2	2
B8	3	3	4	1	3	1	2	0	2	4	2	4	3	2	2	3
B9	3	3	2	1	1	1	2	4	0	4	3	4	3	3	3	0
B10	2	3	3	3	3	4	2	3	4	0	3	3	3	3	4	1
B11	3	2	1	2	1	3	2	3	3	2	0	3	2	2	3	1
B12	4	2	4	2	3	3	3	1	3	3	3	0	2	3	2	2
B13	2	2	3	1	2	4	1	1	2	2	2	3	0	4	2	2
B14	3	2	2	3	3	4	3	1	2	2	2	2	2	0	4	2
B15	2	2	3	3	2	3	2	3	2	4	2	3	3	2	0	1
B16	3	2	3	3	2	3	3	3	2	2	2	3	2	2	3	0

provides a platform and policy support for the international cooperation of shale gas development. Moreover, the shale gas enterprises should be encouraged to actively cooperate internationally, and strive to introduce and digest the advanced experience of exploration, exploitation, transport, utilization, and management from foreign shale gas enterprises.

(4) Promote technical cooperation and knowledge flow among domestic shale gas enterprises. The Chinese government should actively support emerging enterprises in upgrading their basic technological capabilities by setting up special technology research and development funds and in formulating related policies for the introduction of domestic and foreign professional personnel talents. The Chinese government should also strengthen

the protection of intellectual property related to the shale gas development technology to provide a policy guarantee for technological innovation and knowledge flow.

However, our study also had the following two limitations: First, only 16 barriers obtained from literature analysis and expert interviews were analyzed; some important barriers may not have been included due to limitations in cognition. Second, only four valid expert questionnaires were collected in this study, which may have affected the reliability of the research conclusions to some extent. To overcome these limitations, additional barriers and data from stakeholders should be collected and analyzed in future studies to provide more scientific management suggestions for China's decision-makers. In addition, it would be meaningful

to conduct future case studies of different typical shale gas blocks in China.

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Appendix

See Tables A.1–A.4.

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