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Review Article

Coalbed Methane Industry Development Framework and Its Limiting Factors in China

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The current average daily gas production of single coalbed methane (CBM) wells in China is less than 1,300 m^3. The low production rate of CBM wells dramatically limits the sustainable development of the CBM industry in China. To promote CBM industry development, three universal geological factors, i.e., gas sources, channels, and driving force of the low production wells are analyzed, considering the various and complicated geological conditions of CBM reservoirs in China. Additionally, we find that the growth in proven CBM reserves should be greatly promoted as the CBM proven rate is only less than 3% by the end of 2020. The widespread CBM extraction mode based on depressurization via dewatering generates very limited effects in coal seams with notable deformation, high in situ stress, or little water. Therefore, a specific design of CBM development modes is proposed, according to the applicable geological conditions of different CBM development modes. It covers depressurization via dewatering, depressurization via stress release, and coal and CBM comining. Moreover, the regional governments play a key role in the development of the regional CBM industry, and favorable policies should be formulated to promote the multipoint development conditions across China. This study is concluded to provide a recommended development framework involving sustainable CBM production in China and its development processes.

1. Introduction

Coalbed methane (CBM), generated and mainly adsorbed in coal seams, is a form of unconventional natural gas [1, 2]. Given the actual energy structure in China, the dominant position of coal in energy consumption over other energy forms would persist for a long time in the future [3]. The extraction of CBM resources can increase the energy supply and reduce mining hazards. Moreover, acknowledged as a type of greenhouse gas, the development of CBM in the process of coal mining is beneficial for reducing greenhouse gas emissions and protecting the environment. Therefore, CBM development is of significance in both economic and environmental respects.

In the past 30 years, China has made great achievements in CBM exploration and development, with the production volume of CBM wells exceeding 100×10^8 m^3 since 2020 [4]. Two CBM industrialization bases including Qinshui Basin and the eastern margin of Ordos Basin have been built. Unfortunately, the average daily gas production of single CBM wells in China is currently lower than 1,300 m^3, and the low production rate of CBM wells greatly restricts the development of CBM in China. The limiting factors concerning low CBM production are thought to include geological conditions, engineering technologies, and management policies [5]. Admittedly, under multistage tectonism, the geological conditions of coal-bearing basins in China are extremely variable and complicated. Hence, the preservation conditions of CBM are definitely poorer than those other countries developing CBM [6]. The various and complicated geological conditions of CBM reservoir in China make the development technology meet great bottleneck. In addition, the management policies of the government and enterprises

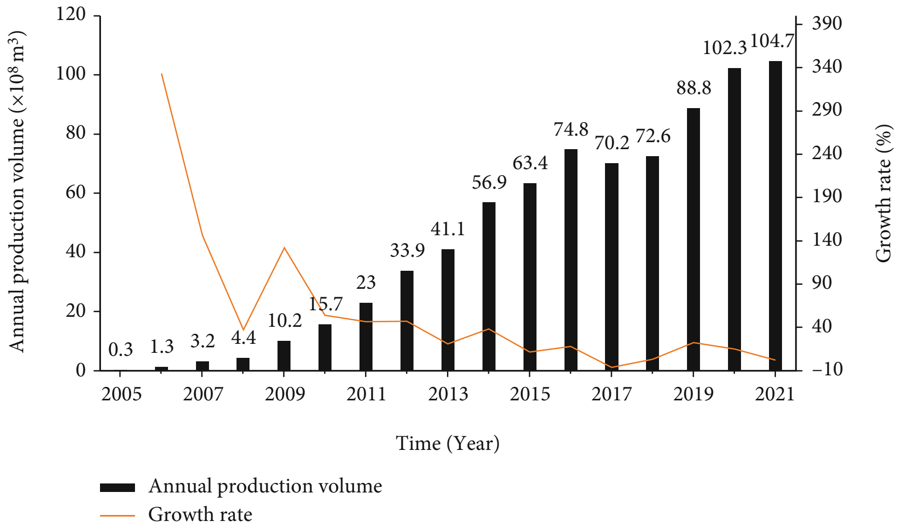

Figure 1: Annual production volume and growth rate of CBM wells in China (2005-2021).

cannot effectively stimulate investment enthusiasm in present hard stage of CBM industry [7]. Therefore, it is urgent to determine the universal limitations based on the movement process of CBM in coal seams. In this way, a recommended framework should be established to achieve a significant increase in CBM production throughout China.

The objective of this study is to reveal the limiting factors of CBM development and provide a fundamental framework for CBM industry development in China. The universal geological reasons for the low production rate of CBM wells are first analyzed. A recommended framework including ensuring the growth of proven CBM reserves, specific design of CBM development modes, and the role of regional governments is developed. This work is intended to promote CBM industry development across China.

2. CBM Industry Progress in China

China's CBM development over the past 30 years, especially the large-scale development of CBM resources since 2006, has been provided notable policy support by the state. Consequently, the CBM industry in China has attained remarkable achievements. From 2005 to 2020, the number of gas accidents in coal mines decreased from 414 to 7, at a reduction rate of 98.3%, with the number of deaths decreasing from 2171 to 30 [8, 9]. The annual production volume of CBM wells has dramatically increased from less than 1×10^8 m^3 in 2005 to 104.7×10^8 m^3 in 2021 [4], as shown in Figure 1. However, CBM production in China still lags far behind that in major countries developing CBM, such as the USA, Canada, and Australia. Moreover, China has failed to meet the annual production target during two consecutive five-year plans, and the implementation of the fourteenth five-year plan barely realized the annual production target [10]. Figure 1 shows that in recent years, the growth rate of CBM production has continuously decreased, even exhibiting a negative growth in 2017, which has resulted in the current CBM industry in China experiencing a rather unfortunate situation, and the confidence of investors and practitioners in the CBM industry is low.

The initial CBM drainage mode is coal mine gas extraction of coal seams or the adjacent layers in the subsurface coal mines. The aim is to reduce gas content and gas pressure, ensuring mining safety. At the end of the last century, drawing lessons from the surface CBM development of depressurization via dewatering in the United States [11], China has developed the development technology systems involving drilling, fracturing, and drainage processes. At present, this is still the main mode of CBM surface development. With the progress of CBM development technologies, the coal and CBM comining in the mining areas gradually formed between 2010 and 2015 [12]. By coordinating the relationship between CBM development and coal mining in time and space dimensions, CBM resources are extracted in coordination with coal mining process to achieve rapid release of reservoir pressure [13, 14]. The coal and CBM comining have achieved an excellent adaptability to CBM reservoirs in coal mine areas [15]. However, successful commercial development of CBM in a few areas is inadequate to support the development of CBM industry in China [16, 17]. A specific design of CBM development modes suitable for the specific geological conditions in China has not been established yet [18]. There is still a great need to innovate development technologies that can cover complicated geological conditions and extract CBM resources efficiently.

Additionally, in the past, due to the urgent demand for CBM production, field trials and error correction became a common means to assess the effect of development methods. This has caused substantial financial and time losses. The relatively extensive technical development and management have hindered the sustainable development of CBM industry in China. Therefore, to overcome the abovementioned bottlenecks of CBM development, improve the production rate of single CBM wells, and complete the long-term planning

Table 1: Universal geological reasons for the low production rate of single CBM wells in China.

Reasons	Gas sources	Channels	Driving force	Applicability of development technologies
Characteristics	(1) Methane occurs the adsorption state (2) The gas saturation is low	(1) Low mechanical strength and high stress sensitivity (2) Easy to produce coal fines (3) Tectonically deformed coal is widely distributed where fracture connectivity is poor [25]	(1) Low reservoir pressure (2) High capillary pressure [26] (3) High water saturation	(1) In the process of drilling, horizontal wellbores easily collapse (2) In the process of fracturing, it is difficult to create effective propped fractures (3) In the process of drainage, it is difficult to ensure the smooth output of CBM
Consequences	(1) The output of CBM wells hardly peaks within a short time (2) CBM production involves a slow process	(1) Gas migration channels are easily blocked (2) It is difficult to construct diversion channel in tectonically deformed coal [27]	(1) This factor influences the development cycle of CBM wells (2) Pressure release within the coal matrix is difficult to obtain [7]	(1) The extraction methods of CBM wells are not fully adapted to the geological conditions of CBM reservoirs (2) The stimulation effect of development methods is poor [28]

target of the CBM industry, relevant development processes must be updated.

3. Geological Factors concerning Low Production of CBM Wells

Studies have analyzed the different geological factors of CBM reservoirs in China and other countries, which probably cause the low production rate of CBM wells, such as the permeability, buried depth, thickness, gas content, gas saturation, coal structure, and coal rank [19–24]. Admittedly, due to repeated plate movements and tectonic activities during historical periods, the geological conditions of coal-bearing basins in China are extremely variable and complicated. However, under the various and complicated geological conditions, investigations of geological factors among different areas are inadequate to guide CBM exploitation. Moreover, CBM development in only limited areas has been promoted. Hence, in China, it is necessary to analyze the universal geological reasons for the low production rate of CBM wells. This could be helpful to optimize development methods that adapted to the various geological conditions and improve the production of single CBM wells.

Generally, the necessary conditions for CBM movement include gas sources, channels, and driving force. From this perspective, the universal geological reasons for the low single CBM well production in China, based on the gas movement process, are listed in Table 1. The objective limiting factors determine that the production rate of single CBM wells cannot reach a peak within a short time as other kinds of natural gas wells, such as wells in tight sandstone gas and shale gas reservoirs. Nevertheless, this table does not indicate that the CBM production rate cannot be greatly improved, on condition that the expected stimulation methods must overcome these three constraints. Furthermore, the current development methods of CBM extraction are not fully adapted to the various and complicated geological conditions of CBM reservoirs, which significantly restricts CBM development. Therefore, if the production rate of CBM wells is expected to distinctly increase across China, a CBM development framework is urgently needed.

4. Recommended Development Frameworks

4.1. Ensuring the Growth in Proven CBM Reserves. Abundant coal reserves provide a basic condition for CBM development. The CBM resources in China are highly abundant, and at a buried depth of 2,000 m, the CBM resources in China total are approximately $30.05 \times 10^{12}\ m^3$, with the recoverable resources reaching approximately $12.5 \times 10^{12}\ m^3$ [29]. CBM development areas with the large-scale CBM exploitation activities in China include the Qinshui Basin in Shanxi Province, the eastern margin of Ordos Basin in Shanxi and Shaanxi Provinces, the Qianxi-Diandong area in Guizhou and Yunnan Provinces, the Junggar Basin in Xinjiang Autonomous Region, and the Erlian Basin in Inner Mongolia Autonomous Region (Figure 2), due to their advantageous geological resources.

At present, the CBM resource evaluation area in China covers $37.5 \times 10^4\ km^2$, and the registered mining right area reaches $4.83 \times 10^4\ km^2$, which only accounts for 12.87% of the total CBM resource evaluation area [31]. After more than 30 years of development, China has successively established two major CBM industrialization bases, namely, the Qinshui Basin and the eastern Ordos Basin. Most high-quality blocks in these areas have been put into development. However, by the end of 2020, China's total proven CBM reserves reached $7857.54 \times 10^8\ m^3$ (Figure 3), with a proven rate lower than 3% [32], mainly distributed in the Qinshui Basin and eastern Ordos Basin, North China. The annual increased proven CBM reserves lacked sustained growth, exhibiting a very low and highly unstable pattern (Figure 3). Furthermore, only Shanxi Province accounted for approximately 88% of the proven CBM reserves in China [33]. Therefore, it is necessary to further conduct geological exploration of CBM-bearing basins and to increase the proven gas reserves, which is an effective way to sustainably develop the CBM industry in China.

4.2. CBM Development Modes. A shale gas revolution swept the USA in the early 2000s. The development mode of horizontal drilling associated with fracturing created a surge in shale gas production in the United States, transforming it from an energy importer into a net energy exporter. Moreover, this surge altered the landscape of energy markets globally. The applicable modes of CBM development have not been determined, which represents the development bottleneck of the CBM industry in China. In the process of CBM exploitation, the extraction mode based on depressurization via dewatering has been increasingly questioned to determine whether this mode is suitable for all the geological conditions in China [34, 35]. Depressurization via dewatering performs well in CBM exploitation of shallow and weakly deformed coal seams in China. However, hydraulic fracturing applied to achieve dewatering generates very limited effects in coal seams with notable deformation, wherein hydraulic fractures rarely propagate (Li et al., 2020; [27, 36]). Moreover, the buried depth of CBM reservoirs increases in the process of CBM development. The basic geological conditions and fluid production characteristics of deep CBM reservoirs distinctly differ from those of shallow reservoirs [37, 38]. Under the high in situ stress conditions of deep coal seams, the damage exerted by stress on the fracture system during dewatering distinctly increases, which greatly limits the flow and output of gas and deformation water [39–41]. Therefore, depressurization involving only dewatering hardly extracts deep CBM resources [42]. The limitation of the depressurization mode via dewatering should be overcome to account for the geological conditions of deep CBM reservoirs.

Depressurization of deep coal seams and strongly deformed coal seams has been suggested to be enhanced via stress release. An increasing number of recent studies have indicated that cavity establishment is a feasible approach for stress release, and directional drilling and hydraulic jetting technologies can create many cavities within coal seams for stress release [43–46]. In terms of gas sources, depressurization via stress release can enhance the desorption rate of coalbed methane. Furthermore, the change of stress condition induces the movement and deformation of coal seams, which can

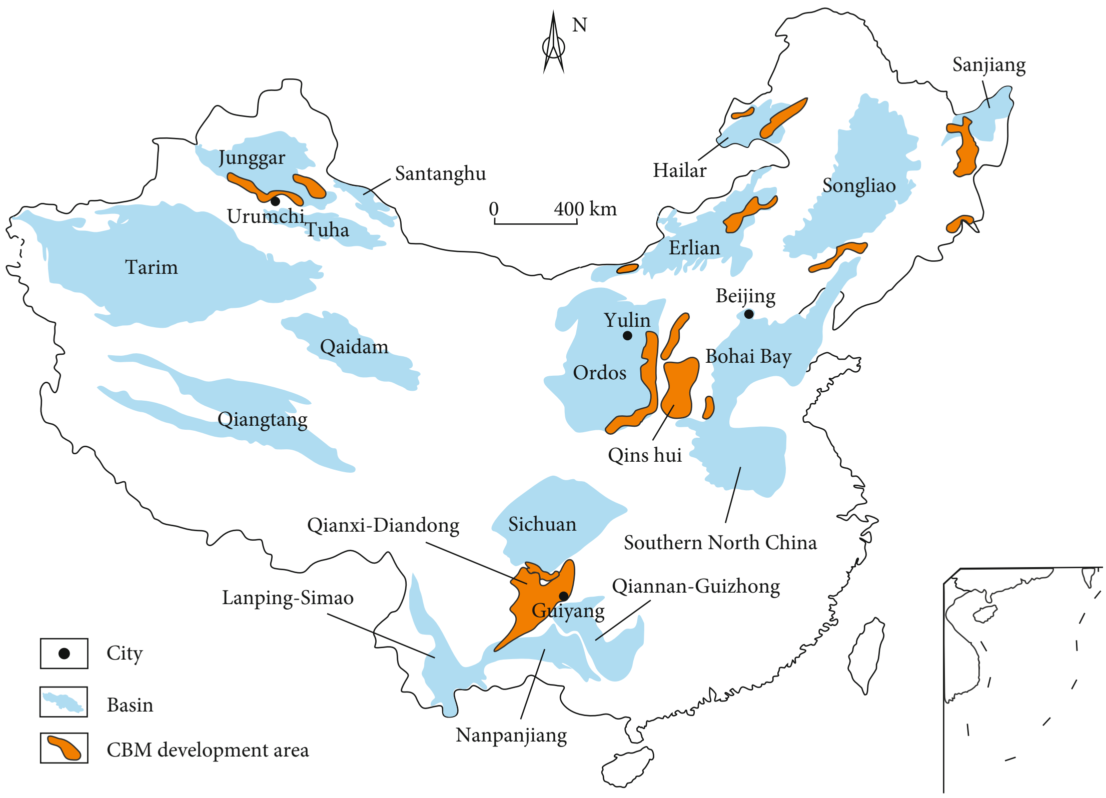

Figure 2: Distribution of the main CBM development areas in China (revised from [30]).

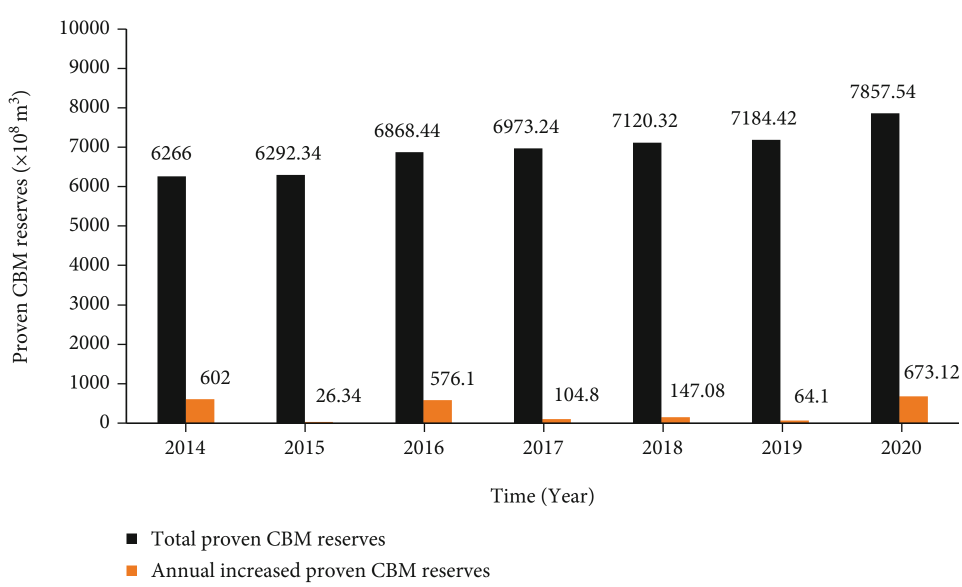

Figure 3: Annual proven CBM reserves in China (2014-2020).

improve reservoir permeability. In addition, the expansion deformation of coal seams enlarges the volume of pores and fractures, which can reduce the capillary resistance of gas migration in flow channels [16]. Therefore, this development mode should be further researched and applied in CBM industry. In addition, in coal mining areas, employing the advantages of rapidly releasing the reservoir pressure through mining, CBM extraction can be significantly enhanced. Hence, the development mode of coal and CBM comining has been demonstrated as a suitable way to develop CBM resources in practice [47, 48]. In China, the maximum depth of coal mining reaches approximately 1500 m. Hence, the coal and CBM comining mode can be employed to develop CBM in mining areas.

According to different CBM development modes and their applicable geological conditions, a certain design of CBM development modes is proposed, as summarized in Table 2.

Table 2: Design of CBM development modes.

Area categories	Buried depth (m)	Stress	Special geological conditions	Suggested development mode
In situ coal seams	Shallow	Low in situ stress	Weakly deformed coal; water-bearing coal	Depressurization via dewatering
			Strongly deformed coal; water-free coal	Depressurization via stress release
	Deep	High in situ stress	Low permeability and high effective stress	Depressurization via stress release
Coal mining areas	<1500	Reservoir pressure release through mining	Continuous coal seams with large thickness	Coal and CBM comining

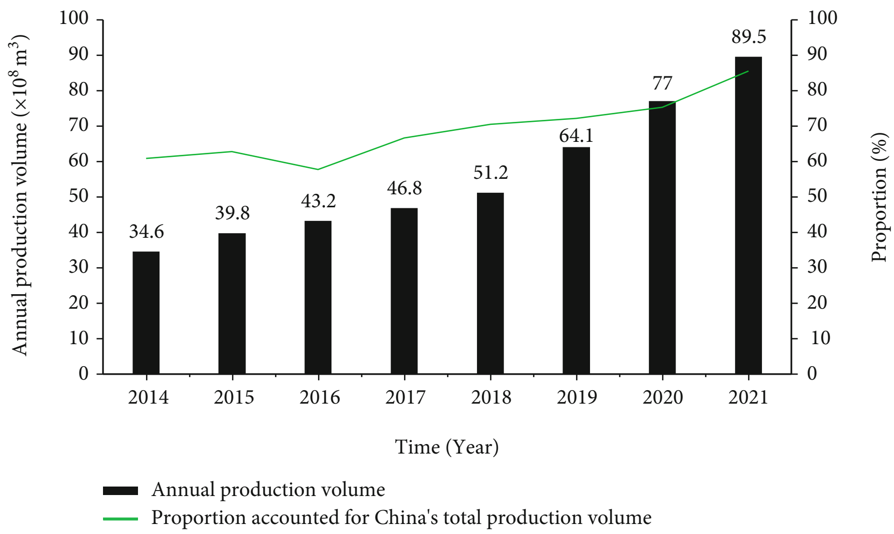

Figure 4: Annual CBM production volume in Shanxi Province (2014-2021).

In shallow weakly deformed coal seams or water-bearing coal seams, the development mode of depressurization via dewatering can be optimized and innovated to further improve the CBM extraction effect, because this development mode exhibits a high geological adaptability. In coal mining areas, coal and CBM comining mode should be continuously developed and popularized. In deep coal seams, strongly deformed coal seams, or water-free coal seams, the development mode of depressurization via stress release should be vigorously developed, as current development modes are inefficient in terms of extraction in these areas. The geological conditions described in Table 2 can cover most CBM development areas in China. Hence, this design achieves a universal geological adaptability. It should be noted that Table 2 does not provide detailed values of the buried depth in in situ coal seams, as there exists no absolute critical conversion value between deep and shallow coal seams.

4.3. Recommended Policies and Managements. Since 2008, China has implemented several National Science and Technology Major Projects for the development of CBM resources from 2006 to 2020 [49, 50]. Nevertheless, considering the low production rate of single CBM wells, it is also difficult to establish a high gas production capacity to satisfy the energy demand in China. Therefore, the support and overall management provided by the central government alone is far from sufficient. CBM resources in China are widely distributed [51]. If the regional governments could strengthen the development of local CBM resources and prioritize fulfillment of the demand of local users, this probably facilitates the formation of multipoint development conditions across China.

In 2010, the Government of Shanxi Province proposed the gasification of Shanxi strategy and issued pump priming policies in investment, fiscal taxation, finance, land, and other areas of the CBM industry [52]. In 2017, the Science and Technology Department of Shanxi Province issued a major project on key and core technologies to realize an energy revolution in this province, explicitly supporting breakthroughs in CBM exploration, development, and utilization [53]. These policies have led to and driven the sustainable and rapid development of the Shanxi CBM industry. In April 2020, Shanxi Province issued the Administration Measures of CBM Exploration and Exploitation in Shanxi Province to further standardize the CBM exploration and development market and ensure ecological protection in this province [54]. Prior policies and effective management measures have

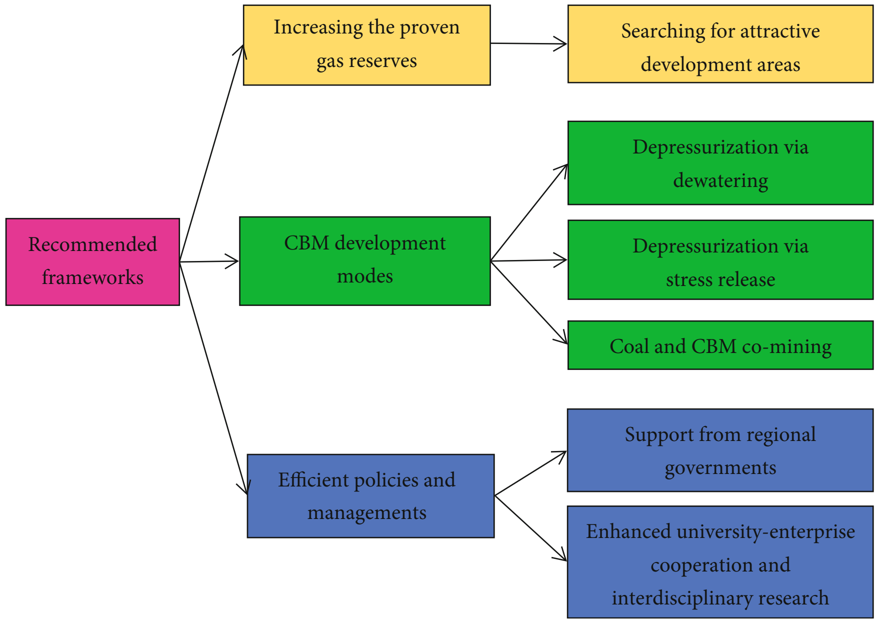

Figure 5: Recommended framework for CBM development.

driven the CBM industry in Shanxi Province to progress rapidly. In recent years, the production volume of CBM in Shanxi Province has always accounted for more than 60% of China's total CBM production volume, as shown in Figure 4 [55]. Particularly, in 2021, the surface CBM production in Shanxi Province reached 89.5×10^8 m^3, and the CBM well production capacity of Shanxi Province alone accounted for 85.5% of the national total well production capacity.

Additionally, more than 100 wells have been constructed in the abandoned mines in Shanxi Province, and approximately 1.28×10^8 m^3 of CBM resources have been extracted and utilized by the end of 2021 [56]. This terrific amount is equivalent to reducing 1.92×10^6 tons of carbon dioxide (CO_2) emissions, with a great significance for the local atmospheric environment.

The abovementioned demonstrate that regional governments play a key role in the development of the regional CBM industry. Therefore, we argue that regional governments should formulate more favorable policies, such as tax relief policies, gas production subsidies, and scientific research projects, to promote the engagement of CBM production enterprises.

In addition, current CBM production management remains extensive, and the extraction methods of CBM wells are excessively uniform across different areas, lacking professional design of CBM development modes as mentioned in Section 4. 2. In this way, the sameness of CBM extraction method in China must be disrupted in the future. Enterprises must strengthen the cooperation between enterprises and universities and establish professional construction teams. The focus of CBM development is to improve the fundamental theories and solve the key technical problems. Based on these aspects, it is also suggested that interdisciplinary collaboration should give full play to breakthroughs in key CBM development technologies. For example, research and development of fracturing fluids and proppant materials should fully utilize the advances of materials science. A breakthrough in reservoir stimulation and permeability enhancement depends on the integration of basic science theories such as physics, chemistry, and biology. In addition, research and development of major CBM extraction equipment require the application of mechanical and electronic sciences, combined with artificial intelligence. Therefore, cooperation and interdisciplinary research are expected to break through the technical restricts in CBM development.

Based on the above discussion, a recommended framework for CBM development in China is proposed, as shown in Figure 5. Increasing the proven gas reserves can ensure a sufficient number of attractive areas for CBM development. The design of CBM development modes can be employed to provide guidance for the development direction of CBM extraction technologies. Support by regional governments and cooperation between enterprises and universities are important for the CBM industry across China.

5. Conclusions

The low production rate of CBM wells limits the development of the CBM industry in China. In this study, the limiting factors of CBM development in China are analyzed involving the geological reasons for the low gas production, proven CBM reserves, CBM development modes, and managements. On the basis, a recommended framework of CBM development is established to promote the CBM industry in China. In this study, the following conclusions are obtained:

(1) There are three objective limiting factors restricting gas movement and production in CBM reservoirs, including gas sources, channels, and driving force.

CBM stimulation methods must overcome these three constraints

(2) The proven rate of CBM resources in China is much less than 3%, and the annual increase in proven CBM reserves in recent years exhibits a very low and highly unstable pattern. It is suggested to greatly increase the proven CBM reserves

(3) Depending on the applicable geological conditions of different CBM development modes, a specific design of CBM development modes is proposed, including depressurization via dewatering, depressurization via stress release, and coal and CBM comining

(4) Regional governments can play a key role in the development of the CBM industry and should formulate more favorable policies to promote the multipoint development conditions across China. Cooperation and interdisciplinary research are expected to break through the technical restricts in CBM development

The limitation of this study is that the favorable policies are not elaborated, as the development status of CBM in different regions is variable across the country. Further works are needed to survey the market and formulate detailed policies that can be implemented by different regional governments.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Acknowledgments

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