



The shale gas revolution in China—problems and countermeasures

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ABSTRACT

Shale gas development throughout the world has resulted in a revolution in the field of global energy and has also become an important topic in China in recent years. While organic-rich shale is widely distributed in China and the initial commercialization of shale gas has been achieved, the research, exploration, and development of shale gas remain at an early stage. Problems exist with crucial technologies, innovation, institutional mechanisms, environmental protection, and other aspects of the industry. The shale gas exploration and development industry in China can learn from the experiences of other countries and strengthen its position in the market, with the support of new government policy. Given its unique geological conditions, China should speed up the introduction of technical innovation and establish its unique systems and methods for shale gas exploration and development.

Keywords: shale gas; exploration and development; problems; countermeasures.

La revolución del gas de lutita en China-problemas y contramedidas

RESUMEN

El desarrollo del gas de lutita en el mundo ha significado una revolución en el campo de la energía; en China, durante los últimos años se ha convertido en un tema importante. Las lutitas, ricas orgánicamente, están ampliamente distribuidas en China y la comercialización inicial de gas de lutita ha sido lograda; sin embargo, la investigación, exploración y desarrollo de este producto permanece en etapas prematuras. Los problemas se presentan en las tecnologías clave, la innovación, los mecanismos institucionales, la protección ambiental y otros aspectos de la industria. La exploración del gas de lutita y el desarrollo industrial en China se pueden mejorar a partir de las experiencias de otros países y con su fortalecimiento en el mercado, acompañado del apoyo de políticas gubernamentales. Gracias a sus condiciones geológicas únicas, China puede acelerar la introducción de innovación técnica y establecer sus sistemas y métodos únicos para la exploración y desarrollo del gas de lutita.

Palabras clave: Gas de lutita; exploración y desarrollo; problemas; contramedidas.

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Introduction

The successful commercial exploration for shale gas in the United States led to an energy revolution, which ended America's dependence on imported energy and made the US an energy-rich country. This situation brought the shale gas industry under the spotlight throughout the entire world. While China is also aiming to develop its shale gas reserves, it faces challenges with technology and marketing. The international community generally acknowledged that shale gas exploitation revolutionized the global energy landscape, which not only increased the output of natural gas but also enormously influenced the global gas market, global energy supply structure, global climate change policy and even geopolitics. In recent years, shale gas exploration and development has become an important topic in China. Organic-rich shales under the right conditions for gas accumulation are widely distributed in China, including marine shales in southern China, northern China, and the Tarim Basin of Xinjiang, and lacustrine shales in north of China, the Junggar Basin, Turpan-Hami Basin, Ordos Basin, Bohai Bay Basin, and Songliao Basin, which represent a considerable resource potential (EIA, 2010; Zou, et al, 2016)

It is predicted that the recoverable resources of shale gas are about 22×10^{12} m³ (Ministry of Land and Resources of People's Republic of China, 2016), which exceeds the conventional natural gas resources of China. At present, although commercial production has been rapidly achieved in three districts of the Sichuan Basin, China is still in the early stages of evaluation, exploration, and development of shale gas and key technologies are still not well integrated. Large-scale commercialization is challenging due to the commonly complex geological structure and the high cost of drilling and fracturing services.

To overcome the bottlenecks in technique, marketing and industrialization that are restricting shale gas exploration and development in China would be necessary the following actions. 1. Increasing basic theoretical research. 2. Developing shale gas theory by introducing innovative thinking and methodology. 3. Improving exploration and development technology as well as relevant environmental technology; 4. Establishing a sophisticated marketing system with better relations between industry and local government.

2. The status of shale gas exploration in China

The United States has greatly benefited from the development of shale gas and other unconventional petroleum resources. In 2010, the United States had shale gas production of more than 1379×10^8 m³, accounting for about 23% of the national output, and has now surpassed Russia to become the world's largest gas producer (EIA, 2010). The United States shale gas revolution has reshaped the global liquefied natural gas market, and its influence will become even more remarkable over time. The enormous success of shale gas development and exploration has attracted considerable attention from governments and energy companies all over the world and set off a boom in exploration for shale gas. It has categorically changed the global energy picture. With the rapid development of the national economy in China, the demand for energy, and exceptionally clean energy continues to increase. According to the Ministry of Land and Resources (MLR) of China, the country's gas shortage will exceed 1350×10^8 m³ by 2020. Therefore, active, systematic exploitation of China's unconventional gas resources is a significant way to meet the country's future energy demands. The exploration and development of global non-renewable energy resources show that shale gas is one of the realistic replacements for conventional petroleum.

The Twelfth Five-Year Plan for the national economy and social development in China stated explicitly "to promote the exploitation and utilization of shale gas and other unconventional petroleum." On March 16th, 2012, the National Energy Administration issued the "Shale Gas Development Plan (2011–2015)" in which the government requested emphasis on the following strategies: 1. researching into shale reservoir geology and key accumulation factors for shale gas; 2. establishment of the

evaluation methods and criteria for shale gas target optimization, based on sedimentary facies, tectonic evolution, burial depth, organic matter content (TOC), thermal maturity and gas content. It aims to increase the annual shale gas production rate from a current level of 13×10^8 m³ up to 300×10^8 m³ per year by 2020.

China has achieved substantial progress regarding the exploitation of shale gas in recent times. PetroChina identified Weiyuan, Changning, Zhaotong, and Fushun–Yongchuan as the four most favorable districts for shale gas exploration in south Sichuan and north Yunnan, and more than 20 wells were put into production (Figure 1). SINOPEC (China National Offshore Oil Corporation) has completed several appraisal wells in eastern Guizhou, Anhui, northeast Sichuan and the Chongqing Fuling area, and the Jiaoye 1HF well in the Fuling district produced a high-yield commercial shale gas flow of approximately 20.3×10^4 m³ per day. CNOOC (China National Offshore Oil Corporation) has carried out pilot work for the exploration of shale gas in the Anhui and Zhejiang areas, and Yanchang Petroleum has discovered lacustrine shale gas at Yanan in the Shanxi province.

At present, shale gas reserves in China are estimated to be nearly 500 billion m³ with an annual production rate of approximately 1.5 billion m³. According to the MLR, up until the end of July 2015, CNPC, SINOPEC, and Yanchang Petroleum had cumulatively produced 680 million m³ of shale gas. By the end of 2015, the cumulative production reached 6.5 billion m³ (Dong et al., 2016).

This progress shows that China has great potential when it comes to shale gas exploration. However, although shale gas exploration and research has made some advances, the exploration and development of shale gas in China still has much further potential.

Compared with the United States, the commercialization of shale gas in China has been challenging, due to the more complex geology, the presence of older strata, more complex tectonism, more complicated thermal histories, and higher levels of thermal maturity. Considerable difficulties in specific fields need to be overcome if future shale gas exploration is to be successful, including understanding accumulation mechanisms, laboratory testing, evaluation and forecasting of sweet spots, productivity analysis and prediction, hydraulic fracturing technology, geological steering, and reservoir stimulation.

In recent years, China has intensified its efforts into shale gas exploration and development, and some examples of its industry's promotion are as follows:



Figure 1. The status of shale gas exploration in China (After Dong et al., 2016).

(1) Investment in researching and development has been increased, and technical systems were formed and improved

With the support of the National Energy Administration, the Research Institute of Petroleum Exploration & Development of PetroChina set up a National Energy Shale Gas R&D Center to address the critical technical problems related to shale gas exploration. A specific sub-project for research into the key technologies of shale gas exploration and development has been set up from the National Key Science and Technology Special Project “Large oil–gas fields and coalbed methane development.”

Also, major oil corporations, as well as local governments, such as Sichuan and Chongqing, have set up research institutions and laboratories to research the evaluation of gas reservoir potential and the selection of advantageous exploration areas.

2) A diversified investment and multi-type enterprise participation pattern has emerged

The State Council of China has approved shale gas as being the 172nd independent mineral in China, which means that the oil and gas franchise will no longer restrict shale gas exploration and development, and any companies who have the financial ability and qualifications for gas exploration can bid for it. In the field of natural gas prospecting, only PetroChina, SINOPEC, CNOOC and Yanchang Petroleum had Chinese government approval and were eligible for gas prospecting in the past. On September 10th 2012, in the second round of public bidding for shale gas exploration in China, the Ministry of Land and Resources demanded that those companies qualified to explore for oil and gas or gas minerals, had registered capital of more than 300 million RMB, no matter their domestic enterprise or independent legal entity (Ministry of Land and Resources of the People's Republic of China, 2012). Many private enterprises who had planned on investing in shale gas in the past had been blocked previously because of the requirement for registered capital. On the 30th October 2013, the National Energy Board issued the “Shale Gas industry policy”, which removed the registered capital limitation. It only made requests for investment capability, moderate financial status and the ability to be responsible for civil liability, which created new opportunities for private enterprises who were willing to invest in the shale gas industry. The Ministry of Land and Resources has held two open tenders for exploration permits, and private enterprises were welcomed. In the second round of public bidding, through state-owned enterprises won most of the bids for the exploration rights, about one-third of the original 83 bids were from private enterprises, and they won 2 blocks out of the 19 up for bid (Ministry of Land and Resources of the People's Republic of China, 2013). This results marked a significant breakthrough in the bidding mechanism for oil and gas exploration rights in China. Although foreign firms are not allowed to participate in oil and gas exploration and development directly, the Chinese government encourages them to take part in joint ventures. It shows a desire by the Chinese government and local enterprises in obtaining specialized foreign technologies and international development experience.

3) A policy system for industrial shale gas development has been formed

The central government is a strong supporter of the development of shale gas and lists the shale gas industry as an industry of growing national strategic importance (National Energy of the People's Republic of China, 2013). To encourage enterprises to accelerate the commercialization of shale gas, the Ministry of Land and Resources, the National Development and Reform Commission, the Ministry of Finance, the Ministry of Commerce, the Ministry of Science and Technology, the Environmental Protection Bureau, the Central Ministries and Commissions and other National Ministries have launched a series of detailed policy measures for promoting shale gas exploration and development, encouraging foreign investment, increasing financial subsidies, guiding industry development, constructing a demonstration zone, and supporting science and technology research (China Geological Survey, 2014).

At the central government level, the Development and Reform Commission is responsible for formulating general policy and supervises the price of natural gas. The National Energy Administration is competent for setting up shale gas production goals. The Ministry of Land and Resources is accountable for shale gas mineral exploration and development rights as well as for organizing and implementing the shale gas tendering process for exploration blocks. The Ministry of Finance is responsible for shale gas exploration subsidies. The Science and Technology Department is qualified for funding support for shale gas related technology research and development. The Environment Protection Bureau is responsible for monitoring and preventing environmental pollution. The Ministry of Commerce is responsible for examining Chinese–international cooperative projects. The State Administration of Work Safety is responsible for monitoring work safety at sites of production.

The policies of central government related to shale gas development are mainly regarding to the setting of production goals, calculation of government subsidies, administration of taxes and fees, handling of market access, mineral classification of shale gas, and publishing of the shale gas industry standard (Table 1).

Annual shale gas production in China in 2017 reached $91 \times 10^8 \text{ m}^3$ by 2017. The Chinese government planning target is for $30 \times 10^8 \text{ m}^3$ by 2020 and requests PetroChina and SINOPEC to take a series of measures to ensure they achieve these goals on time.

The central government used to subsidize shale gas development enterprises, paying 0.4 RMB per m^3 of gas produced. These subsidies expired in 2015, but the Ministry of Finance has issued a new subsidy policy and will now pay 0.3 RMB per m^3 of gas produced from 2016–2018. The subsidy will drop to 0.2 RMB per m^3 of gas produced from 2019–2020.

The Ministry of Land and Resources lists shale gas as the 172nd independent mineral. The decision has far-reaching significance and gives other private enterprises an opportunity to invest in shale gas development.

In August 2014, the Sichuan provincial government classified the shale gas industry as being one of the top five highly advanced sectors of the future.

The current shale gas policy of China is similar to that of the United States, during the early development stage of shale gas in that country. China has set up procedures for government subsidy, arranged financial support for technology research and development, removed shale gas price control, opened a natural gas pipeline network system, and made other advancements. However, shale gas development in China is still dominated by large state-owned enterprises, and in a situation which differs from the United States, United Kingdom, and other western countries, as these entities are not required to release geological information or production data.

3. Problems affecting the development of China's shale gas industry

Although China's shale gas industry has achieved initial success, there are still some problems relating to the areas of critical technology, innovation, environment, institutional mechanisms, environmental protection and other aspects which are discussed below.

3.1 A technical system for exploration and development adapted to China's geological characteristics has not been established

Although some achievements relating to the exploration and development of shale gas have been made in China, a systematic investigation and evaluation of the national shale gas resources have not yet been completed. The theory of shale gas reservoir geology still needs to be studied in more detail. Significantly, more work is required for the study of the accumulation of shale gas, field of sweet spot optimization methods, evaluation of productivity, dynamic mechanisms, characterization of gas flow through micro–nanoscale pore systems, complex multi-field seepage coupling theory, as well as other aspects of this science.

Table 1. The policies of the central government to promote shale gas development

Timing	Policy Name	Agency	Main Content	Valid Time
2011	Outline of the 12th five-year plan for economic and social development.	SC.	Promote shale gas development and utilization of multiple clean energy development planning.	2011–2015
2011	Catalog of industry adjustment guidance.	NDRC	List of shale gas exploration and development projects to be encouraged.	Long-term
2011	Chengdu–Chongqing economic zone regional planning.	NDRC	Speed up Sichuan shale gas exploration and development	Long-term
2011, 2015	Catalog for the guidance of foreign investment.	NDRC. MOC	List of shale gas exploration and development projects (joint ventures) to be encouraged.	Long-term
2012	The 12th five-year national strategic emerging industry development planning.	SC.	Class shale gas industry as a critical developing direction and primary tasks.	2012–2015
2012	Shale gas development plan (2011–2015).	NDRC. MOF. MOLR. NEA.	Clear objectives, tasks, and measures of the shale gas industry.	2012–2015
2012	“12th five-year” energy conservation and environmental protection industry development plan.	SC.	Improve the level of overall utilization of shale gas in critical areas.	2012–2015
2012	Energy conservation and emissions reduction “twelfth five-year” plan.	SC.	Promote shale gas development and utilization as the primary task of adjusting and optimizing the energy structure.	2012–2015
2012	Notice about strengthening shale gas resources, prospecting, and exploitation, supervision, and administration of relevant work.	MOLR	The management of shale gas exploration, mining and the administration of exemptions from mineral resources compensation fees and mineral rights use charges.	2012–2017
2012	Opinions about further encouragement and a guide to the private capital investment in the field of land and resources.	MOLR. ACFIC	Encourage and guide private capital to participate in shale gas resource prospecting and exploitation.	Long-term
2012, 2015	Notice about shale gas development and utilization of subsidy policy.	MOF.	Shale gas definitions and subsidies standards.	2012–2020
2012	Advice on encouraging and guiding private capital to further expand the implementation of energy sector investment.	NEA.	List of shale gas exploration developments within the scope of private capital investment.	Long-term
2012	Enforcement advice on utilizing price level to encourage and guide the development of private investment.	NDRC.	Shale gas production price should be determined by mutual consent so that private capital is encouraged into the shale gas field of production.	Long-term
2013	The shale gas industry policy.	NEA.	Shale gas development should be financially supported so that the development of shale gas exploration may be increased.	Long-term
2013	The announcement about oil and gas enterprises, development of CBM and shale gas VAT related issues.	SAT.	Provision of a VAT tax rate for shale gas production of 17% that is applicable for the development of oil and gas.	Long-term
2014	The strategy of energy development action plan (2014–2020).	SC.	Aim to enhance shale gas production up to 300 billion m ³ by 2020.	2014–2020
2014	Open regulatory measures for oil and gas pipeline network facilities (trial).	NEA	Promote the oil and gas pipe network facilities. Improve the utilization efficiency of pipe network facilities. Regulate the behavior of oil and gas pipe network facilities and relevant open markets.	2014–2019
2015	The announcement about the urban land used tax policy for oil and gas production enterprises.	MOF. SAT.	Oil and gas production construction. Suspend leaving urban land use tax.	Long-term

NDRC: National Development and Reform Commission; MOF: The ministry of finance. NEA: The national energy administration. MOC: The ministry of commerce. SAT: State administration of taxation. ACFIC: The national federation of industry and commerce. MOLR: The ministry of land and resources. SC: The state council.

The rapid development of the United States shale gas industry occurred mainly due to breakthroughs in large-scale horizontal drilling and massive multi-stage hydraulic stimulation, which significantly reduced the cost of exploiting shale gas, and made resources economically viable upon they were initially worthless.

China's service companies are just beginning to acquire these two key technologies, which are partly still only mastered by foreign enterprises. The experience of shale gas development in the United States shows that different mining technology is required in different regions, as reservoir conditions change from place to place. As a latecomer to the shale gas development industry, the number of drilled wells is relatively limited in

China and the technical knowledge for drilling and producing needs more time to develop. Similarly, equipment and industry standards are still in the process of being developed and implemented. Due to this underdeveloped technical environment, only three state-owned oil companies have currently fully mastered the latest technology. New enterprises that are starting to enter the field of shale gas development are finding technical services to be deficient. Also, China's shale gas reservoirs are different from those in the United States. Shale gas is currently commercially produced in the Sichuan Basin from marine shales. The producing zone is the Lower Silurian Longmaxi Formation, which is older than shales in the United States. It has had a long geological history and has been transformed into an “over mature,

highly reworked” shale. The present burial depth of the shale in the Sichuan Basin ranges from 2000–4000 m, which is more profound than that in the United States, which is mainly at depths of 800–2600 m

Furthermore, the mountainous topography of the Sichuan shale gas areas poses challenges for ground engineering. Although commercialization of shale gas at burial depths of around 2000 m is possible, the drilling, completing and fracturing technologies for depths of 3000–4000 m have not yet been developed.

3.2 The cost barrier for shale gas industrialization

Based on the American experience, the central controlling factors for the development of the shale gas industry are resource abundance, technology, government policy, and input-output relationships. The rapid expansion of shale gas in the United States benefited from national policy support, an integrated technical system and a well-developed infrastructure (pipe-network); conditions which helped lower cost.

The cost of shale gas development remains high in China. Immature technology, an imperfect industry chain (which has resulted in a shortage of equipment), and an undeveloped pipe-network have stalled progress within the shale gas industry of China.

Shale gas development is still at an early stage, and low rates of production are making increases in scale challenging to achieve. Compared with other energy sources, shale gas has no advantage when it comes to price. Although the government has issued a subsidy policy of 0.4 RMB/m³ for shale gas, it takes a long time to commercialize shale gas projects fully, and most companies have still not yet qualified for the government subsidy.

Most shale gas districts in China are located in mountainous areas where transportation is difficult, and this further increases the cost of exploration and development.

3.3 A non-competitive environment for industrial development

The United States shale gas industry benefited not only from improvements in technology and innovation but also from its mature market system. In contrast, China's shale gas industry still faces problems with the market.

A dynamic, competitive market has still not been established. Large state-owned enterprises have dominated China's petroleum industry for a long time, and it is mostly a closed market. Only the three major state-owned oil companies have experience in exploration and development. Moreover, shale gas blocks overlap with the traditional oil and gas blocks and, as a result, the three major oil companies possess most of the shale gas blocks. It has meant a monopoly when it comes to exploration rights.

Besides, local governments in places such as Chongqing, Guizhou and Sichuan Province have begun to set up energy investment companies for shale gas exploration, and this will form local monopolies. As an essential support facility for the development of the shale gas industry, China's oil and gas pipeline network is also a monopoly and its distribution is not suitable for shale gas transportation because the current shale gas production wells are mostly in remote areas, over which the existing pipeline network does not extend. A new regional pipeline network needs to be built.

Also, the absence of sharing of shale gas data and technology between these companies has greatly hindered the progress of the industry and technology. The technical services for shale gas are still in their infancy. Although some new specialized service companies for shale gas have started up in recent years, the majority of them lack vital technologies and experienced personnel. Many of the new shale gas exploration and development enterprises have little experience in the oil and natural gas exploration and development. In the second round of bidding for China's shale gas blocks in 2012, for example, four of the companies that won bids had only been established three months earlier. As such, the lack of experienced technical and management personnel makes shale gas exploration difficult.

Development of the shale gas industry in the United States showed that while many companies may begin shale gas exploration, only the fittest survive, which inevitably leads to companies entering and leaving the industry. With the introduction of relevant policies in China, a competitive environment for the shale gas industry will emerge.

Shale gas exploration and development needs a lot of capital investment in the early stages and has an extended investment recovery period, which means that profits are difficult to realize in the short-term. Therefore, financial obstacles are an essential issue for some small and medium enterprises. The shale gas industry is a high-investment, high-risk sector and development of China's shale gas industry will be affected without a good investment and financial basis.

3.4 Environmental problems in the development of shale gas

Due to water resource limitations, and even though China possesses the world's largest shale gas reserves, massive exploitation without suitable water protection will be disastrous.

According to the United States Environmental Protection Agency (EPA), the average water consumption of a single shale gas well in 2010 was 0.76×10^4 to 2.39×10^4 t (depending on the depth, horizontal section length and fracturing scale), of which 20%–85% remained underground (EPA, 2012). In the United States, the average water requirements for drilling each well is 200–2500 m³, and the water demand for hydraulic fracturing each well is as high as 7000–23000 m³ (Vengosh, 2014). United States counterparts have noted that water protection and conservation is a huge issue for the industry. In the United States shale gas drilling industry, about 70% of the water used comes from hydraulic fracturing water recovery.

Although China's total water resources are 2.8124×10^{12} m³, accounting for almost 6.7% of total global freshwater resources, the actual amount of water available is only 0.8×10^{12} m³ (Wang, 2010). In total water resources, China ranks sixth in the world, after Brazil (6.95×10^{12} m³), Russia (6.54×10^{12} m³), United States (3.056×10^{12} m³), Canada (2.9114×10^{12} m³), and Indonesia (2.8113×10^{12} m³), according to Wang (2011). However, according to the ranking released by the World Water Development Report (2012) on water resources in 180 countries and regions, China ranked 128th in the world, having only 2260 m³ of water per person/per year, which is just one quarter of the world's average, and only half of that in Japan, one quarter of that in the United States, 1/12 of that in Russia, and 1/58 of that in Canada.

According to data from the United States EPA, for each horizontal shale gas well, the water used for fracturing accounts for 85–98% of the total water consumption for the well. Shale gas wells in different plays have different water consumptions. For example, in the Marcellus shale gas field, the average water consumption for a well is about 1.5×10^4 m³, in the Barnett shale the average water consumption is about 1×10^4 m³, in the Fayetteville shale the average water consumption is about 1.2×10^4 m³, and in the Haynesville shale it is about 1.4×10^4 m³ (Rahm, 2011).

Compared with the United States, China's shale is generally more deeply buried, especially in the Changning–Weiyuan district where it is usually found at a depth of 2600–3000 m. The reservoir thickness is 20–800 m, which also means that the demand for water for hydraulic fracturing will be more significant. At present, there are no official figures for water volumes used during the drilling of shale gas wells in China, but according to investigations made by researchers, the drilling and fracturing of each shale gas well will consume approximately 25000 m³ of water on average in China, which is far higher than the average value (15000 m³) in the United States (Lu, et al., 2014). The data from the Weiyuan shale gas district support these findings. Water consumption in the wei201-H1 well for a 10-level hydraulic fracturing job reached 22000 m³, and the total water consumption for the entire well was approximately 25000 m³. Although water is relatively abundant in the Sichuan Province (a vital shale gas production region), its distribution is uneven, resulting in regional and seasonal water shortages. The water resources of the Sichuan Province are principally located in the Ganzi, Aba and Liangshan prefectures, accounting for 50% of the total water

resource. Per capita, the supply there reached 16993 m³ in 2015. However, within the Sichuan Basin, the most water-poor area of the entire province, the per capita water resource is only 1624 m³ (Sichuan Provincial Water Resource Department, 2015). Agricultural water consumption accounts for more than 60% of the total water use in the Sichuan Province, and there has been a water shortage there for a long time.

Several factors contribute to the agricultural water shortage in the Sichuan Province:

- (1) The geographical distribution of the water resource and rainfall is uneven, which leads to severe water shortages within the Sichuan Basin, and water abundance in the mountain plateau areas of western Sichuan.
- (2) Historical issues and inadequate investment in the whole province, but especially the basin and hilly regions, has resulted in a shortage of irrigation systems, making water deployment difficult. The efficiency of water use is low.
- (3) The utilization rate of water for agriculture is low. Due to a lack of water management, water wastage is common. In most areas of the province, canal water utilization efficiency is less than 50%, and generally over half of the water cannot be used.
- (4) The agricultural water resource is commonly used for other activities, due to its lower value when used in the agriculture industry. Local governments regularly use part of agrarian water for other industrial activities.

The national demonstration shale gas areas of Weiyuan, Changning, and Huangjinba are located in the Weiyuan, Changning, Gong, and Xingwen counties, and all suffer long-term, or seasonal, water shortages.

For example, Weiyuan has had an annual precipitation of around 1000 mm for several years. Total accumulated precipitation is 15×10^8 m³, the gross water resource is 7.4227×10^8 m³, and the per capita water resource is just 994 m³, resulting in severe water shortages. Agricultural water consumption is more than 1×10^8 m³, accounting for 51% of the total water consumption. The standard water resource of the Changning, Gong, and Xingwen counties is around 10×10^8 m³, the per capita water resource is just 2521 m³, the total agricultural water consumption is less than 3×10^8 m³, and there is a severe water shortage.

The national demonstration shale gas areas of the south Sichuan Basin are all in the main rice cultivation areas, with a rice planting area of approximately 680 km². The rice planting areas of Changning, Gong, Juanlian, and Xingwen counties are around 451.72 km² in size and about 228.06 km² in Weiyuan. Fu et al. (2014) calculated that 1177 m³ of water per year were needed to produce 1000 kg of rice. There are more than 160 horizontal shale gas wells drilled in the Sichuan, Yibin and Weiyuan regions. Assuming that the water consumption of each well is 2.5×10^4 m³, the total water consumption during 2014–2015 would have been at least 4×10^6 m³, which is equivalent to the irrigation water used for 26.7 km² of paddy fields for one year, and therefore accounts for 4% of the five counties' annual water consumption. Taking the total number of wells that will be put into production (about 353) for these three shale plays, it is possible to calculate that the annual water consumption will reach 8.8×10^6 m³, which would be 9% of the five counties' annual irrigation water consumption. According to the plans made by the local government of the Sichuan Province, 1000 wells will be added, every year, over the next few years. As a result, the water consumption of shale gas development will increase by 2.5×10^7 m³ every year over the near future, which is equivalent to the irrigation water consumption of an additional 166.7 km² of rice growing area every year.

Therefore, in line with the exponential increase in the number of shale gas wells, there will be an exponential increase in water consumption. The rice growing industry, which demands a great deal of water, will suffer a severe water shortage. This conflict between agriculture and the shale gas

industry, and who is going to use the dwindling water supply, will become more severe over the next few years.

The fracturing fluid, including the fracturing water and a small amount of formation water from the shale, will gradually flow back into the ground after the massive multi-stage hydraulic stimulations of the shale gas wells. Shale gas well fracturing flowback fluid (mainly fracturing fluid) differs from conventional fracturing fluid, in that it contains abundant chemical additives used in the hydraulic stimulation process, and poses a considerable risk for the environment if not carefully handled. How to deal with this massive flowback drainage is critical for the successful development of the shale gas industry in China.

About 30%–70% of the high-pressure injection fluid flows back to the ground after the hydraulic stimulation of a shale gas well in the United States (United States Environmental Protection Agency, 2012). Measures taken to process these flowback fluids include 1. reinjecting them underground using re-injection wells; 2. reusing them for hydraulic stimulations after simple treatment; 3. treating them into fresh water.

The abundant chemical additives make the processing of flowback fluid difficult and costly. At present, treatment equipment or factories for the processing of flowback fluid have not been set up in Sichuan shale gas production areas. All of the flowback fluid is transported by truck and injected back underground using re-injection wells to reduce the cost. This process prevents the reuse of flowback fluid and increases the overall water consumption of the shale gas developments.

It is essential to establish processing facilities for flowback water, so that the water may be reused. Currently, the United States has taken measures to encourage the purification and recycling of flowback water. For example, the reused flowback fluid ratio of the Marcellus shale gas region has increased from less than 10% in 2008 to more than 70% in 2011, which has greatly reduced the water consumption (Rahm et al., 2013). Nevertheless, the New York environmental protection ministry recently announced the prohibition of hydraulic fracturing operations in New York State, after a seven-year investigation. It considers hydraulic fracturing to be a significant risk to land, air and water resources, as well as posing a potential public health risk, which may lead to a negative perception that is impossible to remedy.

4. Countermeasures for shale gas industrialization in China

Shale gas industrialization in China should follow the successful model of the United States, taking into account the differences that exist in China.

4.1 Improvements in exploration and development technology

Advanced technology is the key to shale gas development in China. With the rapid economic growth of our country and the additional demands for energy, energy structure adjustment, energy security, energy savings and other factors, it is necessary for shale gas industrialization of our country to speed up.

The Shale Gas Development Plan (2011–2015) specified the following goals to be achieved by 2015: 1. completion of an assessment of the potential and distribution of shale gas resources; 2. prioritization of prospective areas and sweet spots, establishing several shale gas development zones and achieving commercial production; 3. conducting international cooperation with regards to shale gas technology and increasing research investment.

Shale gas exploration represents the basis for the rapid development of the shale gas industry in China. With the support of the national policy for the shale gas industry, future work should focus on the geological research of the “over mature, high reworked” shale and accurately assess the potential and distribution of shale gas in China, especially in the Sichuan, Chongqing, Guizhou, Hunan, Hubei, Yunnan, Jiangxi, Anhui, Jiangsu, Shanxi, Henan, Liaoning and Xinjiang Provinces, and to establish new shale gas development zones.

4.2 Reinforcing the market and reducing the input costs

The exploration for shale gas in our country is at an early stage. Investment cannot yet reach the well-developed levels seen in the United States, at least in the short term.

However, once China's service companies acquire technology for large-scale horizontal drilling and massive multi-stage hydraulic stimulation, the process of shale gas industrialization will accelerate, and the costs will reduce. This process will result in enormous demand for specialized equipment from domestic suppliers, providing the equipment manufacturers with opportunities for rapid development. Gradual improvements in the structure of the industry will stimulate shale gas industrialization in China, and a more competitive industry model will develop.

4.3 Forming a greener outlook for the shale gas industry by making water resource protection a core issue and placing equal emphasis on resource development and ecological protection

The development of shale gas will not only bring about the challenge of protecting water resources but will also raise environmental issues such as land disturbance, greenhouse gas emissions and the potential leakage of underground water.

Therefore, during the revolution in shale gas, the implementation of policies relating to water resource protection and environmental pollution prevention should proceed simultaneously. Due to the nature of the contaminants involved in shale gas development, research into pollution reduction and treatment should be encouraged and developed.

Shale gas in China is mainly distributed in mountainous and hilly areas, such as the Sichuan and Guizhou provinces, which experience water shortages and have transportation issues. Hence, launching the development of, and exploration for shale gas in these areas may bring about adverse impacts on local vegetation, aquatic biology, municipal water and the usage of industrial and agricultural water.

Large-scale river water fracturing only applies to experimental development at an early stage. Water shortage and environmental pollution will be a significant issue for mass commercial production of shale gas.

It is, therefore, necessary to utilize the combined technologies of horizontal drilling and hydraulic stimulation, to help reduce water consumption, during the development of shale gas. The installation of water treatment facilities will be indispensable for reusing flowback fluid, thereby improving water use efficiency, as well as for groundwater protection. The use of oil-based muds for drilling should be reduced, and the use of water-based muds should be encouraged.

Drill cuttings should be collected and disposed of properly, which will help to reduce land contamination. Noise control in populated areas and functional relationships between corporations and communities are also necessary for the long-term future of the shale gas industry.

Optimization methods for the drilling process include the use of "cluster wells," "multi-well pads," "gas terminal standardization designs" and the rehabilitation of agricultural land after construction. Optimization of the site selection process will avoid damaging ecological and environmentally sensitive areas and will reduce tree felling and vegetation destruction. Plans to restore vegetation and rejuvenate the land should be designed before construction and executed adequately after construction.

Use of the methods mentioned above will ensure that shale gas development, and environmental protection progress hand in hand.

Conclusions

Shale gas exploration and development in China should learn from the experiences of other countries and cultivate an active market, with the support of government policy. A geological theory applicable to the unique geological conditions found in China is indispensable for the future of shale gas exploration and should be established as soon as possible. Shale gas development technology should be improved to protect the water and land resources, as well as prevent pollution.

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