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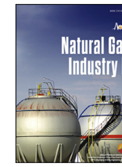

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Research Article

Progress and prospects of natural gas development technologies in China☆,☆☆

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Abstract

Under the present situation of low global oil prices and vigorous development of green energy resources, China has turned to focus on natural gas in oil and gas sector, both production and consumption of which are soaring high these days and the role of which is gradually prominent in energy sources. With the aims to help promote the further rapid development of natural gas business in China, this paper analyzed natural gas development process and summarized the new advances in natural gas development technologies in the recent years. On this basis, this paper analyzed the prospects of natural gas development in China in the four aspects of production rates, demand potential, import volume, future position of natural gas. The following results were obtained. (1) Since the 12th Five-Year Plan, natural gas business has been doing well with a rapid increase of consumption, diversified supply sources, steadily increasing of reserves and production rates, obviously satisfactory benefits from exploitation. (2) Breakthroughs have been made in technical bottlenecking problems with an improved innovation capacity in the respects of deep-strata gas development, large-scale gas field development adjustment, tight-gas recovery enhancement, development of shale and CBM gas, engineering techniques, and development strategies support system. (3) With the deepening of development, influenced by policies, environment concerns and geological conditions, continuous efficient natural gas development will face up with such challenges as lower ratio of quality reserves, higher gas field development expenses, more difficult benefit development of unconventional gas reservoirs, further compressed upstream benefits, less stable production capacity of those major gas fields, increasingly fierce competition in the energy market, etc. In conclusion, it is demonstrated that natural gas development in China will enter into a new stage of attaching equal importance to both unconventional and conventional gas; natural gas demand potential will be great and its consumption structure will become more diversified; gas imports will rise year by year, resulting in the vigorously increasing external dependency; and natural gas will become the main growth engine in the process of energy mix adjustment.
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Keywords: China; Natural gas; Development technology; Production rate; Demand; Import; Deep gas; Tight gas; Shale gas; Coalbed methane; Development strategy

1. Overview of natural gas development in China

In recent years, China's natural gas development has achieved a series of major breakthroughs [1], and natural gas has become the core business in the petroleum industry, with the rapid rise of production and consumption. During the "13th Five-year Plan", in the background that the government robustly advocates low-carbon and green energy and positively carries out energy transformation, the positive development of natural gas based on the philosophy of "quality, benefit, and sustainability" is of great importance in guaranteeing energy supply and realizing energy transformation in China.

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1.1. Rapid consumption growth and strengthened competitiveness helps facilitate China's energy transformation

China's natural gas consumption quickly increased from 1112×10^8 m^3 in 2010 to 2100×10^8 m^3 in 2016, up from 4% to 6.2% with regard to its proportion in the energy mix (Fig. 1). However, compared with major energy consumers around the world, China reveals a much lower proportion of clean energy consumption, so natural gas will play a greater role in the adjustment and optimization of energy mix. According to the National Energy Development Strategy of China, in 2020, the proportion of natural gas in the energy consumption will increase from the current 6–10%, and the annual consumption is expected to reach 3000×10^8 m^3. The improvement of natural gas proportion in the energy consumption will be conducive to boosting China's energy transformation and bring new opportunities to natural gas development. Natural gas is a resource characterized by high calorific values and low prices. The Chinese government has launched several policies for natural gas market reform recently, which will further reduce the costs of terminal users, thus making natural gas apparently more competitive than other energy resources.

1.2. The supply sources are diversified and natural gas market is more competitive

China's natural gas supply is mainly sourced by domestic gas, imported pipeline gas and imported LNG, with the domestic gas in dominance. The three major national oil companies in China, CNPC, Sinopec and CNOOC, have put forward the strategy to accelerate the development of natural gas. CNPC, which keeps a principal status in natural gas production, contributes about 70% in the domestic production. However, its principal status has been clearly impacted by other companies whose natural gas business develops rapidly. The imported pipeline gas is less competitive due to its price and long-distance transmission, although its stable supply is guaranteed by long-term trade contracts. LNG emerges quickly to trigger the extensive intercontinental trade of natural gas and help further reduce the price spread among the three largest consumer markets in the world, i.e. North America, Europe and Asia–Pacific. As for LNG in China, a diversified competition pattern of central enterprises, local enterprises and private enterprises is formed. LNG, domestic gas and imported pipeline gas rank in a descending order of competitiveness in price and flexibility.

1.3. Conventional gas develops steadily and unconventional gas production accelerates

Natural gas production comprises conventional gas and unconventional gas (tight gas, CBM and shale gas). Overall, conventional gas develops steadily and unconventional gas production accelerates quickly. Conventional gas will maintain a steady development within a certain period of time, and will remain as the dominator domestically in a long time. Shale gas production rises quickly – from 44.6×10^8 m^3 in 2015 to 78.9×10^8 m^3 in 2016, and CBM production increases steadily – from 16×10^8 m^3 in 2015 to 17×10^8 m^3 in 2016. In the future, natural gas production will maintain a continuous growth, but the production composition will change significantly, since the proportion of unconventional gas will grow gradually (Fig. 2).

1.4. Reserves and production grow stably and gas supply capacity is continuously enhanced

The reserves and production of natural gas grow stably, thus laying a solid foundation for guaranteeing the gas supply capacity. Since 2000, the annual average newly-added proved gas reserves have been maintained above 6600×10^8 m^3, and that in the past five years was more than 8800×10^8 m^3. In 2016, the newly-added and cumulative proved gas reserves were 7656×10^8 m^3 and 14.9×10^{12} m^3, respectively, consolidating the resource base for further development. Tight gas, deep gas and shale gas were major contributors to the reserves growth recently. In the past few years, natural gas production has been grown continuously, being 1371×10^8 m^3 in 2016. China's natural gas production will turn from a rapid growth stage to a steady growth stage.

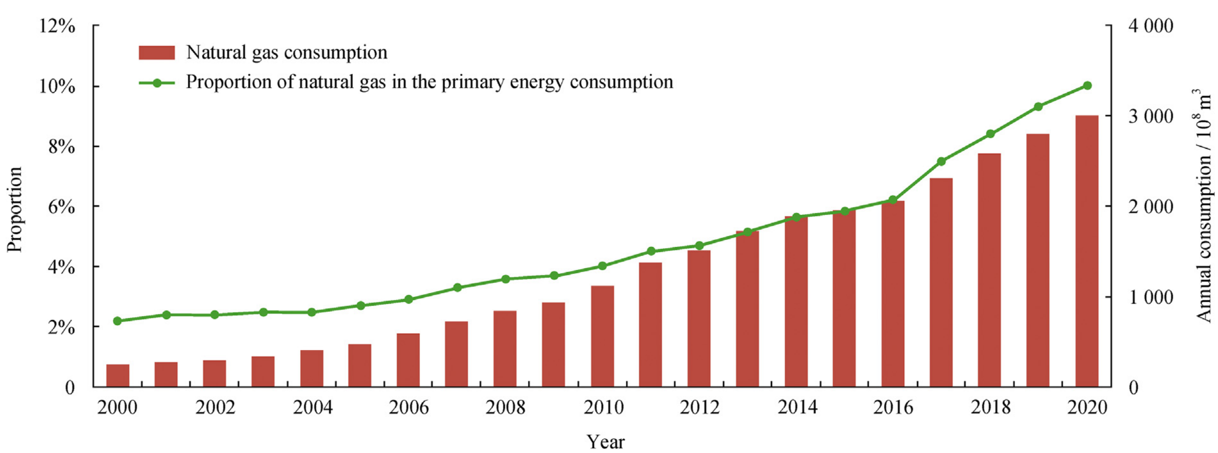

Fig. 1. Annual consumption of natural gas and its proportion in the energy mix in China.

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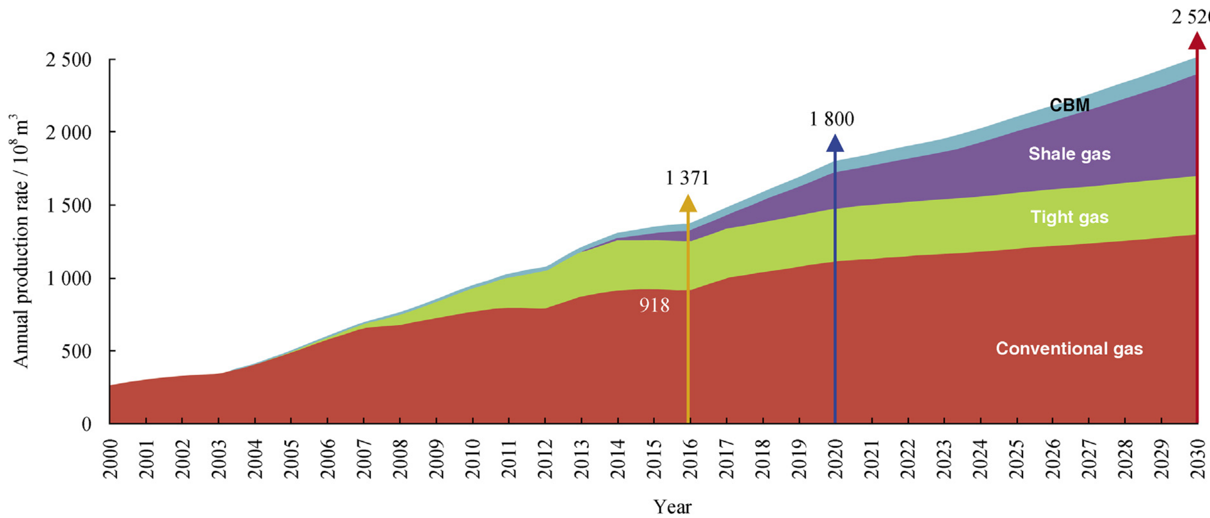

Fig. 2. Conventional and unconventional gas production plan of China.

1.5. Key gas regions maintain good development indexes, and natural gas becomes a major profit contributor

Through a leapfrog development of the natural gas industry in 3 stages for nearly 70 years, four major gas production bases, Ordos, Tarim, Sichuan and offshore area, have been established. They share 89% and 87% in China's total proved gas reserves and production, respectively. In these regions, the development indexes are good generally; the recovered geological reserves in gas reservoirs are 8.4×10^{12} m^3, and the cumulative gas production is 1.45×10^{12} m^3; the recovery percentage is 56%, the remaining recoverable reserves are 5.4×10^{12} m^3, and the reserves–production ratio is 39. So, a solid foundation is available for the long-term steady development.

Due to the low oil price, the upstream profits of oil and gas companies shrink greatly; however, natural gas business has relatively good profitability, with high net cash flow and net profit, alleviating the upstream business pressure of these companies to a large extent. As natural gas production further rises, domestic oil production and oil equivalent of natural gas production will hold the same line basically, which will remarkably help enhance the risk immunity of oil and gas companies. Thus, the role of natural gas as a core upstream business will be more outstanding.

2. New progress in natural gas development technologies

Technical advancement has driven the shift of natural gas development from single gas reservoir to complex gas reservoir and from conventional gas reservoir to unconventional gas reservoir. The improvement of such technologies in gas reservoir description, productivity evaluation, drilling and completion, reservoir stimulation and gas production process has supported the successful development of various gas reservoirs in Sulige, Kela 2 and Jingbian gas fields [2–5]. During the "13th Five-year Plan", great changes have taken place in development situations. Typically, the structure of the newly-added proved reserves changes to the dominance of deep gas, low-permeability tight gas and unconventional gas, implying greater difficulties in development. Main gas fields enter the stable production period in succession, where the production stabilization and recovery enhancement become focuses in technical studies. Unconventional gas grows quickly in view of development scale by virtue of the breakthroughs in bottleneck techniques. More efficient engineering technologies are required to improve the single well output and development benefit. More instructive gas field development plans and more scientific development indexes should be available. Under the new situation, natural gas development technologies have achieved the following progress.

2.1. Remarkable improvement of development technologies for deep gas reservoirs and scale expansion of new potential contributors to production capacity construction

The deep/ultra–deep gas reservoirs in the central and western basins have been revealed as new potential contributors to the increase of natural gas reserves and production. Such reservoirs are represented by the Lower Cambrian Longwangmiao and Upper Sinian Dengying deep carbonate gas reservoirs in the Sichuan Basin, and the multi-fault-block deep tight sandstone gas reservoir in the Dabei–Keshen area of the Tarim Basin. Primarily, two technological series are formed.

2.1.1. For deep carbonate gas reservoirs

For the karst gas reservoirs of Longwangmiao Fm and Dengying Fm in the Sichuan Basin, which are characterized by strong heterogeneity and complicated gas–water distribution [6], four major development technologies are formed.

(1) Dolomite karst reservoir description technology: The grain beach and bioherm beach karst development modes are

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innovatively proposed, the seismic identification methods are developed for different types of reservoirs, and the high-yield well deployment technology is formed.

(2) Development optimization technology for fracture−cavity water-bearing gas reservoirs: The research is intensified on the characteristics of different water influxes, and water influx monitoring and regulation are conducted to mitigate the risks of water influx.
(3) Highly-deviated well/horizontal well cluster development technology: The wellbore−reservoir contact area can be increased.
(4) Modular, skid-mounted and intelligent construction mode of large gas fields: Based on new design philosophy, this mode records a new representative in terms of gas field construction speed, intelligent level, safety and environmental protection.

In 2016, the 110×10^8 m^3 production capacity of Longwangmiao Fm gas reservoir was completely constructed, and the 18×10^8 m^3 production capacity of Dengying Fm gas reservoir was constructed in a steady way, laying a foundation for CNPC Southwest Oil and Gas Field Company to create a strategic gas region with a capacity of 300×10^8 m^3.

2.1.2. For deep tight sandstone gas reservoirs

For the multi-fault-block gas reservoir in the Dabei−Keshen area of the Tarim Basin, for which the reservoir description and engineering operations are extremely challenging, four major development technologies are formed.

(1) Gas reservoir description technology represented by structural modeling: Broad-azimuth 3D seismic survey is conducted to ascertain the structural geometry, and the fracture pattern at different structural parts is established, so that the well location can be optimized.
(2) Fast drilling technology based on local vertical drilling system: The independently developed vertical drilling system, oil-based drilling fluid, anti-impact and anti-grinding PDC drill bits and other tools are used to greatly reduce the drilling period and cost.
(3) Reservoir stimulation technology represented by fracturing: Typically for Class II and Class III reservoirs, acid fracturing and sand fracturing are adopted for stimulation. As a result, the daily gas production of single well increases from less than 30×10^4 m^3 to more than 50×10^4 m^3.
(4) Development optimization technology represented by ultra-high pressure test: Retrievable downhole pressure tool (DPT) for ultra-high pressure well is developed. With this DPT, the connectivity of fault-block gas reservoir is evaluated in a progressive way, and the number of development wells is optimized to realize high yield with a sparse well pattern.

In 2016, the annual production of gas fields in the Dabei−Keshen area broke 70×10^8 m^3, recording as the major contributors in the Tarim gas region to realize continuous increase of production after the development adjustment of Kela 2 and Dina 2 gas fields.

2.2. Continuous improvement of development adjustment technologies for large gas reservoirs further enhances development effects

During the “13th Five-year Plan”, natural gas development evolves to a stage when production increase and production stabilization are regarded as equally important. Many large gas fields witness their development adjustments, such as Jingbian, Kela 2 and Sebei. For these gas fields, three modes of production stabilization are formed.

2.2.1. Mode of production stabilization by rolling replacement through extension and new discovery

Large lithologic gas reservoirs contain gas in multiple series of strata and have no edge/bottom water, so they are very suitable for progressive development. The Jingbian gas field in the Ordos Basin is just a typical example. This gas field has multiple suites of gas layers in Upper Paleozoic and Lower Paleozoic, with the fifth member of Majiagou Fm (Ma 5 Member), Lower Ordovician, as the major pay zone. With a stable annual production of 55×10^8 m^3 for 13 years, the Jingbian gas field is one of the major contributors to the production stabilization in the Changqing gas region. Key development technologies include thin-layer horizontal well development technology and rich-zone selection & evaluation technology. By virtue of the capillary groove and small amplitude structural depiction, the 2 m thin-layer horizontal well development was achieved to promote an annual productivity construction of 5×10^8−6×10^8 m^3 in surrounding extension zones, making up for the production decline. Meanwhile, further efforts were made to select favorable rich gas zones of Upper Paleozoic, thus helping confirm the reserves of 2441×10^8 m^3, which serve as the main replacement for stable production during the “13th Five-year Plan”. These technologies have supported gas field extension and new discovery, thus ensuring the rolling replacement for production stabilization.

2.2.2. Mode of balanced recovery through index optimization and scale adjustment

For large monolithic massive gas reservoirs with active edge/bottom water, the optimization of gas well index and production scale are essential, so that the edge/bottom water coning can be prevented and the primary recovery ratio of well pattern can be maximized. If the gas production rate is too high, the flooding of some gas wells and heterogeneous water influx of gas reservoir may occur, bringing difficulties to gas field production stabilization. In the Kela 2 gas field, the sparse well high-yield development mode is adopted to achieve a high peak-shaving capacity, with the peak annual production exceeding 110×10^8 m^3, thus enabling the gas field to efficiently secure the supply to the West−East Gas Pipeline. Primarily, through the dynamic analysis of water influx, the judgment mode of water influx in high pressure gas well is

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established, and the dynamic early warning mechanism of water influx through numerical modeling at ten-million nodes is formed. By virtue of the balanced development technology, the gas production rate is further optimized, and the development scale is adjusted. These technologies have helped realize the development index optimization and balanced production of gas field.

2.2.3. Mode of water/sand control and multi-strata coordinated recovery for production stabilization

In the Sebei gas field, a typical loose sandstone gas reservoir, the peak annual gas production reaches 65×10^8 m^3, and the stable production is about 50×10^8 m^3. It is the cornerstone for stable production in the Qinghai gas region. The gas reservoir contains more than a hundred of gas layers in multiple sets of gas−water systems. This reservoir has such features as sand/water production, uneven reserves recovery, and great difficulty in stable production. The separate-strata development technology based on multiple well patterns, and the integrated water and sand control technology are formed. The development of 5 series of strata using the well pattern with the density of 5.1 wells/km^2 has mitigated the disturbance among multiple series of strata and thus promoted the balanced development of gas reservoir. Moreover, the coiled tubing sand washing technique in combination with optimized parameters of fracturing filling sand prevention process has achieved a better sand prevention performance.

2.3. Continuous upgrade of recovery enhancement technology for tight gas reservoir effectively supports scale stable production

The success of Sulige gas field has led the scale development process of tight gas in China [7−9]. So far, over 9000 wells have been put into production, and the annual production is 220×10^8−230×10^8 m^3, accounting for 16% of China's total gas production. During the "13th Five-year Plan" when the stable production period will be welcomed, considering the features of multiple low-yield wells and low recovery ratio (about 30%), two technological series are formed in respect of reserves recovery and gas field recovery enhancement.

2.3.1. Well pattern optimization technology for large-area low-abundance gas reservoir development

Through the depiction of sandbody scale, fracturing sweep scope and gas well drainage radius, well spacing is optimized. On the basis of evaluation of sandbody geometry and in-situ stress orientation, the geometry of well pattern is defined. The economic limit well pattern density for blocks with different abundances is demonstrated. The mixed well pattern with vertical wells in dominance and horizontal wells for centralized main reservoirs is adopted. Through the pilot test in areas with dense well pattern, it is testified that the development benefit of rich zones is still superior to that of non-rich zones. The reasonable recovery sequence of reserves zones with variable grades is demonstrated. It is verified that the recovery ratio increases by 15−20% from 30% under the basic well pattern of 600 m × 800 m to 45−50% after well infilling to 4 wells/km^2.

2.3.2. Supporting technology for recovery enhancement of tight gas reservoir

Based on the geology, gas reservoir engineering and stimulation process, a series of supporting technologies for recovery enhancement of tight gas reservoir are formed. It is specified that the optimization of gas well working system may increase the recovery by 1% [10], the stimulation of unrecovered layers in old well may increase the recovery by 1−2%, the sidetracking to favorable target layers in old well may increase the recovery by 1−2%, and the water drainage gas production in the low yield period may increase the recovery by 2−3%. In other words, the comprehensive supporting technologies for recovery enhancement may increase the recovery by 5−8% based on well pattern optimization.

2.4. Increasingly mature development technologies for shale gas and CBM bring about remarkable production increase and cost reduction

In recent years, the development technologies for marine shale gas above 3500 m are basically mature [11−15], triggering shale gas production to rise rapidly to more than 27×10^8 m^3 in 2016. In addition, CBM production steadily grows. The development technologies for medium and high coal rank are mature, and the low coal rank development achieves breakthroughs for the first time. The main development technologies for these two types of unconventional gas reservoirs are described as follows.

2.4.1. Shale gas development technologies

2.4.1.1. Scale-based shale gas reservoir evaluation technology. Layer division technology is formed for major producing interval. The vertical target scale is refined from dozens of meters to meters and the target position is optimized to Layer $L1_{11}$ in the Lower Silurian Longmaxi strata. Meanwhile, the technology of geological reserves estimation by dynamic reserves is formed. By virtue of this technology, the reserves abundance of producing intervals in the Changning block in the Sichuan Basin is estimated to be about 4.13×10^8 m^3/km^2, and the reserves abundance of Wufeng Fm−L1 Member, Upper Ordovician, is about 12.3×10^8 m^3/km^2. These technologies provide a geological basis for the effective development of shale gas (Fig. 3).

2.4.1.2. Drilling/completion and reservoir stimulation technology for shale gas above 3500 m. Shale gas resources above 3500 m in the Sichuan Basin and its periphery are 2×10^{12} m^3. Through various efforts in the past five years, 233 horizontal wells have been drilled, and the development technologies are basically mature. Such technologies include: optimized and fast drilling technology based on rotary geosteering, volume fracturing technology based on low-viscosity slickwater + low-density proppant, and engineering

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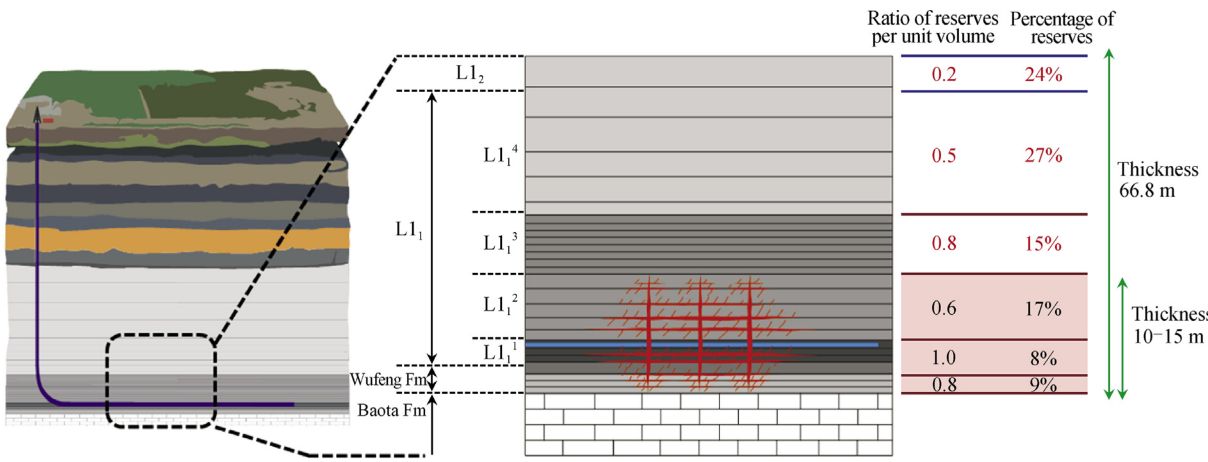

Fig. 3. Stratum structure and layer reserves estimation technology in the Changning block.

technology based on large cluster factory-like operation. By virtue of these technologies, the comprehensive costs per well are reduced to less than CNY55 million, supporting the scale effective development of shale gas.

2.4.1.3. Gas well development index evaluation and production system optimization technology. The multi-level fracture (microfracture + secondary fracture + primary fracture) model is established, the probability productivity prediction method is formed, and several key development indexes are proposed, providing effective guidance to shale gas production. According to the evaluation, the average cumulative shale gas production of single well is 8070×10^4 m^3, the daily production is 6.5×10^4–10×10^4 m^3 in the first year of production, and the initial annual decline rate is 46−62% and then drops to 30% in the first three years. The quantitative description method for fracture and reservoir matrix stress sensitivity is formed to evaluate the cumulative production of single well under the two production modes (bleed-off pressure and managed pressure). The optimal production mode is determined, and it is pointed out that the cumulative production of single well under the managed pressure production mode may increase by more than 30%.

2.4.1.4. Shale gas development well spacing optimization technology. The dynamic prediction method for effective facture length is proposed, and the development well spacing optimization technology based on production interference analysis is formed. According to the research, the well spacing in the Changning−Weiyuan and Zhaotong Blocks may be reduced from current 400−500 m to 300 m, and the recovery percentage of well-controlled reserves may be increased from 25% to about 35%.

2.4.2. CBM development technologies

So far, China has realized medium and high rank CBM development [16,17]. Major mature development technologies include: coal reservoir description technology dominated by geophysical and reservoir evaluation, single well productivity enhancement technology dominated by horizontal well drilling/completion and fracturing stimulation, wellbore drainage and production technology dominated by water drainage gas production and pulverized coal prevention, and development adjustment technology dominated by production profile test and dynamic monitoring. These technologies have boosted the steady development of CBM industry.

Besides, important progress is made in the development technology for low coal rank CBM. For example, by the sand filling and layering together with low-concentration guanidine gum technology, Well JM 4 in the Erlian Basin achieved significant breakthroughs in the low coal rank CBM development for the first time. This is favorable for liberating 6.75×10^{12} m^3 low coal rank CBM resources that account for 51% of total quantities in the licenses of CNPC, and has opened a new field for CBM exploration and development.

2.5. Engineering technology upgrading strongly supports cost reduction and benefit increase

The accelerated natural gas development benefits from progress and development of China's natural gas engineering technology to a large extent. The localization of core technologies and great reduction of costs boost the beneficial development of natural gas. Mainly, the technological series in 3 aspects are formed.

2.5.1. Extensive application of large-cluster − multi-well-type − factory-like drilling technology

In recent years, natural gas development well types evolve from vertical well and cluster well to pad-based horizontal well. So far, natural gas drilling and completion have fundamentally changed to large-cluster factory-like operations, so the drilling period is greatly shortened, the costs are reduced and the efficiency is improved. In the east of Ordos Basin, a typical example of multi-well-type large-cluster stereoscopic development, the 3D detouring, 3D horizontal well track control, low-friction drilling fluid and other supporting

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technologies are developed, and the maximum pad-based well cluster contains 15 wells. By the end of 2016, the multi-well-type large-cluster development technology had been applied in 1200 well clusters, with much land area saved.

2.5.2. New breakthroughs in reservoir stimulation process and equipment

Previously, multi-layer vertical well and multi-stage horizontal well reservoir stimulation treatments were popular. Volume fracturing is a new stimulation technique just emerged in recent years [18,19]. The volume fracturing technology independently developed by China is mature, and has been applied extensively. It combines with the factory-like operation mode to serve as a key option for unconventional low-cost development. Primary techniques include large bore bridge plug staged fracturing and low-viscosity slickwater system, and the supporting techniques include bridge plug pumping and clustering perforation, continuous mixing and continuous sand transportation, and fracturing fluid recycling. In terms of equipment, the soluble bridge plug fracturing technology independently developed by China has reached the international advanced level, and has shifted from technological imitation to technical leading. In 2016, 10 well-times of site tests were conducted, with 141 intervals fractured, suggesting a success rate of 100%.

2.5.3. Gas production technology series suitable for multiple gas reservoir types

Depending on the development characteristics of different types of gas reservoirs, corresponding water drainage gas production technologies are formed [20,21], such as the foam drainage, velocity string, plunger gas lift and other technologies for low-pressure, low-abundance and low-permeability gas reservoirs, the foam drainage and cross-well interconnected gas lift technologies for loose sandstone gas reservoirs, the foam drainage and velocity string technologies for volcanic rock gas reservoirs, and the electric submersible pump drainage gas production technology for old gas fields of Carboniferous in the Sichuan Basin. The test and application of skid-mounted and mobile drainage gas production equipment have proved the flexibility of the equipment and the cost effectiveness.

2.6. Establishment of development decision-making system effectively supports the scientific development of natural gas

With the progress of gas field development, a scientific and perfect development decision-making system for natural gas has been gradually established. Specifically, the key index system for main types of gas reservoirs in different development stages is determined, including gas production per unit pressure drop, production, and recovery percentage, thus providing a basis for the gas reservoir development design (Table 1). The technical solutions are formed for long-term stable production of large gas fields to maximize the overall development benefit of gas fields, so that the main gas fields and satellite gas fields are developed collaboratively. A set of development strategic planning and decision-making support system which is capable of fast evaluation, benefit highlighting and risk control is established, including the multi-scenario gas supply scale analysis model and the lifecycle gas reservoir technical and economic evaluation method, which has effectively supported the strategic planning and decision-making.

3. Challenges to natural gas development

With the deepening of development, influenced by oil price fall, policies, environmental concerns and geological conditions, the proportion of high-quality reserves in gas reservoirs domestically decreases, the gas field development costs go up, the beneficial development of unconventional gas reservoirs becomes more difficult, the upstream benefits are further reduced, the stable production capacity of main gas fields weakens, and the market competition is increasingly fierce. In respect of technology, benefit, management and other aspects, 6 challenges to China's natural gas development are summarized.

3.1. Challenge in growth maintaining due to the reserves−production ratio changes

The ratio of newly-added proved reserves to production in the year decreases from 8 in 2005 to about 5 currently, and the resource guarantee for continuous production increase declines to some extent. In the newly-added reserves, low permeability, tight and other unconventional reserves account for more than 70%, while the proportion of high-quality reserves is too low; the average estimated recovery ratio presents a decline trend. The reserves replacement ratio is the ratio of newly-added proved recoverable reserves in the year to recovered reserves in the current year, and it reflects the reserves replacement capacity. So far, the reserves replacement ratio has decreased from 4.5 to about 2.5, restraining the high-speed growth of production. In the future, China will enter the stable production growth period.

3.2. Challenge in production stabilization due to the weak capacity of main gas fields

According to the features of natural gas resource in China, except a few gas fields that are capable of naturally production stabilization (e.g. Yulin South, and Kela 2), most gas fields need additional production capacity to realize stable production, including Sulige, Jingbian, loose sandstone and volcanic rock gas fields. The Sulige gas field has entered the stable production period, where the total decline rate is about 20% averagely, the annual production is kept stable at 250×10^8 m^3, so measures should be taken to make up for the production of 50×10^8 m^3 declined annually. These bring a challenge to the beneficial stable production. The Sebei gas field, a typical loose sandstone gas field, is challenged by water production and pressure drop. Currently, the decline rate

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Table 1
Quantitative calibration of key development index changing rules of 3 types of gas reservoirs in different development stages.

Type of gas reservoir	Development stages	Production rate	Pressure drop	Recovery percentage of recoverable reserves	Production rate per unit pressure drop
High-pressure gas reservoirs	A	Small	None	/	Stable
	B	Rapid rise	None basically	<10%	Stable
	C	Stable	70−80%	70−80%	Steady decline
	D	20%	80−90%	80−90%	Rapid decline
	E	<20%	>95%	>95%	Decline tends to be stable
Low-permeability- tight gas reservoirs	A	Small	None	<5%	Rise
	B	Staged rise	None basically	<10%	Rise
	C	Stable	40−60%	50−60%	Rise tends to be stable
	D	20%	60−75%	60−70%	Stable
	E	<20%	>80%	>70%	Stable
Pore-fracture gas reservoirs with edge/bottom water	A	Small	/	/	Stable
	B	Rapid rise	<10%	5−10%	Stable
	C	Stable	60%	55−65%	Stable
	D	20%	80%	75−80%	Rise tends to be stable
	E	<20%	85−90%	>80%	Tends to be stable

Note: The development of different types of reservoirs is divided into 5 stages of appraisal (A), construction (B), stable production (C), decline (D), and low yield (E).

of nearly 40% pay zones is greater than 10%, and the total decline rate of all pay zones keeps at about 8% in the past 5 years.

3.3. Challenge in development benefit due to the rising development costs

With the downgrading resource quality and the increasingly difficult development operations, the full costs of natural gas rose by CNY252/10^3 m^3 from CNY631/10^3 m^3 in 2011 to CNY883/10^3 m^3 in 2015. In the same period, the gas price climbed by CNY300/10^3 m^3. Obviously, the profit gains brought by the gas price rise were almost offset by the cost rise. The development history of global resource enterprises shows that the profit growth driven by the price rise was unsustainable. With the technological development and management promotion, the comprehensive cost reduction is an inevitable trend. For example, the comprehensive costs of tight oil in the USA have decreased from USD70/barrel in 2013 to about USD30/barrel presently.

3.4. Challenge in technical benefit in spite of breakthroughs in unconventional gas development

China's unconventional gas development has made considerable progress. However, there is still a great gap with North America in such aspects as drilling/completion and fracturing stimulation technologies, and single-well development performance (Table 2). Before the technical bottlenecks are broken, unconventional gas development is challenged by further reduction of drilling and fracturing periods. At present, CNPC's total investment in shale gas development is about CNY55 million; considering the actual subsidies, the company only achieves marginal benefit. As the subsidies decrease, the beneficial development will be challenged.

3.5. Challenge in upstream benefit due to the uneven natural gas benefit chain distribution

The natural gas benefit chain distribution is uneven and the upstream profit is low. In the Changqing gas region, for example, when the natural gas is produced from the complex tight reservoir with an average burial depth of 3500 m, the average production profit is CNY0.4/m^3; the average profits from downstream transportation of Shaanxi−Beijing Gas Pipeline and from terminal sales of Beijing Gas are CNY 0.35/m^3 and CNY 0.6/m^3, respectively. In the gas price of downstream industrial users, the gas distribution fees of provincial network and urban pipe network account for 40−50%, and the terminal sales enterprise's profits are higher than the profits of the natural gas production and transportation sector. In the short term, CNPC will still focus on cost control and benefit increase. In the middle and long term, CNPC will procure the national policies for profit splitting among production, transportation and sales, in order to maintain a proper share of upstream in the total benefit chain.

3.6. Challenge in market competition due to the diversification of natural gas supply sources

The natural gas supply sources are diversified. In respect of international sources, imported pipeline gas and LNG are powerful competitors against the domestic gas. The signing of multiple long-term trade contracts guarantees the long-term stable supply of imported pipeline gas, and the price advantage of imported LNG poses a challenge to the supply of domestic gas. BDI decreases from more than 10000 in the peak period to about 1000, and the transportation costs of LNG are greatly reduced. In respect of domestic sources, the natural gas industrial pattern of diversified competition among central enterprises, local enterprises and private enterprises is

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Table 2
Development parameters of representative shale gas wells from China and the USA.

Block	Full length of wellbore/m	Horizontal section length/m	Number of fracturing stages	Fracturing progress/(stages·d^{-1})	Drilling time/days	Fracturing time/days	Single well EUR/10^8 m^3
Purple Hayes 1H (the longest horizontal well in the USA)	8244	5652	124	5.3	17.6	23.5	6.8–9.0
CNPC block	4747	1520	18	2.0–3.0	81.0	10.0	0.5–1.5

formed. Local governments positively participate in the activity, and their LNG terminals dominate the layout of purchase and sales integration. Private enterprises are more flexible. Among the gas regions throughout the country, the Sichuan gas region is a high-end market which suffers from the least impact by LNG, but domestically the diversified producers and sufficient production form competition (total planned production is 620 × 10^8 m^3, market size is about 500 × 10^8 m^3).

4. Prospects of natural gas development

Based on the natural gas development course and situations in China and abroad, the prospects of natural gas development in China are analyzed in four aspects, i.e. production, demand, import and future position of natural gas.

4.1. Natural gas production grows rapidly with both conventional and unconventional gas being equally important

China's total natural gas production was 1371 × 10^8 m^3 in 2016 and is expected to be 1800 × 10^8 m^3 in 2020 and 2520 × 10^8 m^3 in 2030. The natural gas industry in China will enter the stage when conventional and unconventional gas are simultaneously promoted, and will present a trend of stable development of conventional gas, long-term stable production of tight gas, rapid production of shale gas, and steady advancement of CBM. The conventional gas production was 918 × 10^8 m^3 in 2016, and is estimated to be 1115 × 10^8 m^3 in 2020 and 1300 × 10^8 m^3 in 2030. The unconventional gas production was 453 × 10^8 m^3 in 2016 and is estimated to be 685 × 10^8 m^3 in 2020 and 1220 × 10^8 m^3 in 2030, in which shale gas will be the major contributor.

4.1.1. Stable development of conventional gas

The development of conventional gas from 2017 to 2020 should be fully carried out based on new area breakthrough, production increase of gas fields under construction, and stable production of existing gas fields. Typically, in the Tarim gas region, the additional production of the Keshen–Dabei gas fields and Kuqa piedmont new zone is estimated to be 50 × 10^8 m^3 in 2020; in the Sichuan gas region, the additional production of Sinian formations in central Sichuan, high sulfur formations in northeastern Sichuan and marine formations in western Sichuan is estimated to be 120 × 10^8 m^3 in 2020, and that of deep sea areas is estimated to be 30 × 10^8 m^3 in 2020. From 2020 to 2030, most of existing conventional gas fields will enter a decline period, when the newly discovered gas fields are poor in quality, and the newly-constructed production capacity is mainly used to offset the decline. The production will grow slowly to 1300 × 10^8 m^3 in 2030.

4.1.2. Long-term stable production of tight gas

In the Ordos Basin, by virtue of production increase in the periphery of the Sulige gas field and the new zones in Shenmu gas field and the east of the basin, it is estimated that tight gas production will increase from 330 × 10^8 m^3 in 2016 to 360 × 10^8 m^3 in 2020, and will grow slowly to 400 × 10^8 m^3 during 2020–2030 driven by the new zones. The periphery of Sulige gas field mainly covers the rolling extension in the east and south, where the additional production will be 8 × 10^8 m^3 in 2020. In the Shenmu gas field and the east of the Ordos Basin, the designed production in Phase I and Phase II is 18 × 10^8 m^3, and it is estimated that the production will be 35 × 10^8 m^3 in 2020, including additional production of 24 × 10^8 m^3.

4.1.3. Rapid production of shale gas

By virtue of breakthroughs in deep strata, China's shale gas will witness a leapfrog development. In the Sichuan Basin and its periphery, the marine shale gas resources above 3500 m are 2 × 10^{12} m^3, the available working area is 3500 km^2, and 220 × 10^8–260 × 10^8 m^3 production can be realized in 2020; the marine shale gas resources in 3500–4500 m are 10 × 10^{12} m^3, the available working area is 20000 km^2, and the output may rise to 600 × 10^8–800 × 10^8 m^3 in 2030 once the technical and benefit breakthroughs are made.

4.1.4. Steady advancement of CBM

CBM is dominated by medium and high coal rank, and its production is expected to increase from 44 × 10^8 m^3 in 2016 to 75 × 10^8 m^3 in 2020. Typically, in 3 areas of CNPC, namely, Qinnan, East Hubei and Junlian in the south of Sichuan, 40 × 10^8 m^3 production may be realized in 2020; in the blocks of other companies, the production may increase from 28 × 10^8 m^3 in 2016 to 35 × 10^8 m^3 in 2020. Some low coal rank blocks like the Erlian Basin, Jixi, and Baijiahai are expected to achieve scale breakthroughs, boosting CBM production to 120 × 10^8 m^3 in 2030.

4.2. Natural gas demand is strong and the consumption structure is diversified

According to Shell's prediction, the annual demand for natural gas in the world will grow from 3.1 × 10^{12} m^3 in 2010 to 5 × 10^{12} m^3 by 2030, and the trans-regional trade volume will grow to about 1.3 × 10^{12} m^3; Asia will witness a fastest growth of natural gas demand. In the new normal when China's economic growth undergoes a “gear shift”, and the resource and environmental constraints tend to be tighter, energy transformation and consumption revolution will further stimulate natural gas demand. It is estimated that domestic natural gas demand will be 3000×10^8 m^3 in 2020 and 5220×10^8 m^3 in 2030. Compared with the developed countries, China's gas consumption in industry, power generation and households will maintain a low proportion. In the future, the natural gas consumption structure will be diversified. Facilitated by the energy saving and emission reduction policy, the coal replacement by gas in power generation and industry will be accelerated, and then gas is expected to become the dominant energy. Along with the urbanization, urban gas consumption will stably grow. Driven by urbanization and price advantage, natural gas is still prospective for transportation. It is estimated that in China's natural gas consumption, power generation, industry, urban gas and transportation will share 24.5%, 32.0%, 26.4% and 16.3% respectively by 2020, and 30.0%, 25.6%, 20.2% and 15.0% respectively by 2030.

4.3. Natural gas import rises, and external dependence increases

With the development of national economy, the gap between production and demand of domestic natural gas is larger and larger. In the background of loose global energy market supply and demand, the imported pipeline gas and imported LNG are faced with new opportunities. The long-term trade contracts guarantee the long-term stable supply of imported pipeline gas. The rapid development of imported LNG facilitates the scale intercontinental trade of natural gas, and further narrows the price spread among the three largest consumer markets in the world. The imported gas includes pipeline gas from Central Asia and imported LNG at Guangdong Dapeng and Fujian. It is estimated that the import volume of natural gas in China will be 1200×10^8 m^3 in 2020, with the external dependence reaching 40%, and about 2700×10^8 m^3 in 2030, with the external dependence reaching more than 50%.

4.4. Natural gas will become a main growth contributor in the energy structure adjustment

In the global energy mix in 2016, coal, oil and gas shared a relatively balanced proportion, being 28.1%, 33.3% and 24.1% respectively. However, in China's energy mix, coal was still a leader with its proportion of 61.8%. As a clean energy with the highest potential, natural gas is a main force for energy transformation. In recent years, natural gas demand has improved and developed rapidly; its proportion in the energy mix rises to 6.2%, but it is far lower than the world average. As per the *Strategic Action Plan (2014–2020) for Energy Development* of the General Office of the State Council, and the *13*th *Five-year Plan for Natural Gas Development* of the National Development and Reform Commission, the proportion of natural gas in the primary energy consumption of China will be 10% by 2020.

5. Conclusions

In the background that the government robustly advocates low-carbon and green energy, natural gas development business is positively promoted according to the philosophy of “quality, benefit, and sustainability”. During the “13th Five-year Plan”, according to the new changes in the development object and gas field development stage, remarkable technological progress has been made in such aspects as deep natural gas reservoir development technology, large gas field development adjustment technology, tight gas recovery enhancement technology, shale gas and CBM development technology, engineering technology and development decision-making system. As a result, the innovation capacity is constantly promoted, and natural gas production stably grows.

With the deepening of development, influenced by oil price fall, policies, environment concerns and geological conditions, continuous efficient natural gas development will be faced with such challenges as lower ratio of quality reserves of domestic gas field, higher gas field development expenses, more difficult benefit development of unconventional gas reservoirs, further reduced upstream benefits, less stable production capacity of those main gas fields, and increasingly fierce competition in the energy market.

In the future, China will enter a development stage of attaching equal importance to conventional gas and unconventional gas. It is estimated that China's natural gas production will be 2520×10^8 m^3 in 2030, of which the conventional gas accounts for 51.6% and the unconventional gas accounts for 48.4%. Natural gas demand will be continuously strong, and the diversified consumption structure in which power generation gas, industrial fuel gas, urban gas and transportation gas act as main bodies will be presented. The gap between production and demand of domestic natural gas constantly expands, the imported gas volume persistently rises, and the dependence on imported natural gas continuously increases. The vigorously growing natural gas industry is the main force to promote national energy structure transformation.

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