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Shale gas potential in China: A production forecast of the Wufeng-Longmaxi Formation and implications for future development

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ABSTRACT

Developing the abundant shale gas in China is a potential means to address the country's challenges in air pollution and carbon emissions. The purpose of this paper is to evaluate the production potential of the most promising shale gas play—the Wufeng-Longmaxi Formation (WL) in China. We use a Difference-Index analogy method and well-level U.S. shale gas drilling data to estimate the production potential and use a scenario simulation method to propose optimal drilling plans. The results show that the Wufeng-Longmaxi Formation has the potential to produce 70 billion cubic meters of natural gas per year (Bcm/yr), which is 60% of the gas imported into China in 2018. With technology improvement and drilling of more wells, the target of 80–100 Bcm/yr set by the government can be achieved solely by extraction from WL. We find that shale gas drilling is profitable with a well-head price of 1.5 Chinese Yuan per cubic meter. The study indicates that a shale gas boom in China is possible, depending on a more competitive market both upstream and downstream. The successful development of shale gas will change the country's energy mix to become cleaner and lower-carbon.

1. Introduction

China has been facing two-fold challenges from air pollution and climate change, primarily due to the dominance of coal in its energy mix. In 2018, China's coal consumption accounted for 51% of global coal consumption, and around 60% of domestic primary energy consumption (BP, 2019). A national transition to clean and renewable energy sources, such as solar, wind, and hydrogen energy, will be the fundamental solution to these challenges. But in the short to medium term, such a complete transition is unlikely to happen due to technological difficulties and high economic costs. Instead, using natural gas—a cleaner and less carbon-intensive fuel—to replace coal can substantially reduce the emissions of air pollutants and CO_2 (Jaramillo et al., 2007; Qin et al., 2018).

China consumed 283 billion cubic meters (Bcm) of natural gas in 2018, which was 7% of the country's primary energy consumption. The fraction was much lower than that in the United States (31%) and the European Union (23%) in the same period (BP, 2019). China has made plans to increase the natural gas fraction to 10% by 2020 and 15% by 2030 (NDRC, 2017). However, the plans have been challenged by the shortage of domestic gas supply (Hou et al., 2018; Liu, 2010), high gas prices, and concerns about over-dependence on imported natural gas. All the challenges could be alleviated if China could replicate the shale gas boom in the United States, as China has abundant shale gas resources. Therefore, shale gas development in China has received much attention since 2010. But the development pace in the last decade has not been as fast as expected, which leads to a pessimistic view about the future of shale gas. A scientific evaluation of China's shale gas production potential based on newly available data is important for China's energy policy in the next decade. However, such analysis is rare, and there are very few peer-reviewed publications.

This study aims to assess the potential role of shale gas in China's future energy structure, by estimating the production potential of shale gas from the Wufeng-Longmaxi (WL) Formation, one of the most promising shale gas plays in China. We introduce the background and status of China's shale gas development and conduct a brief literature review in section 2; describe our methodologies, namely the Difference-Index analogy and scenario simulation methods, in section 3; and present the results in section 4. We discuss the feasibility of the recommended development plan and compare the shale gas exploitation economics and policies in China and the United States in section 5, and provide conclusions and policy implications in section 6. We find that

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the WL Formation has the potential to produce 70 Bcm natural gas per year, which could replace 60% of China's gas imports as of 2018. Further, the development of more shale gas plays could meet a substantial portion of the national gas demand.

2. Background and literature review

2.1. Shale gas development in China

China's shale gas development started much later than that in the United States. Shale gas was formally discovered in 2009 in the Longmaxi Formation (China Geological Survey, 2015) and was listed as the 172nd independent mineral by the former Ministry of Land and Resources (MLR) in 2011 (Ministry of Land and Resources, 2011b), which was transformed into the Ministry of Natural Resources in 2018. Using the benchmark of 2011, shale gas development in China can be divided into two stages: the prospecting stage of 2004–2010 and the exploration and development stage from 2011 until now.

2.1.1. The prospecting stage: 2004–2010

Following the technical breakthrough of shale gas development in the Barnett Formation in the United States in the early 2000s, some institutions and companies started to investigate the shale gas resources in China. The MLR studied shale gas development in the world since 2004, and conducted a preliminary geological evaluation of possible shale gas basins. MLR drilled the first exploration well in 2009 into the shale gas formation Longmaxi, and declared the discovery of shale gas in China (China Geological Survey, 2015). From 2009 to 2012, MLR organized a full evaluation of the nation-wide shale gas resources and selected favorable areas (Ministry of Land and Resources, 2012).

China National Petroleum Corporation (CNPC) started its shale gas survey in 2005, and drilled its first shale gas appraisal well in 2009 (CNPC, 2015). China Petrochemical Corporation (Sinopec) conducted shale gas evaluation from 2006 to 2010, and drilled the first wildcat well in 2010 (Jin, 2015; Shen, 2011).

The main work in this period was learning from the U.S. shale gas development experience, appraising China's shale gas plays, and drilling exploration wells. The work provided a basis for the next stage in the development of shale gas.

2.1.2. The exploration and development stage: 2011-present

There were two milestone events in 2011: the first-round shale gas exploration block tender (Ministry of Land and Recourses, 2011a) and the formal recognition of shale gas as an independent mineral (Ministry of Land and Resources, 2011b). These events were the prelude to formal shale gas development in China, and were followed by the second-round shale gas tender of 20 blocks (Ministry of Land and Recourses, 2012) and the publication of the *Shale Gas Development Plan for 2011–2015* (NDRC et al., 2012). The main work at this stage includes continuous exploration of shale gas resources, further confirmation of the reserves, development in favorable areas, and mastering the key technologies.

By the end of 2018, China had drilled a total of 1,682 shale gas wells, including 667 exploration wells and 1,015 development wells (Table 1). The fraction of development wells increased from about 30% in 2013 to 88% in 2018, coupled with the increase of shale gas production from 0.2 Bcm to 10.9 Bcm (Fig. 1). Shale gas accounted for 6.7% of domestic natural gas production in 2018 (domestic natural gas production data from (BP, 2019)). Most of the shale gas is from the WL Formation in the Sichuan Basin and is produced by CNPC and Sinopec.

By 2016, operators had mastered the technology of drilling reservoirs shallower than 3,500 m (National Energy Administration, 2016), and afterward carried out successful experiments to drill deeper formations (Ministry of Natural Resources, 2019b; National Energy Administration, 2019a). Key indicators of shale gas development have been improved substantially with advances in operators' knowledge. From around 2012 to 2017, the average well-level initial production

Table 1
Summary statistics of the status of shale gas development in China.

Year	E&P Investment	Exploration Well	Development Well	Production	Value[c]
	10^9 CNY			10^9 m^3	10^9 CNY
2018[d]	13.5	40	285	10.9	16.3
2017[d]	9.3	34	106	9	13.5
2016[d]	8.8	50	92	7.9	11.8
2015[d]	13.5	108	187	4.5	6.7
2014[b]	8	236	259	1.3	2
Before[a] 2013	15	199	86	0.2	0.3
Total	68	667	1015	33.8	50.6

[a] Cumulative data as of the end of 2013 (Liu, 2014).
[b] Data for 2014 is computed by subtracting the cumulative data in 2013 (Liu, 2014) from the cumulative data in 2014 (China Geological Survey, 2015).
[c] The value is calculated assuming a natural gas price of 1.5 Chinese yuan (CNY) per cubic meter. All monetary values are in nominal currency.
[d] Data on exploration and development (E&P) investment (column 2), number of exploration wells (column 3), number of development wells (column 4) and annual production (column 5) for 2015–2018 are from the annual government report series *The National Circular on Exploration and Exploitation of Petroleum and Natural Gas Resources*. The link to the 2018 report is in Ministry of Natural Resources (2019a). Reports for 2015–2017 could be found with similar titles.

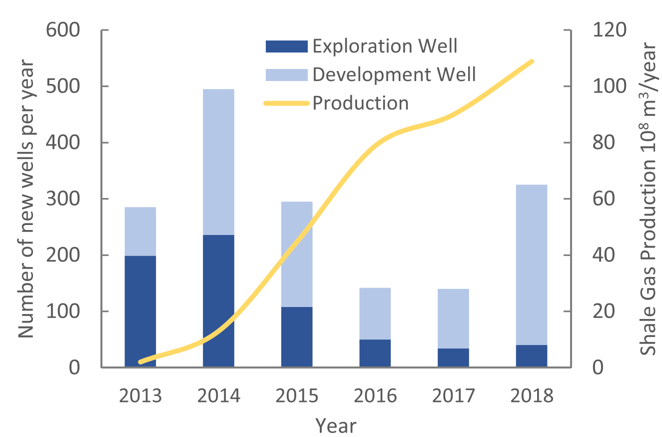

Fig. 1. The annual new exploration and development shale gas wells, and the annual shale gas production from 2013 to 2018 in China. See the notes of Table 1 for data sources.

(IPGD) increased from 109 thousand cubic meters per day (Mcm/d) to 263 Mcm/d in the Changning block in Sichuan Province, and from 116 Mcm/d to 200 Mcm/d in the Weiyuan block in the same province (Ma and Xie, 2018; National Energy Administration, 2019b). The estimated ultimate recovery (EUR) per well varies from 40 million cubic meters (MMcm) to 154 MMcm (Liang et al., 2018; Ma and Xie, 2018). The average horizontal length of shale gas wells was around 1,500 m by 2018 (Liang et al., 2018; National Energy Administration, 2019a), close to the U.S. average perforation interval in 2013 (Chen and Xu, 2019). The average horizontal length, as well as the IPGD of China's shale gas wells, is expected to continue to increase with advances in drilling and completion technology.

The investment in shale gas exploration and production (E&P) by the end of 2018 was about 68 billion Chinese Yuan (CNY). Based on the benchmark city gate gas price and transportation price recently published by NDRC (2019a, 2019b), we assume a wellhead price of 1.5 CNY per cubic meter (CNY/m^3) and estimate that the gross revenue was 50.6 billion CNY for the produced shale gas (Table 1). Although the total gross revenue was lower than the investment, the annual gross revenue became higher than the E&P investment after 2016.

2.2. Resource and distribution

The technical recoverable reserve (TRR) of China's shale gas was estimated to be 31.6 Tcm by EIA (2013), 25.1 Tcm by MLR (2012), and 21.8 Tcm by the Ministry of Natural Resources (2018), compared to 33 Tcm in the United States (EIA, 2013). The TRR is ranked in the top three in the world even with the lowest estimated value (EIA, 2013). Shale gas exists in about 30 sedimentary basins and geologic units, with the Sichuan Basin containing 26% of the total TRR, the Ordos Basin containing 11%, and the Central Guizhou uplift containing 7% (China Geological Survey, 2015). So far, all three commercially developed shale gas fields are in the Sichuan Basin (Dong et al., 2018), but high-productivity exploration wells are reported in the central Yangzi area and the Ordos Basin (Ministry of Land and Resources, 2017).

In terms of geological formation, the most promising shale gas play is the Wufeng-Longmaxi Formation deposited in the Yangtze Sea (Chen et al., 2004) around 447-438 million years ago (Chen et al., 2015; Ma and Xie, 2018). The formation contains organic-rich black shales up to 80 m and is widely distributed in South China (Chen et al., 2015; Zhang et al., 2015a,b). The second promising shale gas play is the Lower Cambrian (about 520 Ma) Niutitang/Qiongzhusi/Shuijingtuo Formation deposited in a deep-water shelf environment in South China (Zhao et al., 2019). Most exploration wells in this formation did not show high gas flows (China Geological Survey, 2015), which may be caused by poor gas preservation conditions due to strong tectonic movements (Li et al., 2020; Yu et al., 2018). But the E'Yiye-1 and E'Yangye-1 wells in Hubei province showed high gas flows of more than 100 Mcm/d (China Geological Survey, 2018, 2017). Therefore, sweet spots do exist in less-deformed areas like the slope of the paleo- Huangling uplift in western Hubei province and should be the next-stage exploration targets (China Geological Survey, 2017; Wang et al., 2018).

In North China, shale gas was discovered in the Lower Permian (272–299 Ma) Shanxi Formation and Taiyuan Formation and the Triassic Yanchang Formation (Wang, 2018; Zhang et al., 2018). The shale in these formations was deposited in lakes, delta, or river environments (Wang et al., 2014; Xiao et al., 2008). Drilling results showed that the IPGD of wells in the Shanxi Formation in the Ordos basin was about 20–53 Mcm/d (Yanchang Petroleum, 2018) and, in the Yanchang Formation, IPGD was 8 Mcm/d (Li and Zhang, 2019). The productivity of shale gas plays in North China is much lower than in South China. However, the Yanchang Formation has some natural gas liquid and belongs to the wet gas reservoir (Li and Zhang, 2019). It also has shallower depth, and therefore, lower development cost. Development in this play may still be economically promising. The shale gas reserve in Northwest China is estimated to be comparable to that in the south (Zhang et al., 2009). But its E&P is still in an infant stage.

In summary, China has large shale gas reserves and has made substantial achievements in developing shale gas in the past decade. The drilling and fracking technology has been improved continuously through experimentation. The well productivity has increased substantially. However, the commercial development of shale gas is still confined to the Wufeng-Longmaxi Formation in the Sichuan Basin and the total production is low. Since there are multiple developed shale gas plays in the United States and most of them were deposited in marine environments, it is possible to select one shale gas play that has similar geological conditions to the marine-deposited WL Formation, and forecast WL's shale gas production using the U.S. analog.

2.3. The production potential estimates

China's total shale gas production reached 11 Bcm in 2018 (Ministry of Natural Resources, 2019a). But the production is only 3.8% of the 283 Bcm natural gas consumption in 2018 (BP, 2019). NDRC et al. (2012) set the goal of producing 60-100 Bcm shale gas per year by 2020, which was adjusted to 30 Bcm by the National Energy Administration (2016). The production target in 2030 was 80–100 Bcm/yr (National Energy Administration, 2016), consistent with the forecast by EIA (2017a), which predicted shale gas production of 100 Bcm/yr by 2030 and 200 Bcm/yr by 2040. Industry companies seem to be more conservative. Zou et al. (2018) estimated shale gas production of 15–20 Bcm/yr by 2020, which would reach 45 Bcm/yr by 2030 and 60 Bcm/yr by 2050. CNPC (2019) forecasted shale gas production of 65 Bcm in 2035. With all this divergence, we believe that our detailed evaluation of the production potential based on newly available data will provide a more sound basis for China's shale gas policymaking.

3. Methods and data

We use the analogy method to predict the shale gas production potential of the Wufeng-Longmaxi Formation and use the simulation method to forecast production profiles under different drilling scenarios.

3.1. Analogy methods

Analogy methods have been widely used in resource estimation for oil and gas fields with limited information and short production history (Chen et al., 2012; SPE et al., 2018). EIA (2013) used the U.S. analogs to help estimate shale gas resources in other countries. Yue et al. (2017) used the analogy method to estimate China's shale gas resource and reported a reserve of 16.3 Tcm. Besides the estimation of resource volume, it can also be used to forecast production profiles (SPE et al., 2018). In this study, we forecast shale gas production profile and capacity of the Wufeng-Longmaxi Formation using U.S. analogous shale gas plays.

The first step is to select an analog for the target shale gas play. Traditional methods involve a semi-qualitative comparison of the key geological and reservoir characteristics and use the most similar one as an analog (Yue et al., 2017; Zhang et al., 2014). A major disadvantage of this method is that it does not have a clear numeric comparison standard and often leads to ambiguous results. Taking the Wufeng-Longmaxi Formation for example, EIA (2013) used the Marcellus shale as the analog, Zhang et al. (2015a) identified the Ohio and Woodford shales based on mineral contents, and Ma and Xie (2018) thought that the Haynesville and Utica shales are the most analogous plays according to geological conditions. This disparity shows that using a single or a few characteristics cannot fully reflect the similarity between reservoirs, and the qualitative selection method without a numeric standard is hard to replicate.

We develop a new method by constructing a Difference Index that integrates the differences in each characteristic, using a weighted average computation. Table 2 shows the key characteristics of five U.S. shale plays (Barnett, Eagle Ford, Marcellus, Haynesville, Fayetteville) and the Wufeng-Longmaxi Formation in China. The weight of each characteristic is determined according to its relative importance in gas generation and production potential (based on previous studies and our resource evaluation experience, and reflected by the score value) (Jarvie, 2012; Zagorski et al., 2012). Specifically, the thickness, TOC (total organic carbon), area, and porosity determine the volume of shale gas resources in a play. The age and Ro (vitrinite reflectance) are related to the maturity of hydrocarbons. The depth and pressure gradient are closely related to gas-in-place (Zagorski et al., 2012) and well productivity (Karthikeyan et al., 2018). The amount of brittle mineral is related to reservoir engineering properties when fractured and also related to the productivity of a play. The technical recoverable reserve is a direct estimate of how much gas can be produced using existing technology. The EUR is a direct measure of how much shale gas can be produced in a well's lifetime. The depth of a reservoir is partially correlated with the drilling cost. The score values are normalized to unity to get the weights (Table 2).

The difference index for each play is computed using the following equation:

Table 2
Key characteristics and the computed Difference Index for major shale gas plays.

Shale Play	Barnett	Eagle Ford	Marcellus	Haynesville	Fayetteville	Wufeng-Longmaxi	Weight	Score
Absolute Age/Ma	330[a]	95[e]	390[h]	155[j]	330[m]	440[q]	0.03	5
Depth/m	2200[b]	3600[f]	2000[b]	3600[b]	1200[b]	3500[r]	0.05	10
Pressure Gradient kPa/m	11.8[u]	19.9[v]	12.4[w]	19.2[x]	10.0[y]	16.5[z]	0.08	15
Thickness/m	90[b]	60[f]	40[b]	80[b]	35[b]	50[r]	0.15	30
Ro%[†]	1.5[c]	1.6[g]	1.5[h]	1.6[k]	2.5[n]	2.5[s]	0.05	10
TOC[‡] wt%	4[d]	4.25[b]	12[b]	2.25[b]	6.9[b]	2.5[s]	0.10	20
Brittle Mineral %	75[d]	80[g]	65[i]	60[j]	70[p]	59[s]	0.05	10
Porosity %	5[b]	9[b]	8[b]	8.5[b]	5[b]	6[r]	0.08	15
Area 10^4m^3	1.7[b]	0.3[b]	25[b]	2.3[b]	2.3[b]	2[r]	0.15	30
Technical Reserve $10^{12}m^3$	1.2[b]	0.6[b]	11.6[b]	2.1[b]	0.9[b]	2.0[r]	0.10	20
EUR[§]/well 10^8m^3	0.4[b]	1.4[b]	0.7[b]	1.0[b]	0.5[b]	1.0[r,t]	0.15	30
Difference Index	43	48	283	**22**	48			

Notes. a (Abouelresh and Slatt, 2012); b (EIA, 2011); c (Lewan and Pawlewicz, 2017); d (Loucks and Ruppel, 2007); e (Minisini et al., 2017); f (EIA, 2014); g (Chalmers and Bustin, 2017); h (EIA, 2017b); i (G. Wang et al., 2014a); j (Hammes et al., 2011); k (Nunn, 2010); m (Handford, 1986); n (EIA, 2010); p (Bai et al., 2013); q (Chen et al., 2015); r (Ma and Xie, 2018); s (Zhang et al., 2015b); t (Liang et al., 2018); u (Bowker, 2007); v (Gherabati et al., 2016); w (Zagorski et al., 2012); x (Wang et al., 2013); y (Jarvie, 2012); z (Guan et al., 2015).

† vitrinite reflectance in oil.

‡ total organic carbon.

§ estimated ultimate recovery.

$$DI = \sum_{i=1}^{n} \frac{\left|c_i^a - c_i^t\right|}{c_i^t} w_i \tag{1}$$

where DI is the difference index for a potential analog play; c_i^a is the value of characteristic i for the potential analog play a; c_i^t is the value of the characteristic i for the target play t; w_i is the weight for characteristic i; n is the total number of characteristics. The value of DI provides a quantitative and comprehensive measure of the relative difference between two shale gas plays in terms of their reservoir characteristics. A smaller DI indicates more similarities between two plays. The play with the lowest DI (the Haynesville play in our case) is selected as the analog for the Wufeng-Longmaxi Formation.

The second step is to calculate the realized drilling and production profiles for the analog play (here, the Haynesville play) and the target play. We use the "approximate string match" method to select well-level drilling and production data of the Haynesville play from Drillinginfo's database (Drillinginfo, 2017). The method can ensure that all wells from the same reservoir are included (Chen and Xu, 2019). We include only gas-producing wells and exclude utility wells, injection wells, and observation wells. We process the raw data by excluding wells having a spud date later than the first production date, wells missing spud and first production date, and wells with workover history. The final dataset

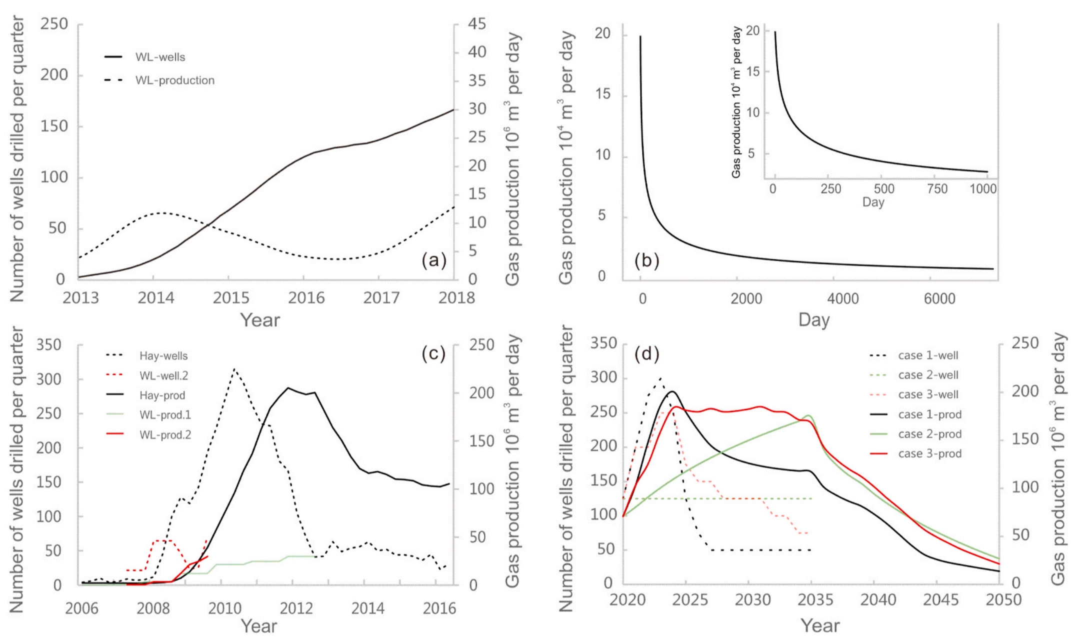

Fig. 2. (a) The production and drilling history of the Wufeng-Longmaxi Formation. "WL-wells" is the quarterly number of new wells. "WL-production" is the average daily production in a year. (b) The synthetic type curve for a WL shale gas well assuming an initial production of 200 Mcm/d, and a decline rate of 0.041. The insert is an enlargement of the production in the first 1000 days. (c) The production and drilling history of the Haynesville shale gas play, and the horizontally moved WL drilling and production profiles. "Hay-wells" represents the quarterly number of new wells of the Haynesville play; "Hay-prod" is the average daily gas production in a quarter; "WL-prod.1" is the horizontally moved production profile of the WL Formation; "WL-prod.2" is the compressed and horizontally moved production profile of WL. "WL-well.2" is the compressed drilling profile corresponding to "WL-prod.2". (d) Synthetic drilling and production profiles for different scenarios. "case 1-well" and "case 1-prod" are the drilling and production profiles to simulate the Haynesville production in the WL Formation. "case 2-well" simulates the CNPC forecast assuming an annual drilling of 500 wells, and "case 2-prod" simulates the corresponding production. "case 3-well" and "case 3-prod" are our recommended drilling and production profiles.

contains 3,956 gas wells drilled between January 2000 and June 2016, with 3,550 horizontal wells, 115 directional wells, and 291 vertical wells. The average IPGD is 218 Mcm/d, and the average perforated interval is 1,313 m. We then compute the number of wells drilled in a quarter and the quarterly average IPGD, perforation and measured depth (Fig. 2c, Fig. 3a). The quarterly IPGD profiles of the Barnett and Marcellus shale plays and the average of eight shale gas plays in the United States are also computed using the same method (Fig. 3a). We calculate the quarterly production profile of the Haynesville play using the play-level dry gas production data from EIA (2018). The original monthly production data is averaged to obtain quarterly data (Fig. 2c).

For the Wufeng-Longmaxi Formation, we divide the annual total well number (exploration and development, Table 1) by four to obtain an average quarterly well number in order to match that in the analog play. We also divide the annual production data (Table 1) by 365 to match the daily production data in the analog play. After establishing the profiles, comparative studies are conducted to estimate the production potential of the target play. We match the production and drilling profiles of the target play to that of the analog play by moving the horizontal axis such that the kick-off points are overlapped. We compress the horizontal axis of the target play so that its profile matches the analog's (Fig. 2c).

3.2. Simulation methods

Using an average production decline curve and the number of wells drilled each year, we can simulate the production profiles of different drilling plans.

Firstly, we need a type curve for shale gas wells in the Wufeng-Longmaxi Formation. Due to the lack of well-level production data, we are unable to calculate an average production profile for China's typical shale gas wells. Instead, we use the modified Duong (2010) decline analysis method and the fitted parameters on shale gas wells in the Sichuan Basin (Li et al., 2019) to synthesize a type curve. The modified Duong decline analysis method by Li et al. (2019) is expressed in equation (2):

$$q(t) = q_1 t^{-\lambda^* \ln(t)} \quad (2)$$

where $q(t)$ is the gas production rate at time t; q_1 is the initial production (IP); t is the days since the first production; and λ is the decline rate specific to a reservoir. The average initial production (IP) has increased from around 100 Mcm/d to 260 Mcm/d in Sichuan Province (Ma and Xie, 2018). About 3.2% of wells produce over one million cubic meters per day (MMcm/d) and 68% of wells produce more than 200 Mcm/d in Chongqing (Liang et al., 2018). The average IP of new wells drilled in 2018 is 200 Mcm/d in the Weiyuan block and 250 Mcm/d in the Changning block (National Energy Administration, 2019b). Therefore, we assume an average initial production of 200 Mcm/d as a conservative estimate for the type curve. The λ value varies from 0.027 to 0.051 according to Li et al. (2019) and shows a larger variation when more wells are analyzed (Wang et al., 2020). After discussion with the author of the two studies, we selected the value of 0.041 reported in Li et al. (2019) to calculate the base-case production type curve for 20 years. We also run a sensitivity analysis for λ values of 0.031 and 0.051 to test the influence on production (see Section 4.2). The daily production data of the type well is added to obtain the annual production profile for a 20-year lifetime, which is used to model the total production profiles of different drilling plans.

The second step is to build a simulation model and establish various drilling plans according to different purposes. We set up a drilling period of 16 years, and simulate production profiles over 31 years. All drilling plans are assumed to start in 2020 and end in 2035, which can be moved forward according to reality. The corresponding production profiles will move synchronically with the drilling plans. We then conduct a sensitivity analysis to examine the influence of different type curves and gas prices on the drilling plan and production profiles. A detailed description of the scenarios is included in Section 4.

4. Results

4.1. Production potential of the Wufeng-Longmaxi Formation

Following the method in Section 3.1, we calculate the Difference Index (DI) value for five major shale gas plays in the United States (Table 2). The DI value varies from 22 in Haynesville to 283 in

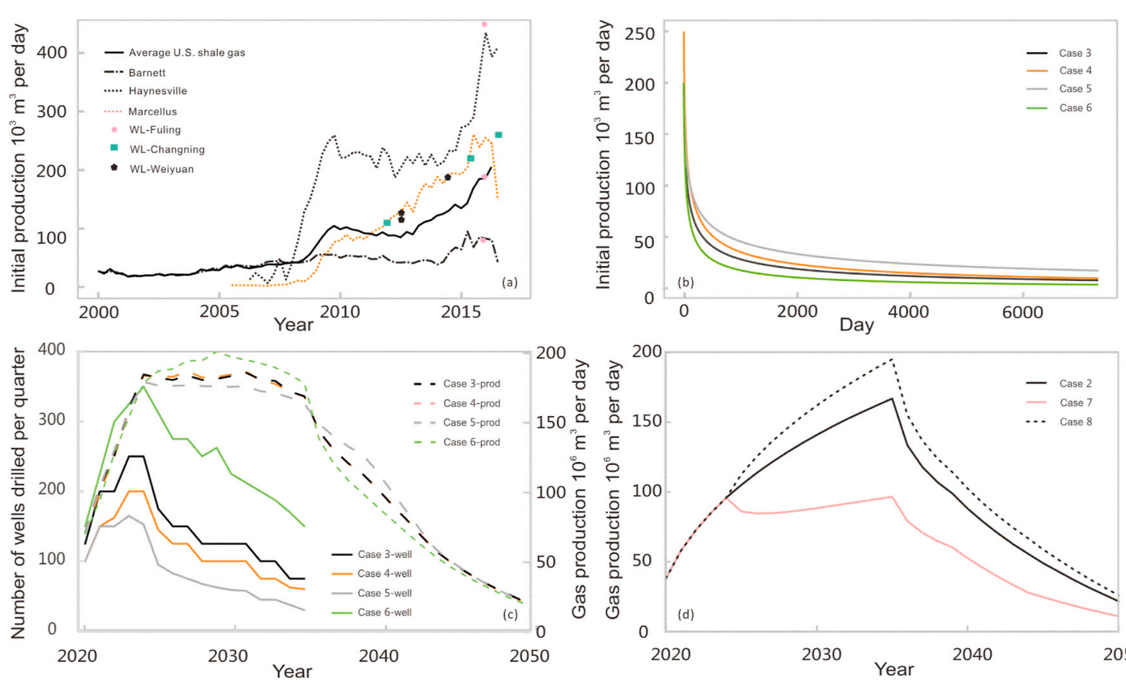

Fig. 3. (a) The average initial production of new wells for U.S. shale gas plays and some Wufeng-Longmaxi blocks; (b) The synthetic production type curves for WL shale gas wells using different initial production and decline rate values. (c) The production and drilling profiles using different production curves as shown in (b); (d) Simulated production profiles for different gas prices and drilling plans show in Table 3.

Marcellus, which indicates that Haynesville is the most similar shale gas play to the Wufeng-Longmaxi Formation. Therefore, we choose the Haynesville play as the analog for the Wufeng-Longmaxi Formation.

The number of new wells drilled in the Wufeng-Longmaxi Formation reached the first peak in 2014 with about 65 wells per quarter, declined to 23 in 2016, and increased back to 71 in 2018 (Fig. 2a). Despite the wavy drilling curve, shale gas production from the WL Formation increased continuously to 30 MMcm/d in 2018. The number of new wells drilled in the Haynesville play was low before 2008, generally less than 10 wells per quarter (Fig. 2c). It increased sharply to 315 wells per quarter in mid-2010, then plunged quickly to 50 per quarter in 2012 and maintained that level in the following 3–4 years. The fast increase of production started in 2009, reflecting about a one-year lag of the increase in drilling activity. Total gas production increased from 14 MMcm/d in early 2009 to 205 MMcm/d in later 2011. Following the plunge in drilling activity, the production also has declined since 2012 (Fig. 2c).

If we move the horizontal axis of the WL profiles such that the starting point of the fast increase in production overlaps with the Haynesville profiles (the green line in Fig. 2c), we find that to increase production from 10 to 30 MMcm/d, WL's speed was about one-fifth of the rate in Haynesville. We then synthesize a production profile by compressing the horizontal axis of the WL curve so that it traces that of Haynesville (the red line in Fig. 2c). The corresponding drilling curves show that the number of new wells drilled in WL is much lower than the number of wells drilled in the Haynesville play since mid-2008 (Fig. 2c). This explains why the shale gas production in China did not increase as fast as that in the Haynesville analog.

Fig. 2b plots the synthesized production decline curve for shale gas wells drilled in the Wufeng-Longmaxi Formation using the method in Section 3.2. The production declines 76% in the first year and 83% in the first two years. The 20-year total recovery is 134 MMcm of natural gas per well.

We designed three drilling plans for our simulation. The first plan matches the drilling and production history of the analog play (case 1 "Hay match" in Table 3). The second plan simulates the production profile of CNPC (2019), which predicts shale gas production of 65 Bcm in 2035 by drilling an average of 500 wells per year through 2035 (case 2 "CNPC" in Table 3). The third plan maintains a plateau production of approximately 65 Bcm/yr for about 10 years by adjusting the number of wells drilled in each year (case 3 "recommend" in Table 3). Because the shale gas production in 2018 was 10.9 Bcm (Table 1), we assume a history production of 12 Bcm in 2020 for all three cases. In all three scenarios, the drilling activities stop after 2035 and the production follows a natural decline thereafter. Cases 4–8 in Table 3 are used to evaluate the impacts of different type curves (cases 4, 5, 6) and gas prices (cases 7 and 8) on shale gas supply, which are discussed in Section 4.2.

Fig. 2d shows the drilling plans and the corresponding production profiles computed using the simulation model in Section 3.2. Case 1 (the Haynesville-match case) shows that peak production of 200 MMcm/d natural gas can be reached with a similar drilling plan as that of Haynesville. The shape of the WL production profile before 2035 is also similar to that of Haynesville before 2017, indicating that the potential of WL in total gas supply is close to that of Haynesville. Case 2 shows the drilling plan of CNPC (2019) and the simulated production profile. The total production increases gradually from 70 MMcm/d (26 Bcm/yr) in 2020 to 174 MMcm/d (64 Bcm/yr) in 2035, which is consistent with the forecast by CNPC (2019). In neither case does production remain at a plateau of stable production for a relatively long time. Since basic infrastructure and surface facilities need to be constructed according to the maximum production volume (e.g., the size of pipelines and the capacity of processing units), a short period of peak production would be a waste of infrastructure and facilities. Therefore, we design the drilling plan in case 3 to maintain a plateau production of approximately 180 MMcm/d (65 Bcm/yr) for ten years.

The total number of wells drilled in cases 1–3 is 7200, 8000, and 9400, which leads to a total production of 960 Bcm, 1058 Bcm, and 1251 Bcm of natural gas in 2020–2050 (Table 4). The drilling and completion cost has decreased from 130 million CNY to 50 million CNY in CNPC's shale gas fields (Ma and Xie, 2018). The total E&P investment in 2018 is 13.5 billion CNY, covering 40 exploration wells and 285 development wells, which indicates an average cost of less than 50 million CNY (Table 1). To do a simple cost-benefit analysis, we assume a drilling and completion cost (CAPEX) of 50 million CNY per well, a nominal gas price of 1.5 CNY/m^3, a nominal unit operation cost (OPEX) of 0.35 CNY/m^3 (Liu et al., 2019), and a 3% discount rate. The results show that the gross profit is more than 500 billion CNY in all three cases (Table 4). Although our cost-benefit analysis does not consider other factors such as taxes, variation in gas prices, and variation in development cost, the large gross profit values still indicate a high chance of profitability. Besides, the environmental benefits of using shale gas to replace coal will further increase its advantages.

4.2. Robustness and sensitivity analysis

Factors influencing the prediction of shale gas production include the selection of analogous shale gas plays, the simulation of production type curves, and the changes in gas price.

Our new method of selecting the analog depends on the weights of

Table 3
The drilling plans in different cases.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Year	Hay match	CNPC	Recommend	IP 250	λ 0.03	λ 0.05	Price 50% lower	Price 20% higher
2020	500	500	500	400	400	600	500	500
2021	800	500	800	600	600	900	500	500
2022	1100	500	800	650	600	1200	500	500
2023	1200	500	1000	800	660	1300	500	500
2024	1000	500	1000	800	610	1400	500	500
2025	500	500	700	580	380	1250	250	600
2026	300	500	600	500	330	1100	250	600
2027	200	500	600	500	300	1100	250	600
2028	200	500	500	400	270	1000	250	600
2029	200	500	500	400	250	1050	250	600
2030	200	500	500	400	235	900	250	600
2031	200	500	500	400	230	850	250	600
2032	200	500	400	300	180	800	250	600
2033	200	500	400	300	180	750	250	600
2034	200	500	300	250	150	680	250	600
2035	200	500	300	240	120	600	250	600
Total	7200	8000	9400	7520	5495	15480	5250	9100

Table 4
Cost-benefit analysis of various drilling plans.

Scenario	Case 1	Case 2	Case 3
	Hay-match	CNPC	Proposed
Well number	7200	8000	9400
Initial production (10^3 m^3/d)	200	200	200
Decline rate (λ)	0.041	0.041	0.041
EUR[3]/well (10^6 m^3)	134	134	134
Total CAPEX* (10^9 CNY)	314	323	394
Total OPEX† (10^9 CNY)	250	256	314
Total production (10^9 m^3)	960	1058	1251
Nominal Gas price (CNY/m^3)	1.5	1.5	1.5
Unit OPEX (CNY/m^3)	0.35	0.35	0.35
Breakeven cost‡ (CNY/m^3)	0.59	0.55	0.57
Lifecycle average price** (CNY/m^3)	1.12	1.04	1.07
Gross revenue (10^9 CNY)	1073	1099	1344
Gross profit (10^9 CNY)	508	519	636

Note: CNY: Chinese Yuan.
*Total capital expenditure (present value) assuming a nominal drilling and completion cost of 50 million CNY per well and a 3% discount rate.
†Total operation cost (present value) assuming a nominal unit operation cost (OPEX) of 0.35 CNY/m^3 of natural gas produced and a 3% discount rate.
‡Breakeven cost = (Total CAPEX + Total OPEX)/Total production.
**Lifecycle average price = Gross revenue/Total production.

key characteristics in calculating the difference index. The calculation of weights is based on the relative importance—reflected by the score value—of each characteristic that lacks a quantitative standard and is dependent on personal experience. We test the robustness of weights assignment by changing the score of one characteristic at a time and compute the new DI for all shale gas plays. Table 5 shows that up to a 100% change in the score of a characteristic leads to less than a 10% change in the Haynesville DI values and that the Haynesville play has the smallest DI (i.e., the most representative match) in all scenarios. Therefore, our method of selecting the analogous shale gas play is robust to the change in weights allocation.

The production decline curve determines how much natural gas can be recovered from a well. The initial production and the decline rate are two major factors influencing the production curve (Equation (2)). Therefore, we vary the initial production and decline rate to generate different type curves and redo the simulations to analyze their sensitivity. In general, the average initial production of new wells in the United States increases with time (Fig. 3a), which is mainly caused by advances in drilling and completion technology. In addition, the variation of initial production among shale gas plays is substantial. Haynesville has higher than average initial production, whereas the Barnett shale has lower than average initial production. The difference among shale gas plays is determined by their innate geological conditions. Fig. 3a also shows that the initial production of the Wufeng-Longmaxi Formation is similar to that of Marcellus and Haynesville. The average initial gas production of the Haynesville wells varies between 180 and 260 Mcm/d in 2009–2014 (Fig. 3a). The National Energy Administration (2019a) reported an average initial production of 250 Mcm/d in the Changning block of new wells drilled in 2018. Therefore, reaching an average initial production of 250 Mcm/d in the WL Formation is possible; this is 25% higher than the value used in the base type curve computation.

We designed four cases to simulate different type curves. Case 3 (200 Mcm/d, 0.041) is the base case; case 4 (250 Mcm/d, 0.041) increases the initial production by 25%; case 5 (200 Mcm/d, 0.031) decreases the decline rate λ by 25%; and case 6 increases λ by 25%. Table 6 and Fig. 3 present the simulation results using different type curves while keeping the same total production and similar production profiles. The results show that a 25% increase in the initial production (from 200 to 250 Mcm/d) leads to a 25% increase in the EUR (from 134 to 168 MMcm), a 20% decrease in the total number of wells and drilling cost, and a 12% increase in the gross profit (case 4, Table 6). The change in decline rate has a higher influence than the change of initial production. A 25% decrease in the λ value can increase the EUR by 71%, which leads to about a 40% decrease in the number of wells and drilling costs (case 5). Similarly, the increase of λ leads to a 40% decrease in EUR and more than a 60% increase in the number of wells and drilling cost (case 6).

The third factor influencing drilling activity and production is natural gas prices. Chen and Xu (2019) reported a price elasticity of 1.0 for drilling activities in the U.S. dry shale gas plays in 2009–2016. We use this result to establish different price scenarios and analyze their influence on shale gas supply (Table 6). Case 2 assumes no price change and drilling of 500 wells per year in 2020–2035. It is used as the base case for our price sensitivity analysis. Case 7 assumes a 50% drop in gas price in 2024, which results in a 50% drop in new well drilling starting in 2025. Case 8 assumes a 20% one-time increase in gas price in 2024 and therefore a 20% increase in drilling since 2025.

Fig. 3d shows the production profiles simulated using the base production type curve and the drilling plans in Table 3. In all scenarios, the total production declines once the drilling stops. In case 7, the drilling declines by 50% starting in 2025, but the production declines only 18% in 2025 and 42% in 2035. Case 7 also shows that a 50% decline in drilling activity can maintain a production plateau as long as the drilling activity continues. In case 8, the drilling increases by 20% starting in 2025, but the production increases only 7% in 2025 and 17% in 2035. Cost-benefit analysis shows that the gross revenue decreases by 66% in case 7 and increases by 35% in case 8, while the gross profit shows an even larger variation (Table 6). The gross profit becomes negative when the gas price drops to 0.75 CNY/m^3 (case 7). The simulation results indicate that, although gas prices have an influence less than unity on shale gas production, they have an impact higher than unity on gross revenue and profit.

5. Discussion

5.1. *Feasibility of the recommended plan*

In our recommended development plan (case 3), annual production

Table 5
Robustness analysis of the influence of weights on the DI values.

Difference Index	Barnett	Eagle Ford	Marcellus	Haynesville	Fayetteville	Change of score
Base case	43	48	283	22	48	score in Table 2
Age	43	49	276	23	47	5 to 10
Depth	43	46	271	21	48	10 to 20
Pressure Gradient	42	46	265	21	47	15 to 30
Thickness	41	50	297	19	48	30 to 20
Ro	44	49	289	21	49	10 to 5
TOC	44	49	288	21	54	20 to 30
Brittle Mineral	43	48	270	21	46	10 to 20
Porosity	42	48	265	23	45	15 to 30
Area	45	46	236	22	49	30 to 20
Technical Reserve	44	47	272	22	47	20 to 10
EUR	43	49	297	23	47	30 to 20

Table 6
Sensitivity analysis on production decline curve parameters and price.

Scenario	Case 4		Case 5		Case 6		Case 7		Case 8	
	IP 250	Δ%[1]	λ 0.03	Δ%	λ 0.05	Δ%	Price 50% lower	Δ%	Price 20% higher	Δ%
Well number	7520	−20	5495	−42	15480	65	5250	−34	9100	14
Initial production (10^3 m^3/d)	250	25	200	0	200	0	200	0	200	0
Decline rate (λ)	0	0	0	−24	0	24	0	0	0	0
EUR^3/well (10^6 m^3)	168	25	229	71	81	−40	134	0	134	0
Total CAPEX* (10^9 CNY)	315	−20	236	−40	636	61	221	−32	365	13
Total OPEX† (10^9 CNY)	314	0	312	−1	316	1	175	−32	289	13
Total production (10^9 m^3)	1251	0	1251	0	1251	0	697	−34	1203	14
Nominal Gas price (CNY/m^3)	1.50	0	1.50	0	1.50	0	0.75	−50	1.80	20
Unit OPEX (CNY/m^3)	0.35	0	0.35	0	0.35	0	0.35	0	0.35	0
Breakeven cost‡ (CNY/m^3)	0.50	−11	0.44	−23	0.76	34	0.57	4	0.54	−1
Lifecycle average price** (CNY/m^3)	1.07	0	1.07	−1	1.08	1	0.54	−48	1.24	19
Gross revenue (10^9 CNY)	1344	0	1337	−1	1353	1	376	−66	1486	35
Gross profit (10^9 CNY)	715	12	789	24	401	−37	−20	−104	832	60

Note: CNY: Chinese Yuan.
*Total capital expenditure (present value) assuming a nominal drilling and completion cost of 50 million CNY per well and a 3% discount rate.
†Total operation cost (present value) assuming a nominal unit operation cost (OPEX) of 0.35 CNY/m^3 of natural gas produced and a 3% discount rate.
‡Breakeven cost = (Total CAPEX + Total OPEX)/Total production.
**Lifecycle average price = Gross revenue/Total production.
[1] Δ% is the percentage change of values relative to the results in cases 2 and 3 (Table 4). Cases 4–6 compare with case 3, and cases 7 and 8 compare with case 2.

of 61–68 Bcm can be maintained for 12 years and a total of 1.3 Tcm natural gas can be produced in about thirty years from the Wufeng-Longmaxi Formation. The realization of this production goal is based on several important foundations and the most important one is the resource foundation in WL: there needs to be enough natural gas underground to support the development plan. Dong et al. (2018) estimated a reserve of 4.5 Tcm natural gas in the parts of WL in the Sichuan Basin that are shallower than 4500 m. EIA (2013) estimated a reserve of 8.1 Tcm in the Longmaxi Formation in the Sichuan Basin. Both estimates are much higher than the total production of 1.3 Tcm natural gas in case 3. Therefore, the reserve foundation of the WL Formation is enough to support the recommended development plan. Since the reserve of WL accounts for only about 20% of China's total shale gas reserve, if other shale gas plays are developed in the future, shale gas can play an important role in China's primary energy mix.

The second important condition is the drilling and completion ability of shale gas companies. Developing shale gas needs to drill long horizontal wells and to fracture them properly, which requires qualified crews and special equipment. The number of rigs in CNPC's shale gas fields increased from 38 in 2017 to 133 in 2018 (CNPC, 2018), and was around 140 in 2019 (personal information from CNPC). Sinopec deployed 28 rigs in the Fuling gas field in 2019 (SINOPEC, 2019) and its service company even had the ability to lease 55 rigs to CNPC for shale gas drilling (SSC, 2020). Currently, there are about 170 rigs in the shale gas fields in China. Since the average drilling period has decreased from 89 days in 2013–2018 to 56 days in 2019 (Sun et al., 2020), if we assume a drilling period of 60 days and 80 days respectively, the 170 rigs can drill about 1,020 wells and 770 wells per year correspondingly. Therefore, the drilling plan of 500, 800, 800 wells in the first three years (Table 3, Case 3) is largely achievable with the current drilling rigs. The highest drilling rate in case 3 is 1000 wells per year in the fourth and fifth year (Table 3), which is also achievable with the existing rigs and the state-of-art drilling efficiency (i.e., 60 days drilling period). Because the rig efficiency will continue to improve (SINOPEC, 2020), and the number of qualified rigs can increase too, the drilling rate of 1000 wells per year has a high probability to be reached in the next five years. Experienced rig teams can be deployed to other unconventional gas fields after the peak drilling time in the WL Formation.

The third factor is the economics of shale gas development. An uneconomic project is a waste of resources and is not sustainable. Our cost-benefit analysis shows that the recommended development plan has a positive gross revenue of 636 billion CNY with a 3% discount rate and 1.5 CNY/m^3 gas price (Table 4). The average pipeline gas price delivered to Hubei province was 2.2 CNY/m^3 in 2015–2019 (SHPGX, 2020a), and the average imported LNG price was 2.41 CNY/m^3 in 2019 (SHPGX, 2020b). The cost of shale gas is much lower than the price of imported LNG. Therefore, unless the development cost increased substantially at a drilling rate of 1000 wells per year, which is not likely to occur, the recommended development plan is cost-effective and competitive compared with imported natural gas.

We also compared the cost of shale gas drilling and gas prices in China and the United States. The drilling and completion cost of a shale gas well decreased from 50–70 million CNY (1 U.S. Dollar = 7 CNY) in 2012 to 40–50 million CNY in 2015 (EIA, 2016), which is close to the 50 million CNY cost in China in 2018 (see Section 4.1 for details). The overall breakeven cost in Haynesville was 1–1.5 CNY/m^3 around 2010 (Kaiser, 2012) and the average Henry Hub spot gas price in 2008–2011 was about 1.3 CNY/m^3 in the United States (EIA, 2020). From 2008 to 2011, about 3000 wells were drilled in the Haynesville play. With comparable development costs but higher gas prices, the profit of developing shale gas in China should be higher than that in the United States.

In addition to economic benefits, developing shale gas will improve China's energy security. Replacing coal with cleaner and less carbon-intensive natural gas and renewable energies is a world-wide trend. The increasing amount of solar and wind power requires more natural gas power stations to ensure system integrity given their fast start and end ability. Therefore, the demand for natural gas will continue to increase in China. Imported natural gas has increased to 43% of the total consumption in 2018 (BP, 2019). The trade war between China and the U.S. has increased the uncertainty of world energy trade, which may lead to an abrupt decrease in gas supply or an increase in gas prices. Under these circumstances, the development of shale gas would be more beneficial.

The peak production rate in Case 3 is 68 Bcm/yr, which is lower than the National Energy Administration's (2016) planned production of 80–100 Bcm/yr by 2030. However, if we shorten the plateau period, or improve well productivity, it is still possible to reach 80-100 Bcm/yr by 2030. The simulated production profile is an estimation of the shale gas potential in WL, which depends on the extent and timing of executing the drilling plan. Although our analysis shows that the recommended development plan is feasible, the actual situation is more complex and the real production profile may deviate from the simulated results.

5.2. Comparison of the policies between China and the United States

The U.S. experience indicates that a real shale gas boom comes after the development of multiple shale plays (Chen and Xu, 2019). Therefore, expanding shale gas development technology to other shale gas plays is crucial for China's shale gas boom. We compared market conditions and governmental policies related to shale gas development in the United States and China (Table 7). Both countries have governmental support for research and development (R&D) in the early stage. They also have incentive pricing policies, subsidies, and tax reduction. However, there are substantial differences between the two countries. The first important difference is that the market structure in China is oligopolistic, while it is competitive in the United States. The oligopoly structure results in a limited number of national oil companies (NOCs), which control most of the oil and gas resources in China, as well as the technology and human resources. The second difference is that China does not have a mature oil service market, which makes it more difficult for new entrants to develop shale gas. Third, in China, the NOCs conduct their own research and control the key technologies for shale gas development, and are not likely to transfer the fruits of their R&D to others. This is different from the situation in the United States, where government-supported institutes provide technical guidance. The above differences make it difficult for new companies to enter the shale gas development sector in China; they explain the failure of the second-round shale gas tendering companies. The lack of enough participants and competition will limit the chances of discovery as well as the expansion of shale gas development in other plays. However, China has begun to conduct market-oriented reforms in the oil and gas sectors. CNPC opened its shale gas drilling market to private oil service companies and Sinopec's service company in 2018 (CNPC, 2018). The recent establishment of an independent pipeline company (SASAC, 2019) will help more competitors enter the upstream gas sector and thus will promote shale gas development in China.

Table 7
Shale gas related policy and market conditions in China and the United States.

	China	United States
R&D	Conducted by NOCs; uneasy to marketize[a]	Government institutes & companies; easy to marketize[b]
Incentive pricing	Yes, no ceiling price[c]	Yes, no ceiling price[d]
Subsidy	[e]2012–2015:0.4 CNY/m^3; 2016–2018: 0.3 CNY/m^3; 2019–2020: 0.2 CNY/m^3	[f]0.13 CNY/m^3
Tax	2018–2021: 30% reduction of resource tax[g]	Yes, tax reduction on tangible drilling cost, intangible drilling cost, and depletion cost; small producer tax exemption[h]
Mineral rights	Government	Private
Market structure	Oligopoly	Competitive
Oil service	NOCs have strong service ability	Service market well developed

Notes.
[a] (China Geological Survey, 2015).
[b] (National Energy Technology Laboratory (NETL), 2007).
[c] (NDRC, 2019a).
[d] (95th Congress, 1978).
[e] (Ministry of Finance and NEA, 2015, 2012).
[f] (Joint committee on taxation, 1981), 1979 US dollars, 1 U.S. Dollar = 7 CNY.
[g] (Ministry of Finance and State Taxation Administration, 2018).
[h] (Lazzari, 2008).

6. Conclusions and policy implications

This study uses the analogy and simulation methods to forecast shale gas production from the Wufeng-Longmaxi Formation in China. We show that the WL Formation has the potential to produce 70 Bcm of natural gas per year, equal to about 60% of China's natural gas imports in 2018. This can play an important role in China's future energy mix. The analysis indicates that China's shale gas development is comparable to the pilot stage of 2000–2008 in the United States. Expansion to more shale gas plays and extensive drilling will be crucial to substantially increasing production, and these in turn will depend in part on increased competition in the upstream oil and gas market.

Our study has three major policy implications. First, shale gas provides a means for China to achieve both natural gas independence and an energy structure that is lower in carbon emissions than its current reliance on coal. Therefore, policies encouraging shale gas development should be adopted. Creating a more open and competitive gas market, both upstream and downstream, is crucial. Allowing more companies to enter the gas industry and bid for gas fields, and fostering a mature gas service market, will leverage more resources in the public and private sectors, promote the diffusion of technologies, and greatly accelerate shale gas development. The recent reform initiatives aimed at opening up the oil and gas upstream market (Ministry of Natural Resources, 2019c) and the establishment of an independent pipeline company (SASAC, 2019) are two major steps toward building a competitive market. However, since the oil and gas industry is capital- and technology-intensive, these competitive markets will take time to grow. Developing shale gas in the near term may still rely on CNPC and SINOPEC, but in the long run, it will depend on institutional and market settings that can provide the right incentives to all players.

Second, shale gas development in China is financially viable, and, with increasing EUR and decreasing extraction costs over time, it can provide robust and substantial long-term returns for investors. Our simple cost-benefit analysis shows that drilling shale gas can be profitable with a well-head price of 1.5 CNY/m^3. We believe that this conclusion will still hold even if other important factors, such as changing gas prices and development costs, taxes, and inflation, are considered. Adding environmental benefits would enhance the benefit-cost ratio of shale gas development. Future studies that focus on drilling rig capacity, detailed economic modeling, and life-cycle environmental costs and benefits compared with other energy types (coal, solar, wind) will certainly be needed.

Third, natural gas related infrastructure planning should consider the possibility of a shale gas boom. The planning of LNG-import facilities in China should consider a possible shock from a shale gas boom to avoid wasting LNG-regasification facilities, as occurred in the United States. Planners should also be cautious in the construction of costly coal-fired power plants, because they would not compete with gas-fired power plants under a shale gas boom, which would lead to a lower gas price and more gas supply.

CRediT authorship contribution statement

Yan Chen: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. **Jintao Xu:** Conceptualization, Resources, Writing - review & editing, Supervision, Funding acquisition. **Pu Wang:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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