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Analysis of resource potential for China's unconventional gas and forecast for its long-term production growth

Jianliang Wang [a], Steve Mohr [b], Lianyong Feng [a], Huihui Liu [c,*], Gail E. Tverberg [d]

[a] *School of Business Administration, China University of Petroleum, Beijing, China*
[b] *Institute for Sustainable Futures, University of Technology Sydney, Sydney, Australia*
[c] *Academy of Chinese Energy Strategy, China University of Petroleum, Beijing, China*
[d] *Our Finite World, 1246 Shiloh Trail East NW, Kennesaw, GA 30144, USA*

HIGHLIGHTS

- A comprehensive investigation on China's unconventional gas resources is presented.
- China's unconventional gas production is forecast under different scenarios.
- Unconventional gas production will increase rapidly in high scenario.
- Achieving the projected production in high scenario faces many challenges.
- The increase of China's unconventional gas production cannot solve its gas shortage.

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ABSTRACT

China is vigorously promoting the development of its unconventional gas resources because natural gas is viewed as a lower-carbon energy source and because China has relatively little conventional natural gas supply. In this paper, we first evaluate how much unconventional gas might be available based on an analysis of technically recoverable resources for three types of unconventional gas resources: shale gas, coalbed methane and tight gas. We then develop three alternative scenarios of how this extraction might proceed, using the Geologic Resources Supply Demand Model. Based on our analysis, the medium scenario, which we would consider to be our best estimate, shows a resource peak of 176.1 billion cubic meters (bcm) in 2068. Depending on economic conditions and advance in extraction techniques, production could vary greatly from this. If economic conditions are adverse, unconventional natural gas production could perhaps be as low as 70.1 bcm, peaking in 2021. Under the extremely optimistic assumption that all of the resources that appear to be technologically available can actually be recovered, unconventional production could amount to as much as 469.7 bcm, with peak production in 2069. Even if this high scenario is achieved, China's total gas production will only be sufficient to meet China's lowest demand forecast. If production instead matches our best estimate, significant amounts of natural gas imports are likely to be needed.

1. Introduction

China's role as a major manufacturing country leads to a growing need for energy resources. In fact, in 2010, China surpassed the US as the world's largest energy consumer (BP, 2014). One concern is the high carbon nature of China's current energy mix. In 2013, China consumed 2852.4 million tonnes oil equivalent (Mtoe) primary energy, 67.5% of which was from coal (BP, 2014). In contrast, low carbon energy sources, such as gas and non-fossil fuels, only hold a marginal proportion (in 2013, gas: 5.1%; non-fossil fuels: 9.6%) (BP, 2014).

The substantial use of coal has resulted in serious environmental issues, including significant CO_2 emissions and record levels of haze pollution in a number of major Chinese cities. In 2012, China's total CO_2 emissions were 2625.7 Million tonnes C (MtC), 72.6% of which were from coal (CDICA, 2014). As the world's largest CO_2 emitter, the Chinese government has declared that by 2020, it intends to cut CO_2 emissions per unit of GDP by 40–45% relative to the 2005 level (J.L. Wang et al., 2013). Furthermore,

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* Corresponding author.
E-mail addresses: wangjianliang305@163.com (J. Wang), steve.mohr@uts.edu.au (S. Mohr), fenglyenergy@163.com (L. Feng), liuhui639@163.com (H. Liu), gail.tverberg@gmail.com (G.E. Tverberg).

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severe haze pollution has brought widespread attention to environmental issues (Wang, 2013). In response, Chinese Premier Li Keqiang declared a “war on pollution” in March 2014 (Yan, 2014). The State Council of China (2013) also released *Atmospheric Pollution Prevention Action Plan* in 2013 to deal with haze pollution.

In these plans, one of the key measures is to reduce the proportion of coal in China’s energy mix by replacing part of China’s coal use with energy sources that have lower carbon content and lower pollution potential. Natural gas fits well with these objectives. Reducing the proportion of coal and increasing the proportion of gas in the structure of energy consumption are also key policies in China’s “12th Five Year Plan” (2011–2015) and “13th Five Year Plan” (2016–2020) (CASS, 2013). Therefore, it is reasonable to expect that natural gas demand will increase rapidly in the future.

In 2013, a total of 161.6 billion cubic meters (bcm) of natural gas were consumed in China (BP, 2014). This figure is forecast to reach 260 bcm in 2015, 375 bcm in 2020, and 620 bcm in 2035 (J.L. Wang et al., 2013; CASS, 2013). Even considering the lower forecast by the International Energy Agency (IEA), China’s gas demand in 2035 will also reach 529 bcm (IEA, 2013).

China’s domestic production of natural gas has been growing very rapidly, but its consumption has been growing even faster. Between 2003 and 2013, China’s natural gas production grew at an annual rate of 12.8% per year, increasing from 35.0 bcm to 117.1 bcm, while its consumption grew by 16.8% in the same period, increasing from 33.9 bcm to 161.6 bcm. Both of these rates are far higher than the world’s rate of growth in natural gas consumption in the same period of 2.6% (BP, 2014). In 2013, China imported a total of 44.6 bcm gas to offset a domestic natural gas shortage, implying import dependence of 27.6% (BP, 2014).

With respect to future gas production, a number of recent studies have shown that China’s conventional gas production is likely to peak in the near future (J.L. Wang et al., 2013; EWG, 2013; Lin and Wang, 2012; IEA, 2011; EIA, 2013). Furthermore, most studies suggest that the peak year will be around 2020 (EWG, 2013; Lin and Wang, 2012; IEA, 2011). One study even indicates that China’s conventional gas production may peak and then decline immediately (EIA, 2013). Given the growing gap between China’s natural gas consumption and its production, and the forecasts for slowing production growth or decline in the near future, authorities are hopeful that unconventional natural gas can close the gap. One reason for the interest in unconventional gas is United States’ recent success with shale gas, a form of unconventional gas.

Recently, many studies have focused on Chinese unconventional gas resources. These studies usually limit their analyses to general concepts, types of formations, characteristics, resource potential, and technology of unconventional gas resources (Zou et al., 2012a, 2013; Song et al., 2012). While these reports often give resource estimates, their results tend to differ sharply, so relying on any one study is fraught with risks. Until now, there has been no literature explaining the differences, and no attempt to provide a range of estimates of unconventional natural gas production potential. For production modeling, there is only one peer-reviewed analysis of the long-term production potential of China’s unconventional gas resources, namely a study by Wang and Lin (2014). One problem with this study is that its resource statistics are incomplete and not up to date. Furthermore, the model they use for forecasting, the logistic model, is not suitable because inadequate data is available regarding historical production. Thus, there is a need for further research regarding the China’s expected long-term production of unconventional gas resources.

The purpose of this paper is to develop a broad understanding of China’s unconventional gas production in the past, its prospects for production in the future, and the likelihood that China can meet its own natural gas needs in the future, based on these estimates. We do this by first providing a comprehensive and systematic investigation of China’s unconventional gas resources, based on research performed by others. We then use these resource estimates to provide a range of estimates of the potential growth in long-term unconventional gas production including a low estimate based on current proven reserves, a medium estimate which we consider our “best estimate,” and a high estimate, providing a reasonable upper bound for future production. We next use these indications, together with estimates of conventional natural gas production, to estimate the shortfall in China’s gas production relative to expected demand. We also use our indications as a basis for recommendations regarding governmental policy affecting future unconventional natural gas production. Needless to say, this paper far exceeds any previous paper regarding China’s unconventional gas in the breadth of its analysis.

2. Resources and reserves

In this paper, we analyze three types of unconventional gas: shale gas, coalbed methane (CBM) and tight gas. We also considered including a fourth type of unconventional gas, methane hydrate, but based on our analysis decided to exclude it. While the size of this resource seems to very large, and some countries with very low domestic resources of conventional fossil fuels, such as Japan, are even implementing ambitious projects to develop this type of unconventional gas (BGR, 2013), potentially insurmountable technical and economic issues exist, and no breakthrough has yet been achieved (BGR, 2013; Collett, 2002). Because of these issues, the contribution of this resource to energy supply is expected to be negligible in the 21st century (Rogner, 1997; IIASA, 2012), so there appears to be no reason to include it.

In the next three sections, we summarize our findings regarding resources and reserves for the three types of unconventional gas: shale gas, coalbed methane, and tight gas. Note that we have only used data from three types of sources: (a) Chinese authorities, such as Ministry of Land Resources of China (MLR) and Ministry of Geology and Mineral Resources of China (MGMR); (b) mainstream international or national institutes, such as U.S. Energy Information Administration (EIA) and Federal Institute for Geosciences and Natural Resources of Germany (BGR), and (c) peer-reviewed scientific literature. We use this approach because the quality of the resource and reserve data is very important for our subsequent projection and these data sources tend to be more reliable compared to others. It is beyond the scope of this paper to perform our own resource and reserve evaluations.

2.1. Shale gas

Table 1 summarizes indications with respect to shale gas resources in China. Prior to 2008, there were few studies focusing on Chinese shale gas resources. In 1997, Rogner made an assessment of world hydrocarbon resources, and estimated that total Gas-in-Place (GIP) in Central Asia & China was 100 Tcm (Rogner, 1997). In 2002, Curtis presented a primary study of Chinese shale gas resources and showed that GIP was only 15–30 Tcm, which was significantly lower than Rogner’s estimate (Ning et al., 2009). Neither Rogner’s nor Curtis’s study estimates the portion of GIP that is technically recoverable resource (TRR).

After 2008, many Chinese scholars and institutes began analyzing the resource potential of China’s shale gas. Table 1 indicates that estimates of GIP of Chinese shale gas resources range from10.4 Tcm to 166.0 Tcm (average value: 84.7 Tcm). TRR estimates, which are far more important than GIP for estimating future production, range from 4.0 Tcm to 45.0 Tcm (average value:

Table 1
Statistics of China's shale gas resources.

Institutes/Scholars	Year	GIP [Tcm]	TRR [Tcm]	References
Rogner	1997	100[a]		Rogner (1997)
Curtis JB	2002	15–30		Ning et al. (2009)
LB-RIPED, CNPC	2008	35		Ning et al. (2009)
Liu et al.	2009	50–100		Liu et al. (2009a)
Wei et al.	2009	70–100		Wei et al. (2009)
Zhang et al.	2009		26	Zhang et al. (2009)
Dong and Chen	2009	86–166	15–32	Zhao et al. (2012)
Li and Wang	2010		15.1–33.7	Zhao et al. (2012)
Zou et al.	2010	30–100	10–15	Zhao et al. (2012)
WEC	2010	10.42		WEC (2010)
Pan et al.	2010	31		Pan et al. (2010)
Liu et al.	2010		21.4–45.0	Zhao et al. (2012)
Zhang et al.	2010		15–30	Zhao et al. (2012)
Qiu	2010		18–29	Zhao et al. (2012)
BGR	2011		17.2	BGR (2011)
Medlock et al.	2011		6.34	Medlock et al. (2011)
EIA/ARI	2011	144.5	36.1	EIA/ARI (2011)
Qiu et al.	2011		15–25	Qiu et al. (2011)
Li and Zhang	2011	25–35		Li and Zhang (2011)
Zhang and Li	2011		31	Zhao et al. (2012)
Dong and Wang	2011		12–18	Zhao et al. (2012)
Zhao	2011		7–10	Zhao et al. (2012)
Qiu et al.	2011		9–12	Zhao et al. (2012)
Zhao et al.	2012	45–80	9.2–11.8	Zhao et al. (2012)
Zha	2012	40–120	4–12	Zha (2012)
Zou et al.	2012		15–20	Zou et al. (2012b)
Zhao	2012	31–144	30	Zhao (2012)
Xiao and Bai	2012	86–166	26	Xiao and Bai (2012)
Hu	2012	134		Hu (2012)
Qiu et al.	2012		10	Qiu et al. (2012)
Li et al.	2012	86–166	15–25	Li et al. (2012a)
Qiu and Deng	2012		11	Qiu and Deng (2012)
MLR	2012	134.4[b]	25.1[b]	MLR (2012)
BGR	2012		8.6	BGR (2012)
Zou et al.	2013		10–25	Zou et al. (2013)
EIA/ARI	2013	134.1	31.2	EIA/ARI (2013)
McGlade et al.	2013		6.5–36.1	McGlade et al. (2013)
Summary value		10.4–166	4–45.0	
Average value		84.7	19.5	

Note: GIP: Gas-In-Place; TRR: Technically Recoverable Resources; LB-RIPED, CNPC: Langfang Branch of Research Institute of Petroleum Exploration and Development, China National Petroleum Corporation; WEC: World Energy Council; BGR: Bundesanstaltfür Geowissenschaften und Rohstoffe (BGR) in Germany [Federal Institute for Geosciences and Natural Resources]; EIA/ARI: U.S. Energy Information Administration/ Advanced Resources International Inc.; MLR: Ministry of Land and Resources of China; The data with "a" is for Central Asia & China, not just China; The data with "b" does not include the resources in the Qinghai-Tibet region.

19.5 Tcm). The range in estimates is very wide; for example, the highest GIP estimate is 15.9 times the lowest one. A further analysis of TRR estimates shows a slowly declining trend, although with considerable variation among estimates (Fig. 1). We consider this declining trend in the selection of our best (or middle) estimate of future production.

Of these estimates, the results of U.S. Energy Information Administration/Advanced Resources International Inc. (EIA/ARI) and Ministry of Land Resources of China (MLR) have most influence, since both of their assessments are relatively comprehensive compared to others. According to the 2011 assessment of EIA/ARI, China holds the world's largest shale gas resources, with GIP and TRR of shale gas resources of 144.5 Tcm and 36.1 Tcm respectively (EIA/ARI, 2011). In 2013, EIA/ARI updated their assessment and lowered the estimate of China's shale gas. Based on their most recent analysis, GIP and TRR of shale gas resources are 134.1 Tcm and 31.2 Tcm respectively (EIA/ARI, 2013).

In 2012, MLR released the result of *the National Shale Gas Geological Survey and Priority Locations* (MLR, 2012). MLR's result is the first official assessment of China's shale gas resources. According to MLR, the GIP and TRR of China's shale gas are 134.4 Tcm and 25.1 Tcm, excluding the Qinghai-Tibet region.

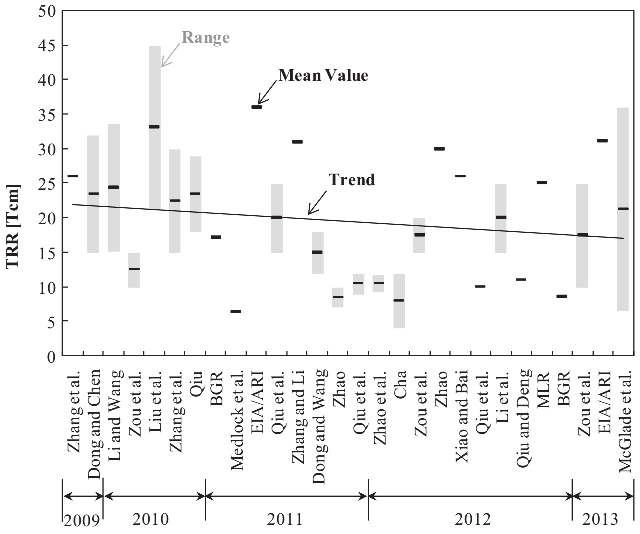

Fig. 1. Linear trend of estimated TRR for shale gas resources. Note: Uses the same data sources as Table 1.

Many scholars claim that the resource potential of shale gas in China may be lower than the results of EIA/ARI and MLR, although they admit that China is rich in shale gas resources. For example, Qiu and Deng (2012) and Kang (2013) estimate that China's TRR of shale gas is only about 10–12 Tcm. However, it is very hard to know which one is more accurate, since all current estimates, including those of EIA/ARI and MLR, are very preliminarily. That is the reason why "*finishing the investigation and evaluation of shale gas resource, further identifying the quantities of shale gas resources and their distributions*" is still the main task in Shale Gas Development Plan (2011–2015), released by China's authorities (NDRC et al., 2012).

Since China's shale gas industry is still in its infancy, there is still no public data showing how much of the resources can be produced economically and technically, i.e. proven reserve (PR). According to the Shale Gas Development Plan (2011–2015), by the end of 2015, the discovered GIP and discovered TRR may reach 0.6 Tcm and 0.2 Tcm respectively, which means even in 2015, China's PR of shale gas in 2015 will be less than 0.2 Tcm since discovered resources that can be produced technically and ecnomically are a subset of discovered resources that can be produced technically.

China's shale gas resources are primarily found in three areas: South-China area (mainly Sichuan basin), North-China area (mainly Ordos and Bohai Gulf basins) and Tarim basin (Dong et al., 2011; Gao, 2012). Total GIP in these three areas accounts for nearly 70% of China's shale GIP (Gao, 2012). Both the North-China area and the Tarim basin have limited water resources. The Sichuan basin has rough terrain and high population density. Very little shale development has been done to date. What little has been done has been primarily in the Sichuan basin (Zeng et al., 2013). Developing shale at scale in any of these areas can be expected to face many challenges, because of the need for water resources if hydraulic fracturing is performed and because of the need to move people and businesses if extraction is done in areas with high population density.

2.2. Coalbed methane

The first study of China's coalbed methane (CBM) resources took place in 1985, when the Ministry of Geology and Mineral Resources of China (MGMR) made its first assessment of China's

Table 2
Statistics of China's coalbed methane resources.

Institutes/Scholars	Year	GIP [Tcm]	TRR [Tcm]	References
MGMR	1985	10.6–25.2		Liu et al. (2009b)
Jiaozuo Mining Institute	1987	31.9		Liu et al. (2009b)
Xi'an Branch of CCRI, HMI, CUMT	1990	32.2		Liu et al. (2009b)
Xi'an Branch of CCRI	1991	30–35		Liu et al. (2009b)
MGMR	1992	36.3	18.2	Liu et al. (2009b)
CNCC	1992	24.8		W.Z. Li et al. (2008)
Liu	1993	38.0		W.Z. Li et al. (2008)
Li et al.	1995	23.9		W.Z. Li et al. (2008)
Guan et al.	1995	25–50		Guan et al. (1995)
Rogner	1997	34.4^{a}		Rogner (1997)
Boyer and Qinghao	1998	30.1–35.2		Mohr and Evans (2011)
CNACG	1999	14.3		Liu et al. (2009b)
LB-RIPED, CNPC	1999	25.0		Liu et al. (2009b)
CUCMC	2000	31.5		Liu et al. (2009b)
LB-RIPED, CNPC	2001	27.3		W.Z. Li et al. (2008)
Niu and Hong	2002	10–35		Niu and Hong (2002)
Zhang et al.	2004	22.5		Zhang et al. (2004)
Li et al.	2005	30–35		Li et al. (2005)
MLR	2007	36.8	10.9	MLR (2009)
Wang	2009	20.1		Wang 2009
Campell and Heaps	2009	28.4		Mohr and Evans (2011)
Cramer et al.	2009	34.0–36.8		Mohr and Evans (2011)
BGR	2009	34–36.8		BGR (2009)
Kuuskraa and Stevens	2009	19.9–36.1	2.8	Kuuskraa and Stevens (2009)
Aluko	2011	30.0–55.1		Mohr and Evans (2011)
Zou et al.	2012		10–15	Zou et al. (2012b)
Zhao	2012	32.9–37.0	11–13.9	Zhao (2012)
Qiu and Deng	2012		12.0	Qiu and Deng (2012)
IEA	2013		9.5	IEA (2013)
McGlade et al.	2013		11.2	McGlade et al. (2013)
Summary value		10.6–55.1	2.8–18.2	
Average value		30.0	11.2	

Note: MGMR: Ministry of Geology and Mineral Resources of China; CCRI: China Coal Research Institute; HMI: Huainan Mining Institute; CUMT: China University of Mining & Technology; CNCC: China National Coal Corporation; CNACG: China National Administration of Cola Geology; CUCMC: China United Coalbed Methane Corporation, Ltd.; IEA: International Energy Agency; The data with "a" is for Central Asia & China, not just China.

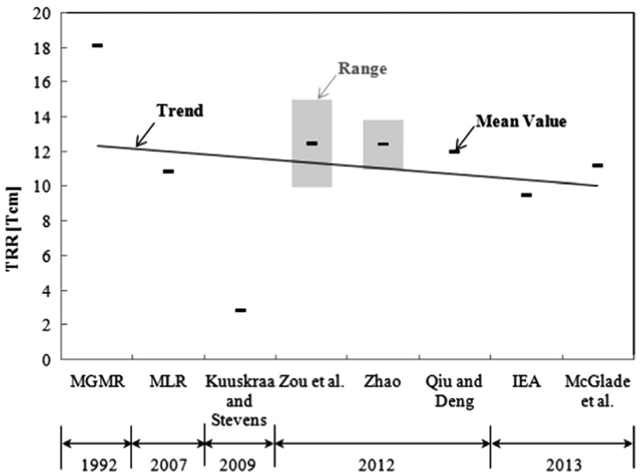

Fig. 2. Linear trend of estimated TRR for coalbed methane resources. Note: Uses the same data sources as Table 2.

Table 3
Statistics for China's tight gas resources.

Institutes or Scholars	Year	GIP [Tcm]	TRR [Tcm]	References
Guan et al.	1995	12		Guan et al. (1995)
Rogner	1997	10^{a}		Rogner (1997)
Zhang et al.	2004	11.5–13.8		Zhang et al. (2004)
Kang and Luo	2007	12–100		Kang and Luo (2007)
Li et al.	2008	90–110		J.M. Li et al. (2008)
Wang	2009	100	11.5–13.8	Wang (2009)
BGR	2009	10		BGR (2009)
Hu	2010	12		Hu (2010)
Pan et al.	2010	12.0	6	Pan et al. (2010)
Li and Zhang	2011	55.8–83.5		Li and Zhang (2011)
Qiu et al.	2011		9–12	Qiu et al. (2011)
Zou et al.	2012		15–20	Zou et al. (2012b)
Zhao	2012	8.4–100	28	Zhao (2012)
Zhang et al.	2012	19.9–26.8	9.2–13.4	Zhang et al. (2012)
Qiu et al.	2012		10	Qiu et al. (2012)
Liet al.	2012	17.4–25.1	8.8–12.1	Li et al. (2012a)
Qiu and Deng	2012		11	Qiu and Deng (2012)
Li et al.	2012	17.0–23.8	8.1–11.3	J.Z. Li et al. (2012)
BGR	2012		12	BGR (2012)
IEA	2013		3	IEA 2013
McGlade et al.	2013		10.7	McGlade et al. (2013)
Zou et al.	2013		9–13	Zou et al. (2013)
BGR	2013		12	BGR (2013)
Summary value		8.4–110	3.0–28	
Average value		36.7	11.7	

Note: The data with "a" is for Central Asia & China, not just China.

CBM resources. The result indicated that GIP of China's CBM resources was 10.6–25.2 Tcm (Liu et al., 2009b). No assessment of TRR was included in MGMR's work. In 1992, MGMR made its second resource assessment of China's CBM and included in its resource assessment both GIP and TRR. Based on its results, GIP and TRR of China's CBM were 36.3 Tcm and 18.2 Tcm, respectively (Liu et al., 2009b). Other studies have also been performed, but most of these studies focus on the type of GIP; only a few recent studies estimate TRR.

Table 2 summarizes the assessment results of China's CBM resources. It can be seen that the GIP ranges from 10.6 Tcm to 55.1 Tcm (average value: 30.0 Tcm), and the TRR ranges from 2.8 Tcm to 18.2 Tcm (average value: 11.2 Tcm). A further analysis of TRR estimates shows a slowly declining trend (Fig. 2), which is similar to the pattern observed with shale gas.

Of these estimates, MLR's assessment in 2007 is the latest national assessment on China's CBM resources from China's authorities. According to this assessment, the GIP and TRR of China's CBM resources are 36.8 Tcm and 10.9 Tcm, respectively (MLR, 2009). MLR's results are widely referenced. However, many international institutes and scholars have developed their own estimates. From Table 2, we can see that after 2007, Kuuskraa and Stevens (2009) present the lowest estimates of GIP and TRR (the lower bound of GIP is only 19.9 Tcm; TRR is only 2.8 Tcm).

According to Zhang's analysis, the discovered GIP and PR of China's CBM resources were 0.5 Tcm and 0.2 Tcm respectively by the end of 2012 (Zhang, 2014).

China's CBM is mainly distributed in seven basins or areas: Ordos, Erlian, Eastern Yunan-Western Guizhou area, Qianshui, Junggar, Tarim and Tianshan basins. Total TRR of CBM in these basins accounts for nearly 80% of China's CBM resources (MLR, 2009). Like much of China, these areas tend to be short of fresh water. While CBM resources are widely distributed, development has only occurred in the Qinshui basin, Shanxi province (Gao, 2012). Exploitation in other basins is still far from industrial or commercial production; only some pilot tests are on-going in east Ordos, Tuha and Junggar basins (Zou et al., 2013).

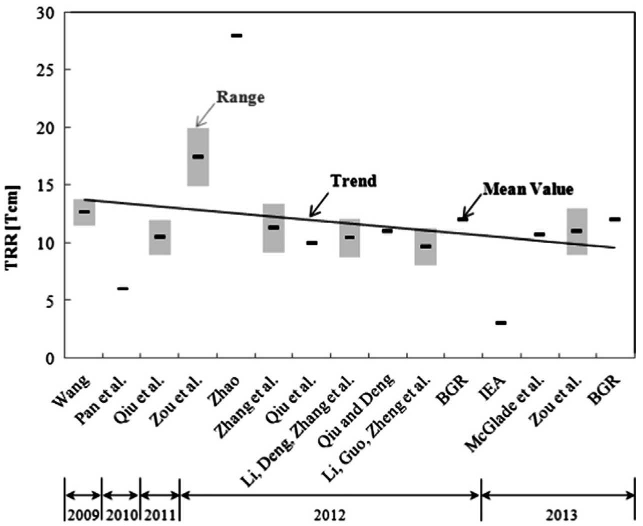

Fig. 3. Linear trend of estimated TRR for Tight gas resources. Note: Uses the same data sources as Table 3.

2.3. Tight gas

Table 3 summarizes the assessment results with respect to China's tight gas resources. It can be seen that the GIP and TRR of tight gas resources range from 8.4 Tcm to110 Tcm (average value: 36.7 Tcm) and 3.0–28 Tcm (average value: 11.7 Tcm), respectively. For TRR estimates, we also present a further analysis and find that a slow decline trend can be observed (Fig. 3). Furthermore, the difference among current estimates is sufficiently large that it cannot be ignored. Without a national estimate from China's authorities, it is very hard to claim which estimate is much more plausible. Historically, China has treated tight gas as conventional gas. For example, according to the 3rd national oil and gas resource assessment released in 2005 by MLR, the GIP of China's conventional gas resources is 35 Tcm, of which 8.4 Tcm is tight gas resources (Zhao, 2012). Based on this analysis, Zhao (2012) showed the lowest estimate of GIP for China's tight gas to be 8.4 Tcm.

According to Zou et al. (2013), by the end of 2012, the discovered GIP and PR of tight gas were 3.6 Tcm and 1.8 Tcm respectively.

C hina's tight gas resources are mainly distributed in five basins: Ordos, Sichuan, Tarim, Songliao and Bohai Gulf basins. TRR of tight gas in these five basins accounts for more than 80% of total TRR in China (Zhang et al., 2012; J.M. Li et al., 2012, J.Z. Li, 2012). Of these basins, Ordos and Sichuan are already mature production areas. New exploration mainly focuses on other basins, including Songliao and Tarim (Zou et al., 2013). Furthermore, even though the resource potentials for Ordos and Sichuan are large, these resources are mainly distributed in mountainous areas making extraction more difficult. Also, the population density in Sichuan basin is high, leading to a need to move people and businesses. These obstacles will need to be overcome if production is to expand.

3. Methodology

3.1. Geologic resources supply–demand model

This paper uses the Geologic Resources Supply–Demand Model (GeRS-DeMo) to forecast future production of China's three types of unconventional gas. This methodology has been successfully used to project the long-term production of conventional and unconventional hydrocarbons, as well as other finite resources, such as lithium, phosphorus and copper (Mohr and Evans, 2010, 2011, 2013; Northey et al., 2014; Mohr et al., 2011, 2012; Giurco et al., 2012). GeRS-DeMo was originally developed by Mohr (2010). A full and detailed description of GeRS-DeMo can be found in Mohr (2010), and briefly in others (Northey et al., 2014; Mohr et al., 2015; Wang et al., 2015).

GeRs-DeMo has two modes, static mode and dynamic mode and two components, supply and demand. In static mode, there is no interaction between supply and demand, while in dynamic mode, the amount of extraction (supply) is reduced if demand is low. We have used the static mode in this paper since we do not have a good way of estimating the impact of reduced demand because of economic, environmental, or other conditions, other than to reduce the selected ultimate recoverable amount. In this paper, our goal is to obtain a range of estimates, including both a "best estimate" and a high estimate, similar to what might occur under best circumstances—continued rising prices, few environmental difficulties, and continued improvement in technology. Static mode, which assumes that extraction is never reduced because of inadequate demand, combined with a suitable range of ultimate recoverable amounts, provides the range of estimates needed.

Furthermore, on the supply side, GeRs-DeMo also has two subcomponents, namely the mining component and the field component, depending on whether a solid or liquid/gas is being extracted. The mining component is generally used for production modeling of coal and some types of very viscous oil, such as natural bitumen, extra heavy oil, and kerogen mining. The field component is usually used for modeling other types of oil and gas production, because as gasses and liquids, their extraction continues for a considerable time after a well is initially drilled. We have chosen the field component to analyze the production of unconventional gas resources. A brief introduction of the field component of GeRs-DeMo is shown in Appendix A.

3.2. Resources scenarios

In GeRS-DeMo, one important input variable is ultimately recoverable resources (URR), i.e. the total amount of unconventional gas that is extracted technically and economically over time (Mohr, 2010). In this paper, three URR scenarios are used: high, medium and low.

In the high scenario, TRR is used to represent the URR (Table 4). This scenario provides an upper bound for the production growth of unconventional gas since TRR is estimated by only considering technical conditions, without consideration of economic conditions. In other words, no consideration is given to whether price

Table 4
Resources scenarios used in this article.

Type	GIP [Tcm]	TRR [Tcm]	PR [Tcm]	Cumulative production [Bcm]	URR scenarios [Tcm]		
					High	Medium	Low
Shale gas	84.7	19.5	0.2	0.3	19.5	5.0	0.2
CBM	30.0	11.2	0.2	86.8	11.2	4.7	0.3
Tight gas	36.7	11.7	1.8	181.9	11.7	6.9	2.0

will ever rise high enough to make it profitable to actually recover these resources. In the low scenario, URR is represented by cumulative production plus proven reserve (CP+PR). This scenario may underestimate actual production since PR is estimated by only considering current technical and economic factors (particularly current prices), without consideration of future technical and economic conditions. It also omits gas that is currently undiscovered. The medium scenario, which represents our best estimate, uses varying percentage mixtures of the high and low estimates, based on the perceived challenges (environmental, economic, and other, as discussed elsewhere in this paper) for each of the types of unconventional oil. For tight gas, which China has had the most experience with, we select a 50–50% weighting of the low and the high estimate URRs, or 6.9 Tcm (Table 4). For CBM, our medium estimate gives 60% weight to the low estimate, and 40% weight to the high estimate, because of expected greater challenges for future production, resulting in a URR estimate of 4.7 Tcm. Shale is expected to represent the greatest challenges, because of its potential adverse impact on the environment and significant water need. Because of this, we have selected as our medium estimate of shale an estimate that gives 75% weight to our low estimate, and 25% weight to our high estimate, or 5.0 Tcm.

It should be noted that both GIP and TRR data in Table 4 represent the average value of current available indications from the literature (see the last rows in Tables 1–3). PR data are also from the record of related literature, which are shown in Sections 2.1, 2.2 and 2.3. It should be noted that the PR data of shale gas shown in Table 4 is the discovered TRR by the end of 2015 as predicted by China's Shale Gas Development Plan (2011–2015), because no company has yet made an estimate of proven reserves. Actual PR of shale gas is surely much lower than this amount. Cumulative production to date is the sum of historical unconventional gas production, which will be described in Section 3.3.

3.3. Historical production data

In China, no official production data for unconventional gas exists. Instead, all unconventional gas production is included in China's conventional gas production, and thus must be determined breakdowns this production. Fig. 4 shows the historical production of the three types of unconventional gas in China, based on current literature.

Fig. 4 shows that China's unconventional gas production has increased rapidly in recent years, with an annual growth rate of more than 30% between 2005 and 2013. In 2013, China's total unconventional gas production reached 54.0 bcm, accounting for 46.1% of total gas production. The largest component of 2013 unconventional gas production was tight gas, amounting to 40 bcm. CBM was the second largest component, amounting to 13.8 bcm in 2013. Shale gas is a relative newcomer. China began to extract shale gas in 2011, and its production was only 0.03 bcm in its first year. By 2013, its production had reached 0.2 bcm.

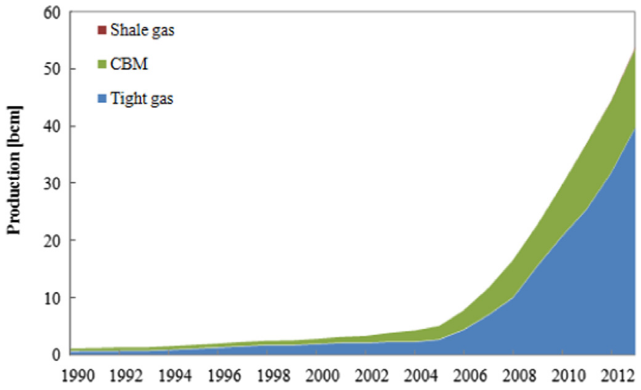

Fig. 4. Historical production of China's unconventional gas.
Data source: CBM: Zhai et al. (2008) (data before 2000); Bu (2011) (2000–2009 data); NDRC and NEA (2011) (2010 data); Hu (2012) (2011 data); Zhou (2014) (2012 data); Cheng (2014) (2013 data). Tight gas: Yang et al. (2012) (data before 2011); Zhou (2014) (2012 data); Guo (2014) (2013 data). Shale gas: Hu (2012) (2011 data); Zhou (2014) (2012 data); Liu (2014) (2013 data).

Some international institutes show much lower unconventional gas production than shown in Fig. 4. This appears to happen because these authors underestimate the contribution of tight gas. For example, according to the statistics of the IEA, China's tight gas production amounted to only 3.4 bcm in 2012 (IEA, 2014), while the statistics we show here indicate it reached 32.0 bcm in 2012. The reason for the understatement is the fact that tight gas is seen as conventional gas, and its production is included in conventional gas production.

4. Forecast results and discussion

4.1. Results

Fig. 5 and Table 5 show the forecast results for China's unconventional gas production. In the high scenario, total unconventional gas production will increase rapidly before reaching peak production of 469.7 bcm in 2069. In the low scenario, production will peak in 2021, which is nearly 50 years earlier than the high scenario's result. Peak production is 70.1 bcm in the low scenario, which is only 15% of the result shown in the high scenario. In our medium scenario, which is our best estimate, production will peak in 2068 at 176.1 bcm.

A comparison of the three scenarios shows sharp difference among them. This occurs because of the very different URRs used in the different scenarios. As noted in Section 1. Introduction we noted that China's government plans to fill its domestic gas shortage by developing its unconventional natural gas, assuming it can ramp up its natural gas production in a pattern similar to that of the U. S. Therefore, one of the purposes of this paper is to analyze if this plan can be achieved with any of the three scenarios modeled. It should be noted that the high scenario is very optimistic, because it assumes that all resources that are technically recoverable will be economically recoverable. This is an optimistic assumption, because usually there are considerable resources that are technically recoverable, but cannot be extracted because the cost would be too high.

Regarding the breakdown by type of unconventional gas, in all scenarios tight gas is very important for the future growth of China's unconventional gas production, especially for the medium and short term. In the low scenario, tight gas holds the dominant position in the growth of China's unconventional gas production for the entire forecast period. Even in the high scenario, where the production of shale gas and CBM will increase much more rapidly than in the other two scenarios, tight gas is the largest contributor to China's unconventional gas production until 2056. Shale gas's contribution to total unconventional gas production varies greatly among the scenarios, depending upon the selected URR. Its contribution is greatest in the high scenario, particularly at late dates. Compared to tight gas and shale gas, the growth of CBM production is relatively moderate in all scenarios except the low scenario, where the production growth of CBM and its contribution to total unconventional gas production are higher than shale gas because the assumed URR of shale gas in this scenario is very low.

These results are generally consistent with qualitative judgments by many of China's experts. Tight gas is the only type of unconventional gas resource that has been extracted on a large

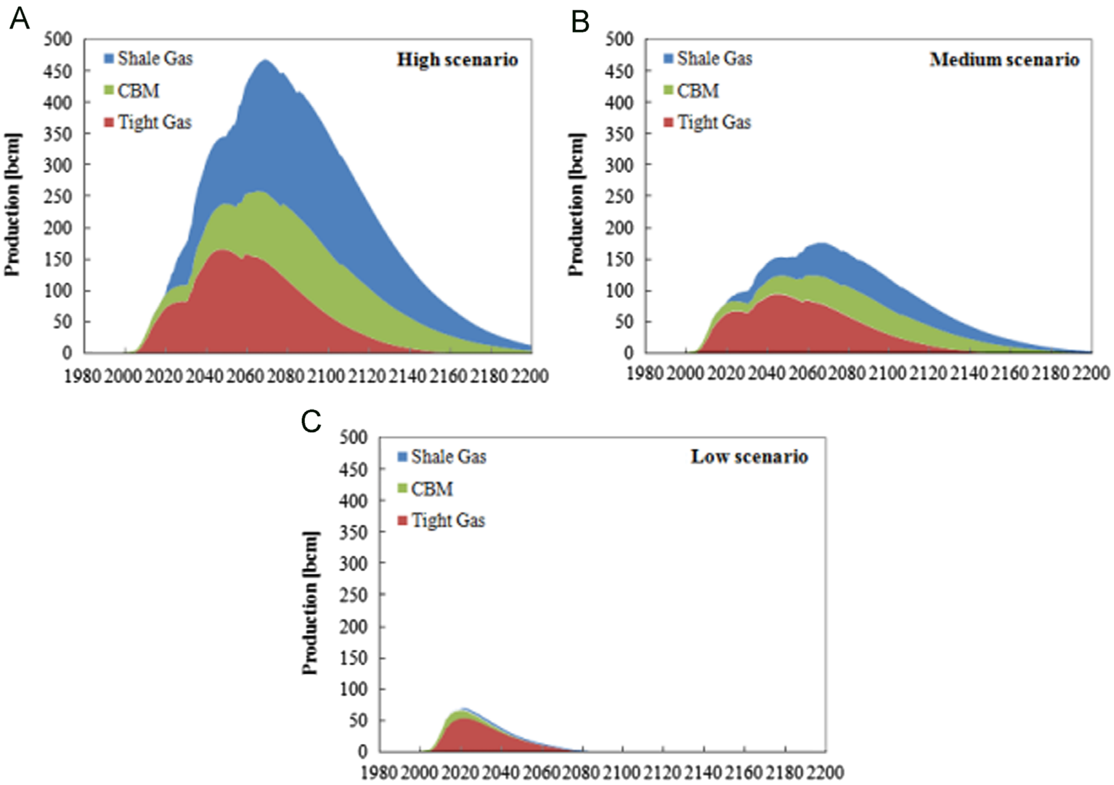

Fig. 5. Three scenarios of future production of China's unconventional gas.

Table 5
Peak year and peak production of Chinese unconventional gas production.

Scenarios	Gas types	Peak year	Peak production [Bcm]
High scenario	Shale gas	2073	214.5
	Tight gas	2049	166.8
	CBM	2083	117.8
	Total	2069	469.8
Medium scenario	Shale gas	2072	54.8
	Tight gas	2046	95.6
	CBM	2083	47.1
	Total	2068	176.1
Low scenario	Shale gas	2034	4.0
	Tight gas	2021	55.7
	CBM	2015	15.1
	Total	2021	70.1

scale for years. However, the contribution of tight gas has been underestimated by most international institutes, including the IEA (2014), since tight gas has been included into the conventional gas resources in the past by China. According to Chinese experts, tight gas is the most significant and reliable contributor to the future growth of total unconventional gas production (Yang et al., 2012). Our analysis indicates a similar pattern. CBM currently holds the second largest position in China's total unconventional gas production, and its production can be expected to increase in the future (Jia et al., 2014). It is unlikely that its growth rate will be very high for many reasons, including low-grade resources, heavy input burden, and the division of mining rights between coal and CBM (Song et al., 2013; Liao et al., 2012a). In fact, the development of CBM has been lagging behind the targeted levels for years (Song et al., 2013). Shale gas appears to have the largest resources available based on GIP and TRR estimates, but shale gas development in China is still in its initial stage and has been confronted with many challenges (Pi et al., 2015). If these challenges can be overcome in the future, the growth potential of its production could be very large in the long term (Tong, 2010), just as shown in our high scenario. However, the production could also be very low if these challenges cannot be solve. Our medium estimate of shale gives 75% weight to the low estimate, in recognition of these problems.

4.2. Discussion

In the high scenario, by using a very high value of TRR, and by further assuming that these TRR resources can be economically produced, we forecast that China's unconventional gas production will grow very rapidly in the future. We consider the medium scenario more likely however. It is even possible that future production will be as low as the low scenario. There are several constraining factors that lead to the possibility of low production.

The first constraining factor is geological and technical issues. Based on Table 4, shale gas has the greatest potential, but at this point estimates are very preliminarily. Furthermore, Fig. 1 shows that in recent years, estimated TRR of shale gas shows a slowly declining trend. This pattern suggests that as researchers learn more about the challenges of extraction, they tend to reduce their estimates of recoverable amounts. This pattern occurs outside of China as well. Several studies have also shown that estimates of resources for U.S. shale gas are overestimated and its production could be much lower than U.S. Energy Information Administration (EIA)'s forecast (Hughes, 2014). Because of this uncertainty, it is important for China to make a detailed investigation of its shale gas resources to better understand the issues (Pi et al., 2015). Furthermore, as shown in Section 2.1, most shale gas resources are undiscovered. Because of this, large-scale capital expenditures are likely to be needed to define precisely the nature of the resources. In addition, even though the resource potential may be very large, China's shale gas reservoir conditions appear to present more challenges for extraction than shales in US. These challenges, which may be overcome with more advanced techniques, include significant fault-related problems, deeply buried formations, and rough terrain (H. Wang et al., 2013; Tian et al., 2014). Geological and technical issues are even a concern for tight gas. While China has produced tight gas for years, there is not yet any nationally comprehensive and systematic resource assessment for it.

The second constraining factor is economic issues. In the high scenario, we use TRR as URR; however, assessment of TRR only considers the current and future technical conditions, without consideration of any economic conditions. The cost of exploration and development of unconventional gas is much higher than conventional gas. Thus, if this gas is to be extracted, the price of gas needs to increase to a high level to cover its cost. In the past several years, China's gas price does show an increasing trend; the price is still not high enough to cover the cost of developing these unconventional gas resources, however. Furthermore, although a high gas price could be helpful for accelerating shale gas development, such a high price is likely to reduce potential demand for gas, because consumers cannot afford a very large quantity of gas if a high price is required. The limitation on use imposed by a high gas price would be contrary to the policy of vigorously promoting the use of gas (CASS, 2013). In a situation of conflicting price requirements, the government will need to determine a suitable price, balancing both the cost of extraction and the amount consumers can afford.

The issue of high required-price has already affected the development of China's unconventional gas. For example, with shale gas, many state-owned companies have obtained the rights to explore and develop shale gas resources, but exploration and development progress is still very slow. China's government has needed to lower its 2020 production target for shale gas and to postpone the third bidding round for shale gas exploration rights (Pi et al., 2015). One of the reasons for this slow growth is economic. According to Tian et al. (2014), the shale operations of both of the major oil companies, China National Petroleum Corporation (CNPC) and China Petrochemical Corporation(Sinopec), have endured heavy financial losses. Shale gas producers in the US are also finding production unprofitable because US natural gas prices are below the cost of shale gas production (Berman, 2015).

The third constraining factor is environmental issues. Currently, environmental concerns regarding unconventional gas focus mainly on shale gas, since extracting this type of resource typically requires two techniques: hydraulic fracturing and horizontal drilling. A number of analyses have studied the environmental impacts of these techniques, including methane emissions, water use, water pollution, induced earthquakes, and reduced air quality (Howarth and Ingraffea, 2011; Entrekin et al., 2011; Frohlich, 2012; Pacsi et al., 2013). Among these, water may be the most significant constraining factor with respect to China's shale gas development. According to Jiang et al. (2014), the average amount of water used for fracturing one shale gas well in US is about 20 thousand cubic meters. In China, water use may need to be higher because of more complex geological conditions; the upper bound of water use could be as high as 44 thousand cubic meters (W.H. Hu et al., 2013, Y. Hu et al., 2013). Thus, large-scale development will surely present a huge demand for water. However, China itself is facing serious water shortage issue (Zhu et al., 2001), and seven of thirteen provinces that have been selected as priority areas for shale gas development by China's government are already suffering from water shortages. The average available water per person in these seven provinces is less than 2 thousand cubic meters, less than one-quarter of the world's average (Yang et al., 2013). By assuming that fracturing Chinese shale wells each consume 1.1–2.4 thousand cubic meters of water, Yang et al. (2013) estimate that it will require 171 million cubic meters water to extract 1.5 bcm of shale gas resources in Sichuan province. This amount is equal to 10.5% of the province's domestic water demand.

In addition to water use, the potential for water pollution is also a concern. Several studies have pointed out that when hydraulic fracturing is used, the flowback fluid often contains radioactive, carcinogenic or mutagenic materials. If this flowback material leaks or spills, or is inadequately treated, it may pollute the ground and surface water (Howarth and Ingraffea, 2011; Kuwayama et al., 2013; Vidic et al., 2013). Considering the huge water use of hydraulic fracturing, the non-negligible potential for water pollution, and China's already serious water shortage, the water issue will surely constrain the development of China's shale gas, just as suggested by World Resources Institute (Reig et al., 2014).

In addition to the above factors, other factors such as inadequate infrastructure and limited regulatory system could also constrain the future massive development of China's shale gas industry (Wan et al., 2014; Wang et al., 2014). Therefore, based on the above analyses, we can conclude that the high scenario is very unlikely. Our medium scenario gives only 25% weight to this high scenario, and 75% weight to the low scenario. It should be considered a more realistic scenario, given the challenges of shale production.

4.3. Implications for China's gas security

Fig. 6 shows how total natural gas supply is likely to compare to expected demand, based on the indications of this paper. If there is a shortfall, this is important for gas security. It can be seen that in the low scenario, China's total gas production will experience a short and slow increase period until 2025. Thereafter, production will maintain its high level for many years, and then decline slowly. In this case, the contribution of unconventional gas is not

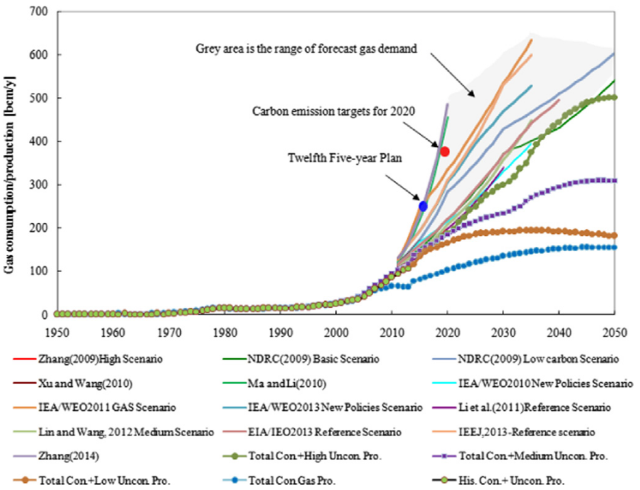

Fig. 6. China's domestic gas supply and its future demand. Note: (1) Historical conventional gas production = total gas production-unconventional gas production. (2) Total gas production data is from J.L. Wang et al. (2013) and BP (2014). (3) Future conventional gas production is forecast by applying the multi-cycle Generalized Weng model, which has proved to be suitable for China's fossil fuels (Wang et al., 2011) and has been used to forecast China's conventional gas production (J.L. Wang et al., 2013). A detailed description of this model can be found in Wang et al. (2011) or J.L. Wang et al. (2013). (4) According to the third national conventional oil and gas resources assessment, the GIP and TRR of conventional gas resources are 35.03 Tcm and 22 Tcm respectively (J.L. Wang et al., 2013). However, part of these resources is actually tight gas (see the description in Section 2.3). Therefore, the TRR of China's conventional gas without including tight gas = 22–8.37*(22/35.03) = 16.75 Tcm. The 16.75 Tcm is therefore used in the multi-cycle Generalized Weng model to forecast future conventional gas production. (5) The estimates of gas demand are from IEA (2010, 2011, 2013), U.S. Energy Information Administration (EIA) (2013), Li et al. (2011), Xu and Wang (2010), Zhang (2009, 2014), NDRC (2009), Ma and Li (2010), Lin and Wang (2012) and IEEJ (2013).

significant. However, in the high scenario, total gas production will increase substantially in the next several decades due to the rapid increase in China's unconventional gas production. According to our best estimate, China's total gas production will increase steadily before 2050, however, the growth rate is much lower than one in the high scenario.

With respect to China's future gas demand, all the forecasts show rapidly increasing demand. Furthermore, with the increased concern about limiting carbon dioxide emissions, many institutes and individuals have been raising their forecasts in recent years. For example, in IEA's World Energy Outlook 2010 (WEO 2010), China's gas demand is forecast to reach 395 bcm by 2035 (IEA, 2010), while this figure has been updated to 529 bcm in WEO 2013 (IEA, 2013). Even this latest forecast seems low compared to some other forecasts. For example, according to the Chinese Academy of Social Sciences (CASS), China's gas demand will be 620 bcm in 2035 (CASS, 2013).

In Fig. 6, if we compare forecast future gas demand and domestic total gas production, it is clear that the highest forecast gas production can just meet the lowest gas demand. Our best estimate, the medium forecast, falls short of the lowest demand. Based on this comparison, we can conclude that China cannot rely only on unconventional gas to solve its gas shortage; it will still need to import a large amount of gas resources in the future. To achieve China's carbon emission reduction targets, necessary natural gas imports in 2020 will amount to at least 191 bcm based on the medium scenario, and at least 176 bcm in the high scenario. Current gas imports are only 44.6 bcm (BP, 2014). Thus, natural gas imports will need to rise to at least four times current levels.

If we analyze the gas import capacity now being put in place, which is expected to be available by 2020, we find that it falls short of even the expected 176 bcm required in the high scenario. What we find is that China's future gas imports will come mainly from four strategic supply passages (Huang, 2012). The first is northeastern (Sino-Russian) passage. In 2014, two contracts between Russia and China for gas supplied via two routes were signed: one is the eastern route known as Power of Siberia (the designed export capacity is 38 bcm per year, and the construction work is expected to be finished in 2018); the other is the western route known as Power of Siberia-2 (the designed export capacity is 30 bcm per year). This western gas route could be postponed indefinitely according to the latest news (Li, 2015), so there is no hope of importing gas from this route before 2020. The second strategic supply passage is northwestern (Sino-Central Asia) passage. China has signed many long-term pipeline gas import contracts with Turkmenistan, Kazakhstan and Uzbekistan. According to these contracts, China can import 85 bcm gas in future via four gas routes, i.e. A/B routes (the total designed capacity is 30 bcm per year), C route (the designed capacity is 25 bcm per year) and D route (the designed capacity is 30 bcm per year). The A/B and C routes have started to export gas to China, and the D route could export gas as early as 2016. The third strategic supply passage is southwestern (Sino-Myanmar) passage. China can import 12 bcm gas via China-Myanmar gas pipeline. The fourth strategic supply passage is a sea passage. China has signed many long-term LNG sales and purchase agreements (SPAs) with Qatar, Iran, Malaysia, Indonesia and Australia. He and Guo (2014) estimate that the maximum amount of imports from these countries could reach 21.3 million tons (about 28.7 bcm) by 2020. Adding the amounts from the four strategic supply passages together, the maximum import capacity for China in 2020 is expected to be 163.7 bcm, which is lower than the minimum amount of imports needed.

It should be noted that the production of unconventional gas resources we forecast and discussed above is only for the quantity of energy output. However, this quantity does not take into the quantity of energy used in the production of this energy. An index evaluating the quantity of energy used in production of energy is energy return on energy investment (EROI). This index is calculated by dividing energy outputs by energy inputs used in creating an energy-producing fuel (W.H. Hu et al., 2013; Y. Hu et al., 2013). Some researchers consider EROI to be an index of fuel quality (Lambert et al., 2014). Compared to conventional fossil fuels, unconventional fossil fuels have much lower EROI values (Hall et al., 2014). Therefore, looking only at the output of unconventional natural gas tends to overstate its benefit to the system. Extracting unconventional natural gas is itself an energy-intensive process. In fact, energy use is a major reason for its high cost of production. If we could calculate the net energy provided by subtracting the energy used in production from the energy produced, we would find that the net energy produced per ton of unconventional natural gas output would be lower than from easier-to-extract natural gas. Thus, the gap between domestic supply and demand will be larger than our analysis indicates.

4.4. *Implications for world natural gas export needs*

Those reading this paper outside of China are interested in China's natural gas import needs. The interest in this case is not the least amount needed, but rather, what is the expected amount needed, if China does not change its energy policy. We know that China is depending on natural gas to reduce its carbon footprint. Thus, even if there is a slowdown in China's rate of economic growth, China growth in natural gas imports may continue to rise.

To calculate the expected amount of natural gas imports for China, we first estimate likely natural gas demand for China in the future. As introduced in Section 1 Chinese gas demand will be 375 bcm in 2020, and 620 bcm in 2035 to meet its goal of energy structure adjustment (J.L. Wang et al., 2013; CASS, 2013). We then combine expected conventional natural gas production with our best estimate of unconventional natural gas production, to produce estimates of China's natural gas production at these dates. The amounts are 183.7 bcm in 2020 and 269.3 bcm in 2035. The difference between these amounts is the expected gas imports in 2020, amounting to 191.3 bcm in 2020 and 350.7 bcm in 2035.

As calculated in Section 4.3, China's import capacity that has already been arranged amounts to 163.7 bcm, leaving a shortfall of 27.6 bcm in 2020 and 187 bcm in 2030 to be imported from other sources. According to BP, there were 325.3 bcm of LNG traded internationally in 2013 (BP, 2014). Thus, the amount of China's shortfall appears likely to be significant in relationship to supplies of LNG available for international trade.

5. Conclusions and policy implications

Our conclusions can be summarized as follows:

1. A comprehensive and systematic investigation of China's unconventional gas resources is presented. The result shows that the average values of GIP and TRR for total unconventional gas resources are 151.3 Tcm and 42.4 Tcm, respectively. Of these, shale gas holds the largest resource potential; its GIP and TRR are 84.7 Tcm (56.0% of total GIP) and 19.5 Tcm (46.0% of total TRR), respectively. Tight gas is the second largest unconventional gas resource in China; its GIP and TRR are 36.7 Tcm (24.2% of total GIP) and 11.7 Tcm (27.6% of total TRR), respectively. Compared to shale gas and tight gas, the resource potential of CBM is relatively small; its GIP and TRR are 30.0 Tcm (19.8% of total GIP) and 11.2 Tcm (26.4% of total TRR), respectively.
2. A quantitative forecast of long-term production of China's unconventional gas resources under three scenarios is carried out. The results under the selected scenarios differ sharply due to

significant difference in URR assumptions. In the high scenario, production will increase significantly in the next several decades and reach its peak in 2069 at 469.7 bcm, whereas peak production in the low scenario will appear in 2021 and amounts to only 70.1 bcm. In the medium scenario, which is our best estimate, production will peak in 2068, and will amount to 176.1 bcm. Further analysis shows that both in the short and medium term period, tight gas presents the largest contribution to the growth of unconventional gas. The absolute contribution of shale gas can only be significant in the long term, because it is starting from a low base.

3. Several other factors that may affect the future development of China's unconventional gas resources are discussed. Based on our analysis, the middle scenario we have created is the most likely scenario. The high scenario, which represents an upper bound for natural gas production is very unlikely, for many reasons, including water constraints, technical issues, economic issues and environmental issues.
4. The expected contribution of future growth in unconventional gas production to China's total domestic gas supply and its gas security is analyzed. According to our analysis, our best estimate of the growth of unconventional gas, the middle scenario, will fall far short of meeting China's natural gas needs. In the unlikely event that the unconventional natural gas production follows the high scenario, total gas production can just meet the lowest forecast gas demand. Since the high scenario with respect to unconventional gas production growth is likely to be very hard to achieve, we can conclude that China cannot rely solely on unconventional natural gas to solve its future gas shortage.
5. It is likely that China's natural gas import needs will be sufficiently high to affect world natural gas markets. In 2020, a reasonable expectation of gas import needs based on our middle scenario, in addition to supplies already contracted for by China would seem to be 27.6 bcm. By 2035, this number will rise to 187 bcm, nearly 60% of current total world LNG trade. Therefore, it can be concluded that the future development of China's gas industry will have a significant influence on international gas market.

Based on these conclusions, we have several policy recommendations:

First, we recommend that a detailed, updated and comprehensive resource assessment be carried out by Chinese authorities, since resources are the basis for future production. This assessment should include an analysis of economically recoverable resources (or URR), something that virtually no one has looked at closely. Currently, only a very preliminary assessment of shale gas resource by MLR in 2012 is available. This assessment did not include the resources in Qinghai-Tibet region. For tight gas, there has not yet been any national resource assessment from China's authorities. In all types of past reports, China's national resource assessment has tended to focus on its GIP and TRR resources. If we can assume that prices will rise arbitrarily high, so that all technically recoverable resources can be extracted, then TRR resources might be all that is necessary for estimating future production. The low fossil fuel prices experienced in most areas of the world in the past year make it clear that energy prices do not necessarily keep rising, as more expensive resources are extracted. For this reason, it would be worthwhile to consider URR at selected price levels in future analyses. Using this approach would seem to be more reliable than depending on the medium and high estimates used in this paper.

Second, we recommend that in the short and medium term, China focus its efforts on developing its tight gas resources, instead of trying to greatly increase shale gas production. Because of the US's apparent success with shale gas (despite low profitability noted previously), the Chinese government has made an ambitious plan for its own shale gas industry. For example, China's Shale Gas Development Plan (2011–2015) released by China's authorities in 2012 targeted shale gas production of 60–100 bcm in 2020 (NDRC et al., 2012). In order to increase production rapidly in the short and medium term, many China's experts recommend that the Chinese government give more favorable policy terms to the shale gas industry (Liao et al., 2012b). However, as we discussed in Section 4.2, the exploration and development progress of shale gas is still very slow in China; this is the reason why China's government reduced its 2020 production target for shale gas to 30 bcm in 2014 (Pi et al., 2015). If it is possible to greatly increase China's shale gas production, this increase will only take place in the long term. Tight gas is the only reliable source for increasing China's total gas production significantly in the short and medium term (Yang et al., 2012).

Third, we suggest that China's government should continue to promote the international operations of its national oil companies. It should also strengthen its ties with Russia and other countries having high export capacity of gas resources. As we noted in Section 1, the Chinese government hopes that that developing its unconventional gas resources will compensate for a domestic gas shortage. According to the analysis in this paper, it is unlikely that unconventional gas resources will meet China's natural gas demand. There are many constraints, including high cost, poor geological conditions, immature technical conditions, serious environmental impacts, and low EROI. As a result, it is very likely that China will still need to import a large amount of gas from abroad. Furthermore, based on current signed gas import agreements, the maximum import capacity still cannot fill the gap. This means that gas security is likely to continue to be a severe issue for China.

Acknowledgments

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Appendix A. Brief description of the field component of GeRS-DeMo

The production for an oil or gas region, $P_R(t)$, is calculated as the sum of the production from all idealized fields in that region, that is:

$$P_R(t) = \sum_{i-1}^{n(t)} P_i(t) \tag{1}$$

where $n(t)$ is the number of fields on-line in year t. $P_i(t)$ is the production of field i in the year t. The profile of an individual field production is shown in Fig. A1. The following are assumptions regarding the production file of the individual idealized fields:

- The time to ramp production up from no production to the production plateau is set to a constant of one year.
- The plateau production level is set by the user as a specified fraction of the URR of the field (this fraction is used for all fields).

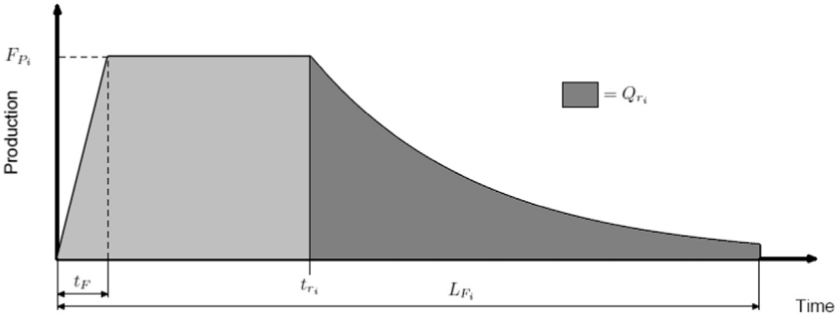

Fig. A1. Production profile from the individual idealized fields.

- The moment the field starts to exponentially decay is determined based on the time the URR remaining in the field reaches a specified fraction of the field's URR (again this fraction is constant for all fields).
- The field is shut down when production reaches 1% of the plateau production level.

Based on the above assumptions, the production of an individual idealized field, i.e. $_{Pi}(t)$ in Eq. (1), is completely determined based only on the URR of the field. Therefore, to forecast the future supply for a certain oil and gas region, two things need to be calculated, the number of fields on-line over time, and the URR of the individual fields.

The total number of fields in a given region, n_T is input by the user. Then the number of fields on-line at given time, $n(t)$ is determined linearly from the cumulative production of the fields, specifically:

$$n(t) = \left\lceil r_F nT\frac{Q(t)}{Q(T)} \right\rceil \tag{2}$$

where r_F is a rate constant typically set to 0.95, $Q(t)$ is the cumulative production, and Q_T is the total URR of the region. It is assumed that in the start year the first field is brought online.

The calculation of the URR of the individual idealized field is determined via the calculation of the exploitable URR. The exploitable URR is the sum of the URR in fields that have already been brought on-line. The exploitable URR, $Q_e(t)$ (that is the amount of URR in the first n fields) is estimated via Eq. (3):

$$Q_e(t) = Q_T(\frac{n(t)}{n_T})^{r_Q} \tag{3}$$

where r_Q is a rate constant typically set to 0.35 and for r_Q greater that 0 and less than 1. Therefore, the URR of the nth individual field brought on line in year t is the difference between the exploitable URR for n field and the exploitable URR in $n-1$ fields, which can be shown as:

$$Q_F(t) = \frac{Q_e(t) - Q_e(t-1)}{N(t) - N(t-1)} \tag{4}$$

where $Q_F(t)$ is the URR of an individual field brought on line in year t.

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