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China's unconventional oil: A review of its resources and outlook for long-term production

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ABSTRACT

Due to the expected importance of unconventional oil in China's domestic oil supply, this paper first investigates the four types of China's unconventional oil resources comprehensively: heavy and extra-heavy oil, oil sands, broad tight oil and kerogen oil. Our results show that *OIP (Oil-in-Place)* of these four types of resources amount to 19.64 Gt, 5.97 Gt, 25.74 Gt and 47.64 Gt respectively, while *TRRs (technically recoverable resources)* amount to 2.24 Gt, 2.26 Gt, 6.95 Gt and 11.98 Gt respectively. Next, the Geologic Resources Supply-Demand Model is used to quantitatively project the long-term production of unconventional oil under two resource scenarios (TRR scenario and Proved Reserve + Cumulative Production scenario). Our results indicate that total unconventional oil production will peak in 2068 at 0.351 Gt in TRR scenario, whereas peak year and peak production of PR (proved reserves) + CP (Cumulative Production) scenario are 2023 and 0.048 Gt, significantly earlier and lower than those of TRR scenario. The implications of this growth in production of unconventional oil for China are also analyzed. The results show that if the TRR scenario can be achieved, it will increase total supply and improve oil security considerably. However, achieving the production in TRR scenario has many challenges, and even if it is achieved, China will still need to rely on imported oil.

1. Introduction

China's oil demand is forecast to keep increasing in the next several decades due to its continuous economic growth. In 2012, a total of 483.70 million metric tonnes (Mt) of oil was consumed in China [1], and this figure is estimated to reach 650 ± 50 Mt in 2030 and 750 ± 50 Mt in 2050, by CAE (Chinese Academy of Engineering) [2]. In the forecast of IEA (International Energy Agency), even in the fairly low-growth New Policies Scenario, the figure will rise to approximately 750 Mt by 2030 [3], 20 years earlier than estimated by CAE for the same consumption.

Most scholars expect that China's conventional oil production will peak before 2020, with peak production of approximately 200 Mt; thereafter, production will decline steadily [4,5]. As a result of limited conventional oil supply and soaring oil demand, China's oil security will face unprecedented challenges. Because of these issues, development of unconventional oil has been recognized as an important and realistic option for China to offset the effects of decline in its conventional oil production and to improve its oil security, especially after the U.S. shale-energy revolution [6].

Recently, a number of studies have focused on Chinese unconventional hydrocarbons. Nearly all of these papers limit their analyses to general concepts, types of formations, characteristics, resource potential, and technology of unconventional oil [7–10]. Furthermore, conclusions regarding resource potential vary considerably. For example, the OIP (*Oil-In-Place*) of Chinese oil sands is estimated by Mohr and Evans [11] to be only 273 Mt, while the corresponding estimate by Zou et al. [7] is 6000 Mt. At present, many scholars have missed that these differences in resource estimates exist, since no comparative analysis or explanatory discussion of current literature are available. In addition, there has been no quantitative research focusing on future production of

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Chinese unconventional oil, although some scholars have made quantitative predictions of world unconventional hydrocarbons' production [11,12].

The primary purposes of this paper are (1) to present a comprehensive and systematic investigation of China's four types of unconventional oil resources, i.e. heavy & extra-heavy oil, oil sands, broad tight oil, and kerogen oil, (2) to use these resource estimates to forecast a range of long-term production amounts, and (3) to analyze the implications of this long-term production growth in unconventional oil resources on future total oil supply (combining both conventional and unconventional oil) and China's oil security.

2. Categories of unconventional oil

Oil can be commonly divided into conventional and unconventional oil. Definition of conventional and unconventional oil differs slightly from one institute to another, and there is no completely consistent definition of these two terms. A general definition of them is based on density, i.e. oil with a density of less than 1.0 g/cm^3 (or its API (American Petroleum Institute) more than 10) belongs to conventional oil, while others belong to unconventional oil [13].

According to this definition, unconventional oil usually includes extra-heavy oil, oil sands and kerogen oil, since their APIs are less than 10 (Fig. 1). The major difference between oil sands and extra-heavy oil is viscosity. Generally, oil sands has a viscosity of greater than 10 000 centipoise (cP), which means it does not flow under reservoir conditions, while extra-heavy oil has a viscosity of less than 10 000 cP and can flow under reservoir conditions [14,15].

Kerogen is mixture of solid organic matter that is a precursor to oil. It is thermally immature and has not been properly transformed into oil by geological processes, thus requiring additional heat treatment to yield useable hydrocarbon liquids. According to the definition of IEA [16], kerogen oil is "*oil produced by industrial heat treatment of shale, which is rich in certain types of kerogen*". The kind of shale used in this process is called oil shale [17–19], and in China, oil from it is usually called "*oil shale oil*" [7,20]. Therefore, the term of "*kerogen oil*" used by international institutes and "oil *shale oil*" used by China is the same, and the term of "*kerogen oil*" is used in this paper (Fig. 1).

Heavy oil is liquid crude oil with an API degree of between 10 and 20 [13]. Therefore, based on the previous definition, heavy oil should be categorized as conventional oil [3]. However, China doesn't differentiate between heavy oil and extra-heavy oil. The term of "*heavy oil*" is usually used by China to represent the total of both heavy oil and extra-heavy oil, implying that resources of extra-heavy oil are also included in statistics of "*heavy oil*" resources. Consequently, it is nearly impossible to find the separate analyses of extra-heavy oil resources in China. Based on this reasoning, this paper uses the term of "*heavy & extra-heavy oil*" to represent the total of heavy oil and extra-heavy oil, and treat it as unconventional oil, although part of these resources belong to conventional resources (Fig. 1).

Light tight oil refers to two different types of reservoirs: oil in shale or claystone rocks, and oil in other rocks [13,16]. Oil in the first type of reservoir is still in the formation where it was generated, i.e. source rock = reservoir. Since these kinds of rocks normally consist of shales, crude oil produced from these formations is also called "*shale oil*" (labeled as ❶ in Fig. 1) [13]. In the second type of reservoir, oil has actually migrated (from its source rock) over a relatively short distance into other, usually low permeability, rock formations, such as sandstone and carbonate rocks, i.e. source rock ≠ reservoir [13,16]. Crude oil from these kinds of formations is called "*tight oil*" (labeled as ❷ in Fig. 1) [17]. It is challenging to differentiate these two types of formations clearly due to the high degree of similarity [13]. Consequently, many studies combine both types under the term "*light tight oil*" [13,16,21].

In China, scholars tend to analyze the oil resources from the two types of formations separately [6,22]. The term "*narrow shale oil*" is used to represent oil in the first type of formations, and the term "*narrow tight oil*" is used to refer to oil from other low permeability formations [17,23]. When "*narrow shale oil*" and "*narrow tight oil*" are referred to together, the term "*broad tight oil*" is used [17,23]. In this paper, the term of "*broad tight oil*" is used.

Broad tight oil is originally divided into conventional oil, since its API degree is much higher than 10, just as IEA classified it prior to 2012 (Fig. 1) [16]. However, after 2012, IEA treat it as unconventional oil, since it is an analog of shale gas, using the similar technologies, i.e. horizontal wells and multi-stage hydraulic fracturing, and shale gas is seen as unconventional gas [24]. Therefore, this paper also treats it as unconventional oil.

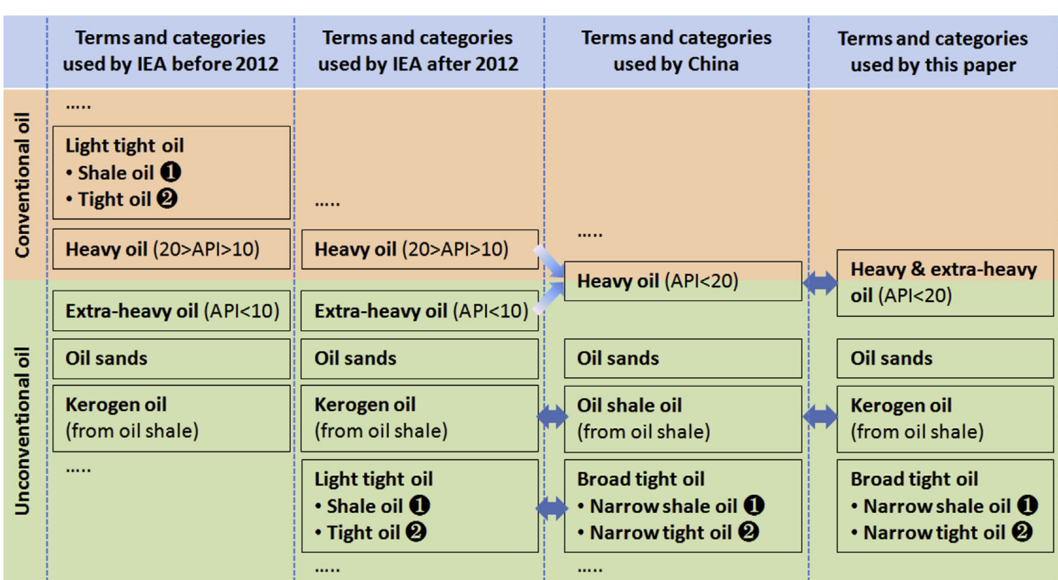

Fig. 1. The terms and categories of unconventional oil resources.

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3. Resources and production

3.1. Comments on data collection

Resource data are very important for subsequent forecast. To improve the reliability of resource data, only data from (1) peer-viewed literatures, (2) national official assessment reports released by China's authorities such as MLR (Ministry of Land and Resources of China), NDRC (National Development and Reform Commission of China), and (3) international institutes' reports such as the reports from WEC (World Energy Council), BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), IEA, U.S. EIA (Energy Information Administration), IIASA (International Institute for Applied Systems Analysis) and IPTS (Institute for Prospective Technological Studies) are collected, most of which are authoritative in oil and gas industry.

Data collected from scientific literature include original assessments made by the authors themselves, such as [6,8,22,25–27], while some are referred from some other sources, for example [7]. For the data from the national official reports, they are all original assessment results, such as assessment results of oil sands [28] and kerogen oil [29]. The methods used by literatures' authors and Chinese authorities are usually analogy method [6,8,22,25,28], volume method [26,28,29], gravimetric method [28], and all of these methods are widely used in oil and gas industry. Some international institutes estimate the resources by themselves, and the description of the assessment method can also be found in their reports, for example EIA [30], while some use data from various sources as their own data, for example IIASA [31].

To ensure the comparability after data collection, data expressed in various units were converted to the same unit in this study.

3.2. Heavy & extra-heavy oil

3.2.1. Resources and reserves

In China's oil industry, heavy & extra-heavy oil is always explored and exploited as conventional oil [7]. Furthermore, part of these resources is also included in estimates of conventional oil resources. For example, in the Third National Conventional Oil and Gas Resource Assessment created in 2003–2005, Chinese authorities estimated that the OIP and TRR (technically recoverable resource) of conventional oil are 76.50 gigatonnes (Gt) and 21.20 Gt respectively [32] However, 7.73 Gt of OIP and 1.90 Gt of TRR are heavy & extra-heavy oil resources [7,33].

To date, there have been 60 years of history of the exploration of heavy & extra-heavy oil resources, but China never has made a separate national assessment of these resources. Therefore, current resource estimates are mainly from scholars or international institutes (Table 1). It can be seen from Table 1 that all estimates of heavy & extra-heavy oil resources are from Chinese scholars, whereas all estimates of extra-heavy oil resources are from international scholars or institutes.

For total resources of heavy & extra-heavy oil, with the exception of Chen et al. [34] and Liu [35] estimates are consistent and show that OIP is 19.0–19.8 Gt (mean value: 19.64 Gt). Looking at the fourth column of Table 1, three estimates show that the value of DOIP (discovered oil-in-place) is 7.95 Gt, whereas estimates by Zou et al. [7] and Jin [36] are 6.74 Gt and 2.06 Gt respectively. Furthermore, TRR is 1.9–2.9 Gt (mean value: 2.24 Gt), according to literature. With respect to these resources, Zou et al. [7] estimate that PR (proved reserves) are 1.1 Gt.

For the extra-heavy oil resources, estimated OIP ranges from 0.57 Gt to 5.59 Gt. If the lowest and highest values of OIP are excluded, then the range of OIP will reduce dramatically and become 0.93–1.41 Gt (mean value: 1.19 Gt) (Table 1). Furthermore, the URR (ultimately recoverable resource) is estimated to be 0.11–0.39 Gt (mean value: 0.23 Gt). Of these resources, 0.10–0.12 Gt (mean value: 0.11 Gt) has been proved to be recoverable under existing economic and technical conditions, according to BGR [19], WEC [37] and IIASA [31].

Table 1
Statistics of China's heavy oil and extra-heavy oil resources.

Institutes or scholars	Type	OIP [Mt]	DOIP [Mt]	PR [Mt]	TRR [Mt]	URR [Mt]
Yang et al., 2006 [38]	Heavy & extra-heavy oil	19 800	7950	–	–	–
Jin, 2007 [36]		–	2060	–	–	–
Zhong and Chen, 2008 [9]		19 800	7950	–	1910	–
Liu, 2010 [35]		22 600	–	–	–	–
Yao et al., 2010 [39]		19 800	7950	–	–	–
Zhao, 2012 [33]		19 000	–	–	2900	–
Chen et al., 2013 [34]		30 000	–	–	–	–
Zou et al., 2013 [7]		19 800	6740	1100	1900	–
Masters et al., 1987 [40]	Extra-heavy oil	928	–	–	–	–
IPTS, 2005 [15]		573	–	–	–	109
BGR, 2009 [19]		1411	–	119	–	395
WEC, 2010 [37]		1211	–	102	–	–
Mohr and Evans, 2010 [11]		1211	–	–	–	177
IIASA, 2012 [31]		5587	–	119	–	–

Note: OIP: Oil-in-Place, DOIP: Discovered Oil-in-Place, PR: Proved Reserve, TRR: Technically Recoverable Resource; URR: Ultimately Recoverable Resource. -: not given.

In summary, current estimates, especially those from Chinese scholars, indicate that China's heavy & extra-heavy oil resources are abundant and have been discovered in 70 oilfields throughout 15 basins, with the largest deposits in Bohai-Gulf Basin, Huabei Basin, Junggar Basin and Tarim Basin [7,19]. However, it is not possible to draw a completely consistent conclusion with respect to how much heavy & extra-heavy oil resources China has from these estimates, since some estimates differ significantly. Furthermore, it is difficult to determine the reasons behind these differences because most of the reports show only a single figure for the estimated resource instead of a complete estimating process, such as is shown by Yang et al. [38], Jin [36] and Zhao [33].

3.2.2. Production

Exploration for heavy and extra-heavy oil in China started many years ago. Commercial production was not started until 1982, when the first CSS (Cyclic Steam Stimulation) pilot test was successful in Liaohe oilfield [41]. CSS is then applied frequently as one important technique, which accounts for more than 60% of the annual heavy oil production [42]. Since 1982, production of heavy and extra-heavy oil has continued to increase, and first exceeded 10 Mt in 1992. Since 1992, production has remained above 10 Mt for more than 20 years. Currently, there are five heavy and extra-heavy oil producing areas or oilfields: Liaohe, Xinjiang, Shengli, Henan, and Bohai Bay oilfields [36].

In 1996, production reached its first peak at 13.1 Mt. It then kept declining for several years, began to increase again after 2000, and reached 14.3 Mt in 2005 [43]. After 2005, it is nearly impossible to find production data in public sources. For the year 2012, several information sources can be found with widely diverging results. For example, Zou et al. [7] claim that the production in 2012 is more than 10 Mt. However, the production data in Zhang et al. [44] and CALRE [45] are 15 Mt and 50 Mt respectively. In addition, some literature points out that heavy & extra-heavy oil production usually accounts for around 10% of total oil production [36,46,47], which means the production in 2012 should be about 20.7 Mt since China's total oil production in 2012 is 207.5 Mt [1]. Therefore, the average value, i.e. 23.93 Mt ((10 + 15 + 50 + 20.7)/4), of current estimates is used to represent the 2012 production data. Then we

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can calculate a compound annual growth rate of 7.62% based on the production data of 2005 and 2012. We have then estimated production from 2006 to 2011 by assuming that production grows with an annual growth rate of 7.62% (Fig. 2).

3.3. Oil sands

3.3.1. Resources and reserves

Exploration and development of Chinese oil sands did not begin nearly as early as the heavy oil industry, and there is no national assessment for oil sands resources before 2003. Since 2003, with the rapid increase in oil prices, Chinese authorities and many scholars started to focus on the oil sands industry. In 2004–2006, China carried out its first national oil sands resource assessment [28]. The results show that OIP, DOIP, TRR and DTRR (discovered TRR) are 5.97 Gt, 2.81 Gt, 2.26 Gt and 1.22 Gt respectively [28]. These resources are distributed in 106 deposits across 24 basins in 5 major regions. Detailed resource distribution in the main basins is shown in Table 2. It can be seen from Table 2 that more than 50% of OIP and 60% of TRR are located in the Western Region. Furthermore, Junggar and Tarim Basins are the two largest basins, with 44.65% of OIP and 48.72% of TRR.

In addition, resource estimates can also be found in current literature, shown in Table 3. From Table 3, it is apparent that the results estimated by Chinese scholars (the first four shown in the table) are significantly higher than ones by international institutes or scholars. For example, OIP is estimated to be 6.0–6.1 Gt by Chinese scholars. In fact, Zhao [33] and Zou et al. [7] just refer the Chinese authorities' results, therefore, their results are similar to those in Table 2. However, OIP estimated by international institutes or scholars is only 0.09–0.27 Gt. Furthermore, only two studies estimate the PR and their results differ significantly: one is 10 Mt [7], the other is 0.14 Mt [37]. Of current studies, only Mohr and Evans [11] estimate the value of URR, which is assumed to be 15% recovery from OIP.

3.3.2. Production

Currently, China's oil sands industry is still at a preliminary stage. In 1998, a feasibility study of exploitation in Tarim Basin was performed. No real production started at that time due to the low price of oil. Since 2003, with the rising oil price, some Chinese institutes, for example, RIPED of CNPC (Research Institute of Petroleum Exploration & Development of China National Petroleum Corporation) and CUPB (China University of Petroleum in Beijing), started to analyze the features of the various oil sands basins and began developing techniques for extracting oil from oil sands [49]. Starting in 2006, China officially began to produce its oil sands in the Wuerhe Oil Deposit of Junggar Basin and the Tumuji Oil Deposit of Songliao Basin. Total production capacity is less than 0.1 Mt [28].

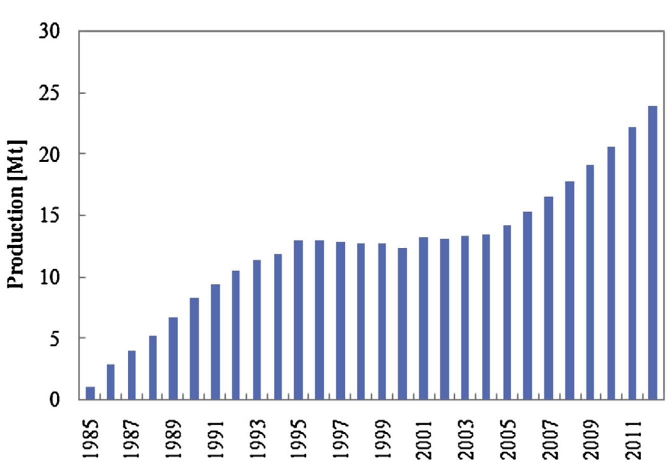

Fig. 2. Historical production of heavy & extra-heavy oil in China.
Data source: [48] (1985–1991 data); [41] (1992–2004 data); [43] (2005 data).

Table 2
Distribution of oil sands resources.

Regions	Basins	Resources (Mt)		Proportion of total (%)	
		OIP	TRR	OIP	TRR
East	Songliao	475	175	7.96	7.75
	Erlian	55	22	0.92	0.97
	Sub-total	530	197	8.88	8.72
Middle	Ordos	350	124	5.86	5.49
	Sichuan	376	154	6.30	6.82
	Sub-total	726	278	12.16	12.31
West	Junggar	1430	636	23.95	28.17
	Tarim	1236	464	20.70	20.55
	Qaidam	494	210	8.27	9.30
	Kumukuli	111	44	1.86	1.95
	Others	18	7	0.30	0.31
	Sub-total	3289	1361	55.09	60.27
South	Majiang-Weng'an	222	96	3.72	4.25
	Guizhong Depression	144	62	2.41	2.75
	Others	84	39	1.41	1.73
	Sub-total	450	197	7.54	8.72
Qingzang	Qiangtang	931	215	15.59	9.52
	Others	44	10	0.74	0.44
	Sub-total	975	225	16.33	9.96
China	Total	5970	2258	100.00	100.00

Data source: [28].

3.4. Broad tight oil

3.4.1. Resources and reserves

With the rapid development of tight oil in North America, China started to focus on its own tight oil industry and accelerate the pace of studies on resource potential and suitable technologies for exploration and development. Table 4 summaries the resource estimates of tight oil from current literature. These estimates are divided into three categories: narrow tight oil, narrow shale oil and broad tight oil. Resources in the first two categories are all estimated by Chinese scholars. Based on these estimates, OIP of narrow tight oil and narrow shale oil are 7–13.5 Gt and 10–15.5 Gt respectively, whereas TRR are 1.3–4.0 Gt and 3–6 Gt respectively. Furthermore, Zou et al. estimate PR of narrow tight oil is 0.37 Gt [7].

Resources in the third category are all from international institutes. According to these results, OIP and TRR of broad tight oil are 2.29–87.22 Gt and 0.27–8.46 Gt. Of these resources, about 0.19–0.21 Gt is expected to be recoverable with current technology and economic conditions.

The distribution of OIP of tight oil resources is shown in Table 5; it should be noted that all of these estimates are from Chinese

Table 3
Estimated oil sands resources and reserves by institutes/scholars.

Institutes/Scholars	OIP [Mt]	TRR [Mt]	PR [Mt]	URR [Mt]
Zou et al., 2013a [7]	6000	2300	10	–
Zhao, 2012 [33]	6000	2300	–	–
Zou et al., 2012a [22]	–	1000–1500	–	–
Zhong and Chen, 2008 [9]	6140	>3000	–	–
Mohr and Evans, 2010 [11]	273	–	–	40.95
BGR, 2012 [13]	–	25	–	–
BGR, 2009 [19]	253	89	–	–
IIASA, 2012 [31]	89	–	–	–
WEC, 2010 [37]	217	–	0.14	–

Table 4
Estimated tight oil resources.

Institutes/Scholars	Type	OIP [Mt]	TRR [Mt]	PR [Mt]
Liu et al., 2012 [50]	Narrow	7000–9000		
Pang et al., 2012 [8]	tight oil	11 250–13 470	–	
Jia et al., 2012a [6]		7400–8000	1300–1400	–
Jia et al., 2012b [25]		10 670–11 150	–	–
Zou et al., 2012a [22]		–	3500–4000	–
Zou et al., 2012b [27]		11 000–13 500	–	–
Zou et al., 2013a [7]		–	2000–2500	370
Zou et al., 2012a [22]	Narrow	>10 000	–	–
Zou et al., 2013a [7]	shale oil	–	3000–6000	–
Zou et al., 2013b [20]		11 500–15 500	3000–6000	–
BGR, 2009 [19]	Broad	2290	427	210
IIASA, 2012 [31]	tight oil	2290	–	191
McGlade, 2012 [51]		–	273–8458	–
EIA/ARI, 2013 [30]		87 722	4393	–
IEA, WEO2013 [3]		–	4393	–

scholars. From Table 5, we can see that narrow tight oil resources are distributed in 10 basins in 3 major regions. Of these basins, Ordos, Junggar, Bohai Bay, Songliao, Sichuan and Qaidam are the largest, each with OIP of more than 1 Gt. Of these regions, the Western Region has the largest potential, with OIP of 3.52–6.47 Gt.

According to the analyses of Zou et al. [20] and Yang et al. [26], narrow shale oil resources are distributed in 11 basins of 3 major regions. Further analyses show that Ordos, Junggar, Bohai Bay, Songliao and Sichuan are the five biggest basins, with OIP exceeding 2 Gt for each of them (Table 5). In these 3 regions, the Eastern Region has the highest resource potential with estimated OIP of 4.3–5.6 Gt.

By summing resource volumes of narrow tight oil and narrow shale oil, we can get the resources quantities of broad tight oil. Our results show that OIP of broad tight oil is 18.98–32.51 Gt, distributed in 13 basins of 3 major regions in China (Table 5). Comparison of OIP data of broad tight oil in Tables 5 and 4 shows that estimates from Chinese scholars are significantly higher than those of BGR [19] and IIASA [31], but dramatically lower than the estimate of EIA/ARI [30].

3.4.2. Production

Broad tight oil is seen as unconventional oil, since it is an analog of shale gas, using the similar technologies, i.e. horizontal wells and multi-stage hydraulic fracturing, and shale gas is seen as unconventional gas [24]. However, several years ago, it was classified as conventional oil, just as IEA classified it prior to 2012 [16]. The situation in China is similar.

China's first barrel of narrow tight oil was produced in the 1960s in Guihua Oilfield, Sichuan Basin. Production of this field amounted to 645.93 tonnes in 2008, with a cumulative production of 47835.64 tonnes from 1960s to 2008 [54]. This production was recorded as conventional oil, however [55]. Currently, Yanchang Formation in Ordos Basin and Jurassic Reservoir in Sichuan Basin are the only two mature and realistically large-scale development areas with exploitation of narrow tight oil [8]. For narrow shale oil, there is still no record of exploration and development in China [56].

Table 5
Distribution of OIP of broad tight oil resources in China.

Regions	Basins	Narrow tight oil [Mt]	Narrow shale oil [Mt]	Broad tight oil [Mt]
East	Songliao	1580–2130	2000–2500	3580–4630
	Bohai Bay	980–2540	2000–2500	2980–5040
	Jianghan	–	100–200	100–200
	Nanxiang	–	100–200	100–200
	Subei	–	100–200	100–200
	Sub-total	2560–4670	4300–5600	6860–10 270
Middle	Ordos	1900–4060	1000–3500	2900–7560
	Sichuan	1000–1800	1500–2000	2500–3800
	Sub-total	2900–5860	2500–5500	5400–11 360
West	Junggar	1200–2900	2000–2500	3200–5400
	Tarim	1590	–	1590
	Qaidam	360–1046	500–800	860–1846
	Jiuquan	180–230	200–300	380–530
	Santanghu	90–560	300–500	390–1060
	Turpan-Hami	100–150	200–300	300–450
	Sub-total	3520–6467	3200–4400	6720–10 867
China	Total	8980–17 006	10 000–15 500	18 980–32 506

Data source: narrow tight oil: [6,8,25,26,52,53]. Narrow shale oil: [20,26]. Broad tight oil = Narrow tight oil + Narrow shale oil.

3.5. Kerogen oil

3.5.1. Resources and reserves

In 2004–2006, China undertook its first national kerogen oil resources evaluation [18]. Based on its evaluation results, China has vast and widespread kerogen oil resources in 80 deposits across 47 basins [29]. Total OIP and TRR of kerogen oil are 47.64 Gt and 11.98 Gt, respectively. Of them, DOIP and DTRR are 2.74 Gt and 1.09 Gt (Table 6). At this point, PR of kerogen oil is only 0.3 Gt [29].

Table 6 shows the distribution of kerogen oil resources. By region, OIP is distributed as follows: East (35.19%), Qiangzang (26.57%), Middle (20.56%) and West (15.28%); TRR has the same distribution as OIP. By contrast, DOIP and DTRR are mainly located in the East and South. Taking DOIP as an example, these two regions account for 90.44% of total DOIP.

In Table 6, the total amount of OIP and TRR are shown as 47.64 Gt and 11.98 Gt, as estimated by Chinese authorities. These amounts are cited by many Chinese scholars and some international institutes. Because of this, the OIP and TRR values estimated by many studies (see the first six shown in Table 7) are nearly the same as those in Table 6. However, PR indications differ among the varying authors. For example, PR indications are 1.34 Gt in WEC [18], but are

Table 6
Kerogen oil resources from Chinese authorities and their distribution.

Regions	Basins	OIP [Mt]	DOIP [Mt]	TRR [Mt]	DTRR [Mt]
East	Songliao	15 413	1366	3823	400
	Fushun	215	215	126	126
	Dayangshu	374.42	0.02	105.32	0.02
	Dunmi	75	48	31	24
	Luozigou	65.95	15.04	20.65	7.28
	Yilan-Yitong	55.78	3.57	12.61	1.65
	Yangshugou	33.19	17.24	13.23	9.04
	Others	534.46	263.4	177.48	107.96
	Sub-total	16766.8	1928.27	4309.29	675.95
Middle	Ordos	9620	118.15	2353.16	36.53
	Sichuan	171.85	0	48.34	0
	Others	2.83	2.83	0.76	0.76
	Sub-total	9794.67	121.01	2402.25	37.28
West	Junggar	5452	32	1521	13
	Qaidam	1632.3113	6.8813	367.67	1.99
	Minhe	138.32	52.51	42.73	18.15
	Others	55.5087	41.5387	14.45	15.24
	Sub-total	7278.14	132.93	1945.85	48.38
South	Maoming	1001	418	377	235
	Beibu-Gulf	133.83	131.38	93.35	92.7
	Others	11.09	3.76	3.12	1.31
	Sub-total	1145.92	553.14	473.47	329.01
Qingzang	Qiangtang	3995.5	8.32	899.33	2.21
	Lunpola	8662.61	0	1949.09	0
	Sub-total	12658.11	8.32	2848.41	2.21
China	Total	47643.64	2743.67	11979.27	1092.83

Note: DTRR: Discovered Technically Recoverable Resources.
Data source: [29].

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Table 7
Estimated kerogen oil resources and reserves by institutes/scholars.

Institutes/Scholars	OIP [Mt]	TRR [Mt]	PR [Mt]	URR [Mt]
Zou et al., 2012a [22]	47 600	–	–	–
Zou et al., 2013a [7]	47 600	12 000	1460	–
Zhao, 2012 [33]	47 600	12 000	–	–
Che et al., 2008 [58]	47 640	11 980	–	–
Liu et al., 2009 [10]	47 600	–	2000	–
WEC, 2013 [18]	47 600	–	1344	–
Qian et al., 2010 [57]	–	–	2800	–
Mohr and Evans, 2010 [11]	45 020	–	–	30 100
BGR, 2009 [19]	2290	639	–	–
IPTS, 2005 [15]	2290	–	–	–

2.8 Gt in Qian et al. [57]. Furthermore, both of these indications are much higher than 0.3 Gt estimated by Chinese authorities.

In addition, Mohr and Evans [11], BGR [19] and IPTS [15] also analyzed Chinese kerogen oil resources (Table 7). However, their results differ sharply. Mohr and Evans [11] forecast that OIP of China's kerogen oil is 45.02 Gt, which is close to the Chinese authorities' result, and the URR is 30.01 Gt (calculated by applying a final recovery rate of 65% to OIP). By contrast, both BGR [19] and IPTS [15] forecast that OIP is only 2.29 Gt, which is significantly lower than others. Furthermore, TRR reported by BGR [19] is only 0.639 Gt, which is also significantly lower than results of Chinese authorities.

3.5.2. Production

The Chinese kerogen oil industry was first established in the 1920s in Fushun, Liaoning Province [59]. The Fushun-type retort, combined with pyrolysis and gasification sections, was then developed to extract kerogen oil from produced oil shale. Between 1930 and 1945, 200 Fushun-type oil shale retorts were built, and the highest production reached 0.25 Mt [60]. At the end of 1950s, there were a total of 266 Fushun-type retorts in operation, and total kerogen oil production from Fushun Refineries reached 0.60 Mt, which was the highest production in the history of Fushun. Fushun was also the biggest kerogen oil producing area in the world during that period [60,61]. In addition to Fushun, some other retorts with smaller capacity were also operated in Maoming in Guangdong province, Huadian and Luozigou in Jilin province [62].

After 1960, with the discovery of Daqing oilfield, Chinese conventional oil industry entered a period of rapid development. Kerogen oil production began a long decrease until 1995, due to the rapid increase in cheap conventional oil production [60]. During this period, some oil shale refineries, such as Maoming and Fushun refineries Nos 1 and 2, nearly shut down [59]. Since 1995, with the rapid increase of Chinese oil demand and rising dependence on imported oil, the kerogen oil industry began to come back to life and production began to rise again, although the rate of increase was still very low. Beginning in 2003, the price of international crude oil started to rise rapidly. Because of the high oil prices, many projects in Huadian, Luozigou, Fushun, Maoming and Longkou were put into operation one after another [62]. As a result, total production of kerogen oil began to increase rapidly after 2005 and reached 0.70 Mt in 2012, with an average growth rate of 22.67% between 2005 and 2012 (Fig. 3). By the end of 2012, the total cumulative production of kerogen oil reached 21.57 Gt.

Currently, China is the largest producer of kerogen oil in the world [18]. There are a total of 7 major oil shale retorting facilities in China: Fushun, Huadian, Wangqing, Baipiao, Longkou, Yaojie and Dongning, located in 5 different provinces [63].

4. Modeling approach

4.1. Geologic Resources Supply-Demand Model

In this paper, the Geologic Resources Supply-Demand Model (GeRS-DeMo) is used to model the future production of China's four types of unconventional oil. GeRS-DeMo was originally developed by Mohr [68]. The model has been used to successfully develop projections for coal, conventional and unconventional oil, conventional gas and unconventional gas, lithium, phosphorus, copper and various other metallic and mineral resources [12,68–73]. A full and detailed description of GeRS-DeMo can be found in Mohr [68].

There are two key modes in GeRS-DeMo, namely static mode and dynamic mode [68]. Supply and demand do not interact in static mode, whereas they are influenced by each other in dynamic mode [69]. For China, based on previous analyses future oil demand is large enough, i.e. China can consume any quantity of unconventional oil that can be produced profitably at the international oil price. Furthermore, it seems likely that Chinese unconventional oil

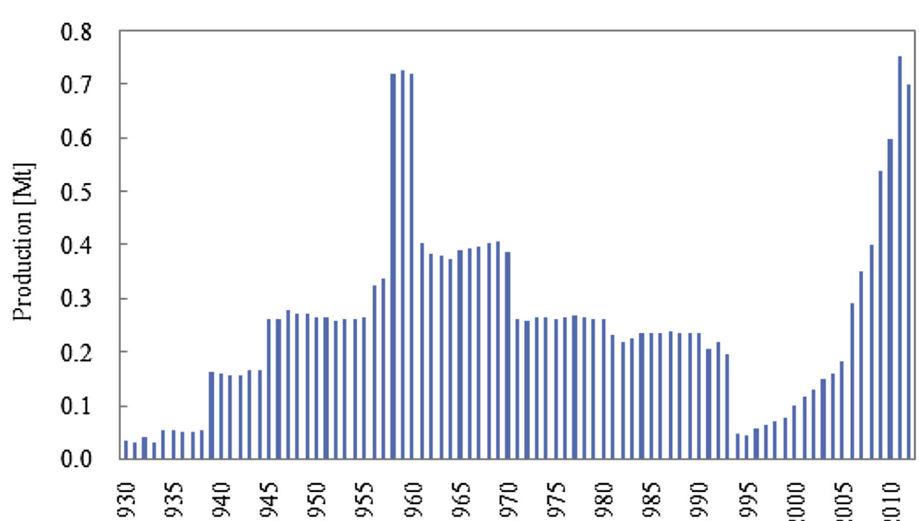

Fig. 3. Historical production of China's kerogen oil. Note: Kerogen oil production in 1930–1995 is calculated by multiplying [64]'s data by 0.031 because [64]'s data is oil shale production, and Qian et al. [59] claims that it takes about 33 tons oil shale to produce 1 metric ton of oil.
Data source: [64] (1930–1995); [65] (1996–2010 data); [66] (2011 data); [67] (2012 data).

Table 8
Resources Scenarios used in this article.

Type	OIP [Gt]	TRR [Gt]	PR [Gt]	Cumulative Production [Mt]	URR scenarios [Gt]	
					High	Low
Heavy & extra-heavy oil	19.64	2.24	1.1	352.39	2.24	1.452
Oil sands	5.97	2.26	0.01	1*	2.26	0.011
Broad tight oil	25.74	6.95	0.37	1*	6.95	0.371
Kerogen oil	47.64	11.98	0.3	21.57	11.98	0.322

Note: data with * is assumed by authors since no available data can be used.

producers can produce as much as oil as they can profitably produce at the international oil price without saturating Chinese oil demand. In addition, one main purpose of this paper is to estimate the potential maximum production capacity of China's unconventional oil. Because of these considerations, the static mode has been chosen for this paper.

In addition, GeRS-DeMo has two distinct production methodologies: one for mining and the other for production from fields. In terms of broad tight oil and heavy and extra-heavy oil, production was determined using the fields' component, and kerogen and oil sands production was determined by the mining component. The reason for using the mining model for kerogen is because historic production to date has been via conventional mining techniques and this method of extraction has been assumed to be used for future extraction of kerogen in China. For oil sands, by far the biggest producer in the world to date has been Canada, where both conventional mining techniques and in-situ methods are used. Although the in-situ methods are not a form of conventional mining, the production profile of individual in-situ operations have a very similar profile to that of conventional mining techniques and for this reason the mining component of the model is used to model both in-situ and mining productions of oil sands. The two components of GeRS-DeMo are described briefly in the Appendix A.

4.2. Resources scenarios

A very important input variable is Ultimately Recoverable Resources (URR), i.e. the total amount of unconventional oil that is extracted technically and economically over time [68]. In this paper, two scenarios are used to develop projections of unconventional oil. One is high scenario, i.e. TRR is used to represent the URR, however, it should be noted that TRR is likely higher than the actual URR since TRR is estimated by only considering current and future technical factors, without consideration of feasibility of extraction at international oil prices. For example, TRR will include oil that is far distant from needed water supplies and oil that lies under cities that would need to be moved. The other one is low scenario. In this low scenario, "PR + Cumulative Production" (or PR + CP) is used to represent the URR. This estimate 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 oil that is currently undiscovered.

Table 8 summarizes the resource scenarios used in this paper. The amounts of heavy and extra-heavy oil resources are based on Table 1; cumulative production is calculated by summing production from 1985 to 2012. Resources relating to oil sands and kerogen oil are mainly based on national resource assessments implemented by Chinese authorities. Furthermore, the PR of oil sands estimated by Zou et al. [7] is used since they estimate this figure based on the same OIP and TRR as China's authorities. In addition, OIP of broad tight oil is based on Table 5, whereas TRR and PR are based on Table 4 (TRR of broad tight oil is calculated by summing the average TRR of narrow tight oil and the average TRR of narrow shale oil). Other detailed information can be found in previous sections.

5. Forecast results and discussion

5.1. Forecast results

Fig. 4 and Table 9 show the estimates of China's long-term unconventional oil production, based on this model. In the TRR scenario, total unconventional oil production will keep increasing rapidly until to 2068, when it reaches a peak of 0.351 Gt, which is 1.69 times China's current total oil production (In 2012, China's total oil production was 0.2075 Gt [1]). Looking at the components of the total unconventional oil production, it can be seen before 2035, heavy and extra-heavy oil is the largest source of unconventional oil production. After 2035, broad tight oil takes the lead, replacing heavy and extra-heavy oil in its role. In 2072, the proportion of kerogen oil in total unconventional oil reaches 44.26% and becomes the largest production source. In the PR + CP scenario, total unconventional oil production is projected to increase in the next decade and then peak at 0.048 Gt in 2023. In this scenario, most produced oil comes from heavy and extra-heavy oil resources, whereas oil sands and kerogen oil only make a marginal contribution to total unconventional oil production.

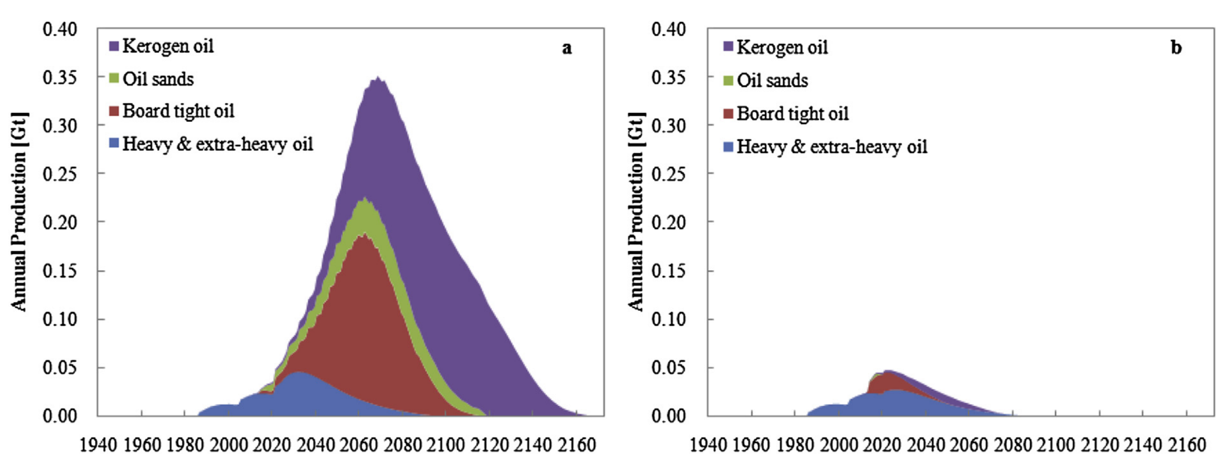

Fig. 4. Forecast results for China's unconventional oil production by different types under two scenarios. a-TRR scenario; b-PR + CP scenario.

Table 9
Peak year and Peak production of Chinese unconventional oil production.

Scenarios	Types	Heavy & extra-heavy oil	Broad tight oil	Oil sands	Kerogen oil	Total
TRR scenario	URR [Gt]	2.24	6.95	2.26	11.98	23.43
	Peak year	2031	2062	2070	2086	2068
	Peak production [Gt]	0.0464	0.1746	0.0381	0.1677	0.3511
PR + CP scenario	URR [Gt]	1.452	0.371	0.011	0.322	2.156
	Peak year	2025	2020	2017	2047	2023
	Peak production [Gt]	0.0278	0.0204	0.0027	0.0084	0.0487

5.2. Discussion of results

5.2.1. Impacts of uncertainties of resources on production growth

By comparing Fig. 4a and b, it can be seen that there are significant differences in forecast results, for example in peak year and in peak production. The main reason for the difference is the value of URR we used: 23.43 Gt in Fig. 4a and 2.156 Gt in Fig. 4b. Therefore, the first step to increase the unconventional oil production is to increase the volume of unconventional oil that can be produced technically and at a sufficiently low price, i.e. URR.

As we have discussed previously, neither TRR nor PR + CP is the actual URR. The TRR scenario looks magnificent. However it is very difficult to achieve the results shown in the TRR scenario. The first reason is that in the TRR scenario, only 7.6% of these resources can be extracted technically at current price levels; nearly 90.8% of these resources are only estimated to be recovered technically, without consideration of price levels. Furthermore, most of these resources haven't yet been discovered. Taking kerogen oil as an example, it can be seen from Table 8 that kerogen oil has the largest resource potential, with the TRR of 11.98 Gt. However, of these resources, only 1.09 Gt has been discovered, and 10.89 Gt is yet to be discovered [29]. Discovering and extracting these resources needs not only advanced exploration and exploitation techniques, but also massive capital investment and in many cases, higher prices than today's oil prices. However, there are significant uncertainties with respect to future economic conditions and capital investments.

With respect to economic conditions, world oil prices have remained flat at approximately $110 per barrel (Europe Brent Spot Price FOB (Free On Board)) since 2011 [74], while a major portion of extraction costs is rising rapidly (exploration and production capital expenditures have risen at a compound annual growth rate of 10.9% per year since 1999) [75]. Some companies are finding current oil prices too low to justify as much investment as in the past. The company “Total” has been in the news recently for cutting its losses in the Canadian oil sands [76]. For the future, some studies have shown that future oil price may not be expected to rise indefinitely, for example, Tverberg [77].

With respect to capital investments, the IEA's latest report “World Energy Investment Outlook 2014” indicates that the world needs $48 trillion in investment to meet its energy needs between now and 2035. Most of this amount will be used in the fossil fuel industry, to offset declining production from existing oil and gas fields [78]. IEA's estimate doesn't include other investments, such as relocation costs due to moving people from the affected areas. Therefore, the actual required investment is likely more than IEA's indicated amount. Unconventional oil is expensive to produce, and many of its costs are front-ended. Thus, expansion of unconventional oil production is especially likely to lead to a high need for investment capital.

5.2.2. Impacts of environment issues on production growth

Another potentially significant constraint on future development of unconventional oil resources is environment issues. Farrell and Brandt [79] claim that environmental risk is a major risk in the transition away from conventional oil to sources such as unconventional oil and coal-to-liquids. The first major environmental concern is the higher GHG (Greenhouse Gases) emissions in the extraction and processing of unconventional oil compared to conventional oil [79–83]. For example, Mangmeechai [84] shows that the life cycle GHG emissions of oil shale surfacing mining, oil shale in-situ process, oil sands surface mining and oil sands in-situ process are 43%–62%, 13%–32%, 5–22% and 11%–13% higher than those of U.S. domestic conventional crude oil.

The other major concern relates to water availability and quality. Taking broad tight oil as an example, the main technique used in exploiting it is hydraulic fracturing, in which high-pressure fracturing fluid, usually a water-based fluid mixed with sands and other chemical additives, is injected into the shale formation to increase fissures in the rock. This process could be water-intensive. Current studies show that it may need 7.6–37.8 million liters (average: 20 million liters) of water per well per fracture [85–87]. Besides, the other technique, horizontal drilling which is also a well-known technique used in broad tight oil industry, also needs large volumes of water, since drilling fluid is also water-based. For each well, the actual quantities of water use depend not only the number of times of fracturing (a well may need several times of fracturing), but also the length of the drilled lateral. Large scale drilling and fracturing activities in US have already raised serious public concerns about the depletion of regional water resource [85,87]. A recent study released by WRI (World Resources Institute) first analyzes water availability across all potentially commercial shale gas and broad tight oil worldwide, and highlights that the water availability is a very important constraint limit the ability to develop these unconventional resources [88]. And in its report, China is labeled as “high” average exposure to water stress over the broad tight oil play area [88].

Compared to the water availability, the impacts of hydraulic fracturing on water quality could be much more serious and should be given more attention [89]. The fracturing fluid contains a lot of different types of chemical additives, and many of them are toxic, carcinogenic or mutagenic, and many other compositions are not disclosed, which may contains some other hazardous substances [86,87]. This fracturing fluid enters into the formation, and some will stay in the formation, while some will return to the surface as flowback. Besides, the flowback fluid may be also accompanied by the formation water, which has been there for millions of years and includes constituents such as natural salts, benzene, heavy metals, naturally occurring radioactive material [86,89–91]. The leaks and spills of these flowback fluids and inadequate treatments of them may pollute the ground and surface water, posing risks to ecosystems and public health [89]. For example, one study shows that the median concentration of barium in flowback water in Marcellus shale play exceeded 200 times the U.S. 'sEPA (Environmental Protection Agency) maximum concentration limit of barium in drinking water [92]. A number of studies have analyzed these impacts on water quality and some comprehensive and detailed analyses can be found in Refs. [89,93].

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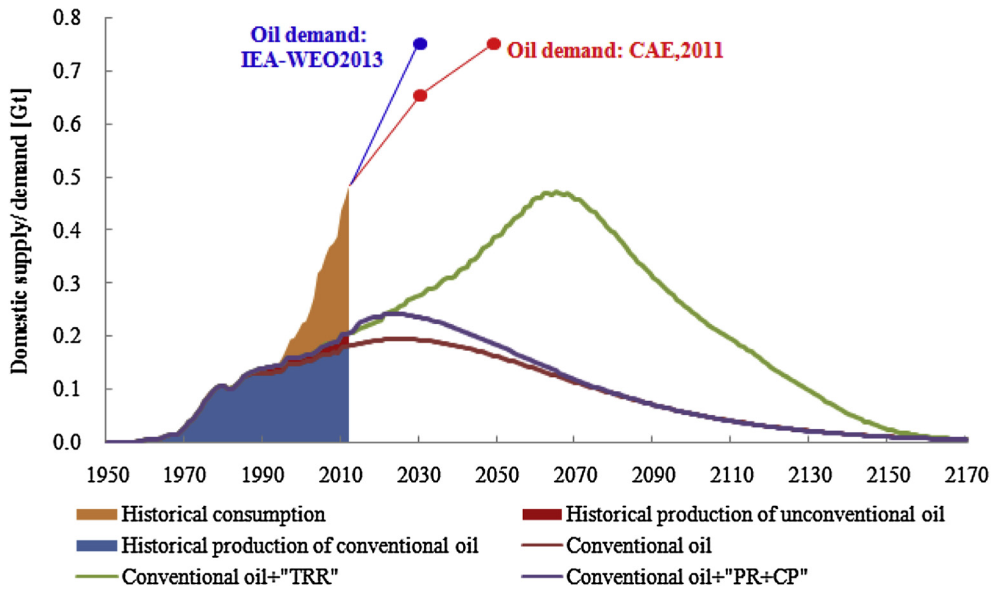

Fig. 5. China's domestic oil supply and its future demand.
Data source: historical production and consumption data from NBSC (National Bureau of Statistics of China) [98] and BP (British Petroleum) [1]; future conventional oil production is forecast by applying the multi-cycle Generalized Weng model (two-cycle), which has proved to be suitable for China's fossil fuels [99] and has been used to forecast China's conventional gas production [95]. A detailed description of this model can be found in Wang et al. [99] or Wang et al. [95]. The URR of China's conventional oil used in multi-cycle Generalized Weng model is calculated to be 21.2 Gt (this data is based on the third national conventional oil and gas resources assessment [32]) minus 1.9 Gt (this data is the TRR of heavy oil which is included in conventional oil resources [32,33]). The results of oil demand are from IEA [3], and CAE [2], which we have shown previously.

China must take a more prudent approach toward the development of its unconventional oil resources, facing the challenges of a reduction in target carbon emissions, serious smog since 2013, and limited water resources [94–97].

5.3. Implications for China's energy security

Fig. 5 shows the potential impact of the increase in unconventional oil production on China's oil security. It can be seen that production in the “PR + CP” scenario makes little contribution to future total oil supply and oil security, whereas production in the TRR scenario can change total supply curve significantly and greatly improve oil security. In the TRR scenario, total oil production will increase steadily until 2065, reaching peak production of 0.47 Gt. However, even if the lower oil demand is considered (i.e. oil demand from CAE) and higher total oil supply (i.e. conventional oil + “TRR” in Fig. 5), the gap will still reach 0.36 Gt in 2050, which is 1.3 times as much as the amount of oil imported by China in 2012. CAE [2] indicates that their forecast for China's long-term oil demand is conservative, so future oil demand will very likely to be higher, perhaps similar to the IEA's indication [3]. On the other hand, as discussed in 5.2, future oil production in the TRR scenario is very difficult to achieve because of the many uncertainties and potential environmental constraints. Therefore, China's need for imported oil is likely to rise in the future, even with a rapid increase in unconventional oil production.

6. Concluding remarks

The findings can be summarized as follows:

1) A comprehensive and systematic investigation of China's unconventional oil resources was performed. The result shows that total OIP of Chinese unconventional oil is about 98.99 Gt, 1.44 times as much as the amount of total OIP for conventional oil (excluding the heavy oil resource which is included in conventional oil resources). Furthermore, 23.43 Gt of total OIP can be recoverable technically. Of these resources, 0.38 Gt has been produced, and 1.78 Gt has been proved to be currently recoverable technically and economically.
2) Two scenarios (namely TRR scenario and PR + CP scenario) are used to quantitatively analyze future possible production of China's unconventional oil resources. The result shows that production will increase significantly in the future and reach its peak in 2068 at 0.35 Gt in the TRR scenario, whereas the peak production in the PR + CP scenario will appear in 2023 and is only 0.05 Gt, which is significantly lower than peak production in the TRR scenario.
3) Potential challenges regarding future production of unconventional oil are also presented. It can be concluded that production of the TRR scenario is likely to be challenging to achieve because of significant uncertainties in availability of resources, cost issues, and environment issues. The biggest environmental issues are expected to be GHG emissions and availability of water resources.
4) The expected contribution of future production growth in unconventional oil to China's total oil supply and its oil security is also shown. It can be claimed that production in the TRR scenario can increase total production and improve oil security considerably, whereas the PR + CP scenario only presents a marginal contribution. However, the higher production in the TRR scenario does not mean that China can solve its oil shortage by simply relying on unconventional oil.

Acknowledgments

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Appendix A. Briefly description of two components of GeRS-DeMo

The two components of GeRS-DeMo are described here. Note, the model operates on a discrete time basis updating all variables each year, however in order to make the equations less complex to explain they are presented as though time was continuous.

Fields component ([12,68]):

For the fields component, production is determined by summing the production for all fields production. The profile of an individual fields production is shown in Fig. A1, and is completely determined based only on the URR of the field. In particular:

1) The time to ramp production up from no production to the production plateau is set to a constant of 1 year.
2) 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).
3) 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 fields URR (again this fraction is constant for all fields).
4) The field is shut down when production reaches 1% of the plateau production level.

The number of fields n_f for a region is inputted by the user, so to determine production we need to know the URR of each field and the year the fields came online. The URR of each field is determined by a power law relationship between the exploitable URR Q_E (that is the amount of URR in the first n fields) versus the number of fields n brought online, namely:

$$\frac{Q_E(n)}{URR} = \left(\frac{n}{n_f}\right)^{p_f}.$$

The URR of the *n*-th field istherefore the difference between the exploitable URR for *n* fields and the exploitable URR in *n-1* fields. Note that p_f is typically set to 0.35 and for p_f greater than 0 and less than 1 the URR of the *i-1* field is bigger than the URR of the *i*-th field for all *i*.

The number of fields online at any given time, $n(t)$ is determined linearly from the cumulative production of the fields, $CP(t)$, specifically:

$$n(t) = \left\lceil r_f n_f \frac{CP(t)}{URR} \right\rceil.$$

where r_f is a rate constant typically set to 0.95. It is assumed that in the start year the first field is brought online.

Mining component ([68])

For the mining component, production is determined by summing the production for all individual mines production. The profile of an individual mines production is shown in Fig. A2, in particular:

1) A 4 year ramp up to the maximum production level
2) The mines production level and mine life are determined by the technology
3) A 4 year ramp down to ceased production at the end of the production life.

The size and lifespans of mines change over time as new technologies have made it easier to mine ever greater quantities of resources. As a result of this technology, the maximum production level and mine life are determined by the technology functions using the year the mine in brought on-line, specifically the mines maximum production level $M_P(t)$ is:

$$M_P(t) = \frac{M_H + M_L}{2} + \frac{M_H - M_L}{2}\tanh(r_t(t - t_t))$$

And the mine life $L_M(t)$ is:

$$L_M(t) = \frac{L_H + L_L}{2} + \frac{L_H - L_L}{2}\tanh(r_t(t - t_t))$$

where r_t and t_t are the technology rate constant and time constants, M_L and M_H are the minimum and maximum mine production levels and L_L and L_H are the minimum and maximum mine lives and all of these variables are inputted by the user. Note that in year t_ta new mines production level and mine life are half way between the minimum and maximum levels.

The production of a region is determined by summing the production of the individual mines, hence the only thing left to determine is the number of new mine is brought on-line in a given year. This is achieved via the exploitable URR and an estimation for the exploitable URR, first as before let $Q_E(n)$ denote the amount of URR in the first *n* mines. Now let $Q_e(t)$ denote the estimated amount of exploitable URR, described as:

$$Q_e(t) = \frac{URR - URR_1 e^{-r_Q}}{1 - e^{-r_Q}} - \frac{URR - URR_1}{1 - e^{-r_Q}} e^{-r_Q \frac{CP}{URR}}$$

where URR_1 is the URR in the first mine (that is assumed to be placed on-line in the start year), and r_Q is a rate constant. This function denotes an exponential function with the following properties:

1) The estimated exploitable URR when the cumulative production is zero is URR1 namely the URR of the first mine brought online.
2) The estimated exploitable URR is the URR when the cumulative production reaches the URR.
3) The exploitable URR is always greater than or equal to the cumulative production.

Note that from the profile of the mines and the technology functions, the URR of a mine brought on-line in year *t* is: $M_P(t)$ $(L_M(t)$-4).

With the exploitable URR the number of mines α brought online in year *t* can be determined from the inequality:

$$(\alpha - 1)M_P(t)(L_M(t) - 4) < Q_e(t) - Q_E(t - 1) \le \alpha M_P(t)(L_M(t) - 4).$$

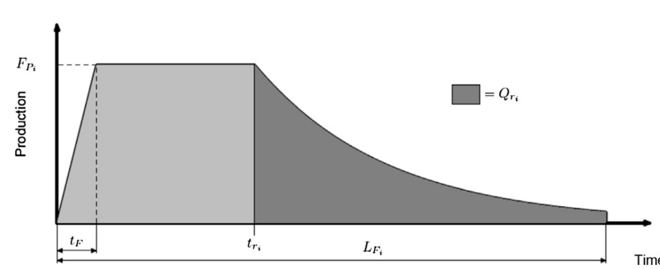

Fig. A1. The production of an individual field.

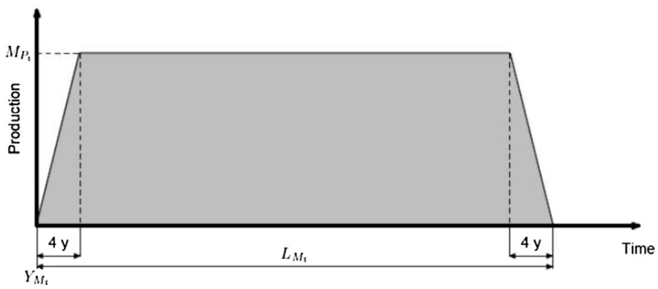

Fig. A2. The production profile of an individual mine.

Appendix B. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2014.12.042.

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