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Chinese coal supply and future production outlooks

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Abstract

The energy supply of China is completely dominated by coal, making future coal production projections for China important. Recent forecasts suggests that Chinese coal production might reach a peak in 2010-2039 with widely different maximum production levels. Estimated ultimately recoverable resources (URR) significantly influence the projections. However, widely different URR-values were used and due to poor understanding of the Chinese coal classification. To mitigate these shortcomings, a comprehensive investigation of this system and analysis of historical evaluation of resources and reporting issues are performed. A more plausible URR is then derived, indicating that many analysts underestimate volumes available for exploitation. Projections based on the updated URR using a modified curve-fitting model indicate that Chinese coal production could peak as early as 2024 at a maximum annual production of 4.1 Gt. By considering other potential constraints, it can be concluded peak coal in China appears inevitable and immediate. This event can be expected to have significant impact on the Chinese economy, energy strategies and greenhouse gas (GHG) emissions reduction strategies.

Key words: Chinese coal, production modelling, resource/reserve classification

1. Introduction

Chinese energy supply is completely dominated by coal. In 2010, China produced 3.24 billion metric tons (Gt) of coal, making up 76.5% of the total Chinese energy production and consumed 3.39 Gt coal, equal to 68.0% of its energy consumption [1]. In all foreseeable future, coal will remain the dominating fuel and demand is likely set to continue increasing [2, 3]. Therefore, reasonable analysis of future coal production trajectories is helpful and necessary for China.

Coal, like any non-renewable resource, is limited. This implies that the resource gets depleted and at some point in time, annual extraction will cease to grow. This means that availability of extractable coal must be considered in long-term production projections. Recently, several studies have given their attention to such long-term production trends for Chinese coal by applying similar curve-fitting models but with widely diverging URR figures [4-11]. The resulting outlooks are affected the used URR values and varies considerably. To bring clarity to this situation, a more plausible URR value is needed.

An investigation of current literature indicates that the quality of URR data used by most studies is - unfortunately - poor. Two main reasons are found. The first is poor understanding of the Chinese coal classification system due to its complexity and inconsistency with more internationally established frameworks. The second is use of available information. In many cases, analysts choose to rely on the reported data presented by some international institutes or energy companies, such as World Energy Council (WEC) or BP [4, 6]. However, these are apparently poor sources as the Chinese coal reserves have basically been constant since 1992 despite rapid production increases. These problems need to be illuminated, discussed and alleviated to better address the Chinese coal question and its importance.

The purposes of this article are:

- A comprehensive review of the Chinese coal classification system and its differences compared to international frameworks;
- A time evolution study of historical resources/reserves assessment results and comparison of reported data from different authorities to show development over time and highlight internal reporting inconsistencies;
- A plausible URR will be estimated under the latest evaluation and classification. This figure will be compared to URR figures used in recent coal studies;
- A modified curve-fitting model that considers potential constraints from depletion rate of remaining recoverable resources is used to produce an improved long-term production outlook;
- Other possible restricting factors on Chinese coal production are also discussed, as well as possible implications of for China.

2. Chinese coal classification system

There are few available overviews of the classification system used by China to assess its coal resources. This section describes the historical development of the Chinese classification system and compares it to other frameworks in use worldwide.

2.1 Development and overview

The Chinese classification system for mineral reserves and resources is derived from the framework originally used by the Former Soviet Union (FSU) [12]. In 1954, *Solid Mineral Reserve Classification Standards* of FSU was reprinted by National Mineral Reserve Committee of China (NMRC) as the main reference for the Chinese classification systems [13]. In April 1959, the first formal Chinese standard of *Provisional Specifications for Mineral Reserve Classification (General Principles)* was issued [13]. Thereafter, China has made several modifications of its classification systems in June 1977, December 1992, June 1997, June 1999, August 2002, July 2009, and November 2010 [14, 15].

Before 1999, the Soviet and the Chinese classification systems were similar as both countries used centrally planned economic systems [16]. As a result, the main purpose of exploration activities was to identify the quantities of mineral resources available for the central government and these systems are based primarily on geological and technological conditions, with little attention being paid to economic factors [17]. The old framework made comparison with other countries using more market-oriented classification systems difficult [16].

As China was reformed and developed, it became urgent to revise this old system to better address the requirements of the new economic policy. An improved foundation for exploitation of Chinese mineral resources was created and the new framework called *Classification for Resources/Reserves of Solid Fuels and Mineral Commodities (GB/T 17766-1999)* was adopted as a national standard in June 1999 to mitigate the shortcomings of the earlier system [18]. The new system was based on the *United Nations International Framework Classification for Reserves/Resources (ENERGY/WP.1/R.70)* [19] and *Principles of a Resource/Reserve Classification for Minerals* [20]. A document called *General Requirements for Solid Mineral Exploration (GB/T 13908-2002)* contains detailed rules for implementation of the new classification system and was released in August 2002 [21].

Further modifications of the *GB/T 17766-1999* system followed in 2007 and a revised draft (named *GB/T 17766-revision*) was released in July 2009 to the public to solicit opinions from all sides. Even after receiving feedback, the government did not formally release a revised edition until November 2010, when *Specification for Comprehensive Exploration and Evaluation of Mineral Resources (GB/T 25283-2010)* was presented as a complement to *GB/T 13908-2002* with additional guidelines for implementing the classification system of GB/T 17766-1999. Currently, *GB/T 17766-1999* is the first consistent framework that evaluated Chinese coal resources based on expected economics of extraction as well as geology and technological feasibility. It divides the resources into three major categories: *reserves*, *basic reserves* and *resources* [21]:

- *Reserves* are the minable part of basic reserves on which the factors such as economic, mining, metallurgical, environmental, legal, marketing, social and governmental has been considered and corresponding modification has been made during the feasibility study, pre-feasibility study and preparation of the annual mining plan. The results demonstrate that this part is economically minable; it is expressed by actual minable tonnage or volume, from which the losses of designing and mining have been deducted.
- *Basic Reserves* are a part of total identified mineral resources, which can satisfy the index (includes grade, quality, thickness and technical conditions for mining, etc.) requirements or

current mining, and is expressed in terms of tonnage or volume, in which the losses of designing and mining have not been deducted. It is located in the measured and indicated reserve extending area, in which detail exploration or general exploration and feasibility study or pre-feasibility study have been done, and the results demonstrate economic or marginal economic.

- *Resources* consist of a part of total identified mineral resources and undiscovered resources. The former includes resources for which mining is not economically viable or technologically feasible at the time by feasibility study or pre-feasibility study; the resources upon which some kinds of exploration or prospecting have been done, but for which feasibility or prefeasibility studies have not been carried out, are also included. The latter belongs to undiscovered mineral resources, upon which only reconnaissance has been done.

The relationship between these categories is illustrated in Figure 1. *Reserves* are the main category of interest since this is the part of the resource that can be produced under existing economic and political conditions, with existing technology. It should be noted that estimated reserves can change with time. Both increases and decreases can arise from new exploration, changes in technology, new economic conditions, or from political or environmental regulations.

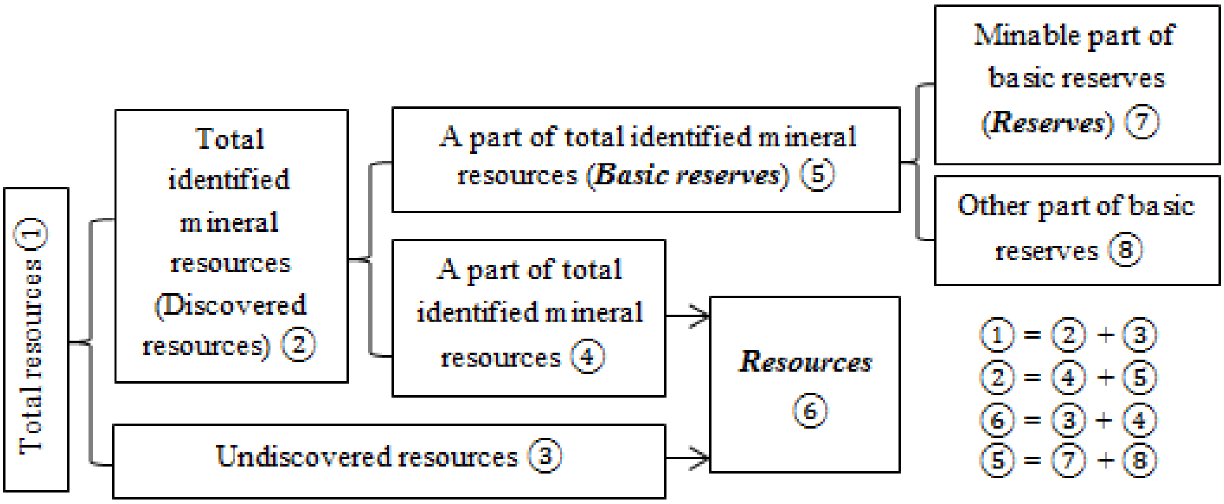

Figure 1. *The relationship of Resources, Basic reserves and Reserves. Note: "Total resources" is a very important term in resources assessment before 1999. However, it is not a formal resource category in GB/T 17766-1999. It is showed here because the term is still widely used in China and can be commonly seen in literature even after 1999.*

2.2 Comparison with other systems

World Energy Council (WEC) and Federal Institute for Geosciences and Natural Resources (BGR) are two important institutes that publish annual reports on global coal resources and reserve estimates. Their assessments are widely referred to by many other institutes, companies and scholars [6, 22-24]. Therefore, it is interesting to compare their reported systems with China's current classification system. WEC distinguishes between amounts in place and quantities recoverable, as well as proved and additional (i.e. non-proved). Combining these concepts, resources and reserves are divided into four categories: *proved amount in place (PAIP)*, *proved recoverable reserves (PRR)*, *additional amount in place (AAIP)* and *additional reserves recoverable*

(ARR) (detailed definition and explanation can be found in [6] or [25]). BGR divides coal resources and reserves into two categories: *reserves* and *resources* (detailed explanation can be found in [6] or [26]). Their relationship is shown in Figure 2, also including the USGS and Joint Ore Reserves Committee of Australia (JORC) systems. More detailed information about these systems can be found in [27-29].

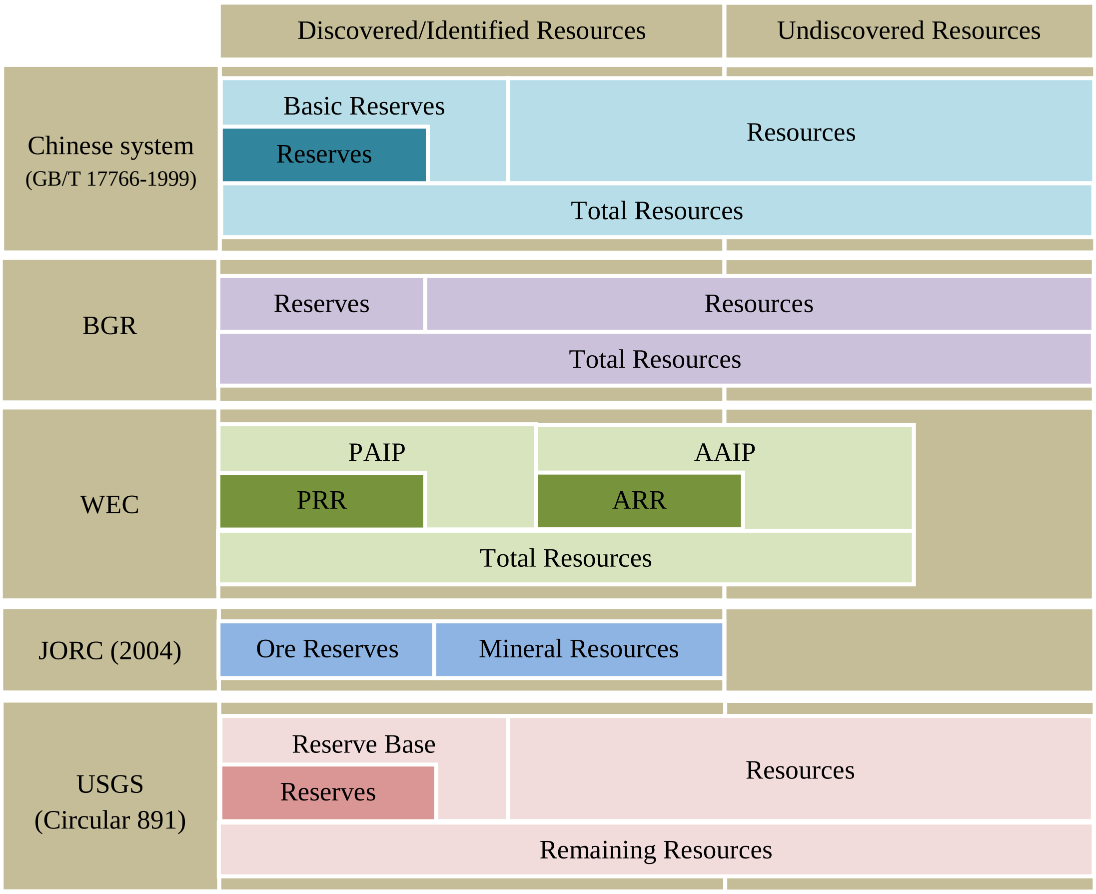

Figure 2. *Relationship among different reported systems.*

Notes: 1) The figure does not represent accurate relationships between the different parts of the classification systems and the boxes that are the same size in the figure does not necessarily cover the same fraction of the resource. For example, Reserves in China excludes mining and processing losses while, Ore Reserves in JORC includes diluting materials and allowances for losses. 2) It is unclear which may be bigger of the value of Basic Reserves and PAIP because WEC never published the data of PAIP for China. 3) According to JORC, in some situations there are reasons for reporting Mineral Resources inclusive of Ore Reserves and in other situations for reporting Mineral Resources additional to Ore Reserves. 4) Undiscovered resources are divided into Hypothetical Resources and Speculative Resources in USGS, while only one category, i.e. Reconnaissance Resources, exists in undiscovered resources in GB/T 17766-1999.

3. Investigation of Chinese coal resources, reserves and URR

3.1 Chinese coal resources

Since the establishment of the People's Republic of China in 1949, three major assessments of Chinese coal resources/reserves have been performed by the Ministry of Coal Industry (MCI). In 1998, MCI was abandoned by the central government and no further studies have been made ever since. Table 1 describes the results of the three assessments of Chinese coal resources/reserves by the MCI. It should be noted that all studies were done prior to 1999, meaning that the old classification systems without much attention paid to economic factors were used, reporting three categories: *coal reserves* (similar to *total identified mineral resources* in GB/T 17766-1999), *prognostic resource* (similar to *undiscovered resources* in GB/T 17766-1999 in Figure 1) and *total coal resources* (i.e. *total resources* in GB/T 17766-1999) [30].

Table 1. *Results of three national forecasts of coal resources and reserves in China expressed in Gt. Source:* [31, 32]

	1st (1958-1959)	2nd (1973-1980)	3rd (1992-1997)
Total coal resources	9377.9	5059.2	5569.7
Coal reserves	-	566.5	1017.6
Prognostic resources	-	4492.7	4552.1

Note: The results of the second forecast of Coal Resources are at the end of 1975; the results of the third are at the end of 1992. "Coal reserves" in this table is just used before 1999, and the actual meaning of this term is identified coal resources.

WEC and BGR have also reported estimations for total coal resources in China (Table 2), but their estimations differ significantly to the Chinese assessments by the MCI. A possible reason for this may be that these institutes overlooked the complexity of the Chinese classification systems and its development over time, leading to misinterpretation of the given statistics. MCI (Table 1) and data from WEC and BGR (Table 2) differ significantly. These differences illustrate the challenges of estimating the size of Chinese coal resources, as data availability and interpretation seems tricky.

Table 2. *China coal resources reported by BGR and WEC in Gt. Sources:* [6, 33, 34]

Year	**1924**	**1929**	**1937**	**1974**	**1980**	**1986**	**1989**	**1992**	**1993**
BGR	n.a	n.a	n.a	n.a	1463	n.a	n.a	n.a	935
WEC	996	1213	10113	1000	1463	2737	1094	954	n.a
Year	**1995**	**2001**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
BGR	n.a	668	1090	1090	4367	4367	5509	5509	5509
WEC	954	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a

Estimations of *identified coal resources* (i.e. *coal reserves* before 1999) are important since this category, together with *annual discoveries of identified coal resources,* are the only information that have always been reported to the public besides *basic reserves* after 2000. Estimates published by China National Coal Association (CNCA), National Bureau of Statistics of China (NBSC) and

Ministry of Land and Resources of China (MLR) are reasonably consistent, except for a time lag for NBSC and minor statistical differences (Table 3), but differ compared to MCI assessments.

There are also considerable differences among reported annual discoveries (Table 4). For example, CNCA [35] reports discoveries in 1978 as 25.1 Gt, compared to only 8 Gt in the *Statistical Communiqué of the People's Republic of China on the 1978 National Economic and Social Development* reported by NBSC (Table 4). In 2006, reported discoveries by NBSC is 36.7 Gt, while 122.4 Gt is claimed by MLR.

There are also inconsistencies within publications made by the MLR. The 2010 edition of the *Gazette* of *China's Land and Natural Resource* reports discoveries of 211.5 Gt for that year. However, this value was revised to 57.51 Gt in the 2011 edition of the same report (Table 4). Adding further to the confusion, MLR also reports discoveries of 71.16 Gt for 2010 in the *2011 China Mineral Resources* (Table 4). Such differences are obvious and easy to find, but no explanations are given by the MLR.

In conclusion, it is hard to know the accuracy of reported data for Chinese coal as significant differences existing among and even within published estimates from various agencies. Furthermore, it is also challenging to connect annual discoveries to total identified coal resources.

Table 3. *Reported identified coal resources by different Chinese administrations (Gt). Data sources:* [32, 35-37]

Institute/ Year	CNCA	NBSC	MLR	MCI	Institute/ Year	CNCA	NBSC	MLR	MCI
1975	n.a	n.a	n.a	567	**1996**	1002	1001	n.a	n.a
1981	n.a	643	n.a	n.a	**1997**	1008	1002	n.a	n.a
1982	n.a	742	n.a	n.a	**1998**	1007	1007	n.a	n.a
1983	n.a	728	n.a	n.a	**1999**	1006	1007	n.a	n.a
1984	n.a	737	n.a	n.a	**2000**	1003	1006	n.a	n.a
1985	n.a	769	n.a	n.a	**2001**	1020	1003	1020	n.a
1986	n.a	846	n.a	n.a	**2002**	1019	n.a	1019	n.a
1987	n.a	859	n.a	n.a	**2003**	1021	n.a	1021	n.a
1988	n.a	874	n.a	n.a	**2004**	n.a	n.a	1031	n.a
1989	n.a	901	n.a	n.a	**2005**	n.a	n.a	1043	n.a
1990	n.a	954	n.a	n.a	**2006**	n.a	n.a	1160	n.a
1991	967	967	n.a	n.a	**2007**	n.a	n.a	1180	n.a
1992	986	983	n.a	1018	**2008**	n.a	n.a	1246	n.a
1993	1002	1002	n.a	n.a	**2009**	n.a	n.a	1310	n.a
1994	1009	1002	n.a	n.a	**2010**	n.a	n.a	1341	n.a
1995	1001	1009	n.a	n.a					

Note: CNCA = China National Coal Association; NBSC = National Bureau of Statistics of China; MLR = Ministry of Land and Resources of China; MCI = Ministry of Coal Industry.

Table 4. *Reported discoveries of identified coal resources in Gt as reported by Chinese administrations. Sources:* [35, 37-39]

Institute/ Year	CNCA	NBSC	MLR	MLR	Institute/ Year	CNCA	NBSC	MLR	MLR
1953	0.70	n.a	n.a	n.a	**1982**	79.70	71.16	n.a	n.a
1954	2.76	n.a	n.a	n.a	**1983**	55.70	n.a	n.a	n.a

1955	5.24	n.a	n.a	n.a	**1984**	20.99	24.00	n.a	n.a
1956	7.01	n.a	n.a	n.a	**1985**	19.67	34.20	n.a	n.a
1957	10.00	n.a	n.a	n.a	**1986**	50.74	n.a	n.a	n.a
1958	61.93	n.a	n.a	n.a	**1987**	84.26	31.00	n.a	n.a
1959	57.03	n.a	n.a	n.a	**1988**	14.82	9.30	n.a	n.a
1960	33.72	n.a	n.a	n.a	**1989**	35.72	12.50	n.a	n.a
1961	2.50	n.a	n.a	n.a	**1990**	19.93	n.a	n.a	n.a
1962	4.74	n.a	n.a	n.a	**1991**	26.86	n.a	n.a	n.a
1963	9.11	n.a	n.a	n.a	**1992**	19.45	n.a	n.a	n.a
1964	5.39	n.a	n.a	n.a	**1993**	41.71	0.76	n.a	n.a
1965	26.47	n.a	n.a	n.a	**1994**	17.67	8.20	n.a	n.a
1966	20.08	n.a	n.a	n.a	**1995**	n.a	4.28	n.a	n.a
1967	14.28	n.a	n.a	n.a	**1996**	n.a	3.50	n.a	n.a
1968	36.35	n.a	n.a	n.a	**1997**	n.a	2.30	n.a	n.a
1969	12.38	n.a	n.a	n.a	**1998**	n.a	6.40	n.a	n.a
1970	117.84	n.a	n.a	n.a	**1999**	n.a	0.40	n.a	n.a
1971	2.083	n.a	n.a	n.a	**2000**	n.a	1.46	n.a	n.a
1972	16.80	n.a	n.a	n.a	**2001**	n.a	1.60	1.64	n.a
1973	19.08	n.a	n.a	n.a	**2002**	n.a	0.76	0.76	n.a
1974	14.24	n.a	n.a	n.a	**2003**	n.a	5.20	5.20	n.a
1975	25.88	n.a	n.a	n.a	**2004**	n.a	9.65	9.65	n.a
1976	26.78	n.a	n.a	n.a	**2005**	n.a	69.80	n.a	n.a
1977	18.33	n.a	n.a	n.a	**2006**	n.a	36.70	n.a	122.39
1978	25.06	8.00	n.a	n.a	**2007**	n.a	40.62	40.63	53.81
1979	22.90	14.90	n.a	n.a	**2008**	n.a	23.11	23.11	105.69
1980	29.39	24.84	n.a	n.a	**2009**	n.a	50.36	n.a	56.14
1981	28.19	10.31	n.a	n.a	**2010**	n.a	n.a	211.50*/57.51**	71.16

*Note: the data with * is from 2010 Gazette of China's Land and Natural Resources; the data with ** is from 2011 Gazette of China's Land and Natural Resources.*

3.2 Coal reserves estimates and a plausible URR

As mentioned earlier, the term *coal reserves* used in the old framework (i.e. systems before 1999) are actually a type of resource estimate, not paying any attention to economic factors. This is easily misleading for analysts not paying enough attention to definitions. The old terminology is simply fundamentally different from the current use of the term *reserves* in GB/T 17766-1999.

Since there have been no additional or newly completed resources or reserve assessment after 1999, MLR released *Modifying Technology Requirement of Solid Mineral Resources/Reserves* in 2001. It contains guidelines for converting assessments based on the old systems to the new framework [40]. In the same year, applying these guidelines, MLR published converted figures of 334.1 Gt *basic reserves* and 189.1 Gt *reserves* [41].

Thereafter, NBSC has consistently reported basic reserves each year in *China Statistical Yearbook*, but accompanying reserve data are not given. The Chinese government and some scholars claim that reserves can simply be calculated by multiplying basic reserves by a recovery rate [42, 43]. However, no average recovery rate for the whole country is specified. There are also some published reserve figures presented by various agencies, and an average recovery rate can be obtained from these. Using this average, it is then possible to estimate reserves from known basic reserve figures (Table 5).

The ultimately recoverable resources (URR), can be defined and estimated in different ways. Oone common way is to take the estimated reserves and add the cumulative production (labelled as the R+C approach), to obtain an estimate of the total amount that will ever be produced of the resource. Noted that a estimated URR can vary with time as reserve estimations change.

Table 5. *Statistics of China's basic reserves, reserves and URR in Gt. Data sources: production data:* [44] *(data before 2010) and* [45] *(2010 data); basic reserves data:* [41] *(2001 data) and* [1,46] *(2002-2010 data); reserves data:* [41,47] *(2001 and 2002 data),* [48] *(2003 data),* [49] *(2005 data),* [50,51] *(2006 and 2007 data).*

Year	Production	Cumulative Production	Basic Reserves	Reserves	Recovery Rate	URR
2001	1.4	32.8	334.1	189.1	56.6%	221.9
2002	1.5	34.3	331.8	188.6	56.9%	222.9
2003	1.7	36.0	334.2	189.3	56.6%	225.3
2004	2.0	38.0	337.3	188.0*	-	226.0
2005	2.2	40.2	332.6	184.2	55.4%	224.4
2006	2.4	42.6	333.5	182.5	54.7%	225.1
2007	2.5	45.1	326.1	176.8	54.2%	221.9
2008	2.8	47.9	326.1	181.8*	-	229.7
2009	3.1	50.9	319.0	177.8*	-	228.7
2010	3.2	54.2	279.4	155.7*	-	209.9
Average	-	-	-	-	55.7%	223.6

*Note: recovery rate = reserves / basic reserves; URR (ultimate recoverable resources) = Cumulative production + reserves. Reserves with *= basic reserves × average recovery rate.*

Li [52] estimated the reserves before 2001 by multiplying identified coal resources by a ratio of 20% (this ratio can be calculated by dividing identified coal resources after 2001 by reserves after 2001). In this paper, Li's method is applied to calculate reserves and URR before 2001 to illustrate a trend of Chinese coal reserves and URR. Combining such estimations of reserves and URR illustrates a underlying trend (Fig. 3). It can be seen that the growth rate of both estimated URR and reserves shows a steady trend, resulting the value of URR and reserves at a basically constant level in last decade, and even shows a slight decline in 2010.

WEC and BGR report different reserve numbers (Table 6). Most striking is the constant reserve figures reported by WEC since 1992, as more recent Chinese updates for unclear reasons have been excluded. However, this data is still is widely used and frequently occurs in worldwide statistics. In contrast, BGR data after 2006 seems to be closer to the Chinese figures, but it still lacks annual updates.

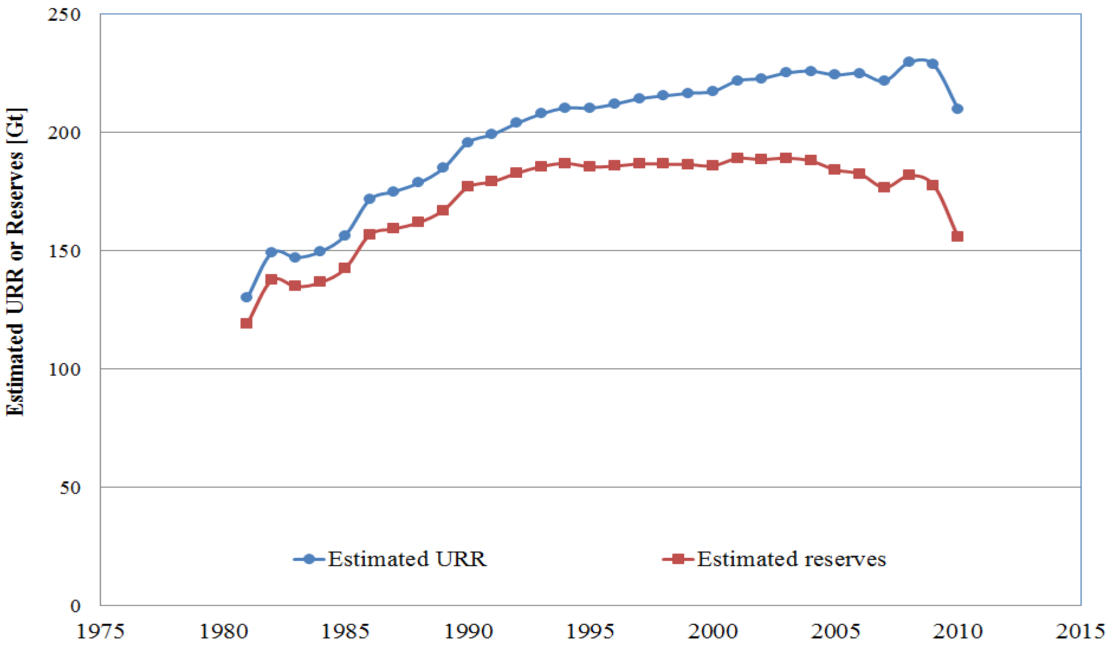

Figure 3. *Trends of estimated URR and Reserves for Chinese coal*
Note: 1) data of identified coal resources before 2001 comes from Table 3 (1981-1990: NBSC; 1991-2000: CNCA); 2) the ratio used to identified coal resources to estimate the value of reserve before 2001 is 18.5%, which is calculated based on the data of identified coal resources and reserves in 2001 from Table 5; 3) Data of Reserves and URR after 2001 comes from Table 5.

Table 6. *Chinese coal reserves reported by BGR and WEC in Gt. Source:* [6, 33, 34]

Year	**1924**	**1929**	**1974**	**1980**	**1992**	**1993**	**1995**	**1998**	**2000**	**2001**
BGR	n.a	n.a	n.a	140	n.a	110	n.a	n.a	n.a	n.a
WEC	996	1213	80	140	115	115	115	115	115	115
Year	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	
BGR	n.a	n.a	115	115	192	192	192	192	192	
WEC	115	115	115	115	115	115	115	115	n.a	

3.3 Comparison with URR estimates found in literatures

Table 7 shows the URR figures of Chinese coal applied by published studies. It can be seen most estimates rely on interpretations or assumptions based on reserve figures and cumulative production with the R+C approach, making the URR estimates exceedingly dependent on the assumed reserves. However, most URR figures are inconsistent with ones shown in table 5 due to outdated and problematic data sources, such as BP, WEC or BGR [4-6]. Other studies refer to reserve estimates published by MLR, but do not fully explain the coal classification system or update underlying statistics [8, 9,11].

An alternative way to get the URR is to rely on some techniques, such as Logit-probit Transforms (LPT) and Hubbert Linearization (HL) shown in table 7 [5, 44]. These techniques have their merits, provided that the trends used are consistent. However, there are also drawbacks as described in [53]. For China there appears to be a linear trend from 1970 to 2002, but this breaks down afterwards and the URR value becomes sensitive to the length of the time series used for extrapolation (Fig. 4). The LPT-technique shows similar problems as the Chinese data do not show any stable trend, unlike, for instance, Pennsylvania anthracite production (Fig. 5). The use of these techniques for URR estimation appears problematic for China and will likely give URR estimates with large variations in result depending on the time period used. Consequently, it is recommended that such techniques cannot be seen as plausible for China before the production trend has stabilized.

Table 7. *Investigation of URR estimates in literatures*

Author (Year)	URR [Gt]	Method	Author (Year)	URR [Gt]	Method
Höök et al. (2010) [6]	161*	R+C	Patzek and Croft (2010) [7]	147	HL/R+C
	275		Energywatch Group (2007) [4]	136	R+C
Tao and Li (2007) [8]	223	R+C	Li (2008) [9]	250	R+C
Lin and Liu (2010) [11]	221	R+C	Li (2010) [10]	380**	R+C
Rutledge (2010) [44]	139	LPT	Mohr and Evans (2009) [5]	136	HL/R+C

*Note: the data with * is recommended by the authors; the data with ** is calculated by pulsing basic reserves and cumulative production; URR applied by Patzek and Croft (2010) is from Mohr and Evans (2009); LPT means Logit-Probit Transforms; HL means Hubbert Linearization.*

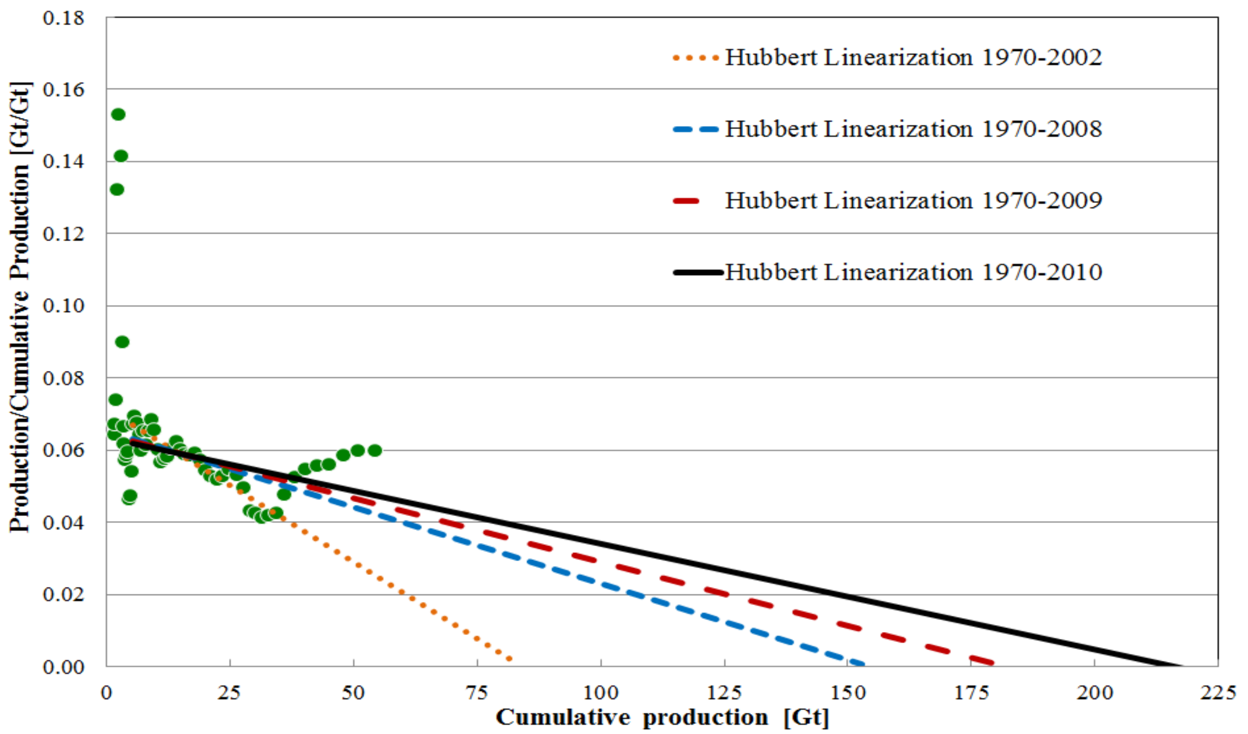

Figure 4. *URR estimations using Hubbert Linearization. The result becomes highly dependent on the length of the time series.*

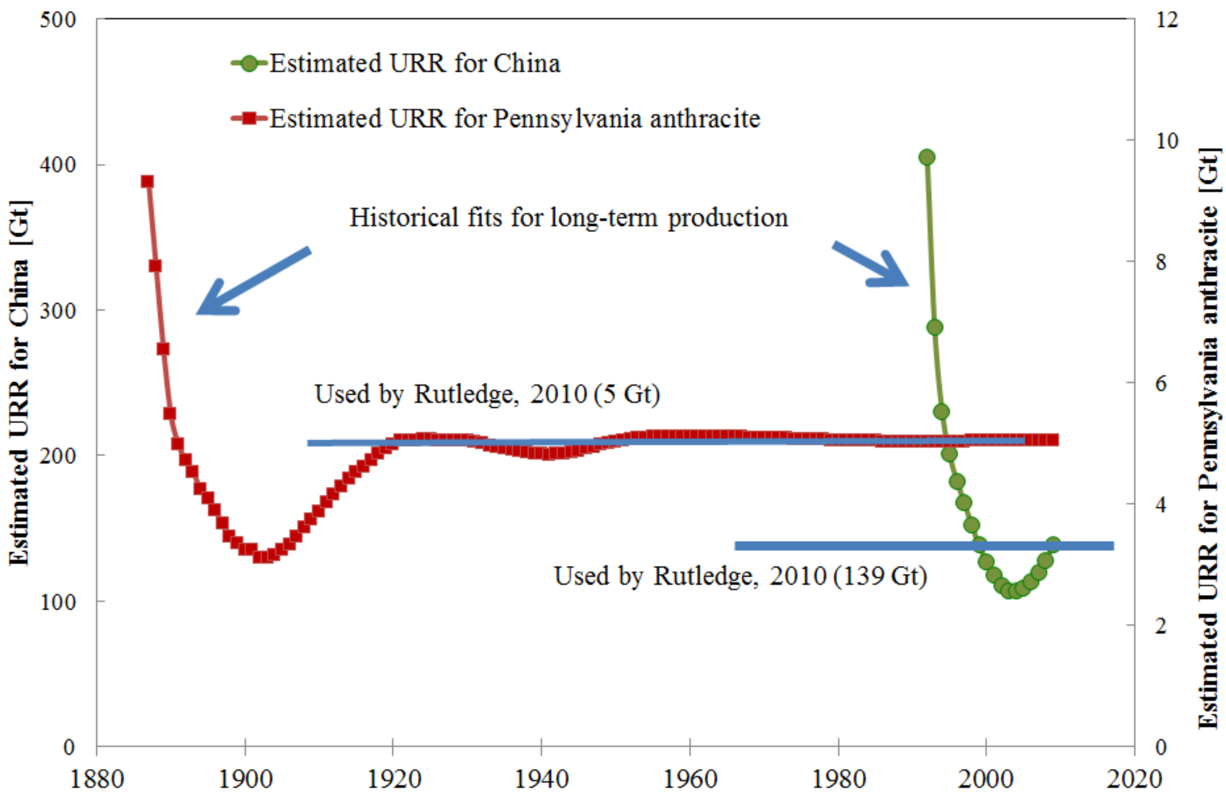

Figure 5. *Estimated coal URR of China and Pennsylvania anthracite using LPT technique. Source:* [44].

4. Modified curve-fitting model for coal projection

For a given URR figure, the forecasting model is also an important factor for projected results. Compared to other models, curve-fitting models are the most widely used models in prediction of Chinese coal supply [4, 6, 7, 9–11]. In this paper, a simple Hubbert model is used for two reasons. The first purpose is to investigate the URR and analyse its impact on future coal production instead of differences arising from different models. Secondly, it is desired to give readers a sense of continuity and comparability with current literatures. The basic form of Hubbert model can be expressed as follows [7, 54]:

$$q(t) = \frac{b \times URR}{2\{1 + \cosh[b(t - t_m)]\}} \quad (1)$$

where $q(t)$ is coal production at time t, b a parameter which accounts for the slope of the curve, and t_m the year corresponding to the peak. From Equation 1, one can see the direct importance of URR in the model and this is why this paper comprehensively discusses coal resources and reserves.

Furthermore, this paper does not propose a new modelling approach. Rather we propose some slight modifications on the curve-fitting model used to get more plausible results. This is primarily done by considering a potential constraint from the observed maximum depletion rate of remaining recoverable resources. This constrains forecast results by discriminating the appearance of extremely high and unreality production rates unmatched by historical experience [55-60]. The depletion rate of remaining recoverable resources, *d(t)*, is defined as the ratio of the annual production, *q(t)*, for the year to the amount of remaining recoverable resources, *URR-Q(t)*, i.e.

$$d(t) = \frac{q(t)}{URR - Q(t)} \tag{2}$$

where *Q(t)* is the cumulative production.

For maximum depletion rates, Höök and Aleklett investigated and concluded that for American coal production the highest depletion rates were at most around 3% per year in relatively small regions, such as Pennsylvania anthracite, while most others are significantly lower [59]. This study also investigated several smaller post-peak coal producing countries, including Japan, France, Belgium and Spain. The depletion rate at peak – typically the highest value – is generally found to be lower than around 5% per year (Fig. 6).

A higher URR appears to result in a lower depletion rate, why it appears unlikely that China with vast coal amounts would reach depletion rates in the same magnitude as Japan and Belgium. Therefore, a maximum depletion rate of 5% per year is used as a upper bound in this study to avoid mathematically optimal curve-fits that would give projections reaching implausibly high depletion rates.

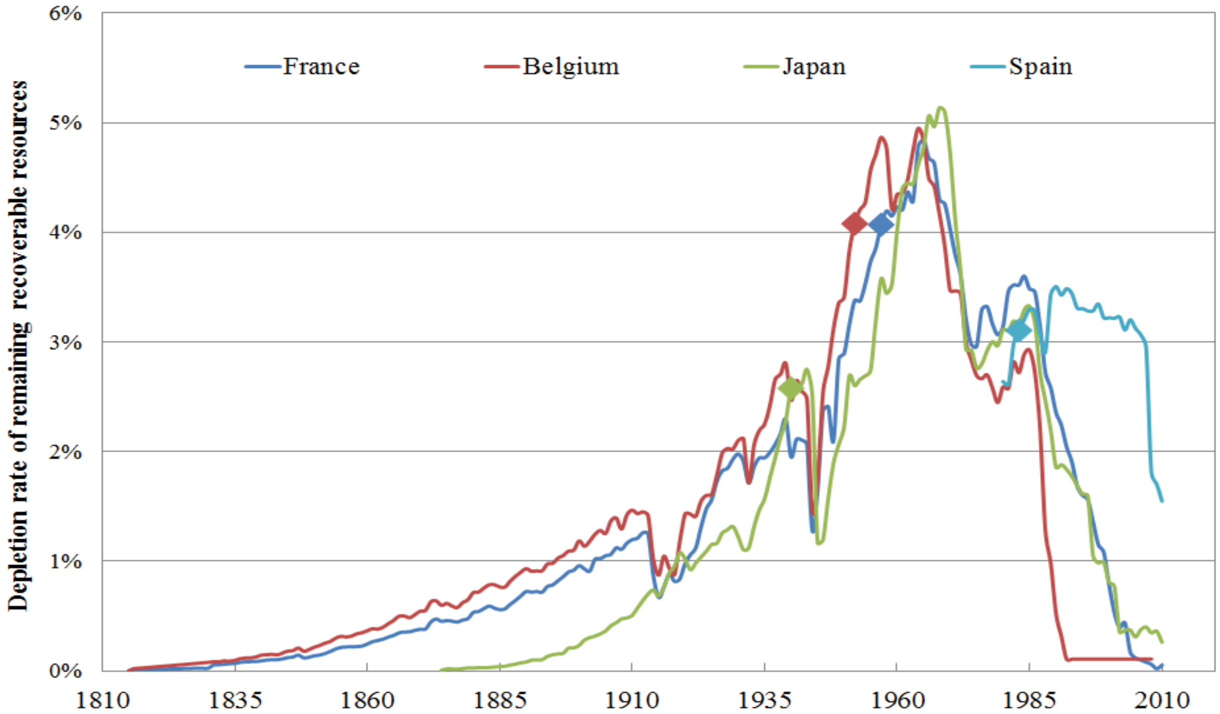

Figure 6. *Depletion rate of remaining recoverable resources for post-peak coal production regions. The diamonds indicate when the peak production occurred for each country.*

5. Modelling results and comparison with others

5.1 Forecast results

The results of the modelling are presented in Fig. 7. The depletion rate constraint gives a more flat peak and somewhat slower decline rate afterward. Without such a constraint, the production peak becomes sharper followed by a more rapid decline. The recommended result in this paper shows that Chinese coal production will peak around 2024 at a peak production of approximately 4.1 Gt.

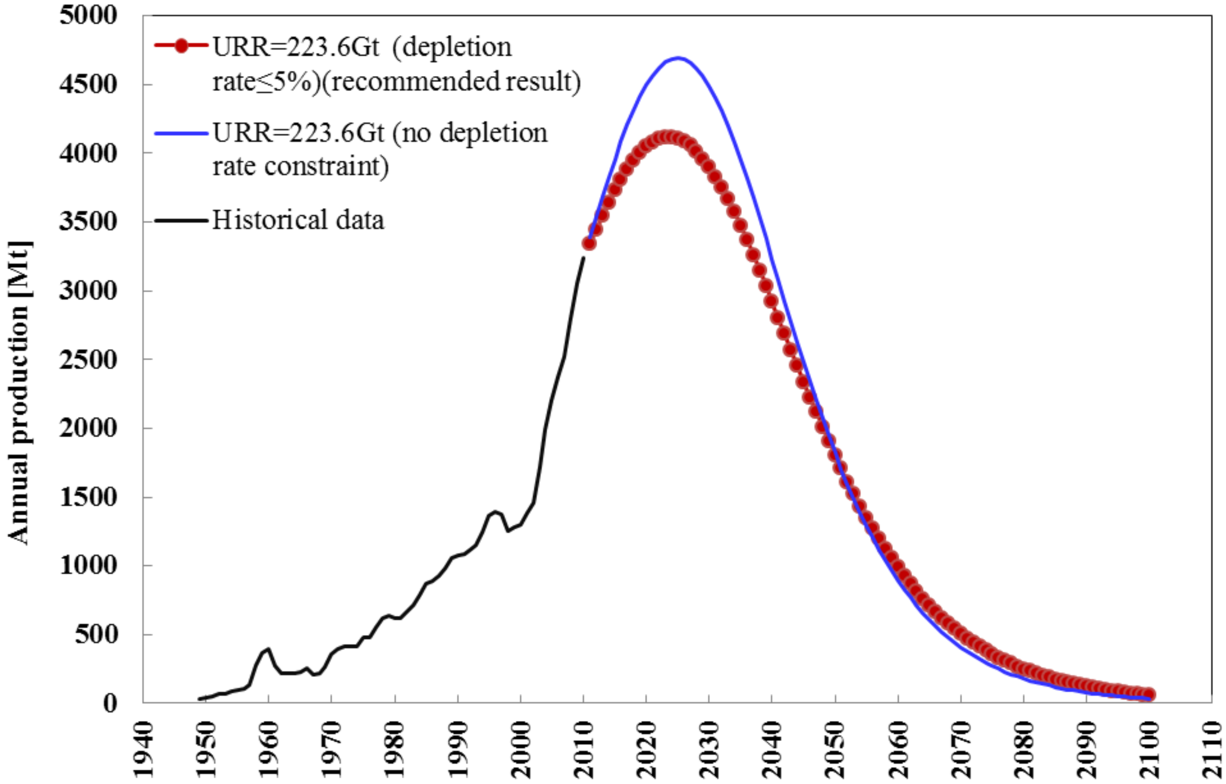

Figure 7. *Forecast results for Chinese coal production*

5.2 Sensitivity analysis

A sensitivity analysis is done to illustrate how URR affects peak production and peak time (Table 8 and Fig. 8). From Fig. 8, it can be seen that the results with depletion rate constraint are slightly more sensitive to the changes of URR compared to those without depletion rate constraint. Furthermore, peak time is essentially insensitive to the changes of URR in contrast to the peak production (Fig. 8). This phenomenon is also observed by Sorrell et al. [61, 62]. This implies that even if China's coal reserves undergo a substantial future increase, this has little impact for the coming of a peak in coal production. Table 8 shows even a doubling the Chinese coal URR only delay the peak year by 16.1 years respectively 13.7 years under the situations with or without depletion rate constraint. Regardless, the peak would still arrive before 2040.

Table 8. *Results of sensitivity analysis of changes in the URR.*

URR		No depl. rate cons.		Depl. rate cons.	
Cases	Value[Gt]	Peak production [Gt]	Peak year	Peak production [Gt]	Peak year
Recommended URR	223,6	4,70	2024,9	4,12	2023,6
URR*(1+10%)	246,0	5,01	2026,8	4,41	2025,9
URR*(1+20%)	268,3	5,32	2028,5	4,71	2028,0
URR*(1+30%)	290,7	5,65	2030,1	5,01	2029,9
URR*(1+40%)	313,0	5,98	2031,6	5,31	2031,6
URR*(1+50%)	335,4	6,31	2032,9	5,61	2033,2
URR*(1+60%)	357,8	6,65	2034,2	5,92	2034,7
URR*(1+70%)	380,1	6,98	2035,4	6,23	2036,1
URR*(1+80%)	402,5	7,34	2036,5	6,54	2037,3
URR*(1+90%)	424,8	7,67	2037,6	6,85	2038,6
URR*(1+100%)	447,2	8,00	2038,6	7,16	2039,7

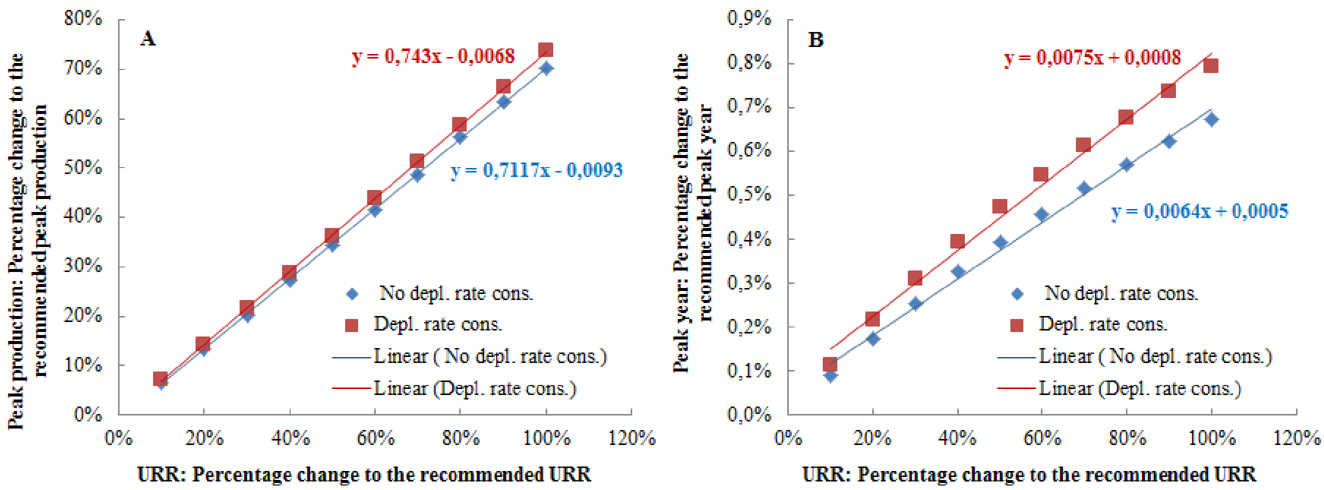

Figure 8. *Sensitivity analysis of the impacts of changes in URR on peak production and peak year*

5.3 Comparison with other studies

There are major differences between forecasts for Chinese coal production in published studies (Fig. 9). Peak production levels span from 2.3–6.1 Gt (mean value is 3.7 Gt), while corresponding peak year ranges from 2010 to 2039 (mean year is 2024). Several reasons contribute to the diverging outcomes. URR and models are the important reasons which we have shown in the previous section of this article (for example section 3.3). Besides those factors, the applied time series can also affect the results. For example, both this paper and Lin and Liu [11] use similar models with nearly identical URR values, but still reach different peak production levels, possibly due to the different length of historical production data (this historical data period used in this paper and [11] is 1949-2010 and 1949-2006, respectively). In the end, it appears likely that Chinese coal production will reach a maximum before 2040, with expected peak year in 2024.

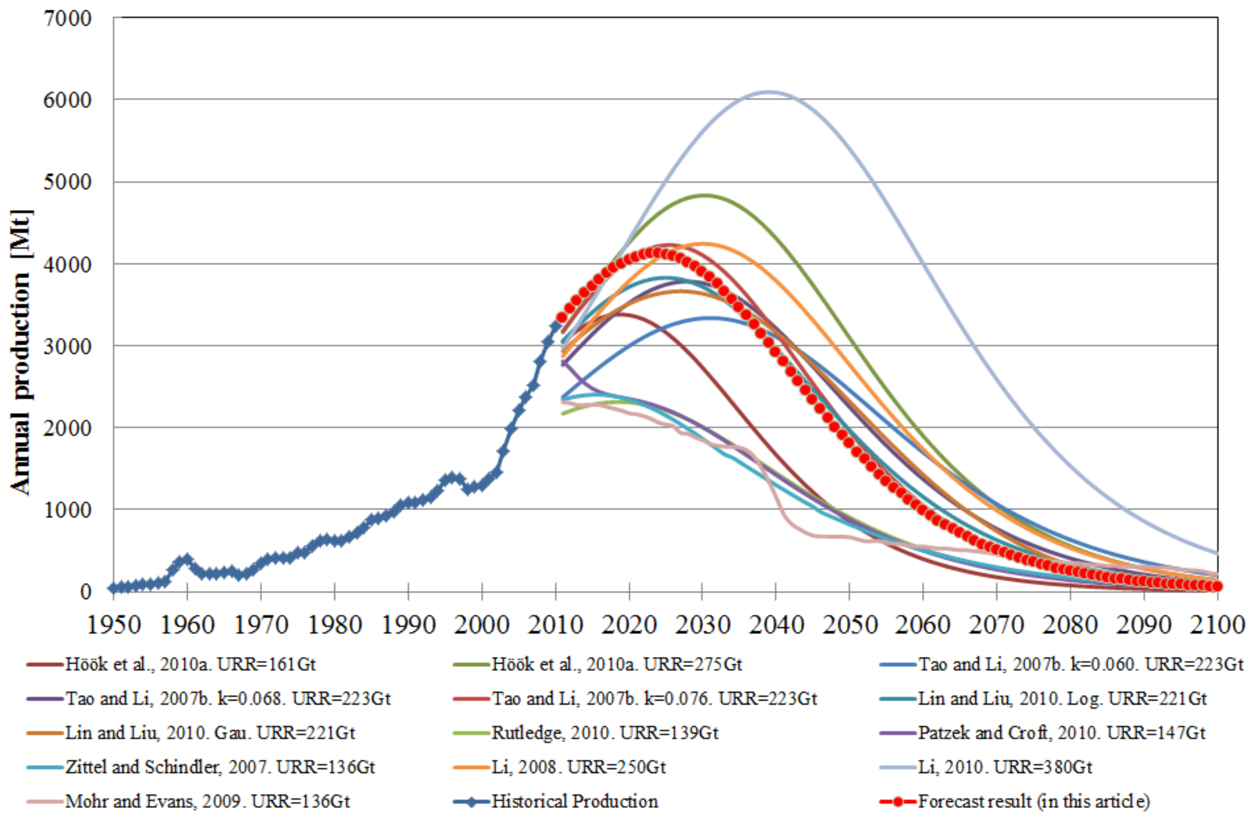

Figure 9. *Comparison of different results seen in published studies*

6. Discussion on results and its implications for China

6.1 Other potential constraints on Chinese coal production

Geological availability of coal resources and reserves is important. However, this is not the only factor affecting future production. Energy politics, environmental concern, future demand and price trends, technological development, and social acceptance can also affect coal production. What matters is recoverability and this is a complex parameter affected by both geotechnical factors and socioeconomic parameters [59].

Future production is dependent on more factors than just geology. This is why it is important to consider a depletion rate constraint to avoid extremely high production rates resulting from curve-fits only considering the geological availability of coal. In future, the following factors may also constrain the increase of coal production in China.

One factor that might negatively influence future production capabilities is water availability. Chinese coal industry is water intensive, and this also holds for coal consuming sectors like power generation and chemical industry. Pan et al. [63] estimate that more than half of the industrial water in China are used by the coal sector. Significant decreases in ground water table levels can be seen in some mining areas. For example, groundwater level has decreased from 105 m of 1952 to 71 m in 1993 in Jiaozuo coal mining area in Henan province [64].

China is already facing a serious problem with water resource scarcity due to rapid industrialization and urbanization [65]. For coal mining, 71% of 96 key state-owned mines are somewhat short of water, and 40% of them suffer from serious water shortages [66]. Chinese water resources are largely located in South China, while most coal occurs in the north. For example, Shanxi province possesses 31% of the coal reserves [67], while only accounting for 0.3% of the total water resources [1]. Water constraints will likely mainly affect possible annual production rates, and some studies have found that coal production will not exceed 3.8 Gt annually for this reason [66, 68]. The fact that water shortages could become a major barrier for coal industry development as discussed in more detail by [63].

Another possible limiting factor for production rates is transport capacity. Most coal mining occurs in northern and north-western China [69, 70], while demand is concentrated to eastern and south-eastern regions [11]. About 50% of all coal is transported via railways and insufficient capacity has already become a bottleneck affecting the coal market [71]. The growth of coal freight on railroad is only 8.8%, which is remarkably lower than the 13.7% growth rate of coal production from 2000 to 2008 [72]. Previous studies often underestimated the influence of transportation and current railway capacity has been almost fully occupied [70].

Zhao and Yu [73] proposed that large scale coal pipelines should be developed to alleviate the situation, but such projects face many difficulties [74]. Long-distance transportation by highway is not practical either, effectively limiting China to railroads for domestic coal transport. It is crucial to expand transport capacity and related infrastructure to sustain increased coal production [11], but this problem is often overlooked.

Environmental problems associated with coal production, such as mining accidents, land subsidence, water pollution, waste disposal and air pollution, is another challenge that could affect both possible production rates, but could also affect the amount of resources that will be extracted [75]. Mining accidents is still a serious problem for Chinese coal industry, and have been covered in detail by others [76, 77]. From 2006 to 2010, average annual fatalities reported by Chinese authorities were 3362 and the yearly average production was 2.9 Gt, implying a death rate of 1.2 deaths per Mt [78]. In contrast, the USA reported average annual fatalities of 35.4 and average annual production of 1.0 Gt [79,80], corresponding to only 0.03 deaths per Mt. China accounts for nearly 80% of the global fatalities due to coal mining accidents [81].

Land subsidence is another issue as nearly 95% of Chinese coal production originates from underground mining and every mined Mt of coal has been estimated to result in 20 hectares of subsiding land [75]. Pollution of groundwater is another problem. Xie et al. [68] found that 2.2 billion m^3 of groundwater resources are polluted annually due to coal mining. Furthermore, the volume of methane emission from coal mining in China is estimated to reach 20 billion m^3 in 2008, which is six times as much as in the United States [82]. Comprehensive discussions on mining waste disposal, landscape change and air pollution from coal mining have been made by others [75, 82]. Environmental costs of Chinese coal exploitation China is significant and will likely increase along with rising coal demand. Rising concern over impacts on health and environment may very well call for policies or even legalisation that restricts future coal projects.

6.2 Implications of peak coal for China

As a manufacturing-based economy, future developments of Chinese economy must rely on an adequate supply of affordable energy in the foreseeable future. Currently, this kind of energy is typically from coal. Although Chinese government has claimed to reduce the growth rate of coal consumption for years, coal usage still maintains a rapid growth during the last decade and is always out of its planned target. For example, the actual coal consumption is 32.4% higher than planned target in its official 11th Five-year Plan [83]. The rapid growth in Chinese coal consumption is also a main reason of increasing energy intensity in China after 2002 [84]. For future, Chinese coal demand is expected to keep increasing under current economic structure even considering a relatively conservative annual GDP target of 6.5% for the next fifteen years [3]. The only way to achieve a significant decrease in coal demand is to adjust energy mix and industrial structure [85]. However, this would need long time frames and considerable technology improvements. Therefore, it can be expected that a supply shortage due to an unexpected peak coal event is likely to threaten further growth of Chinese economy.

The coming of peak coal will also affect the current energy policies or strategies which rely on the assumption of abundant URR and adequate supply of coal. To meet the rapid increasing demand of oil and gas and relieve the import pressure since nearly 60% Chinese oil demand and about 30% of gas demand is met by imports, the strategies of replacing oil and gas with coal and its relevant policies have been implemented for years. In 2009, the capacity of coal to liquids (CTL) projects has reached 1.6 million metric tons (Mt) and been planned to further increase to 12 Mt in 2015 and 50 Mt in 2020 [86]. Plenty of coal resources would be exhausted to achieve this target because producing one barrel of liquids (i.e. about 0.136 metric ton) needs to consume 1-2 metric tons coal [87]. Besides, China also established coal to gas projects, such as underground coal gasification and planned to expand their scale in next few years [88]. All of these strategies or polices face a dilemma in near future: a significant investment on infrastructures and techniques but without enough coal. As shown in this paper, China should take more measures to replace its coal with oil, gas or other alternative energy resources.

The coming of peak coal is good news for China's environment, especially for reduction of greenhouse gas (GHG) emissions. Climate change has been seen as the biggest environment threat in the present and future development of human society [89], and anthropogenic GHG emissions, especially CO_2 emissions mainly due to the usage of fossil fuels, have been considered as the dominant cause of the observed change in global climate [90]. To prevent the potentially serious impacts of climate change on human society, a number of countries have tried to take efficient measures to reduce its domestic GHG emissions. As the largest GHG emitter, China has declared in 2009 to lower its carbon dioxide emissions per unit of GDP by 40–45% by 2020 relative to the 2005 level [91]. Furthermore, China's government also seeks to peak its carbon emission as early as possible [92]. Several studies suggest the peak date for carbon emissions should be 2020-2050 [93-95]. Since coal producing and combustion is the dominant source of GHG emissions (81% of energy-related CO_2 emissions in China comes from coal combustion [23]; more than half emissions of non-CO_2 GHG emissions, such as NO_x and SO_x comes from coal combustion [2]; coal mine methane emissions during producing process have been also drawing much attention over the past few years [82]), it can be expected that the coming of peak coal before 2040 (with a very likely year of 2024) will benefit the reduction of Chinese carbon emissions and make it possible to peak its carbon emissions in the period of 2020-2050.

7. Concluding remarks

Chinese coal classification system and historical evaluation and statistics of coal resources and reserves are presented first in this article. Then, a plausible and consistent with latest classification system and reported system coal reserves is estimated and indicates that the URR of Chinese coal appears to be around 223.6 Gt, which is higher than estimates used in many other studies.

A possible Chinese future coal production is estimated using a modified Hubbert model, a combining the previously mentioned URR and a constrained depletion rate, suggests that Chinese coal production could reach its peak around 2024, with a peak production of approximately 4.1 Gt. It is possible for China to increase its coal's URR, however, as shown in section 5.2 and 6.1, peak time is insensitive to the change of URR and even a doubling URR is given, Chinese coal production still will be peak before 2040. A compressive conclusion of the data of peak coal is before 2040, with a very likely year of 2024.

Other potential constraints on Chinese coal production are also presented here and indicate that it is very difficult to increase Chinese coal production further even if coal reserves were abundant. The coming of peak coal is inevitable and immediate. Due to the importance of coal to Chinese economy, it can be expected that the coming of peak coal will threat the further growth of Chinese GDP, and energy strategies or policies based on abundant coal reserves and adequate coal supply must be adjusted as soon as possible to minimum its negative influences greatly. However, the coming of peak coal benefits to deal with China's environmental problems, especially reduction of GHG emissions. It is possible for China to reduce its carbon emission greatly and make its peak in an early date with considering the peak coal issue.

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