An analysis of China’s coal supply and its impact on China’s future economic growth

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\textbf{HIGHLIGHTS}

\begin{itemize}
  \item We analyze an issue of prime importance for the future of China’s economy.
  \item The decline in coal supply will present a challenge to China’s economic growth.
  \item Rising coal price will also have an adverse impact on economic growth.
\end{itemize}

\textbf{ABSTRACT}

Many people believe that China’s economic growth can continue almost indefinitely. For a manufacturing-based economy such as China’s to continue to grow, it needs an adequate supply of inexpensive energy. To date, this energy growth has primarily come from coal, but China’s indigenous coal supplies are now falling short of the amount needed to support this growth. In this situation, the status of China’s future coal supply will be very important for China’s future economic development. Our analysis shows that China’s ultimate recoverable coal reserves equal $223.6 \times 10^9$ MT, and its production will peak between 2025 and 2030, with peak production of approximately $3.9 \times 10^9$ MT. The extent to which China can import coal in the future is uncertain. With rising coal demand, this combination is likely to create a significant challenge to China’s future economic development.

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\textbf{1. Introduction}

As one of the dominant engines of the world’s economic growth, the future of the Chinese economy is of great interest to scholars around the world. The debate as to whether China’s growth can continue usually centers on issues such as the real estate bubble, the debt crisis of local governments, the high level of inflation, the low efficiency of government investment, wealth disparities, environmental pollution and destruction, and the aging population. These problems truly exist; however, they are not the fundamental factors that will decide the future course of the Chinese economy.

The hidden issue that has the power to hold back economic growth is an inadequate supply of cheap energy. China is a country that bases its economy on manufacturing (China’s primary, secondary and tertiary industries accounted for 10.1%, 46.8% and 43.1% of its GDP in 2010) \textit{(National Bureau of Statistics of China (NBSC), 2011a)}, and manufacturing depends on an adequate supply of affordable energy, typically inexpensive and only accounting for a small amount of the total cost. The primary source of this affordable energy is currently coal; coal accounts for more than 76.5% of China’s energy production and about 68.0% of its energy consumption in 2010 \textit{(National Bureau of Statistics of China (NBSC), 2011a)}, making it far more important than oil, gas and other energy resources. We know that coal, like any non-renewable resource, is finite, and thus, at some point the amount extracted each year will cease to grow as the resource gets depleted. Yet China’s energy policy today is based on the premise that China has a virtually inexhaustible supply of coal resources \textit{(Wang, 2007a; Li et al., 2010)}. In fact, China became a net coal importer in 2009 \textit{(Pan and Wang, 2010)}, because its own production is already falling short of the amount needed to maintain economic growth. China’s inability to raise supply as quickly as desired raises questions about China’s long-term coal supply.

In this paper, we perform an analysis that shows that China’s annual extraction of coal is likely to begin to decline in the 2025 to 2030 time period. This study is based on our analysis of China’s coal resources, and how much of these resources are likely to be ultimately recoverable. The lack of future supply, together with...
the lack of suitable alternatives and the expected rise in the price of coal that is available can be expected to have adverse economic consequences.

The structure of this paper is as follows. Section 2 provides a detailed analysis of China’s ultimate recoverable reserves (URR) for coal because of the importance of URR in forecasting future coal production. Section 3 analyzes future coal supply, coal demand and coal imports of China. Section 4 analyzes the availability of other energy sources that might be used as alternatives to coal. Section 5 summarizes the main findings of this paper.

2. China’s coal reserves

While China’s authorities report very large coal resources, the portion that can be produced under existing economic and political conditions, with existing technology, is limited. In the years since 1949, when the People’s Republic of China was founded, three analyses of China’s coal resources/reserves have been performed by the Ministry of Coal Industry (MCI) (Table 1). In 1998, MCI was abolished by China’s central government, and since then, no further estimates of coal resources have been made. The only exception to this is a study by the Ministry of Land and Resources (MLR) that was started in 2007, covering many different resources, but is not yet complete. This project is called The Current Situation Survey of Mineral Resource Utilization; it is being performed to carry out the guidelines of the Decision of the State Council on Strengthening Geological Work (Issued by State Council in 2006).

Table 1 shows the results of the three national forecasts of coal resources/reserves in China. Coal reserve, which is also called discovered resource, is the quantity of coal estimated to be contained in known accumulations; prognostic resource, which is also called undiscovered resource, is the estimated quantity of coal in accumulations yet to be discovered; total coal resource is the sum of coal reserve and prognostic resource (Wang, 2007).

From Table 1, we can see that all of these forecasts were prepared prior to 1999 and used the old classification systems of mineral resources/reserves. These old systems were very similar to the classification system of the Former Soviet Union (FSU), under its system of central economic control, but modified by China to reflect its own conditions. The main purpose of exploration activities under these old systems was to know the quantities of mineral resources for use by the central government rather than to exploit them directly by businesses. Therefore, these systems reflect primarily the existence of coal based on geological conditions, with little consideration to whether it would be economically feasible to extract these resources in the future. This means that part of reserves assessed in these systems may never be extracted (Chen et al., 2002). Moreover, The Chinese Mineral Resources/Reserves Classification System and its Application, which was submitted by the Chinese government to the United Nations (UN) (2001), indicates that the classification system was problematic:

The above edition (i.e. old classification system), which was different from the international well known normal practices, had made it very difficult for mining industry of China to communicate in common language with that of other countries, and hence, it has impeded the progress of China in developing market economy and opening its door to the world for investments in the mining industry.

To make its system more similar to those of market economies, in June 1999, China’s government issued a new edition of its classification system named Classification for Resources/Reserves of Solid Fuels and Mineral Commodities (GB/T 17766–1999) as a national standard (General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China (AQSIQ), 1999). This new system was established based on the classification systems of the United Nations (UN) (1997) and U.S. Geological Survey (USGS) (1980) and was the first one which evaluated resources based on likely economics of extraction, in addition to geology and feasibility of extraction.

The new classification system provides three major categories: reserves, basic reserves and resources (General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China (AQSIQ), 1999). Resources consist of a part of total identified mineral resources (the same as coal reserves in Table 1) and undiscovered resources (the same as prognostic resources in Table 1); basic reserves are a part of total identified mineral resources; reserves are those in basic reserves based on all relevant considerations, including economic (General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China (AQSIQ) 1999). Thus, reserves are the real item of interest because only they can be produced under existing economic and political conditions, with existing technology. More information and detailed definition of these items on the 1999 change in classification systems can be found in Appendix A.

The question then becomes how resource/reserve data, prepared prior to 1999 should be modified, to be consistent with the new definitions, since no new analyses have been issued since 1999. On March 8, 2001, the circular of Modifying Technology Requirement of Solid Mineral Resources/Reserves, which was used to convert forecast results of resources/reserves under old classification systems into ones under the new classification system, was issued by MLR (2001a). In the same year, MLR (2001b) published the modified results of basic reserves and reserves under new

Table 1
Results of three national forecasts of coal resources/reserves in China (10^9 MT).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total coal resources</td>
<td>9377.9</td>
<td>5059.2</td>
<td>5569.7</td>
</tr>
<tr>
<td>Coal reserves</td>
<td>–</td>
<td>566.5</td>
<td>1017.6</td>
</tr>
<tr>
<td>Prognostic reserves</td>
<td>–</td>
<td>4492.7</td>
<td>4552.1</td>
</tr>
</tbody>
</table>

Table 2
Statistics of China’s basic reserves, reserves and URR (10^9 MT).

<table>
<thead>
<tr>
<th>Year</th>
<th>Production cumulative production</th>
<th>Basic reserves</th>
<th>Reserves</th>
<th>Recovery rate</th>
<th>URR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>1.38</td>
<td>32.82</td>
<td>334.09</td>
<td>189.12</td>
<td>56.61%</td>
</tr>
<tr>
<td>2002</td>
<td>1.45</td>
<td>34.27</td>
<td>331.76</td>
<td>188.84</td>
<td>56.86%</td>
</tr>
<tr>
<td>2003</td>
<td>1.72</td>
<td>35.99</td>
<td>334.20</td>
<td>189.27</td>
<td>56.63%</td>
</tr>
<tr>
<td>2004</td>
<td>1.99</td>
<td>37.98</td>
<td>337.34</td>
<td>188.03</td>
<td>–</td>
</tr>
<tr>
<td>2005</td>
<td>2.21</td>
<td>40.19</td>
<td>332.64</td>
<td>184.24</td>
<td>55.39%</td>
</tr>
<tr>
<td>2006</td>
<td>2.37</td>
<td>42.56</td>
<td>333.48</td>
<td>182.54</td>
<td>54.74%</td>
</tr>
<tr>
<td>2007</td>
<td>2.53</td>
<td>45.09</td>
<td>326.13</td>
<td>176.80</td>
<td>54.21%</td>
</tr>
<tr>
<td>2008</td>
<td>2.80</td>
<td>47.89</td>
<td>326.14</td>
<td>181.79</td>
<td>–</td>
</tr>
<tr>
<td>2009</td>
<td>3.05</td>
<td>50.94</td>
<td>318.96</td>
<td>177.79</td>
<td>–</td>
</tr>
<tr>
<td>2010</td>
<td>3.24</td>
<td>54.18</td>
<td>279.39</td>
<td>155.73</td>
<td>–</td>
</tr>
</tbody>
</table>

Note: Recovery rate = reserves/basic reserves; URR (ultimate recoverable reserves) = cumulative production + reserves. Reserves with *= basic reserves × average recovery rate.
classification system, which were $334.1 \times 10^9$ MT and $189.1 \times 10^9$ MT, respectively. Thereafter, National Bureau of Statistics of China (NBSC) has reported basic reserves each year in its annual publication, i.e. China Statistical Yearbook, but does not report data on reserves. Some scholars and the Chinese government claim that reserves can be calculated by multiplying basic reserves by a recovery rate, but they do not give the average recovery rate for the whole country (Xu and Sun, 2008; Project Office of the Current Situation Survey of Mineral Resource Utilization (PO), 2011).

Table 2 shows some discontinuous reserve data from various data sources. Based on these discontinuous reserve data and corresponding basic reserves, the average recovery rate can be calculated. Then, the average recovery rate will be used to calculate other unknown reserve amounts from corresponding known basic reserves. After making these calculations, we obtain continuous reserve data, and then, estimate ultimately recoverable reserves (URR), which are defined in this paper as reserves plus cumulative production (Table 2).


In summary, according to the 3rd national prediction of coal resources/reserves, the total coal resources are $5569.7 \times 10^9$ MT, however, the total identified coal resources (named coal reserves before 1999) are only $1017.6 \times 10^9$ MT at the end of 1992. In the identified coal resources, basic reserves and reserves at the end of 2001 are $334.1 \times 10^9$ MT and $189.1 \times 10^9$ MT, respectively, and these two data decline slowly after 2001, with the average decline rate of 2.1% and 0.6%. For the estimated URR, the results are basically constant except a slight decline in 2010, with an average URR of 223.6 $\times 10^9$ MT. Therefore, the actual reserves that can be produced under existing economic and political conditions, with existing technology, are limited and are less than many scholars assumed.

3. Outlook for China’s coal supply, demand and imports

3.1. Coal supply

Because of the importance of coal in China, many scholars have studied China’s domestic coal supply and developed models to forecast future coal production. Their research can be divided into two major categories. The first category is research on short-term (less than five years) coal supply; this work is mainly done by Chinese scholars (Wang and Zhao, 2003; Huang and Shao, 2007; Liu and Wu, 2008; Wang et al., 2010, 2011a, 2012). They usually adopt an output elastic coefficient method, simple linear regression and Gray Model (1,1) (GM) framework to forecast future coal production without considering the limitation of coal resources. The results of all of these analyses show rapid growth in China’s coal production in coming years.

The second category is research on long-term (more than 15 years) coal supply, performed by both international scholars and Chinese scholars (Zittel and Schindler, 2007; Mohr and Evans, 2009; Höök et al., 2010a; Patzek and Croft, 2010; Tao and Li, 2007; Li, 2008, 2010; Lin and Liu, 2010). These researchers usually consider the limitation of coal resources when they forecast future coal production because they consider coal as a non-renewable mineral resource. As such, they expect that coal production in a given region would be expected to follow a roughly bell-shaped curve. Based on the production characteristics of nonrenewable mineral resources, many scholars adopt a logistic model (a typical bell curve model which was first proposed by Hubbert, 1956) (Zittel and Schindler, 2007; Höök and Aleklett, 2009; Höök et al., 2010a; Lin and Liu, 2010, Li, 2008, 2010), or modified logistic model (Patzek and Croft, 2010; Maggio and Cacciola, 2012), or some other bell curve model, such as Gaussian model (Lin and Liu, 2010) or Gompertz model (Mohr et al., 2011), to forecast future coal production.

This paper mainly relates to expected long-term coal production. The forecast results of China’s long-term coal production are shown in Table 3. Based on Table 3, we can see that expected peak production and peak time differ depending on the URR adopted by scholars. Mohr and Evans (2009) adopt a very low URR to forecast China’s future coal production, indicating peak production of $2.3 \times 10^9$ MT in 2010. However, China’s actual production in 2010 was $3.2 \times 10^9$ MT (National Bureau of Statistics of China (NBSC), 2011b). Compared with a low URR used by Mohr and Evans (2009), Li (2010) adopts a very high URR to forecast future production, with the result of a peak production of $6.1 \times 10^9$ MT in 2039. The reason why URRs adopted by different scholars sometimes differs sharply is the poor data quality of China’s coal reserves/resources (Hu and Jiang, 2000; Thomson, 2003; Zittel and Schindler, 2007; Huang and Shao, 2007). Sometimes, the reported Chinese resources/reserves data by some well-known institutions or companies, such as World Energy Council (WEC) and BP, are also not available (Zittel and Schindler, 2007; Höök et al., 2010a). Therefore, if researchers want to make an accurate analysis of China’s future coal supply, they cannot quote others’ results directly. Instead they must make a detailed analysis of China’s coal reserves/resources, as done in Section 2.

In Section 2, our analysis showed that the URR of China’s coal is basically constant at an average level of $223.6 \times 10^9$ MT. Therefore, we use this value of URR and the logistic model to forecast future coal production (the logistic model is briefly introduced in

Table 3

<table>
<thead>
<tr>
<th>Author</th>
<th>Model</th>
<th>URR</th>
<th>Peak time</th>
<th>Peak production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Höök et al. (2010a)</td>
<td>Logistic model</td>
<td>165.4 (standard case)</td>
<td>~2020</td>
<td>~3.37</td>
</tr>
<tr>
<td>Tao and Li (2007)</td>
<td>STELLA model</td>
<td>222.6</td>
<td>2025-2032</td>
<td>3.34-4.45</td>
</tr>
<tr>
<td>Lin and Liu (2010)</td>
<td>Logistic model</td>
<td>222.9</td>
<td>2027</td>
<td>3.67</td>
</tr>
<tr>
<td>Mohr and Evans (2009)</td>
<td>Demand-supply model</td>
<td>136.1 (best guess case)</td>
<td>2010</td>
<td>~2.34</td>
</tr>
<tr>
<td>Zittel and Schindler (2007)</td>
<td>Logistic model</td>
<td>135.6</td>
<td>2015</td>
<td>2.40</td>
</tr>
<tr>
<td>Li (2008)</td>
<td>Logistic model</td>
<td>250</td>
<td>2030</td>
<td></td>
</tr>
<tr>
<td>Li (2010)</td>
<td>Logistic model</td>
<td>380</td>
<td>2039</td>
<td>6.09</td>
</tr>
<tr>
<td>This article</td>
<td>Logistic model</td>
<td>223.6</td>
<td>2027</td>
<td>3.97</td>
</tr>
</tbody>
</table>
Appendix B). The forecast shows that China’s coal production will peak in 2027, with peak production of 3.97 × 10^9 MT (Table 3), which is very close to results of Lin and Liu (2010) and Tao and Li (2007). Based on a comprehensive consideration of the results of Lin and Liu (2010), Tao and Li (2007) and this article, we anticipate that China’s coal production will reach its peak between 2025 and 2030, with peak production of approximately 3.9 × 10^9 MT.

One important thing of note is that the forecast result is based on an estimate of URR and does not consider other factors, such as technology. Theoretically, improvement of technology will tend to increase the value of URR and then increase the production and delay the peak time, which means that URR estimates need to be considered in relation to technological improvements over time. However, in the last ten years, as we can see from Table 2, the value of URR of China’s coal has been stable and even shows some slight decline in 2010. Besides, other factors, such as water availability, land availability, transportation capacity and climate change are likely to also affect future coal production (Wang and Guo, 2007; Zhang et al., 2008; Yang, 2007; Shealy and Dorian, 2010; Xie et al., 2011). Taking water availability as an example, producing coal not only pollutes groundwater (in China, 2.2 × 10^9 m^3 of groundwater resources are polluted every year due to producing coal), but also consumes huge amounts of water (Xie et al., 2011). However, China is already facing a serious problem of water resource scarcity (Wang, 2001). Rong and Victor (2011) claim that water constraint is one of the chief reasons behind the coal-to-liquids (CTL) policy reversal in China after 2006. For coal mining, 71% of 96 key state-owned mines are short of water, and 40% of them have serious water shortages (Xie, 2011). If a person considers water constraints, China’s coal productive capacity is only 3.4–3.8 × 10^9 MT (Xie et al., 2011; Xie, 2011). If these additional constraints are considered, maximum coal production may be even lower still.

3.2. Coal demand

Based on the previous analyses, it can be concluded that China’s actual reserves and production will be lower than many scholars have forecast, especially Chinese scholars. In contrast, China’s future coal demand may be higher than most scholars and institutions’ have forecast. For example, a few years ago, most forecasts of coal demand in 2010 were between 2.51 × 10^9 MT and 2.89 × 10^9 MT (Lin et al., 2007; Wang and Li, 2008; Yu and Deng, 2008), including an estimate of 2.56 × 10^9 MT from the official 11th Five-year Plan (2006–2010). However, actual coal consumption in 2010 was 3.39 × 10^9 MT (Lin and Yu, 2011), which was 32.4% higher than the official plan.

The phenomenon of actual coal demand being higher than forecast can be explained by indirect impacts of the importance of GDP growth in China. The central government needs a high GDP growth rate to alleviate income disparities and to maintain social stability. Furthermore, local officials need high GDP growth rates to be promoted because GDP is the chief measure of progress in their performance reviews (Ma, 2005; Xia and Wang, 2006; Xu, 2007; Wang 2007b). Therefore, when the central government targeted an annual average GDP growth rate of 7.5% in the 11th Five-Year Plan (Lin et al., 2008), local governments seemed to be inclined to pursue higher GDP growth rates than targeted. Consequently, China needed more energy than its original plan to achieve the higher growth rates, especially coal. Domestic coal was favored over other energy resources because local governments believed that China had plenty of coal and because coal was commonly less expensive than other energy sources. However, coal is also associated with environmental degradation and even deaths (Chen and Li, 2011; Shealy and Dorian, 2010; Xie et al., 2011; Tu, 2011). For example, in the period of 11th Five-year Plan (2006–2010), average annual fatalities reported by China’s authority are 3362, and average annual production is 2.88 × 10^9 MT in the same period, implying a death rate per million metric tons of 1.17 (Tu, 2011). In comparison, the United States, which is the second largest coal producer in the world, reported average annual fatalities of 35.4 and average annual production of 1.02 × 10^9 MT (Department of Labor (DOL) of United States, 2012; Energy Information Administration (EIA), 2011a), implying a death rate per million metric tons of 0.03. However, these problems were overlooked. Thanks to the large amount of energy consumed, especially coal, China’s actual annual average GDP growth rate was 11.2% over the last five years (Wen, 2011).

Looking ahead, the 12th Five-year Plan establishes an annual GDP growth target of 7% (National People’s Congress (NPC) of People’s Republic of China, 2011), with projections that coal demand could reach 3.9 × 10^9 MT in 2015 (National Development and Reform Commission of China (NDRC), 2012). Based on the experience of the last five years, it seems likely that actual coal consumption will exceed official projections. Shealy and Dorian (2010) also claim that most other forecasts of China’s future coal demand are too low. Using a relatively conservative annual GDP growth target of 6.5% for the next fifteen years, they forecast that coal demand will reach 4.13 × 10^9 MT in 2015, 5.9% higher than official data. With respect to coal demand in 2025, their result – 6.12 × 10^9 MT – is 35.5%, 36.3% and 47.6% higher than the results of the International Energy Agency (IEA) (2010), U.S. Energy Information Administration (EIA) (2010) and National Development and Reform Commission of China (NDRC) (2009), respectively (Fig. 1). With a 6.5% growth target, the estimated annual average growth rate of coal demand from 2011 to 2020 is only 4.8%, which is far lower than 11.3% of the last 10 years.

3.3. Coal imports

The year of 2009 was a turning point for China. Up until 2009, China was self-sufficient in coal, and even exported coal to other countries. However, in 2009, domestic demand first exceeded supply, making China a net coal importer despite having arguably the world’s second largest coal reserves. According to EIA statistics, in 2009, China’s net coal imports reached 102.16 × 10^6 MT (based on imports of 136.95 × 10^6 MT (Energy Information Administration (EIA), 2011b) and its exports reached 34.79 × 10^6 MT (Energy Information Administration (EIA), 2011c)), or 3.24% of China’s coal consumption. However, even this small figure caused China’s imports to exceed those of many traditional net coal importers, such as South Korea (99.7 × 10^6 MT), India (67.3 × 10^6 MT), and...
China's coal demand, even with conservative assumptions about Chinese GDP growth, will keep increasing rapidly in the future. We estimate that China's coal trade in 2009 was 943.25 MT, can have a big impact on the international coal market (total world coal trade of 106 MT/year in 2009 (Energy Information Administration (EIA), 2011b). Therefore, world coal trade must increase by 135.36% over the next 15 years to meet China's coal demand, even under the assumption that other coal importers do not import any coal from the international market. And after 2025, the amount of world coal trade must increase even more rapidly than before to meet China's need for imported coal because China's domestic coal supply will stop increasing and then decline after 2030.

Unfortunately, it is doubtful that China will be able to import enough coal to meet domestic demand for two reasons. First, some scholars have argued that world coal resources are potentially more limited than that assumed by policy makers to date (Mohr and Evans, 2009; Höök et al., 2010a; Patzek and Croft, 2010). Therefore, actual peak of world coal production may come earlier than policy makers thought. For example, one study even forecasts that the peak global coal production from existing coal fields will occur in the year 2011 (Patzek and Croft, 2010). Second, it is not realistic to assume that other importers will not import more coal. In fact, coal imports for other importers are also likely to increase rapidly. Taking India as an example, the rapid development of the economy leads to rapid growth in coal consumption. However, the growth of domestic coal production cannot rise as rapidly as the growth in coal demand. As a result, India's coal imports will also need to increase rapidly. In fact, India's net imports have been rising at an average annual rate of 21.08% for the last seven years (2003–2009) and reached 67.32 × 10^6 MT in 2009 (Energy Information Administration (EIA), 2011b, 2011c). According to the statistics of International Monetary Fund (IMF) (2011), India's GDP growth first exceeded China's rate, and reached 10.4% in 2010. With respect to future economic growth, India plans to target GDP growth of 9% for the next Five-Year Plan period, which is higher than China's target GDP growth rate of 7%. Therefore, it is reasonable to expect that India's net coal imports will continue to rise rapidly in the future.

Furthermore, the nuclear power capacity of Japan and Europe seems unlikely to expand as planned because of the Fukushima nuclear crisis, and this lack of expansion may result in shortages of electricity in the future. To compensate for this shortage, Japan and Europe may import more thermal coal, even though in the recent past their net coal imports have remained stable or declined slightly. Therefore, as we have shown in this section, a 135.36% increase of world coal trade over the next fifteen years is rather extreme and does not appear very likely, especially with increasing transportation costs caused by peak oil (Curtis, 2009).

4. What will replace coal?

China has been trying to reduce the proportion of coal in its primary energy consumption in order to reduce its carbon emissions and improve its mix of energy sources. Such a change would also be helpful because China cannot import enough coal to meet its demand. Because of these issues, China would very much like to find sufficient energy of other forms to replace coal. It would also be desirable for China to change its energy system into something less dependent on coal. However, several researchers note that this energy transition is very difficult, has many potential risks and is also relatively slow on the millennium-long time horizon (Bardi, 2007; Bashmakov, 2007; Smil, 2010; Fantazzini et al., 2011). Besides, the peak of finite fossil fuels tends to throw countries into sociological trajectories not prone to easy energy transitions, and the increasing of price due to the peak can be expected to slow an energy source transition (Bardi, 2007; Friedrich, 2010). Another factor which may hinder or slow the energy transition is low EROI (energy return on investment) of some alternative energy, for example, solar and wind energy (Fantazzini et al., 2011). For these reasons, we believe it will be very hard for China to achieve its substitution target. The following is what we find for potential alternative energy sources for coal:

4.1. Oil

Oil cannot realistically replace coal. One reason is that there are big differences between oil and coal. Coal is a solid fuel with low quality and high carbon content and is mainly used to generate electricity in China. Oil is a high quality liquid fuel with lower carbon content and is mainly used for transport. Because of these differences, it is difficult for China to replace coal with oil.

The other important reason oil cannot realistically replace coal is that China's oil resources are quite limited. In 2010, 54.5% of China's oil consumption was imported (Li, 2011). Furthermore, imports are likely to grow in future, because the fields which are the backbone of Chinese oil production are maturing and reaching a point of terminal decline (Tang et al., 2010; Höök et al., 2010b), while China's consumption continues to grow. Additional evidence of limits on Chinese oil supply is increasing tension surrounding petroleum resources in the South China Sea, a source of possible growth in China's oil supply which is uncertain due to technological and political factors (Wang et al., 2011b; Zhang, 2012).

One way China copes with the current shortage of oil supply is by developing coal to liquids (CTL) projects (a process by which liquids such as gasoline and diesel are made from coal), because the government believes that China is rich in coal. China's CTL policy has made some reversal due to water constraint and other factors after 2006 (Rong and Victor, 2011); however, CTL capacity is still expanding and reached 1.6 × 10^6 MT/year in 2009 (Yang, 2010a). Capacity is forecast to reach 12 × 10^6 MT/year in 2015, 50 × 10^6 MT/year in 2020, and expand further after 2020 (Yang, 2010a). Unfortunately, replacing oil with coal is not a workable solution because coal resources are also limited. Furthermore, CTL projects exhaust a large quantity of coal resources. Conversion ratios for CTL are generally estimated to be between 1 and 2 barrels/metric tons coal (Höök and Aleklett, 2010). This means that producing 50 × 10^6 MT of oil would exhaust 183.3–366.5 × 10^6 MT coal, which is 1.8–3.6 times the amount of coal imported in 2009.

4.2. Natural gas

Replacing coal with natural gas is also impossible, because China has even less natural gas resources than oil resources. According to estimates by Chinese scholars, China's conventional natural gas ultimately recoverable reserves (URR) amount to 5.99–13.32 × 10^12 m³, with the average URR equal to 9.64 × 10^12 m³ (Zhang, 2002), which is far less than the 22.03 × 10^12 m³ estimated by the
government (Dai et al., 2008). Even if an adjustment is made for the difference in the official URR compared to that of Chinese scholars, production in 2020 will only be 164.6 x 10^9 m^3, while gas demand will be much higher, reaching 260 x 10^9 m^3 in 2015 and 350–400 x 10^9 m^3 in 2020, according to the Chinese official 12th Five-Year Plan (Qu, 2011; Hou, 2011; Liu et al., 2010a). Therefore, the gap between demand and supply in 2020 will reach 185.4–235.4 x 10^9 m^3, while China can only import 114 x 10^9 m^3 natural gas based on current import plans (Qiu and Fang, 2009). As a result, China will need to find 71.4–121.4 x 10^9 m^3 natural gas to meet its demand.

China has given more attention to developing unconventional gas resources, such as coalbed methane (CBM) and shale gas, to meet this expected gap in gas supply and demand. The resources of unconventional gas are potentially substantial (Liu et al., 2009; PES, 2011); however, only a small part of them are discovered (Yang et al., 2011). Furthermore, according to the Energy Information Administration (EIA), (2016)’s forecast, production of unconventional gas will reach about 39.2 x 10^9 m^3 in 2020, which is still less than the gap of 71.4–121.4 x 10^9 m^3. In addition, China has also established some coal-to-gas projects, such as underground coal gasification (UCG), and is planning to expand their scale by breakthroughs in key technologies in 2011–2017 (Liu et al., 2010b; Yang, 2010b; Feng, 2011; NEA, 2011). For the same reasons as with CTL projects, many Chinese scholars believe that China is rich in coal but lacks gas (Liu et al., 2010b; Yang, 2010b). Trying to use natural gas to substitute for coal, therefore, would seem to be impossible.

4.3. Non-fossil fuels

Non-fossil fuels are alternative sources of energy that do not rely on exhausting limited supplies of coal, oil or natural gas. China would use less fossil fuel, if more non-fossil fuels are available. To increase its energy supply and to lower its carbon emissions, China has set very ambitious short-term targets for increasing the proportion of non-fossil fuels in its total energy consumption.

China’s non-fossil strategy includes both nuclear and renewable energy. In 2010, the capacity of nuclear power was 10.82 gigawatts (GW) (China Electricity Council (CEC), 2011a), and this capacity will increase to 40 GW by 2015 (compared with 890 GW of coal-fired power in 2015), according to the 12th Five-Year Plan, with an average annual growth rate of 29.9% (Seligsohn, 2011; Liu, 2012). China Electricity Council (CEC) (2011b) forecasts that this number will still keep rising and reach 90 GW in 2020. Therefore, China’s nuclear power industry will experience its golden development period, even though a serious radioactive leakage accident just took place in Fukushima nuclear power plants in Japan in 2011.

In addition to the rapid development of nuclear power, China is also installing renewable energy at an unprecedented rate. The capacity of hydropower, wind power, solar power (including solar PV and solar thermal) and other non coal-based power in 2010 were 213.40 GW, 31.07 GW, 0.24 GW and 0.02 GW, respectively (China Electricity Council (CEC), 2011a). According to the latest official plans, China will have 330 GW of hydropower capacity by 2020, which is nearly equivalent to building a “Three Gorges Dam” every three years. Furthermore, the capacity of wind power, solar power and other renewables in 2020 is planned to be 180 GW, 20 GW and 5 GW, respectively, with annual growth rates of 19.20%, 55.78% and 70.56%, respectively (China Electricity Council (CEC), 2011b). These numbers are so amazingly large that it is hard for us to imagine how these goals will be achieved. Even if China can achieve its goals, coal will still account for 60% of total primary energy consumption in 2020 (Chen et al., 2011). In summary, there are few options for China to reduce its reliance on coal.

5. Discussion and summary

Based on the above analyses, we reach several important conclusions. First, a detailed analysis of China’s coal resources/reserves classification system is performed, and then the URR numbers over time are analyzed based on the resources/reserves classification. It is found that the URR of China’s coal is basically constant after 2001 except for a slight decline in 2010, with an average value of 223.6 x 10^9 MT.

Second, China’s coal production is forecasted based on the estimated URR and a logistic production model. The result indicates that coal production will peak in 2027, with a peak production of 3.97 x 10^9 MT. Then, considering and combining other similar analyses, it is estimated that China’s coal production will peak between 2025 and 2030, with peak production of approximately 3.9 x 10^9 MT. Furthermore, it is noted that actual production may peak earlier and the maximum production may be lower if some other factors are considered, such as water availability, land availability, transportation capacity and climate change. However, extensive treatment of such factors where outside this study.

Third, it is concluded that estimates of China’s future coal consumption trend to be underestimated by most scholars. According to Shealy and Dorian (2010), even using a relatively conservative annual GDP growth target of 6.5% for the next fifteen years, China’s coal demand will still reach 6.12 x 10^9 MT in 2025, which is higher than some major institutions such as International Energy Agency (IEA) (2010), Energy Information Administration (EIA) (2010), National Development and Reform Commission of China (NDRC) (2009) have forecast. However, China’s domestic production is forecast to be limited to 3.9 x 10^9 MT, which means the gap between demand and supply will reach 2.22 x 10^9 MT in 2025. We also show that it may be very difficult for China to meet its gap by importing coal and developing alternative energy sources, which means that China’s economic growth may be affected due to the shortage of coal supply.

In addition, rising coal price can be expected to seriously influence China’s economic growth (Ding et al., 2011). China’s coal will become more expensive in years ahead for several reasons.

First, increasing domestic coal demand, limited domestic coal reserves and production will tend to lead to a rise in the price of coal (Li, 2009).

Second, increasing gap between domestic coal demand and production will lead China to import more coal from international markets. Some studies have suggested a likely significant increase of world coal prices in the coming decades (Kavalov and Peteves, 2007; Heiberg and Fridley, 2010), and rising international coal price will surely promote the increase in domestic coal prices because of the higher costs of imported coal.

Furthermore, the cost of imported coal is likely to be further increased by high transportation costs arising from increasing world oil prices (Kouznotzoff et al., 2008; Transportation Economics & Management Systems, Inc. (TEMS), 2008). In fact, China’s coal prices have already been rising since China’s coal pricing entered the Market-oriented pricing period in 2002 (Tu, 2011), and are expected by some to continue to rise in future (Wang and Zhang, 2011).

To sum up, Tverberg (2012) has shown that limited oil supply and the concomitant rising oil prices can have an adverse impact on economic growth. Other studies have also shown that high oil prices can lead to recession (Kilian, 2008, 2009; Hamilton, 2009; Fantazzini et al., 2011). China’s economic growth requires an adequate supply of affordable and inexpensive coal, and currently, coal is more important than oil in China. It is believed that limited coal supply and rising coal prices will present a significant challenge to China’s economic growth.
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Appendix A. Historical evolution of China’s classification system for mineral resources/reserves

History of classification for Chinese mineral resources/reserves

China’s classification of mineral reserves is derived from the system used by the former Soviet Union (FSU). In January 1954, Solid Mineral Reserve Classification Standards of FSU was reprinted by National Mineral Reserve Committee of China (NMRC) as a main reference for Chinese classification systems. In April 1959, the first formal Chinese standard of Provisional Specifications for Mineral Reserve Classification (General Principles) was issued, which divided reserves into five categories: A1, A2, B, C1 and C2. In June 1977, new classification systems for metallic and non-metallic minerals called General Requirements for Metallic Mineral Exploration (Trial Implementation) and General Requirements for Non-Metallic Mineral Exploration (Trial Implementation) were introduced. Mineral reserves in the new classification systems were divided into four categories: A, B, C and D. In December 1992, a new classification system for all minerals called General Requirements for Solid Mineral Exploration (GB/T 13908-1992) (“GB” means “National Standards”) was released to replace all the previous systems. Mineral reserves were divided in priority order of geological confidence into A–E categories.

All of the classification systems before 1999 are very similar to the classification system used by the FSU as part of its system of central economic control. Over the years, China revised these systems several times in the light of its own conditions. The main purpose of exploration activities under these old systems was to know the quantities of mineral resources for the central government, rather than to exploit them directly for enterprises. Therefore, these systems are based primarily on geological conditions, with little attention to economic conditions. This means that some coal which cannot be extracted economically (for example, coal that is too deep or in too thin seams) may not be extracted in the future (Chen et al., 2002). Moreover, the old system made comparison with other countries difficult. The Chinese Mineral Resources/Reserves Classification System and its Application, which was submitted by the Chinese government to the United Nations (United Nations (UN) 2001) states:

The above edition (i.e. old classification system), which was different from the international well known normal practices, had made it very difficult for the mining industry of China to communicate in common language with that of other countries, and hence, it has impeded the progress of China in developing a market economy and opening its door to the world for investments in the mining industry.

Therefore, with the formation and development of the socialist market economic system in China, it has been an urgent matter to revise the old mineral reserve classification system in order to fit the requirements of the new economic system, in order to be in a better position to exploit Chinese mineral resources (United Nations (UN) 1999). Finally, in June 1999, the Chinese government issued a new edition of classification system called Classification for Resources/Reserves of Solid Fuels and Mineral Commodities (GB/T 17766-1999) as a national standard in June 1999 to solve this problem. The new classification system was based on the United Nations International Framework Classification for Reserves/Resources (ENERGY/WP.1/R.70) (United Nations (UN), 1997) and Principles of a Resource/Reserve Classification for Minerals (U.S. Geological Survey (USGS), 1980). Using this approach represented a revolutionary reform for the mining industry of China (United Nations (UN) 2001). Detailed rules for implementing the new classification system were released in August 2002, in a document called General Requirements for Solid Mineral Exploration (GB/T 13908-2002) which replaced the implementation rules of 1992 (GB/T 13908-1992).

In 2007, China decided to make some modification of GB/T 17766-1999 because the new classification system was still not regarded as being particularly suitable for reporting in a market economy and because its use created operational difficulties for both local companies and foreign companies operating in China (Stoker, 2009). Therefore, in July 2009, Ministry of Land and Resources of China (MLR) released a revised draft of GB/T 17766-1999 (named GB/T 17766-revision) to the public in order to solicit opinions from all sides. However, even after the solicitation of public opinion, the government did not formally issue a revised edition.

Finally, in November 2010, the Chinese government issued a further revised classification approach called Specification for Comprehensive Exploration and Evaluation of Mineral Resources (GB/T 25283-2010). The classification system of GB/T 17766-1999 was still in use until the issuance of GB/T 25283-2010.

In summary, GB/T 17766-1999 has been brought into wide use, although it is now being further improved. We therefore will give a further introduction of it.

Classification for resources/reserves of solid fuels and mineral commodities (GB/T 17766-1999)

GB/T 17766-1999 adopted a three-dimensional classification model as recommended by UNFC to classify resources/reserves (Fig. A1). The first axis in this three-dimensional classification model is the degree of Geological Assurance (G axis), which is based on the result of exploration. The stages of mineral exploration work are divided into four parts: detail exploration, general exploration, prospecting and reconnaissance; therefore, the degrees of Geological Assurance are also divided into four parts: measured (G1), indicated (G2), inferred (G3) and reconnaissance (G4). The second axis in the model is the stages of the Feasibility Assessment (F axis). Based on the different level of assessment work, the stages of the Feasibility Assessment are divided into three parts: feasibility study (F1), pre-feasibility study (F2) and geological study (F3). The last axis in the model is the degrees of the Economic Viability (E axis), which can be divided into four parts: economic (E1), marginal economic (E2), sub-economic (E3) and intrinsic economic (E5).

Based on this classification model, mineral occurrences are sub-divided into sixteen categories within three major categories, i.e. reserves (three sub-categories), basic reserves (six sub-categories) and resources (seven sub-categories) (General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China (AQSIQ) 1999) (Fig. A1 and Table A1).

Reserves are that minable part of basic reserves on which the factors such as economic, mining, metallurgical, environmental, legal, marketing, social and governmental have 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 or has already been mined; it is expressed by actual minable tonnage or volume, from which the losses of
designing and mining have been deducted; it is divided into three sub-categories: their codes are 111, 121, and 122, respectively.

Basic Reserves is 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. It also can be divided into six sub-categories: their codes are 111b, 121b, 122b, 2M11, 2M21 and 2M22, respectively.

Resource consists 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. It is divided into seven sub-categories: their codes are 2S11, 2S21, 2S22, 331, 332, 333 and 334, respectively.

### Appendix B. Introduction of logistic model

Logistic model (or Hubbert model) is described by the following equation (Patzek and Croft, 2010):

\[
Q = \frac{2Q_{\text{max}}}{1 + \cos h[b(t-t_m)]} 
\]

\[
N_p = \frac{N_R}{1 + e^{-b(t-t_m)}} 
\]

\[
N_R = 4Q_{\text{max}}/b 
\]

where \( Q \) is oil production at time \( t \), \( Q_{\text{max}} \) peak production, \( N_p \) cumulative production, \( N_R \) ultimate recoverable reserves (URR), \( b \) a parameter which accounts for the slope of the curve, and \( t_m \) the year corresponding to the peak.

---

**Table A1**

<table>
<thead>
<tr>
<th>Total identified mineral resources</th>
<th>Undiscovered resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>Indicated</td>
</tr>
<tr>
<td>Economic</td>
<td></td>
</tr>
<tr>
<td>Proved extractable reserve (111)</td>
<td>Basic reserve (111b)</td>
</tr>
<tr>
<td>Basic reserve (111b)</td>
<td>Probable extractable reserve (122)</td>
</tr>
<tr>
<td>Marginal economic</td>
<td></td>
</tr>
<tr>
<td>Basic reserve (2M11)</td>
<td>Basic reserve (2M21)</td>
</tr>
<tr>
<td>Sub-economic</td>
<td></td>
</tr>
<tr>
<td>Basic reserve (2M21)</td>
<td>Basic reserve (2M22)</td>
</tr>
<tr>
<td>Resources (2S21)</td>
<td>Resources (2S22)</td>
</tr>
<tr>
<td>Intrinsic economic</td>
<td>Resources (333)</td>
</tr>
<tr>
<td>Resources (333)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Of the codes (111–334) used in the table above, the first digital number indicates the degree of economic viability: 1 = economic, 2 M = marginal economic, 2 S = sub-marginal economic, 3 = intrinsic economic, ? = economic interest undefined; the second digital number indicates stages of feasibility assessment: 1 = feasibility study, 2 = pre-feasibility study, 3 = geological study; the third digital number indicates geological assurance: 1 = measured, 2 = indicated, 3 = inferred, 4 = reconnaissance, b = before the deduction of extractable quantities lost in the process of designing and mining. Source: General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China (AQSIQ) (1999).
Wang et al. (2011c) introduce the equation-solving process, which is shown as follows. By changing Eq. (2), we get:

\[
\frac{N_F - N_p}{N_p} = e^{-bt_m - bt}
\]

(4)

By taking logarithms on both sides of Eq. (4), this gives:

\[
\ln \left( \frac{N_F - N_p}{N_p} \right) = bt_m - bt
\]

(5)

Then, provided \( A = bt_m, B = -b \), Eq. (5) can be rewritten as:

\[
\ln \left( \frac{N_F - N_p}{N_p} \right) = A + Bt
\]

(6)

According to Eq. (6), we can obtain the value of intercept \( A \) and slope \( B \). Furthermore, parameter \( b \) and \( t_m \) can be calculated. Then, peak production \( Q_{\text{max}} \) can be calculated by Eq. (3) and forecast production can be obtained by substituting \( Q_{\text{max}}, b \) and \( t_m \) into Eq. (1).

References


