Modelling India's coal production with a negatively skewed curve-fitting model

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Abstract

India's coal demand is forecast to increase at a rapid pace in the future due to the country's economic and population growth. Analyzing the scope for future production of the India's domestic coal resources therefore plays a vital role in the country developing sound energy planning and policies. This paper presents a quantitative scenario analysis of India's potential future coal production by combining a negatively skewed curve-fitting model with a range of estimates of the country's ultimately recoverable resource ('URR') of coal. The results show that the resource base is sufficient for India's coal production to keep increasing over the next few decades, to reach between 2400 and 3200 Mt/y at 2050, depending on the URR value assumed. A further analysis shows that the high end of this range, which corresponds to our 'GSI' scenario, should be seen as the probable upper-bound to India's domestic coal production. Comparison of production even under this 'GSI' scenario with India's predicted demand shows that the domestic production of coal will be insufficient to meet the country's rising demand, with the gap between demand and production increasing from its current value of about 268 Mt/y reach 300 Mt/y in 2035, and 700 Mt/y by 2050. This increasing gap will be challenging for the energy security of India.

Keywords: India; Coal production; Ultimately recoverable resources; Curve-fitting models

1. Introduction

India's energy use is experiencing a rapid increase due to both population growth, and to its rapidly rising economic growth, the latter assisted by the economic reforms in 1991 (Chakraborty and Nunnenkamp, 2008). According to the World Bank (World Bank, 2016) and the BP *Statistical Review of World Energy* (BP, 2016a), the average annual growth rate (AAGR) of Indian GDP was 6.8% from 1991-2015, while the AAGR of its primary energy use was 5.3% during the same period. Empirical analyses have shown that there is a significant relationship between Indian energy consumption and its economic growth (Mallick, 2009). Further economic and population growth, allied to structural trends, such as urbanization and industrialization, will contribute to continued rapid expansion in the country's demand for energy (IEA, 2015; ExxonMobil, 2015). The *World Energy Outlook* published by International Energy Agency (IEA) in 2015 forecasts that Indian annual energy demand will increase from 775 million tons oil equivalent (Mtoe) in 2013 to about 1900 Mtoe in 2040, representing a compound average annual growth rate of 3.4%, which is the highest growth rate in all major economies (IEA, 2015).

In Indian primary energy use, coal holds a very important position. First, coal has the largest contribution to the growth of total energy use in India. According to BP (2003-2015, 2016a), from 2001-2015, the AAGR of coal use was 6.54%, which is higher than the other energy sources (5.97% for nuclear energy, 5.24% for oil, 4.93 % for natural gas, and 4.54% for hydroelectric). Second, coal has the largest share of the country's total energy use; and more importantly, this share has been increasing for many years. In 2007, the share for coal use in total energy use was 51.4% (BP, 2008), and thereafter, this share has increased to be 53.0% in 2010 (BP, 2011), 54.5% in 2013 (BP, 2014), and 58.1% in 2015 (BP, 2016a). This increasing trend for coal's share in total energy use is very different to the trend in other major economies. For instance, coal's share in both the US and China has declined steadily over the same period, in part due to environmental issues. By contrast, much of the literature on the subject, and

studies from many institutes also, suggest that India's future energy use will continue to be dominated by coal (see, for example, Greenpeace, 2015; IEA, 2015; WEC, 2013; BP, 2016b). Furthermore, many institutes have revised upward their predictions for future coal demand in India in recent years. For example, the IEA forecast that Indian annual coal demand would be 781 million tons coal equivalent (Mtce) in 2035 in WEO-2010 (New Policies Scenario) (IEA, 2010). However, this number has been adjusted upwards subsequently; to 883 Mtce in WEO-2011, 938 Mtce in WEO-2012, 972 Mtce in WEO-2013, 975 Mtce in WEO-2014, and 1163 Mtce per year in WEO-2015 (IEA, 2011-2015).

Facing this rapid increase in India's forecast coal demand, a realistic analysis of the country's long-term domestic coal production trajectories would seem to be necessary for India's energy planning purposes.

By reviewing the current literature, it can be found that only a relatively few studies have quantitatively considered the long-term production of Indian coal resources. Höök et al. (2008) published a conference paper forecasting global coal production using a logistic model. As an important coal producer, Indian coal production was also projected in Höök et al. (2008). Thereafter, this group updated their study, and published the results in a peer-reviewed journal (Höök et al., 2010). In addition, four other studies known to us also predicted Indian coal production when they forecast the long-term production of world coal resources (Mohr and Evans, 2009; Patzek and Croft, 2010; Zittel et al., 2013; Mohr et al., 2015).

Based on this limited literature, it can be seen that there are not many studies of future Indian coal production, and where moreover, the forecast results among these studies differ considerably. A number of reasons are probably responsible for these differences, among which the two believed to be most important are: one is the model applied, and the other is the quantities of coal assumed that can be finally recovered from the deposits (the latter is called the *ultimately recoverable resource*, i.e., URR).

For example, assuming the similar values of URR, Höök et al. (2008) used a Logistic model to forecast that Indian coal production would peak at 1350 million metric tons per year (Mt/y) in 2050; while Mohr and Evans (2009) forecast the peak

production for Indian coal resources using a demand-supply interaction model and a roughly similar URR value to be 943 Mt/y in 2037. Furthermore, by using the same forecast model, when Höök et al. (2010) assumed that the URR of Indian coal resources is about 130 gigatons (Gt), then they forecast that Indian coal production would reach its peak in 2055 at around 1725 Mt/y. By contrast, Zittel et al.(2013) assumed a significantly lower coal URR value of about 66 Gt, in which case they forecast the peak production, and peak year, for Indian coal resources to be 800 Mt/y and 2030 respectively. Due to such significant differences in forecasts, policies relying on only one result may have considerable risks.

The main purpose of this paper therefore is to address this uncertainty by presenting a new quantitative analysis of Indian domestic coal production, and to compare these results with those in other published studies, with the aim of better understanding the likely future pathway of Indian coal production, and hence to analyze the impacts of future coal production on Indian coal security.

2. Analysis of Resources availability

2.1 Definition of resource availability

Resource availability is a key factor affecting the long-term production of any fossil fuel, including that of coal. In practice, some authorities treat the *total resources* of a fossil fuel, which are the total quantity that is located under the ground, as the recoverable availability; for example, when the Intergovernmental Panel on Climate Change estimates the potential production pathways of world fossil fuel, the quantities of *total resources* are used as the available resources (IPCC, 2000). But due to a number of reasons, not all *total resources* defined this way can be recovered in reality; and where therefore a production forecast based on such *total resources* may result in some extremely high production levels (Höök and Tang, 2013).

By applying a modified McKelvey diagram, Rogner (1997) divided the *total resources* of coal into four main categories: cumulative production, reserves,

recoverable resources, and additional occurrences.

- *Cumulative production* is defined as the sum of the amounts extracted up to now;
- *Reserves* are defined as the quantities that can be recovered from the known deposits at current prices with current technology;
- *Recoverable resources* are defined as the quantities that could be potentially recovered from the known and unknown deposits with considering the improved economic and technical conditions in the future;
- *Additional occurrences* are those unrecoverable quantities.

Under these definitions the sum of cumulative production, reserves and recoverable resources is usually defined as the term of *ultimately recoverable resource* (URR), and the additional occurrences can be calculated as the total resources in place minus URR.

In modelling, the literature usually treats URR as a term to represent the potential availability of a resource, since it not only includes the quantities that can be currently recovered, but also those that could be potentially recovered in the future by considering the improvement of economic and technical conditions.

2.2 Cumulative production

Producing coal has a very long history in India. However, there was no record or documentation regarding the coal industry until the middle of the 18th century. The first record was appeared in 1774 and showed that shallow mines were used to be operated first in Raniganj field of West Bengal, which is considered as the birthplace of coal mining in India (Chakrabarti, 1989). From the year 1774 to now, India has mined coal for more than 230 years.

In the beginning, coal mining was limited to the Raniganj field but during the later part of the 19th century, production area started to expand to other places of this country, and the production of coal also began to increase. In the year of 1990, India's coal production first reached more than 6 Mt. Subsequently, the country's coal industry was further promoted by the increased demand during the First World War period and the

production rose to more than 21 Mt in 1918. The industry then suffered a setback due to the great depression after the First World War.

In the year 1945, the Singareni Collieries Company Limited (SCCL) was formed as the first state-owned coal company. In 1947, India achieved its independence. Five Yeas Plans were subsequently launched with ambitious targets of coal production due to the importance of coal in the country's energy industry. To promote the development the coal industry, the National Coal Development Corporation (NCDC) was set up in 1956.

During the entire period before 1970s, there were only several state-owned companies having their own coal mines, and most of the coal mines were in the private sector (Chikkatur et al., 2009). There was a complete anarchy and chaos in the production and distribution of coal in spite of increase in demand for coal. Realizing the importance of coal to the development of the country and considering the above situation of chaos, Indian government took the decision to make the nationalization in the country's coal industry in the early 1970s. One main aim of this nationalization is to rapidly increase coal production to meet the needs of consumers (Gupta, 1979). Currently, nearly all of the coal production is from state-owned companies, especially from Coal India Limited (CIL) and SCCL. Since nationalization, India's coal production has increased more than eight-fold with the production in 2014 at 660 Mt (see Figure 1). The cumulative production by the end of 2014 was 14800 Mt.
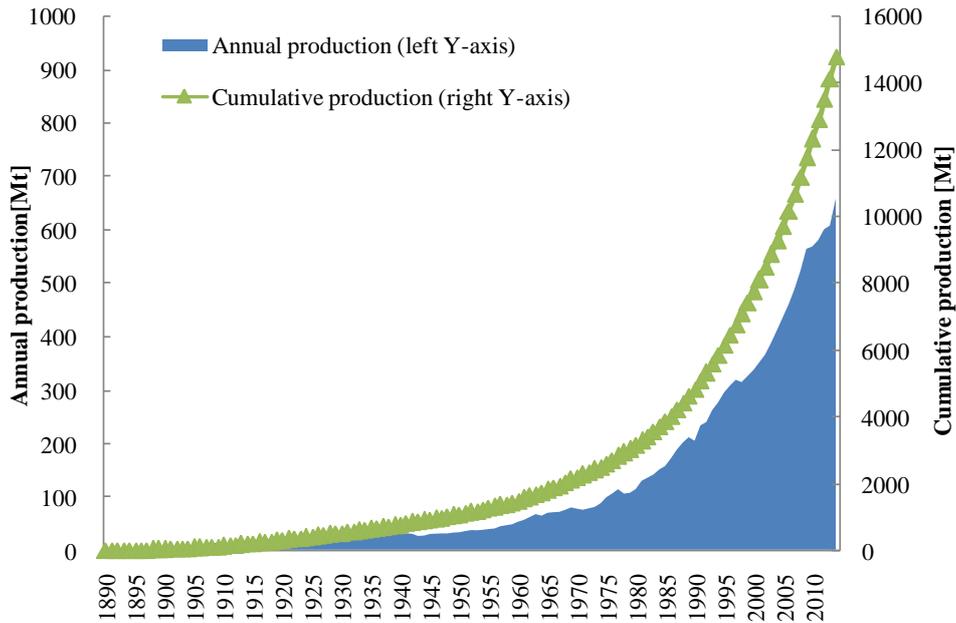
Figure 1. Indian annual coal production, and cumulative production, 1890-2014

Data source: Mohr et al. (2015) and MC (2015)

2.3 Reserves

Data on India's coal reserves can be found from many sources. These include: British Petroleum's (BP) annual *Statistical Review of World Energy*; the *Survey of World Energy Resources* by the World Energy Council (WEC); the annual report on *Reserves, Resources and Availability of Energy Resources* by the German Federal Institute for Geosciences and Natural Resources (BGR); the *International Energy Outlook* from the US Energy Information Administration (EIA); the annual *Inventory of Geological Resources of Coal in India* from the Geological Survey of India (GSI); and the annual *World Energy Outlook* of the International Energy Agency (IEA).

Of these sources, BP, WEC, BGR and GSI report annual time series data for Indian coal; while EIA and IEA only report the data for some specific years. Furthermore, the reserve data reported by EIA (2016) and IEA (2012) are originally from WEC (2013) and BGR (2011). Therefore, we only analyze the coal reserves data from BP, WEC, BGR and GSI (see *Figure 2*).

From *Figure 2*, it can be seen that the reserves data from BP and WEC are largely consistent, and the reason being that WEC is a key original source for BP's data

statistics. After 2010, since WEC does not update its India's coal data, India's coal reserves in the BP data have also remained constant. Furthermore, it can be seen that before 2007, the reserve data from BGR, WEC and GSI are also largely consistent. The main reason is that both BGR and WEC use the data reported by GSI directly. However, technical terms such as *geological resources* and *reserves* are often misused in India (Chikkatur et al., 2009). The reserve data reported by GSI are actually a type of 'geological resources', since the India's classification system of coal resources is primarily based on geological evaluations, without assessing the quality, mineability, or extractability of deposits (Chikkatur, 2008; Chikkatur et al., 2009; Khanna, 2013). In contrast, according to the international classification system, United Nations Framework Classification (UNFC), for example, reserves should be remaining quantities that can be economically mineable, technically extractable, and geologically proven (as defined in our paper). Therefore, using the data reported by GSI may overestimate the actual reserves. In 2013, Greenpeace analyzed the reserves of Coal India Limited (CIL), which is one of the largest coal producers in the world, accounting for 80% of India's coal production, and found that CIL's reserves are overestimated (Greenpeace, 2013).

Considering the data problem of GSI, after 2007, both WEC and BGR report their reserves data by applying a recovery factor to GSI's reserves data (IEA, 2015). By analysing the data reported by WEC, BGR and GSI, we found that the recovery factors applied by WEC and BGR are about 58% and 72% respectively. In 2006, using the UNFC's standards, the Central Mine Planning and Design Institute Limited in India (CMPDIL) estimated the coal reserve and found they were only 52 Gt, accounting for about 56% of GSI's reported data (Chikkatur, 2008), which is consistent with WEC's recovery factor.
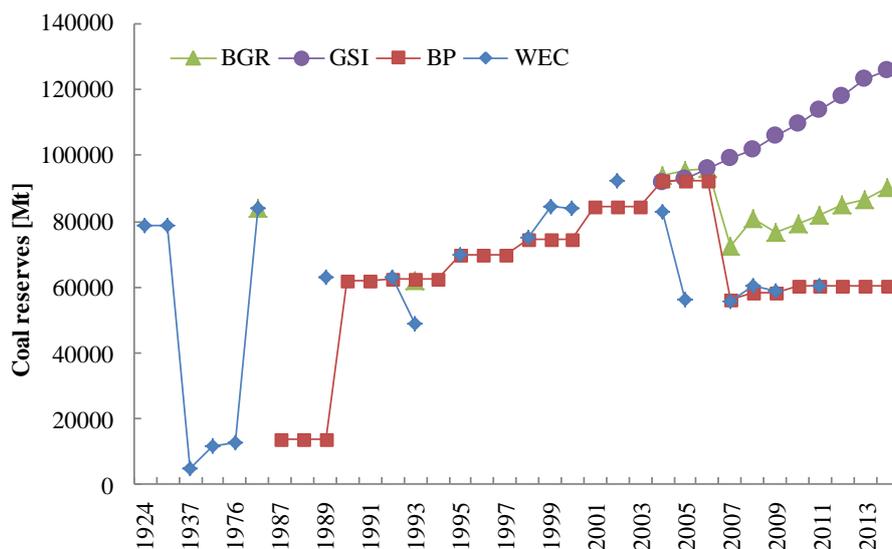
Figure 2. Data on Indian Coal Reserves from 1924-2014

Data sources: Höök et al. (2010), Zittel et al. (2013), BGR (2004-2014), GSI (2004-2014); BP (2003-2015), WEC (2001, 2004, 2007, 2010, 2013).

2.4 Recoverable resources

BGR, GSI and WEC also report India's coal resources data (see *Figure 3*). It should be noted that coal resources reported by these sources are actually the sum of *recoverable resources* and *additional occurrences* if the definitions in this paper are applied (BGR, 2009). Therefore, we cannot use the data from BGR, GSI and WEC directly.

Rogner (1997) used a modified McKelvey diagram to estimate the world coal reserves, recoverable resources, and additional occurrences. Based on Rogner's estimate, the world coal *recoverable resources* are 2397 gigaton of oil equivalent (Gtoe), while the sum of *recoverable resources* and *additional occurrences* are 5243 Gtoe. Therefore, we can get a recovery rate of 45.7% (i.e., 2397Gtoe/5243Gtoe). In this paper, the quantities calculated by multiplying the resources volumes reported by BGR, GSI and WEC by 45.7% are used as the volume of *recoverable* resources defined in our paper.
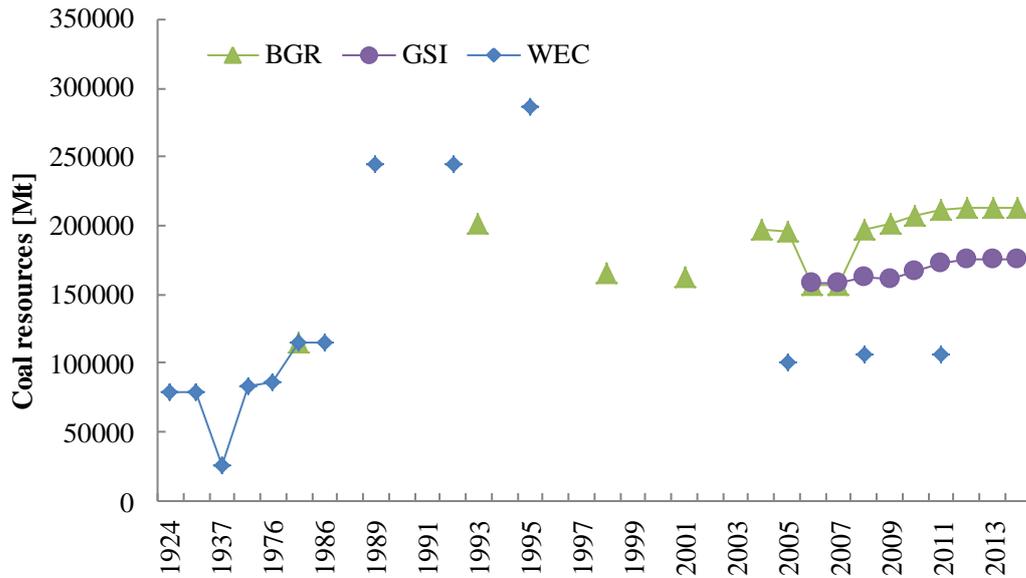
Figure 3. India coal resources reported by BGR, GSI and WEC

Data sources: Höök et al. (2010), BGR (2004-2014), GSI (2004-2014), WEC (2001, 2004, 2007, 2010, 2013).

2.5 Scenario analysis of resource availability

As discussed previously, the URR, which is the sum of cumulative production, reserves and recoverable resources, can be used to represent the resource availability. However, both reserves and recoverable resources are the subjective estimates based on partial information, which gives the URR a high degree of uncertainty. Therefore, to reflect these uncertainties, scenario assumptions that range from low to high resource availability are adopted in this paper.

Specifically, based on the data sources, we set up three scenarios; these are named as GSI scenario, BGR scenario and WEC scenario. "Cumulative production+GSI reserves+45.7% GSI resources" is defined as the URR in the GSI scenario; "cumulative production+BGR reserves+45.7% BGR resources" is defined as the URR in the BGR scenario; while "cumulative production+WEC reserves+45.7% WEC resources" is assumed as the URR in the WEC scenario.

Table 1. URR of Indian coal resources in different scenarios

Scenarios	Cumulative production[Gt]	Reserves [Gt]	Recoverable Resources[Gt]	URR [Gt]
GSI scenario		125.9	80.3	221.0
BGR scenario	14.8	90.3	97.3	202.4
WEC scenario		60.6	48.4	123.8

Note: all data are for 2014 except WEC data, which are for 2013.

The price is a main factor that influences the estimation of URR or reserves. This paper doesn't consider the influences of price on URR directly since the future price itself is very hard to forecast. However, we do consider these influences in two indirect ways: the first is that we use a broader definition of URR. In this paper, our URR not only includes those quantities that can be recovered at current price with current techniques from known reservoirs (i.e., *reserves*), but also quantities that could be potentially recovered from the known and unknown deposits with considering the improved economic and technical conditions in the future (i.e. *recoverable resources*). The second is that the scenario analysis is used in our paper to consider the uncertainty in estimates of URR, and of course, the uncertainty resulted from the change of price is also included. Therefore, the low URR in our paper can be also seen as the low price scenario, while the high URR in our paper can also be seen as the high price scenario.

3. Modelling approach

It should be noted that, in reality, the specific level of coal production at any point in time is determined by a combination of factors related to resource availability, the economics of production, environmental issues, infrastructure bottlenecks, haulage distances and so on. Therefore, it is hard to forecast the specific production level precisely. However, as a finite resource, the upper-bound of production capacity of coal will be determined finally by its resource availability. The model in this paper is therefore not intended to give an exact prediction of the specific level of coal production, but instead an estimate of a reasonable upper-bound of the long-term production capacity for India's coal resources. Furthermore, an ideal way to estimate this production capacity is to use the historical annual production capacity data as the input

of the forecast model, while the actual annual production data are used in this paper due to two reasons: one is the lack of historical annual production capacity data; the other is that it is reasonable to expect that the capacity utilization rate of a nation will be very high enough if it is thirsty for coal and its coal industry is experiencing a rapid development period (and India is this case).

As shown in the Introduction of this paper, in addition to URR, the models applied constitute the other main factor affecting the results. How to establish a perfect model is excluded in this paper. One important reason is that in reality, there are no 'perfect' models. Admittedly, each model is associated with its own analyzed perspectives, objectives, pros and cons (Wang and Feng, 2016). What we can do is to try to choose a suitable model that can achieve our purpose.

Many models can be used to forecast the long-term production capacity of fossil fuels, including curve-fitting models, system dynamic models, and bottom-up models (Brandt, 2010; Wang et al., 2011). Of these models, curve-fitting models are the most widely used to estimate the maximum production capacity of fossil fuels (Wang et al., 2013a; Wang et al., 2013b; Zittel et al., 2013;Patzek and Croft, 2010).

M.C. King Hubbert (1956, 1982), an American geophysicist, first proposed a curve-fitting model to forecast the U.S. conventional oil production (today, this model is known as Hubbert model, which is actually the first derivative of a logistic function (Wang and Feng, 2016). Thereafter, many subsequent studies used the Hubbert model or modified Hubbert model to research the long-term production pathways of fossil fuels (e.g. Szklo et al., 2007; Wang et al., 2013b; Nashawi et al., 2010; Berk and Ediger, 2016; Reaver and Khare, 2014).

Currently, the Hubbert model has already been the model used mostly in the literature. However, a lot of researchers also pointed out some limitations of the Hubbert model (Cavallo, 2004; May et al., 2012). One key limitation or problem is that the model is symmetric. For example, Cavallo (2004) and Berg and Boland (2014) claimed that the accuracy of the Hubbert model requires several strict economic and political conditions, including: political and economic stability, resource pricing that is both affordable and profitable, exponential increases in efficiency of resource

extraction, import availability, as well as reasonable reserve estimates. However, these requirements in reality are very hard to meet, which means that the actual production curve is generally asymmetric. Wang and Feng (2016) also claimed that during the fossil fuel exploitation process, production behaviors can vary significantly as geological, technical, economic, and social parameters interact. Consequently, it is not reasonable to expect that all regions will follow the "Hubbert" curve shape. Michaelides (2017) made a critical examination of Hubbert model and concluded that the symmetric model doesn't account for several important factors that significantly influence the production of fossil fuels. Based on these studies, an asymmetric curve-fitting model should be expected.

Generally, the shape of curve-fitting models can be divided into three categories based on their inflection points[1], i.e. symmetrical curve (inflection point=0.5 or 50%), negatively skewed curve (inflection point>0.5 or 50%), or positively skewed curve (inflection point<0.5 or 50%). The impacts of different curve shape on production behaviors are shown in Figure 4. It can be seen that a positively skewed curve always means an earlier peak and a lower peak production but with a slower decline rate in post-peak period compared to a negatively skewed curve. Wang and Feng (2016) pointed out that the curves with similar or identical inflection points give roughly equal results, that's why the results from Logistic model and Gaussian model are nearly the same.

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[1] Wang and Feng (2016): The inflection point is "where the curvature changes sign, and this point coincides with the maximum production level. Symmetric models always peak when 50% of the URR has been depleted, whereas asymmetric models can have inflection points that occur at an arbitrary depletion level".
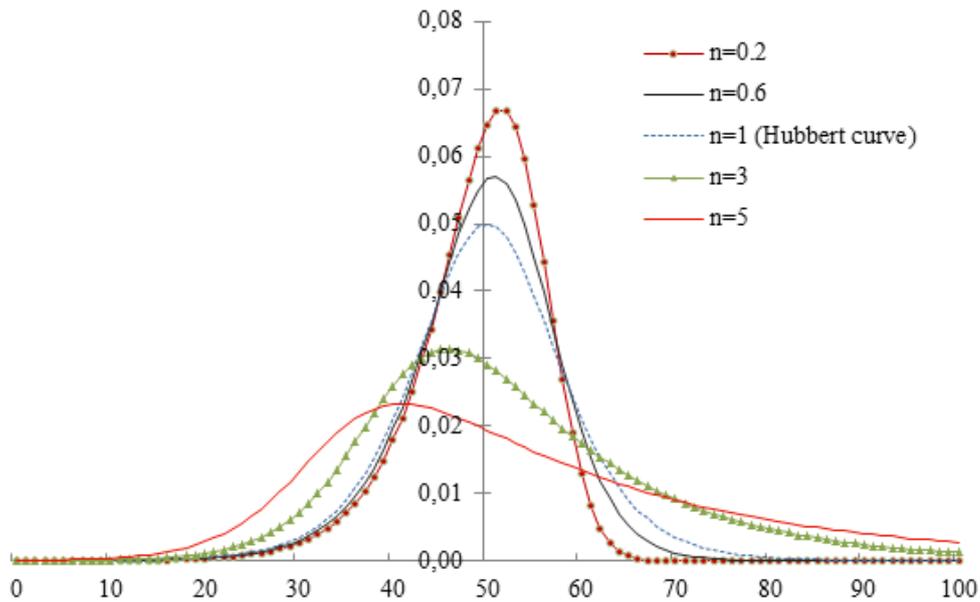
Figure 4. Production behaviours under different curve shape.

Note: the URR for all curves are the same and is 1, n is used to determine the inflection point of the curves: curve shape is symmetric when $n=1$ (for example, Hubbert model); curve shape is positive skew for $n > 1$ and negative skew for $n < 1$. This figure is originally from Wang and Feng (2016).

As stated previously, many studies have already shown that symmetric curve-fitting models, such as Hubbert model and Gaussian model, are not suitable to forecast the future production of fossil fuels. Now the question is which type of asymmetrical curve is more suitable for our forecasting. Brandt (2007) claimed that the positive skewed curve is more suitable compared to other types of curve shapes. However, Bardi (2005) made a detailed theoretical analysis and pointed out that technological improvements which increase the rate at which resources are extracted can reduce the amount of time until peak production occurs, subsequently resulting in a more rapid decline in post-peak production. According to Bardi (2005), the suitable model for forecasting should be the negatively skewed curve. Michaelides (2017) analyzed the historical production of world oil and gas resources and proposed a simple model, which is also a negatively skewed curve. Meanwhile, by analyzing the production behavior of post-peak coal nations (these kinds of data are from Mohr and Evans (2009), this paper also found that the shape of historical coal production in many nations is negatively skewed (see data for some selected nations in Figure 5).
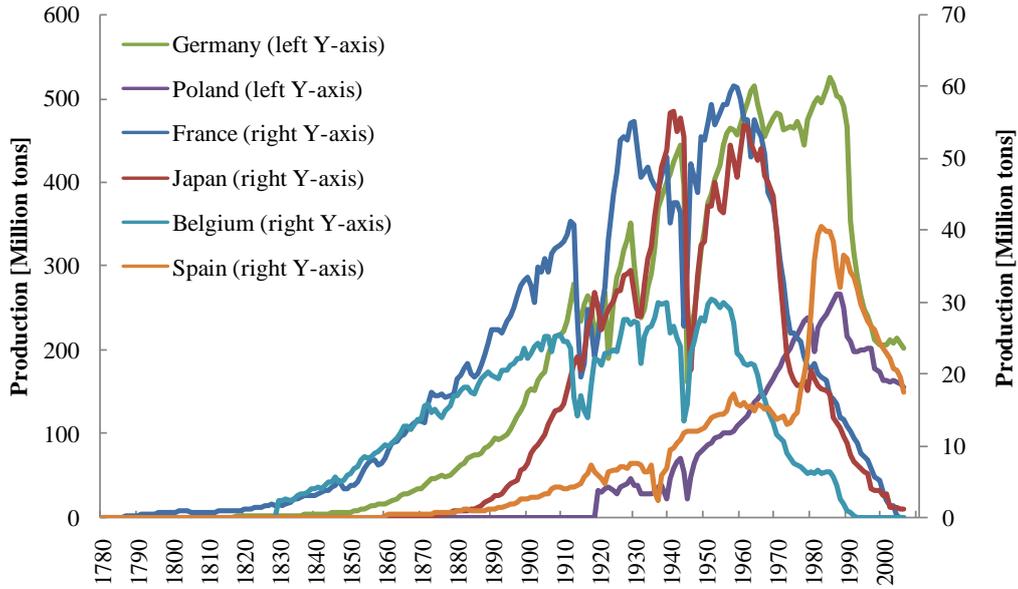
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Figure 5. Negatively skewed coal production curves from selected nations
Data source: Mohr and Evans (2009)

Based on the above discussion, this paper will use a negatively skewed curve-fitting model to forecast the future coal production of India. The model proposed by Michaelides (2017) may be a suitable model. However, by analyzing the historical production data of India's coal resources, we found that there are no obvious signals to show that the India's coal production has entered its linear increase period (which is a key period in the Michaelides model), which means we cannot use the Michaelides model here. Wang and Feng (2016) used the Richards model to analyze the impacts of different types of curve shapes on production forecasts.

The Richards model is as follows (Wang and Feng, 2016):

$$Q(t) = URR \times \left[1 + b \times e^{-k(t-t_m)}\right]^{-1/b} \tag{1}$$

where $Q(t)$ is the cumulative production at time t; URR is the ultimately recoverable resources; t_m is the peak year; b and k are parameters.

The annual production, $q(t)$, can be then calculated by equation (2):

$$q(t) = Q(t) - Q(t-1) \tag{2}$$

It should be noted that Richards model is a flexible model that allows easy variation

of the inflection point location. Different values of *b* in the Richards model are used to create three distinct curve shapes: when *b*=1, the inflection point=50%, and the curve is symmetric; when *b*=0, the inflection point ≈50%, and the curve is positively skewed; when *b*=2.3898, the inflection point=60%, and the curve is negatively skewed (Wang and Feng, 2016).

In this paper, the Richards model with the value of *b* equaling 2.3898 is used to forecast India's coal production. From equation (1), it can be seen that URR is a key input factor and this is why we presented a detailed analysis of URR in the previous part of this paper.

Once the value of the parameter b is set, the only unknown parameters in equation (1) are t_m and *k*, their values can be ascertained by using Excel Solver. The optimization objective is to minimize the value of the following quantitative index, i.e., RMSE (root-mean-square error). The basic formula for RMSE is given by Wang et al. (2011):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(q(t)_{act} - q(t)_{for.}\right)}{n}} \qquad (3)$$

where *n* is the number of data points, $q(t)_{act.}$ is actual annual production, and $q(t)_{for.}$ is estimated annual production.

4. Results and Discussion

4.1 Forecast results

Figure 6 and Table 2 present the forecast results. It should be noted that uncertainty is unavoidable in any prediction for the future. The longer period we forecast; the higher uncertainty we have. To reduce the uncertainty, the forecast period in this paper is only till to 2050. According to our forecast, India's coal annual production can increase over the next several decades and there is no production peak in our forecast period for all URR scenarios. Specifically, the annual production in the GSI scenario is forecast to keep increasing to reach 3230 Mt/y in 2050. The annual production growth pathway in the BGR scenario is similar with the GSI scenario since they have similar URR values. However, the WEC scenario shows a different production growth pathway. In the WEC

scenario, the production will increase with a much lower growth rate (an average annual growth rate between 2014 and 2050 is about 3.7%) and reach 2430 Mt/y by the end of our forecast period. The key reason for the difference is the different assumptions on URR. As we show previously, the significant differences in URR assumptions reflect the high uncertainties in the future. Due to the lack of high quality data and limited information, it is very hard to judge which scenario's results are the more plausible. However, it can be expected that the future coal production in India is very likely not to exceed the results of the GSI scenario, the reason being that the reserves reported by GSI are believed to be highly optimistic (see section 2.3).
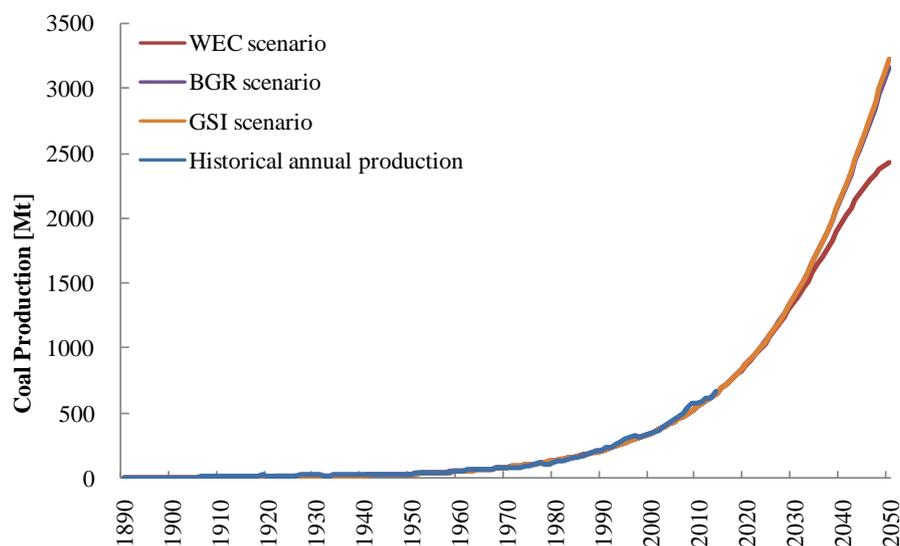

Figure 6. India's domestic coal production outlook in the different scenarios

Table 2. India's coal production in the different scenarios

Scenarios	2014 production [Mt/y]	2030 production [Mt/y]	2050 production [Mt/y]	Average annual growth rate between 2014 and 2050
GSI scenario		1390	3230	4.5%
BGR scenario	660	1385	3160	4.4%
WEC scenario		1350	2430	3.7%

4.2 Comparison of the forecast results of this study with other studies

Figure 7 compares the results from this study to those of others. It can be seen from this figure that there are major differences within published studies. According to Patzek and Croft (2010), India's coal production should have already declined, while based on Höök et al. (2010), the production can still increase until peaking around 2050. As discussed in the Introduction section of this paper, the models chosen and the URR values assumed are two key factors which affect the results (see Table 3). In this paper, we mainly focus on the URR. A main reason why the URR estimates applied by published studies are so different is due to lack of high quality data. We can see that current estimates on reserves and resources all originate from the GSI. However, the classification system and standards used by GSI are different from the international ones, and the data reported by GSI are actually for different types of geological resources. The purpose of GSI's assessment seems to be to know how much resources are located within the country, instead of how much of such resources can be recovered. Due to this lack of high quality data, studies tend to use their own estimates, or incomplete estimates, on URR values. For example, the URR value used by Patzek and Croft (2010) is estimated by the authors themselves; while the URR value used in Zittel et al. (2013) is the sum of cumulative production and reserves (which means recoverable resources are not included). One of the purposes of the present study reported here is to emphasise the importance of showing these differences in URR estimates, so that relevant experts and policy makers realize the problem with the coal data, and take steps to think what industry and government need to do to improve the quality of the data.

Another important reason for the differences shown in the Figure 7 is the model applied. Different from other studies, our paper is the only one that uses a negatively skewed curve-fitting model. It can be seen that most of other studies uses the symmetric Hubbert model (see Table 3). From Figure 4 in section 3, we can see that the negatively skewed curve has higher production growth rate and later peak year but with a rapid

decline rate in post-peak period.

    Due to the higher URR value and the negatively skewed curve used in this paper, it is reasonable to expect that the production in our paper is higher than those in other studies (see Figure 7). In addition, we also include a recent forecast from a 'mainstream' institute, i.e., '*IEA-WEO2015-NPS*' in Figure 7. We can see that IEA's forecast is still lower than our forecast. By comparing the forecast in this paper with those from literature, and from the 'mainstream' institutes, we can conclude again that the production pathway shown in our GSI scenario (i.e. '*GSI-URR=221.0Gt*' in Figure 7) could be seen as reflecting the probable the upper-bound to India's coal production.
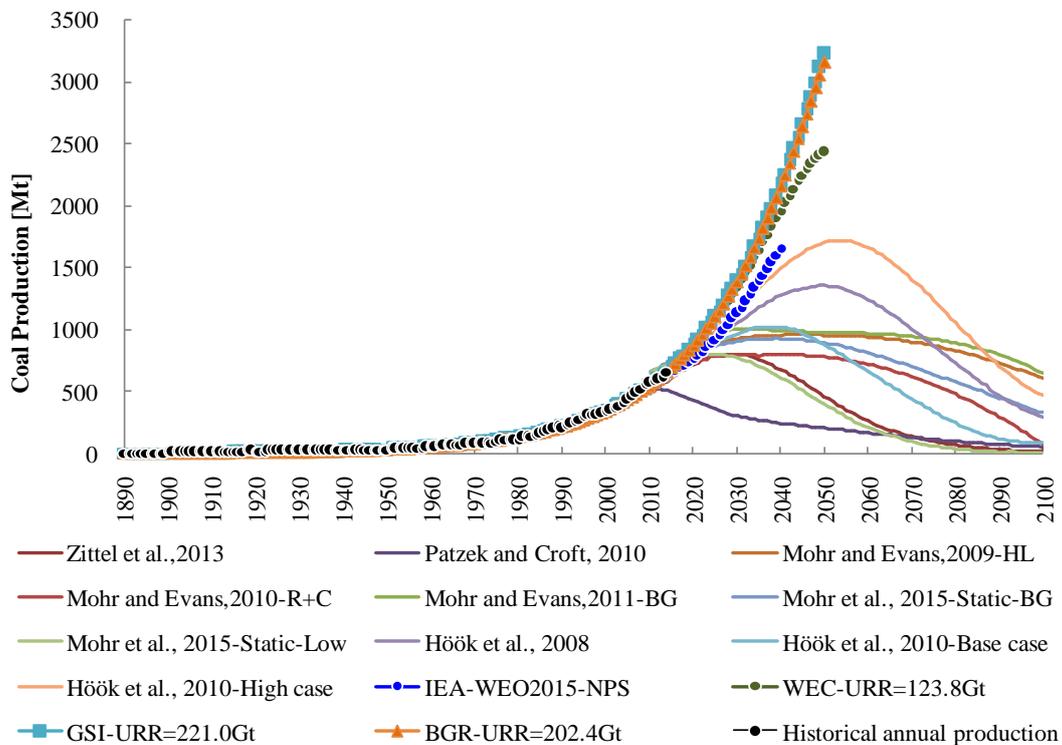

Figure 7. Comparison of different results for India coal production in published studies

Table 3. India's coal production forecasts in published studies

Literature	Model	URR [Gt]	Peak year	Peak production [Mt]
Zittel et al., 2013	Logistic model	66	2030	800
Patzek and Croft, 2010	Multi-Hubbert model	33	2011	520
Mohr and Evans,2009-HL	DSI model	97	2037	943
Mohr and Evans,2009-R+C	DSI model	67	2032	795
Mohr and Evans,2009-BG	DSI model	105	2038	1016
Mohr et al., 2015-Low	GeRS-DeMo model	45	2023	804
Mohr et al., 2015-BG	GeRS-DeMo model	88	2039	930
Höök et al., 2008	Logistic model	92	2050	1350
Höök et al., 2010-Base case	Logistic model	71	2040	1020
Höök et al., 2010-High case	Logistic model	130	2055	1725

Note: DSI model is demand-supply interaction model; GeRS-DeMo model is the Geologic Resources Supply-Demand Model.

4.3 Implications on Indian coal security and international coal trade

Figure 8 shows how India's domestic coal supply is likely to be, compared to the expected demand, based on the outcomes of this paper. Where there is a shortfall, this has important implications for India's coal security.

As can be seen from Figure 8, all studies reported here suggest that India's coal *demand* will keep increasing, and reach the rate of about 2046 Mt/y by 2035, and about 3930 Mt/y by 2050. By contrast, the results from even our highest GSI scenario suggest that domestic production will be no greater than 1740 Mt/y in 2035, and 3230 Mt/y in 2050. Therefore, the gap between demand and domestic maximum supply will be 306 Mt/y in 2035 and 700 Mt/y in 2050, compared to this gap in 2014 of 268 Mt/y.

As we have suggested above, that the production in the GSI scenario should be seen as probably a realistic upper-bound of production capacity for India's coal resources, and hence the actual production level could be much lower due to a number of reasons, such as the lack of sufficient investment in the coal industry, lack of infrastructure, lower coal price, or more stringent environmental regulations. Therefore,

a bigger shortage of coal could be expected in reality, and India will have to meet its demand by yet additional quantities of imported coal.

In the world coal market, China, India, Japan and South Korea are the four major coal importers. China used to be the largest coal importer before 2014, however, due to the slowing economic growth and serious domestic environmental issues (China is the largest carbon emitter and is facing serious air pollution), China's coal consumption has stopped increasing since 2014 (Tang et al., 2016). As a result, China's coal imports have also decreased in recent years. It can be expected that the coal imports in Japan and South Korea could also be declining. So given these factors, it can be seen that in the near future, India will almost certainly overtake China as the biggest coal importer, and be the main driving force for increases in world coal trade.
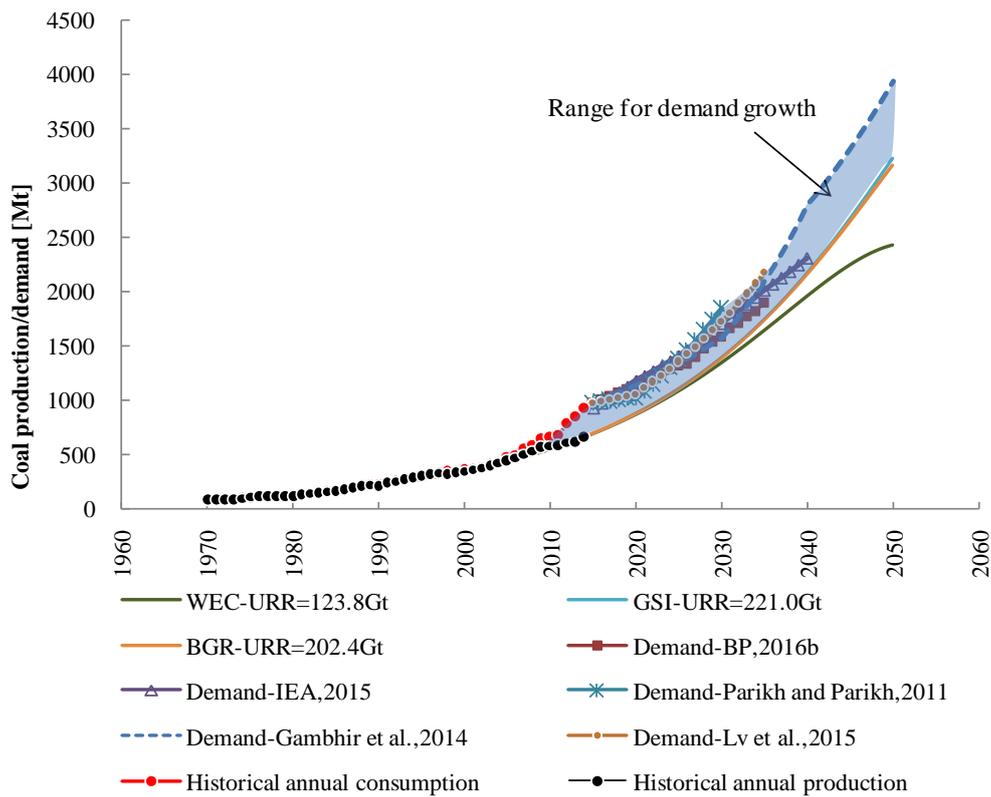

Figure 8. India's domestic coal production and its future demand

Data sources: BP, 2016b; IEA, 2015; Lv et al., 2015; Parikh and Parikh, 2011; Gambhir et al., 2014.

5. Conclusions

The issue of climate change has had serious impacts on global coal consumption, and several main coal consumers have taken measures to cut down their coal consumption. However, India is an exception. Nearly all major institutes, such as IEA (2015), BP (2016b) and WEC (2013), forecast that India's coal demand will keep increasing at a rapid pace in the future, due to the rapid growth in the economy, the constant increase in demand for electricity, and reductions in its levels of 'energy poverty' (where, according to WEC (2013), around 295 million people in India today still live in energy poverty). Considering this rapid growth in coal demand, and to draw possible production pathways based on India's coal resources, this paper presents a quantitative scenario analysis of Indian coal production by combining a negatively skewed curve-fitting model with a range of coal URR estimates.

Our results show that India's coal production can keep increasing over the next several decades, and reach between 2400 and 3200 Mt/y at 2050, depending on the different URR scenarios we model. Based on our analysis, and on comparison with other current published studies, we conclude that the results in our 'GSI' scenario can be seen as setting a probable realistic upper-bound of India's coal production. Actual coal production could be lower than that indicated in the GSI scenario due to a number of constraining factors, including economic and environmental factors, particularly those driven by climate change considerations. However, A comparison of the production in the GSI scenario and the demand growth that most sources predict as outlined above shows that the domestic production will not be able to meet the country's expected soaring demand for coal, and that this gap between production and demand will increase from its present value (in 2014) of 268 Mt/y to reach about 300 Mt/y by 2035, and 700 Mt/y by 2050. This increasing gap will have to be met by foreign coal resources. In this case, coal security (and hence also energy security, as coal dominates energy production in India) will be an increasingly major concern for policy makers.

Acknowledgments

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