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Imminence of peak in US coal production and overestimation of reserves

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ABSTRACT

Coal is the bulwark of US energy production making up about a third of all energy produced and about half of its electricity generation capacity, over the last decade. Current energy policy in the Unites States assumes that there is at least a century of coal remaining within the nation that can be produced at the current rate of consumption. This assumption is based on the large reported coal reserves and resources. We show that, in coal-producing regions and nations, historically reported reserves are generally overestimated by a substantial magnitude. We demonstrate that a similar situation currently exists with US reserves. We forecast future US coal production, in both raw tonnage and energy, using a multi-cyclic logistic model fit to historical production data. Robustness of the model is validated using production data from regions within the US, as well as outside, that have completed a full production cycle. Results from the model indicate maximum raw tonnage coal production will occur in a time window between the years 2009 and 2023, with 2010 being the most likely year of such a maximum. Similarly, energy production from coal will reach a maximum in the years between 2003 and 2018, with 2006 being the most likely year of maximum occurrence. The estimated energy ultimate recoverable reserves (URR) from the logistic model is 2750 quadrillion BTU (2900 EJ) with 1070 quadrillion BTU (1130 EJ) yet to be mined, while the estimated raw tonnage URR is 124 billion short tons (112 Gt) with 52 billion short tons yet (47 Gt) to be mined. This latter value is merely a fifth of the long held estimate of 259 billion short tons (235 Gt).

1. Introduction

1.1. Coal, carbon dioxide, and climate

Coal is a prominent non-renewable fuel composed mostly of carbon and hydrocarbons (EIA, 2013b). Coal has been an increasingly important energy source for the United States and the world since the industrial revolution (Höök et al., 2012). Of the major fossil fuels, coal, oil, and natural gas, it is coal that is the most carbon intensive (Moomaw et al., 2011). Due to its long-term use and high carbon intensity, coal has introduced a large amount of carbon dioxide to the atmosphere. The effects of atmospheric carbon dioxide on the Earth's climate as a greenhouse gas and its connection with the burning of coal are well known. The Intergovernmental Panel on Climate Change (IPCC) has stated it is very likely that most of the observed increase in global average temperature since the mid-20th century is due to anthropogenic greenhouse gas concentrations (Arrhenius, 1896; IPCC, 2007). The IPCC forecasts several scenarios for coal and other fossil fuel production profiles as inputs for their climate models (IPCC, 2000, 2007). Forecasting relies on accurate estimates of remaining coal reserves as well as reasonable estimates of the shape of the future production profile to know how those reserves will be consumed over time. Current IPCC scenarios have been criticized for using unrealistic production profiles (Höök and Tang, 2013; Patzek and Croft, 2010; Rutledge, 2011a). The critical role of coal is understood by noting that approximately 164 billion metric tons or 44% of all historical carbon dioxide emissions from the US fossil fuel consumption came from US coal (EIA, 2011b, 2012d, 2013a). The US has the largest reported coal reserves of any nation, containing approximately 28% of the world's reported reserves (BP, 2010), though it is possible that this percentage is inflated from the inaccurate reporting of China's reserves (Wang et al., 2013). If the US reserves are accurate, their extraction and combustion would amount to an addition of 544 billion metric tons of carbon dioxide to the atmosphere (EIA, 2011b, 2012f, 2013a), which would be about 45 times 2013 global emissions! Over the past 10 years the US has on average emitted 2.077 billion metric tons of carbon dioxide per year from the use of coal, which is approximately 17% of the average total global emissions (EIA, 2014a). Emissions from US coal consumption have historically made up a sizable portion of overall global emissions, and can be expected to have significant contribution in the future. It is therefore an imperative to forecast future US coal production accurately. This is not only necessary for the purpose of accurate climate modeling, but also needed because coal is fundamental to the world's current fulfilment of electrical energy demand and industrial processes.

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1.2. Coal in the USA

Coal has on average provided 31% of all US energy consumption and 48% of electricity production over the past 10 years (EIA, 2012b, e). This makes coal the largest source of electricity in the US. Electricity is vital to modern day civilization in the US, as it has been integrated into almost every aspect of modern life. From lighting and refrigeration to water treatment and health care, without electricity our society cannot function. In addition to being the largest source of electricity, coal also produces the most inexpensive electricity of all the fossil fuels (EIA, 2013c). Given that almost half of US electricity is produced from coal, any unforeseen decreases in the coal supply to electric utilities will have significant economic and social consequences. In addition to being an important energy source for electricity generation, coal is utilized as a raw material in industrial applications. Approximately 5% of the US coal produced is used for activities other than power generation (EIA, 2014b). The largest and perhaps most important use of coal as a raw material is in the production of iron and steel. Iron and steel are the most widely used metals in the US and the world, comprising 95% of all tonnage of metal produced annually (USGS, 2014a). Iron and its alloys are integral parts to almost all industries. Iron production from iron ore requires large quantities of coke, which is derived from coal (WCA, 2014). In the US, approximately 40% of steel is produced in blast furnaces, requiring coal-derived coke, with the remaining 60% produced from recycled steel in electric arc furnaces (AISI, 2014). The importance of coal to iron and steel production is even larger on the global scale, with 70% of the world's production requiring coke (WCA, 2014). A decrease in the supply of metallurgical coal for metal production would have as large of an impact to society and the economy as would a decrease in electrical production from coal.

1.3. Aims and scope of study

In this study, we performed a detailed analysis of the status of US coal production and forecasted future production using a multi-cyclic logistic model. The model was fit only to historical coal production data. This has an advantage over one-cycle logistic models that are fit to reserves as well as historical production data, because the fits are not restricted by potentially biased or inaccurate reserve data, which can skew results. We emphasize our approach uses only historical production data which are reliable, while excluding any consideration of unreliable reserves data. Others have noted the unreliability of reserves (Glustrom, 2009; Höök and Aleklett, 2009, 2010; Rutledge, 2011a; Zittel and Schindler, 2007) and have used modeling and forecasting techniques that do not rely on them (Patzek and Croft, 2010; Rutledge, 2011a). The validity of the multi-cyclic logistic model fits was rigorously tested using production data from several regions that have completed a full production cycle. Using these same regions, we also explored the historical accuracy of reported reserves and discovered a general pattern of gross overestimation of reserves. Our tests indicate that the multi-cyclic logistic model is more robust in predicting future coal production profiles than extrapolating production from reported reserves. In addition the model produces comparable results to previous studies of US coal production. See Sections 3.2, Sensitivity Tests for Year of Peak Production and 3.6, Comparison to Previous Results. Our results reveal that US coal production will peak in the near term i.e. within a decade at the latest. The total US reserves are estimated to be a fifth of generally quoted estimates of over 200 years of supply at current production levels. Both predictions have profound implications for the future scale of (i) climate change potential and (ii) industrial activity of the US and the world.

2. Methods

2.1. Forecasting and prior work

Forecasting future coal production and the lifetime of reserves has been of interest both historically and of late, due to coal's importance to society, the economy, and more recently, climate change. Some of the earliest work on the forecasting of coal production, with emphasis on the United Kingdom, can be credited to Williams Stanley Jevons in 1865 (Jevons, 1865). Early forecasts of US coal production were completed by United States Geological Survey scientists Campbell, Parker, and Garnett between 1908 and 1917. Garnett predicted that all of the easily accessible coal in the US would be exhausted by 2040, and all coal exhausted by 2050 (USGS, 1909). Similar conclusions were reached by Campbell and Parker (Campbell, 1917; USGS, 1909). The understanding of the nature and shape of minable energy resource (i.e. coal) production profiles was advanced by M.K. Hubbert in the 1950s (Hubbert, 1949, 1956, 1969, 1976) whose work provides the basis for the concept of "peak coal," where production reaches a maximum and begins a terminal decline on average. The general form of the production profile is bell shaped, though it is not always symmetric (Bardi, 2005). Recently, there have been several studies and commentaries on forecasting world coal production that utilize the concept of peak coal, including: Zittel and Schindler (2007), S. Mohr and Evans (2009), Patzek and Croft (2010), Heinberg and Fridley (2010), Höök et al. (2010), and Rutledge (2011a). These studies have used various techniques to predict possible production scenarios which include: logistic production growth fitted to estimated remaining reserves (Höök et al., 2010; Zittel and Schindler, 2007), an individual mine production level model incorporating supply and demand (S. Mohr and Evans, 2009), multi-Hubbert cycle fitting to historical production data (Patzek and Croft, 2010), and logit and probit transform fits to historical production data (Rutledge, 2011a). The results of all of these different methods have been remarkably similar in that they all suggest that there is significantly less coal available to the world than reported reserves and resources would indicate.

There have also been studies that focus only on forecasting production of individual countries with significant production, namely China and the US. Forecasting of future Chinese coal production has been done by Tao and Li (2007) and Lin and Liu (2010). Both studies resulted in similar predicted peak years for Chinese production between the late 2020s and early 2030s. Studies specifically related to US production have been done by Glustrom (2009) and Höök and Aleklett (2009, 2010). Glustrom completed a detailed mine-level analysis of the Powder River Basin, in Wyoming. Höök and Aleklett divided the US into three coal-producing regions and used Hubbert linearization and logistic and Gompertz curve fits to historical production data, as well as, reported reserves, to forecast the ultimate recoverable reserves and the timing of peak production. They concluded that the US would likely reach peak production by 2030 unless significant development of reserves in the state of Montana occurred. Based on their analysis the current US reported reserves will likely not be completely realized in the future, and hence likely overstated.

2.2. Model description

A method for predicting the production profile of a finite extractable energy source, such as coal is the multi-cyclic logistic model (Al-Fattah and Startzman, 1999, 2000; Nashawi et al., 2010; Patzek and Croft, 2010). Its single cycle version is historically well known in mining (Bardi, 2005; Hubbert, 1949, 1956, 1969, 1976), as well as, in other areas such as population dynamics and ecology (Lotka, 1910; Verhulst, 1845). We describe here its basic assumptions and resulting production profile and apply it to data of US coal production in the Results section. In the next Section, 2.3, we discuss limitations and considerations that must be taken into account when using the multi-cyclic logistic model. Let $A(t)$ be the cumulative quantity of coal mined at time t. Let $B(t)$ be the quantity of coal remaining below ground at time t. The basic assumptions of the logistic model, for non-renewable energy extraction, may be expressed mathematically by two simple state equations of a first-order nonlinear system:

$$\dot{A}(t) = -\dot{B}(t) \text{ and } \dot{A}(t) = kA(t)B(t), \tag{1}$$

where k is a constant. A dot over a symbol denotes differentiation with time. The first of these is an equation of continuity. It signifies the assumption that the quantity of coal mined adds to the above ground quantity, A(t), while simultaneously subtracting an equal quantity from the coal below ground, B(t). The second equation states that the rate of coal extracted is linearly proportional to two types of quantities: the amount of coal below ground, B(t), and the quantity already mined, A(t). Of these, the first proportionality is easy to understand as the mining activity is proportional to the reserve base, B(t), available. The second is more subtle. It represents a monotonic relationship between the quest for energy sources and the scale of the economy. The scale of the economy in turn depends on the historically mined energy source already in existence, A(t). Thus, the rate of production of coal, $\dot{A}(t)$, becomes proportional to the cumulative production, A(t). Now, the system in Eq. (1) may be analytically solved to obtain,

$$\begin{gathered} A(t) = 2\sigma q\left[1 + \tanh\left[\frac{t-\tau}{2\sigma}\right]\right], \text{ giving } \dot{A}(t) = q\,\mathrm{sech}^2\left[\frac{(t-\tau)}{2\sigma}\right], \\ \text{where } q \equiv \frac{A(t_0) + B(t_0)}{4\sigma}, \\ \tau \equiv t_0 + \sigma \ln\left[\frac{B(t_0)}{A(t_0)}\right], \text{ and } \sigma \equiv [k(A(t_0) + B(t_0))]^{-1} \end{gathered} \tag{2}$$

The time, t_0, is the initial time, the initial energy input to mine coal is $A(t_0)$, which is also related to the size of the economy when society begins mining coal, and finally, the minable coal reserves are $B(t_0)$. The curve for $\dot{A}(t)$ vs. t from the system in Eq. (2) is a bell-shaped curve, which rises exponentially in the beginning, flattens and then decays. Thus it displays a peak, or maximum, in production. This model can be fit to historical coal data of individual mining regions in the US and other coal-producing regions throughout the world. The agreement of the fitted equation to the general bell shape of the raw production data gives credibility to the assumptions in Eq. (1).

For analyzing large spatially separated coal basins a logistical analysis based on Eqs. (1) and (2) needs to be carried out for each individual region and the production profiles summed. This model is called the multi-cyclic model. Such a model is appropriate where the extraction of coal in disparate regions becomes decoupled and individual coal basins act within their own individual logistic model. Parts of the US were mined serially, instead of simultaneously. Such a model is necessary to analyze their production profiles. It is also applicable where production in a single basin is undertaken sequentially in different mines as opposed to being pursued concurrently in every sub-section. Each of these sub-sections then undergoes a separate, generally, bell-shaped curve for its production. As pointed out by (Bardi, 2005), the curve is not necessarily symmetric. The multi-cyclic logistic model is also appropriate when social or political events change the relationship (i.e. change in the k constant in Eq. (1)) between the quest for energy sources and the scale of the economy, resulting in the start of a new cycle. The model may be described by the following set of equations:

$$\begin{gathered} A(t) = \sum_{i=1}^{n} Q_i(t), \text{ where } Q_i(t) = 2\sigma_i q_i\left[1 + \tanh\left[\frac{t-\tau_i}{2\sigma_i}\right]\right], \\ \text{yielding, } \dot{A}(t) = \sum_{i=1}^{n} q_i\,\mathrm{sech}^2\left[\frac{(t-\tau_i)}{2\sigma_i}\right]. \end{gathered} \tag{3}$$

Here τ_i, σ_i, q_i are fitting parameters having an interpretation similar to their corresponding analogues in Eq. (2) for each individual mining region i. The total number of maxima in these curves is n and hence denotes the total number of coal basins that were mined sequentially in a given region. These equations give the cumulative quantity of coal A(t) and the instantaneous production, $\dot{A}(t)$, which shows the growth and decline of coal production. The value $A(\infty)$ provides an estimate of the total coal that may be mined, or ultimate recoverable reserves (URR). In this study the URR is a fitting parameter that is thus derived from historical production data, $\dot{A}(t)$, and not taken from reported reserves from historical databases. It can be obtained by,

$$\mathrm{URR} = \int_{-\infty}^{\infty} \dot{A}(t)dt = \sum_{i=1}^{n} 4\sigma_i q_i. \tag{4}$$

We have applied the solutions in Eq. (3) to historical coal production data from five geographical regions within the US and consequently to the entire US. Our analysis provides an estimate, by region as well as for the entire US, of the quantities of: (i) ultimate cumulative production ($A(\infty)$), (ii) maximum yearly production of total raw coal and the year it occurs, and (iii) the rank and quality of coal. Combining (ii) and (iii) and using a heat energy value associated with each rank of coal we obtain (iv) the quantity of maximum yearly heat energy production from coal and the year it occurs. To test the sensitivity of our analysis to our modeling approach we have analyzed production profiles of 12 completed coal production cycles. A mining cycle can be defined as the initiation and increase of production to the reaching of its maximum and its subsequent decline and end. Of these 12 cycles, two typical examples are presented. The first cycle is for a single country, the United Kingdom. Here the cycle of mining coal is nearly complete. The other cycle is for the mining of anthracite coal in the US state of Pennsylvania.

The ultimate recoverable reserves (URR) are defined as the total amount of coal that can be mined from a specific geographic area. This upper limit can be reached due to a variety of factors. For example, all of the coal in the region could be mined to exhaustion, or the coal that remains in the ground is too expensive, either monetarily or energetically, to be extracted. The URR is generally estimated by the reported coal reserves for a region combined with the cumulative (total) amount of coal that has already been mined from that region. Reported reserves can change over time for a variety of reasons. Reserves can be depleted, new reserves can be found, reserves could have been over- or underestimated in the past and be updated, or changes in energy and environmental policy can affect reported reserves (Höök and Aleklett, 2010). Estimates obtained from fitting production profiles to smooth fits to Eq. (3) often differ from reported reserves. To quantify this over- or underestimation of reserves from predictions of the logistic model, we define a quantity called "estimated error in URR" δURR%(t) at time t. It is defined by the equation:

$$\begin{aligned} \delta\mathrm{URR}\%(t) &= \frac{\Delta\mathrm{URR}}{\mathrm{URR}}(100\%) = \frac{[C(t) + R(t) - \mathrm{URR}]}{\mathrm{URR}}(100\%) \\ &= \frac{[\mathrm{EUR}(t) - \mathrm{URR}]}{\mathrm{URR}}(100\%). \end{aligned} \tag{5}$$

Here C(t) is the cumulative production of coal as of year t computed from past reported production figures, R(t) are the reported reserves at year t, EUR(t) is the estimated ultimate recovery and is the sum of R(t) and C(t), and URR is the total coal mined when reserves have reached zero theoretically and production has ceased. The URR is obtained by fitting Eq. (3) to the production data so that URR ≡ $A(\infty)$. We note the difference of our approach to compute URR from other methods (Höök and Aleklett, 2009, 2010; Zittel and Schindler, 2007), where URR is obtained from different independent methods of reserves determination. For regions where the mining cycle has neared completion (e.g. the United Kingdom, France, Japan, and anthracite coal in Pennsylvania), it is possible to determine if reported coal reserves in that region were historically over- or underestimated since the URR can be calculated directly from the historical production data rather than be generated from a fit of Eq. (3). If δURR%(t) > 0 it implies that the reported reserves R(t) are higher than the theoretical expectation from Eq. (3). Likewise, if δURR%(t) < 0 it implies that R(t) are lower. If the reported reserves match the theoretical estimate then δURR%(t) is precisely zero.

2.3. Considerations in the use of the multi-cyclic logistic model

The multi-cyclic logistic model has been used to describe and forecast the production profiles of a variety of non-renewable extractable energy sources such as oil, natural gas, and coal (Al-Fattah and Startzman, 1999, 2000; Nashawi et al., 2010; Patzek and Croft, 2010). As with the application of any theoretical model it is important to be aware of its limitations. As was stated previously, the multi-cyclic logistic model is appropriate to use when historical data do not follow a single logistic cycle. Deviations of a production profile from the theoretical single cycle can be due to a variety of reasons (e.g. economically decoupled coal regions, wars, depressions, regulations, etc.) It is evident from the historical production data that these disruptions have occurred in the past and can be expected to happen in the future. The multi-cyclic logistic model can only attempt to forecast the future production profile of the last incomplete cycle. For example, US coal production has gone through two productions maximums in the past and is currently in a third cycle. The multi-cyclic logistic model assumes that the third incomplete cycle is the final one in the production profile. There could be future disruptions in production due to a variety of factors, but predicting these fluctuations would require clairvoyance. The model provides the overall trends in future production given that there are not significant disruptions to production. Each cycle of the multi-cyclic logistic model is independent of the others, so the production data are essentially segmented, reducing the importance of long-term trends present from earlier cycles in decline. This can be thought of as a double-edged sword. The reduction of long-term trends can potentially cause the multi-cyclic logistic model to forecast earlier peaks in production and smaller URRs than single cycle methods. However, this reduction in values of the year of peak production and predicted URR is precisely the point of the multi-cyclic logistic model. It is a change to the predictions of single cycle models that goes in the correct direction. It partially decouples the most recent incomplete cycle from previous production disruptions and trends that could skew results of a single cycle analysis. Still, the multi-cyclic logistic model is a curve fitting technique at its core, and one should be cautious in its use to ensure it produces meaningful results.

The multi-cyclic logistic model has 3n free parameters, where n represents the number of cycles. In principle it is possible to improve the fit of the multi-cyclic logistic model to historical coal production data by increasing the number of cycles, and hence the number of free parameters. This can result in statistical over-fitting of the model to the data. Therefore, the "goodness of fit" of the model to the data is not a complete measure of the model's quality. A statistical likelihood ratio test between multi-cyclic logistic models with differing numbers of cycles fitted to the same data can be used to justify the number of cycles used (Anderson and Conder, 2011). We discuss this in depth in Section 2.5 Logistic Model Fitting. Another issue of the multi-cyclic logistic model is that it can potentially have a large number of free parameters. Increasing the number of free parameters can reduce the accuracy of the forecast. However, each of the parameters has a well-defined physical meaning that can be easily estimated for complete cycles from a chart of historical data. This allows for the parameters of early cycles to be determined with a high degree of accuracy. The fitting procedure is effectively reduced to the last incomplete production cycle. It is always advisable to use only the minimum number of cycles needed to describe the data to prevent over-fitting of the model.

Anderson and Conder provide a detailed discussion and critique of the use of the model in forecasting future petroleum production (Anderson and Conder, 2011). Their discussions can also be applied to other non-renewable extractable energy resources, such as coal. The main aim of this study is not necessarily to forecast future US coal production with a very high degree of accuracy of single digit percentage level, but rather to study US coal production from a variety of perspectives to draw overall conclusions of future production. The multi-cyclic logistic model is definitely useful as one of these perspectives.

2.4. Data sources

Historical production data for the major coal-producing regions in the United States were obtained from the United States Geological Survey (USGS) COALPROD Database (Milici, 1997) for the years 1800–1995. Data from the USGS consisted of yearly production quantities of coal, in units of short tons,[1] for all coal-producing states in the US which are divided into five regions: (i) Appalachian, (ii) Illinois Basin, (iii) Gulf Coast, (iv) Great Plains, and (v) Western coal-producing regions. The Appalachian region is comprised of the states Alabama, Georgia, Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. The Illinois Basin region consists of Illinois and Indiana. The Gulf Coast region consists of Louisiana and Texas. The Great Plains region consists of North Dakota and South Dakota. The Western region is comprised of Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. A second source of data was the United States Information Administration (EIA) coal production database (EIA, 2011a) for the years 1960–2008. Data after 2008 were omitted to provide a more conservative fitting procedure. The worldwide economic crisis starting in 2008 and the increase in production of natural gas from hydraulic fracturing in the US have reduced demand for coal. This decline would bias the fitting procedure to predict earlier peak production years and lower URRs. The omission allows for the fitting results to give more conservative forecasts of US coal production as it would have likely proceeded based on the previous trend without these two confounding components.[2] The USGS production data from 1800 to 1995 were combined with production data from the EIA database, for each state, for the years 1996–2008. In the overlapping years 1960–1995 both datasets agreed with each other with a maximum error of 3.3%. In these overlapping years the USGS production data were used. Thus a historical dataset, from 1800 to 2008, of yearly production of coal in million short tons was generated from the combined USGS and EIA databases. There were several states with some coal production included in the EIA database that were excluded from the USGS long-term database, namely Alaska, Arkansas, Kansas, Mississippi, Missouri, and Oklahoma. However, all of these states were observed to be in a post peak declining production phase and had negligible production, only making up 0.5% of US production, and hence were omitted from the analysis. The EIA database further provided average energy content of coal produced in each state per year, in units of million British Thermal Units (BTU) per short ton, for all its years. This energy content factor, converting raw tons of coal to BTU of energy, was multiplied by each state's production for years 1960–2008. For years 1800–1959, the average energy content for coal produced in 1960 was used.[3] The yearly production and yearly gross energy production of coal for each of the five regions were then added to produce a yearly quantity of production for (i) raw coal and (ii) gross energy for the entire United States. Data from the National Coal Resource Data Systems (NCRDS) State Cooperatives Project (USGS, 2014b) list the rank of coal reserves in each state as either anthracite, bituminous, sub-bituminous, or lignite. Each coal rank has an energy content associated with it measured in units of million BTU per short ton. The energy content of each rank of coal has a relatively wide range, so it is not possible to determine the explicit energy content from only the rank information. The energy content ranges of coal

[1] One short ton = 2000 pounds.

[2] It should be noted that since 2008 US coal production has been in steep and monotonic yearly decline, potentially making 2008 the year of peak production. US coal production in 2013 has dropped below 1 billion short tons for the first time since 1993.

[3] It is a historical observation in the state by state, EIA database that energy content of coal on average remains relatively constant or decreases slightly over time for a given state. This may not be a general phenomena but it appears to be the case here. With this observation we can take a conservative approach and safely assume that using the energy content value from 1960 in earlier years to 1800 may slightly underestimate the actual energy produced in these years, i.e. 1800–1959. The EIA appears to have used this method in their database as well. In their database all reported coal energy content values from each state for the years 1960–1972 are constant values.

within each rank vary enough that there can be overlap of these ranges between the various ranks. Anthracite and bituminous coals lie in an energy range of 24–32 with the majority of the supply of the former occupying higher values and majority of the supply of the latter having lower values within these bounds. Sub-bituminous and lignite coals have energy values in the ranges of 16.6–24 and 10–16.6, respectively (Schweinfurth, 2009). Coal rank from each state was classified as either anthracite, bituminous, sub-bituminous, or lignite using this database. The rank assigned was checked to be consistent with energy content factor provided in the EIA database by confirming that it lays in the range given for each rank above (Schweinfurth, 2009; USGS, 2014b). A yearly production dataset was created for Pennsylvania anthracite coal production using the same datasets and procedure as used for the regional and US datasets. A yearly production dataset for the United Kingdom (UK) was created from yearly production data in British Historical Statistics (Mitchell, 1988), in units of million short tons and covering years 1830–1980. This dataset was combined with UK coal production data from 1981 to 2008 from the BP statistical review (BP, 2010). Consistency of values between the two datasets was checked between the years 1980 and 1981, with the values differing by less than 2%.

Historical coal reserve data for the US, UK, and Pennsylvania anthracite coal were obtained from the supplemental material in Rutledge (2011a, b). Historical production data for the additional sensitivity tests performed on Belgium, France, Japan, the Netherlands, Portugal, South Korea, Sweden, Taiwan, and the US states of Georgia and South Dakota, as described in Section 2.6, were obtained from EIA (2011a), Milici (1997), and S.H. Mohr and Evans (2009). Historical coal reserve data for these additional tests were obtained from Rutledge (2011b).

2.5. Logistic model fitting

The multi-cyclic logistic model, as given in Eq. (3), was fit to the various datasets using a nonlinear regression technique, described in this section. The function chosen for optimization for this study was the sum of the squares of the error (SSE) between the multi-cyclic logistic model and historical production data,

$$\mathrm{SSE}(\{q_i\},\{\tau_i\},\{\sigma_i\}) = \sum_{j=1}^{m}\left[\dot{Q}\left(t_j\right) - \dot{A}_f\left(t_j;\{q_i\},\{\tau_i\},\{\sigma_i\}\right)\right]^2. \tag{6}$$

The historical production data are given in the form, $(t_j, \dot{Q}(t_j))$, where $\dot{Q}(t_j)$ is the coal production in the year t_j. The total number of data points available for the fit is m. A trial fit to this dataset with Eq. (3) is $\dot{A}_f(t_j;\{q_i\},\{\tau_i\},\{\sigma_i\})$. Thus SSE is only a function of the fitting parameters in Eq. (3). The values of these parameters which minimize the SSE, and are physically possible (i.e. non-negative), produce the best fit of the multi-cyclic logistic model to the historical production data. The best fit was determined by computationally finding the minimum of the SSE function. This process consisted of assigning initial values to the fitting parameters, $\{\tau_i, \sigma_i, q_i\}$, and iteratively changing the parameter values in the direction of the negative gradient of the SSE function until the gradient was effectively zero, $-\vec{\nabla}\mathrm{SSE} = 0$. It is possible that the SSE function can have multiple minima. The initial values of the fitting parameters were carefully chosen so that the optimization algorithm would find the lowest minimum. The number of cycles, n, in the model, from Eq. (3), along with the an initial trial set of fitting parameters, τ_i, σ_i, and q_i, were determined by visual inspection of the historical production data. From the nature of Eq. (3) it is clear that τ_i are the time values at which maxima or peaks occur for the production in each cycle, The values for q_i are related to the production rates at the maxima or peak of production, while σ_i are the measure of the width or sharpness of the curves.

As stated previously in Section 2.3, the "goodness of fit" or SSE of the model to the data is not a complete measure of the model's quality. A statistical likelihood ratio test between multi-cyclic logistic models with differing numbers of cycles fitted to the same data was used to justify the number of cycles used in each fitting procedure. The likelihood ratio test demonstrates whether or not the decrease in the SSE of the fit is improved more than would be expected by simply adding more model parameters (Anderson and Conder, 2011). The likelihood ratio test utilizes the F-test. The F-statistic for the likelihood ratio test is described as,

$$F = \frac{(\mathrm{SSE}_1 - \mathrm{SEE}_2)/(3n_2 - 3n_1)}{\mathrm{SSE}_2/(m - 3n_2 - 1)}, \tag{7}$$

where SSE_1 (or SSE_2) is the minimum SSE of the fit from model with n_1 (or n_2) number of cycles, where $n_2 > n_1$, and m is the total number of data points used in the fitting. The degrees of freedom for this test are $3(n_1 - n_2)$ and $(m - 3n_2 - 1)$. The p-value obtained from this test gives the probability that the improved fit (i.e. smaller SSE) of the model to the production data, from the addition of an additional cycle, is due to the increase of the number of free parameters, rather than the model describing the data better. p-Values less than 0.05 are generally considered significant, corresponding to a confidence level of 95%.

In all a total of seven best fits were computed: one each for the raw tonnage and gross energy content coal production of the entire US and for the raw tonnage coal production of the five coal-producing regions. The logistic models used in these fits consisted of either two or three cycles. For each of the seven best fits we tested for over-fitting using the likelihood ratio test. Each of the seven fits were compared using the likelihood ratio test to the best fit of a one-cycle, two-cycle, three-cycle, and four-cycle model to the historical data of that coal region. All of the tests gave a confidence level of over 99% that model did not suffer from statistical over-fitting.

In addition to the best fits, lesser quality fits (i.e. with SSEs larger than the best fit) were found with peak years preceding and following the peak year of the last cycle of the best fit model for each of these seven datasets. These fits were found by biasing the initial values of the parameters, τ_{final}, σ_{final}, and q_{final}, for the last, incomplete cycle in the model, so that the optimization algorithm could fall into a nearby local minimum. The lesser quality fits were restricted to having SSEs no larger than 10% of the SSE of the best fit.

2.6. Sensitivity tests

The sensitivity of the fitting procedure to how far a production profile has advanced was tested using data for 12 very different but near complete coal production profiles, namely Belgium (URR of 2611 Mt), France (URR of 4579 Mt), Japan (URR of 2944 Mt), the Netherlands (URR of 585 Mt), Portugal (URR of 27 Mt), South Korea (URR of 589 Mt), Sweden (URR of 29 Mt), Taiwan (URR of 181 Mt), the United Kingdom (URR of 26470 Mt), and the US states of Georgia (URR of 11 Mt) and South Dakota (URR of 1 Mt). Production for only anthracite coal from Pennsylvania (URR of 5053 Mt) was also analyzed. In this article we highlight two typical cases among these 12: (i) the total coal production of the United Kingdom and (ii) only the production for anthracite coal from Pennsylvania. In addition to the highlighted UK and Pennsylvania anthracite, we include three figures of our analysis for France, Japan, and Sweden in Appendix A. These regions' historical peak in production occurred later in the production cycle due to the asymmetry of production profile. However, the logistic model still provides reasonable forecasting of their production profiles. Our validation uses single cycle logistic models fit to truncated historical production data. For this purpose we started by first fitting a logistic model to the entire dataset and obtaining the peak production value for this best fit. Truncated datasets are created by taking data from the start of production up to the production level corresponding to approximately 25%, 50%, 75%, and 100% of the best fit peak production value. Best fit curves were generated using only the truncated datasets. This process illustrates the accuracy of the logistic model's forecasts as the actual production proceeds through time. These fits were compared with the best fit model from the entire dataset.

2.7. Reserves vs. model

We computed the δURR%(t) for 10 regions, namely, Belgium, France, Japan, the Netherlands, Portugal, Sweden, Taiwan, UK, Pennsylvania anthracite, and US. We were restricted to these 10 regions as they had both long-term historical production data and long-term historical reserve data. We highlight the (i) UK and (ii) Pennsylvania anthracite regions as typical cases, and analyze the (iii) US. For the entire US the estimated δURR%(t) was generated using the best fit model to calculate the URR as given in Eq. (5), while for the UK and Pennsylvania anthracite actual production data were used. In addition to the highlighted US, UK, and Pennsylvania anthracite, we include three figures of our analysis for France, Japan, and Sweden in Appendix A.

For Pennsylvania anthracite, the theoretical remaining reserves given by best fit model URR were compared to different varieties of recent EIA reserve estimates (EIA, 2012f). The EIA reserves estimates of "recoverable reserves at producing mines," "estimated recoverable reserves," and "demonstrated reserve base" were divided by URR from the theoretical remaining reserves given by Eq. (3). These calculations produced ratios representing how many more times, larger or smaller, the EIA reported reserves were compared to our model estimates and will be discussed in the results and discussion section.

3. Results and discussion

3.1. Year of peak production

The results of the logistic model fitting for the United States raw tonnage coal production from year 1800 to 2008 are given in Fig. 1. In it, total production is subdivided into the relative components classified by their energy contents: anthracite, bituminous, sub-bituminous and lignite. Fig. 1 also displays the best fit logistic model and the two fits of lesser quality, as described in the previous section. The highest ranked coals, anthracite and bituminous, have been decreasing in production since 1917 and 1990 respectively. The production of lower energy density coals, sub-bituminous and lignite, are still increasing. The highest total coal production occurred in year 2008. The best fit logistic model gives 2010 as the year of peak total coal production. The two other fits of lower quality biased for finding earliest and latest values for the year of peak production, yielded the peak production years of 2009 and 2023 respectively. After this peak occurs, sometime in this window of 2009–2023, it can be expected that production will continue declining on average. The fitting parameters and results of the statistical likelihood ratio tests for Fig. 1 are given in Table 1.

The fact that the lower energy coals are continuing to make up a larger percentage of the total US production, while the higher energy coals are declining is not surprising. In energy extraction it is typical that the sources that are easiest to access and are of the best quality are the ones that are tapped first. It is only after the easy, high quality resources are either depleted and declining, or depleted and cannot support previous extraction rates, that less desirable resources are exploited. The major rise in sub-bituminous and lignite coal production occurred after 1969, in part due to the introduction of the Clean Air Act and its associated sulfur emission regulations. This production rise happened only after two major peaks in production had already occurred in both the anthracite (in years 1917 and 1944) and bituminous production (in years 1926 and 1947). As the lower quality coals increased in production following 1969, anthracite production continued to decrease, while bituminous production increased at a rate three times less than it had before the two previous peaks in its production, in 1926 and 1947. This slow down in production of high energy coal occurred during a time of significant increases in coal burning power plant capacity and coal demand (EIA, 2012a; NETL, 2012). Such a slow down suggests that there was enough depletion of high energy quality reserves to necessitate the production of lower energy quality sources. Additionally, environmental regulations on sulfur emissions made electricity production by the higher sulfur higher energy eastern coals more expensive and less attractive. It can be expected that as the production of higher energy content coals continues to decline, lower energy

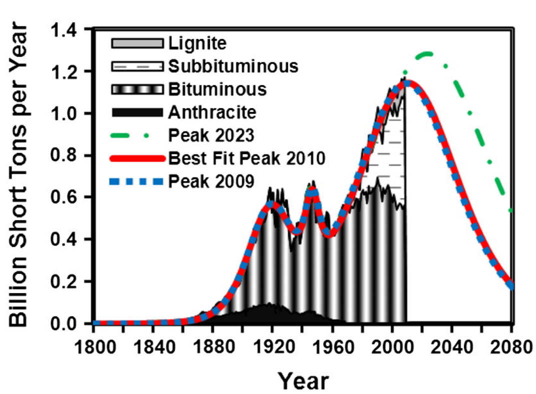

Fig. 1. United States coal production from 1800 to 2008. Production data from EIA (2011a) and Milici (1997). The total production is subdivided into the relative components classified by their energy contents: anthracite, bituminous, sub-bituminous and lignite. The highest ranked coals anthracite and bituminous are decreasing in production since 1917 and 1990 respectively. The production of the lower energy density coals, sub-bituminous and lignite, are still increasing. The best fit three-cycle logistic model giving 2010 as the year of peak coal production is shown. Two other fits of lower quality biased for finding earliest and latest values for the year of peak production are shown, yielding peak production years 2009 and 2023 respectively.

Table 1
Parameters of best fit three-cycle logistic models, of Eq. (3), for US coal raw tonnage production (left two columns) and US coal energy production (right two columns) shown in Figs. 1 and 2. Also given are p-values for likelihood ratio tests for over-fitting between best fit multi-cyclic logistic models containing between one and three cycles. p-Values give the probability that the improved fit to the data of a logistic model with more cycles over one with less cycles is due to over-fitting. 1 minus the p-value gives the probability that the model with more cycles fits the data better than the model with fewer cycles. Typically, a confidence level of 95% is taken as statistically significant, corresponding to p-values less than 0.05. The p-value for the likelihood ratio test between the three- and four-cycle logistic model fits to the production data gives values of 0.14 and 0.15 for tonnage and energy, respectively. This suggests that applying a four-cycle model to the data would result in statistical over-fitting, and hence three-cycle models were used.

Fitting parameters for US coal production			
Tonnage		Energy	
Parameters	Values	Parameters	Values
q_1 ($\times 10^8$ short tons)	4.94	q_1 ($\times 10^{15}$ BTU)	11.80
τ_1 (year)	1918	τ_1 (year)	1918
σ_1 (year)	10.00	σ_1 (year)	9.90
q_2 ($\times 10^8$ short tons)	3.02	q_2 ($\times 10^{15}$ BTU)	7.20
τ_2 (year)	1946	τ_2 (year)	1946
σ_2 (year)	3.05	σ_2 (year)	2.98
q_3 ($\times 10^8$ short tons)	11.40	q_3 ($\times 10^{15}$ BTU)	23.30
τ_3 (year)	2010	τ_3 (year)	2006
σ_3 (year)	22.22	σ_3 (year)	23.26
SSE ($\times 10^{17}$ short tons^2)	2.19	SSE ($\times 10^{20}$ BTU^2)	1.32
p-value, likelihood ratio, 1 vs. 2 cycles	$<10^{-3}$	p-value, likelihood ratio, 1 vs. 2 cycles	$<10^{-3}$
p-value, likelihood ratio, 1 vs. 3 cycles	$<10^{-3}$	p-value, likelihood ratio, 1 vs. 3 cycles	$<10^{-3}$
p-value, likelihood ratio, 2 vs. 3 cycles	$<10^{-3}$	p-value, likelihood ratio, 2 vs. 3 cycles	$<10^{-3}$
p-value, likelihood ratio, 3 vs. 4 cycles	0.14	p-value, likelihood ratio, 3 vs. 4 cycles	0.15

coals will make up a larger portion of the US production, unless significant legal or technological changes occur to allow for increased production from some of the high sulfur coal regions. This increase in lower energy coals is bound to negatively affect the total energy produced from coal.

The energy contained in coal gives the most significant measure of its utility. The cost of production per unit of energy from coal (i.e. $/BTU) will likely decide what coals are mined and how they are used, however this is a secondary measure derived from the coal's energy content and energy returned on energy invested (EROEI). We will revisit the EROEI concept in Section 3.7. Over 80% of coal mined is used in electricity and heat production (NRC, 2007). Even non-energy uses of coal, such as steel production, require higher ranked coal thus correlating with its energy content. The amount of energy released upon burning coal is therefore a more important quantity to measure than raw tonnage produced. Coal's energy content provides a fundamental physical limit on the usefulness of coal. This concept may not be true for individual power plants or processes, which may be locked into a specific type of coal based on the combustion technique they use; however, it will be true for the US as a whole. It is possible for the overall energy production from coal of a region to reach its peak before the coal raw tonnage production peaked if lower energy content coals continued to make up a larger proportion of the total coal mined. A peak in energy production from coal can occur before a peak in raw production also due to decline in the saleable portion of the raw production (Mohr et al., 2011). Not all coal produced is of high enough quality to be sold to the end user-customer and some coal is lost in the processing steps, such as washing. It appears that an increasing proportion of lower energy content coals is resulting in a peak in energy production from coal before a peak in total coal tonnage in the US. The results of the logistic model fitting for the United States gross energy content of coal production from year 1800 to 2008 are given in Fig. 2. It also displays the best fit logistic model and the two fits of lesser quality, as described in Section 2.5 of the Methods. The fitting parameters and results of the statistical likelihood ratio tests for Fig. 2 are given in Table 1. The best fit model produces an energy URR of 2750 quadrillion BTU (2900 EJ), with roughly 1680 quadrillion BTU (1770 EJ) already extracted and 1070 quadrillion BTU (1130 EJ) yet to be mined. The best fit logistic model gives 2006 as the year of peak energy production from coal. The two other fits of lower quality biased for finding earlier and later values for the year of peak energy production yield peak production years of 2003 and 2018 respectively.

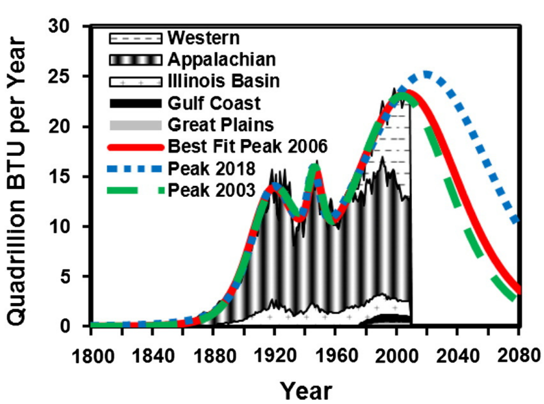

Fig. 2. United States gross energy content of coal produced from 1800 to 2008. Production data from EIA (2011a) and Milici (1997). The total energy production is subdivided into the regions of origin. The Western region's contribution to the total energy production is steadily growing, while the contribution from the four other coal-producing regions has generally been decreasing since 1990 and 1984 respectively for the Appalachian and Illinois Basin regions and since 1990 and 1994 respectively for the Gulf Coast and Great Plains regions. The best fit three-cycle logistic model is shown, which gives 2006 as the year of peak energy production from coal. Two other fits of lower quality biased for finding earlier and later values for the year of peak energy production are shown, yielding peak production years 2003 and 2018 respectively.

Thus logistic model fits, of Fig. 2, suggest that US gross energy content of coal production will or has already peaked within the time frame of 2003–2018. This is an earlier time frame as opposed to the fits from Fig. 1, which gave estimates of the peak year of raw tonnage produced between 2009 and 2023. This is also borne out of the raw production data from Fig. 1 and energy data from Fig. 2 of the latest 20 years from 1988 to 2008. From Fig. 1 we see raw production has gone up from a value of 0.9–1.1 billion short tons per year, about a 25% increase, in 20 years, while the energy content has gone up from 21 to 24 quadrillion BTU per year, only a 15% increase, during this time. These values are consistent with predictions of the best logistic fits in Figs. 1 and 2 with the latter showing earlier production peaks than the former.

Further insights into coal energy production may be obtained by looking at the geographic distribution of coal production. To explore the dependence and robustness of the supply on the spread of geographic distribution of coal reserves we have combined the energy content of coal with the regional distribution of production. In Fig. 2, the energy production is subdivided into the regions of origin. Fig. 2 clearly depicts that four of the five coal-producing regions of the US are in general in a phase of declining energy production though small fluctuations from year to year do occur. The energy production profiles of the Appalachian, Illinois Basin, Gulf Coast, and Great Plains regions have been in a decreasing trend since 1990, 1984, 1990, and 1994 respectively. Only the Western region's contribution to the total coal energy production is steadily increasing. The majority of the coal mined in the Western region is sub-bituminous. These coals have lower sulfur content than much of the eastern bituminous coals. This fact, combined with the stricter sulfur emission regulations of the Clean Air Act, has in part increased consumption of these coals. The increase of the Western region's contribution to the total coal energy production can be explained from the increased proportion of the US coal production coming from sub-bituminous coals, as was shown in Fig. 1. As the other coal-producing regions decrease in production, the only way the US can increase or maintain its current energy usage from coal will be through increased production in the Western region, which is increasingly of the sub-bituminous variety, and hence of lower energy content. We explore these regions in greater detail in Fig. 3. The results of the logistic model fitting for coal production in the major coal-producing regions in the US from 1800 to 2008 are given in Fig. 3. The regions are subdivided in Fig. 3 as follows: (A) Appalachian, (B) Western, (C) Illinois Basin, (D) Gulf Coast and (E) Great Plains. For each region, Fig. 3 displays the best fit logistic model and fits of lesser quality, as described in Section 2.5 of the Methods. The best fit multi-cycle logistic models are shown for each region, giving 1988, 2009, 1988, 1996, and 1996 as the years of peak production for regions Appalachian, Western, Illinois Basin, Gulf Coast, and Great Plains respectively. The fitting parameters and results of the statistical likelihood ratio tests for Fig. 3 (B) are given in Table 2.

As was stated previously, since the Western region is the only coal-producing region that is not past peak production, increased production from this region is likely the only way the US can increase or maintain its current coal production. It could be possible for other regions to theoretically increase their production if sulfur emission standards were relaxed or new significant reserves were developed, notably Illinois and Alaska, as discussed later in this section. However, these scenarios are unlikely to occur on short enough time scales to significantly affect the current production cycle and overcome declines in other regions. This means that the Western region production controls when the entire US will reach maximum production. This western dominance is similar to what was concluded earlier in Höök and Aleklett (2009, 2010). The best fits from the total US and the Western region confirm this, as both produce very similar peak production years of 2010 and 2009 respectively.

Additional evidence supporting the argument that the Western region will determine the sign, positive or negative, of the change in US production comes from analysis of the production profiles of the individual coal-producing states. Of all the current 25 coal-producing states,

Table 2
Fitting parameters of best fit two-cycle logistic model, of Eq. (3), for the Western coal-producing region shown in Fig. 3(B). Also given are p-values for likelihood ratio tests for over-fitting between best fit multi-cyclic logistic models containing between one and three cycles. p-Values give the probability that the improved fit to the data of a logistic model with more cycles over one with less cycles is due to over-fitting. 1 minus the p-value gives the probability that the model with more cycles fits the data better than the model with fewer cycles. Typically, a confidence level of 95% is taken as statistically significant, corresponding to p-values less than 0.05. The p-value for the likelihood ratio test between the two- and three-cycle logistic model fits to the Western coal production data gives a value of 0.35. This suggests that applying a three-cycle model to the data would result in statistical over-fitting, and hence a two-cycle model was used.

Fitting parameters for western coal production	
Parameters	Values
q_1 ($\times 10^7$ short tons)	3.04
τ_1 (year)	1920
σ_1 (year)	9.7
q_2 ($\times 10^7$ short tons)	58.07
τ_2 (year)	2009
σ_2 (year)	10.9
SSE ($\times 10^{16}$ short tons^2)	2.78
p-value, likelihood ratio, 1 vs. 2 cycles	$<10^{-3}$
p-value, likelihood ratio, 1 vs. 3 cycles	$<10^{-3}$
p-value, likelihood ratio, 2 vs. 3 cycles	0.35

20 have gone through a peak in production and have seen substantial production declines (EIA, 2011a). These post production peak states account for 53% of total US production in 2008 with their average percentage, of the total production, decreasing for the last two decades. The remaining 47% of the US production comes from five states that have either reached a plateau in production or have not yet gone through a definite production peak, namely, Alaska, Indiana, Louisiana, Montana, and Wyoming. Alaska and Louisiana have a negligible contribution of 0.5% to the US production, as well as containing only 1% of the estimated recoverable coal reserves of the US (EIA, 2011a, 2012f). These data imply that while Alaska and Louisiana have not reached peak production yet, they will not make any difference of significance in trends of the overall US production. It should be noted that Alaska may contain a large amount of coal that has yet to be produced and that is not reported as official reserves (Flores et al., 2004). However, much of this potential coal may not be mined since most is in areas, such as the north slope, where high costs, transportation constraints, and lack of infrastructure pose significant obstacles to production (Glustrom, 2009). Indiana has remained on an undulating production plateau of 35 million short tons for roughly 30 years. Indiana's production accounts for 3% of the US production, and the state contains only 1.5% of the US estimated recoverable reserves. Therefore, like Alaska and Louisiana, Indiana cannot change the trends observed in the overall US production. Its region, the Illinois Basin, has already reached peak production and is in decline due to declines in its other states. We note that recently (post-2008) production from Illinois has increased slightly, in part due to increased demand for its high sulfur coal as more coal fired power plants add scrubbers. This detailed view leaves us with only the two behemoths of coal production belonging to the Western region, Montana and Wyoming, which have the ability to affect trends in the overall US production. As of 2008 Montana's production accounts for 4% of the US production and the state contains 29% of the US estimated recoverable reserves. Wyoming produces about 40% of the US coal production and contains 15% of the estimated recoverable reserves. There are substantial differences in the economics of mining and transportation between these two states which help to explain the discrepancies between the states' production levels and reported reserves (Höök and Aleklett,

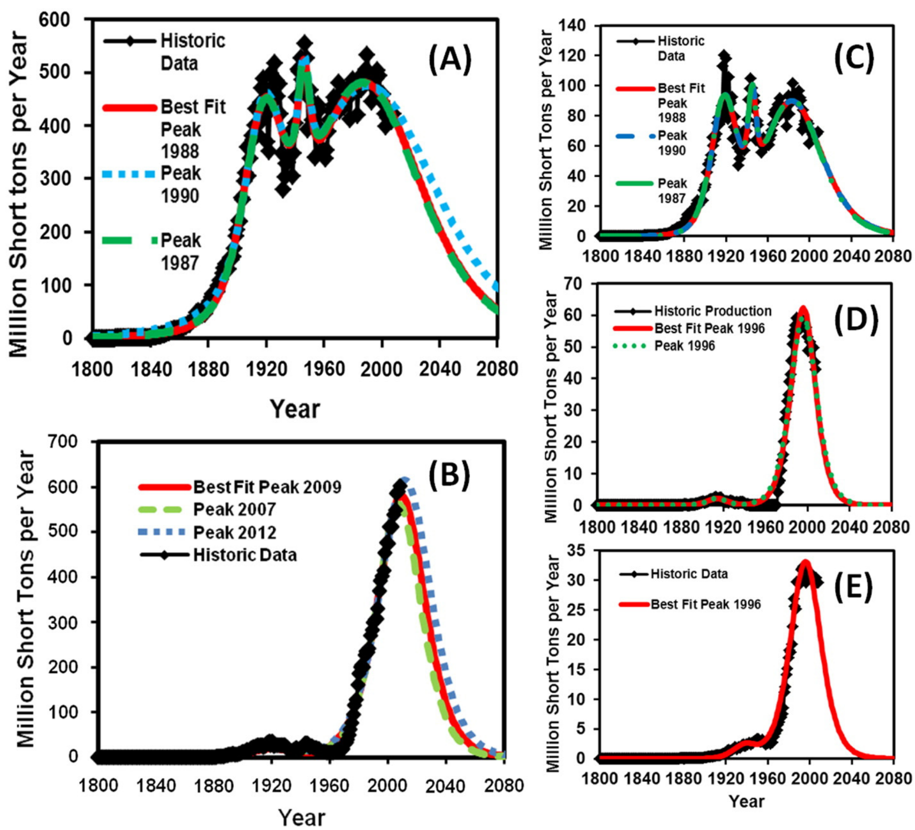

Fig. 3. United States coal production by major coal-producing region from 1800 to 2008. The total US production is divided in regions of origin: (A) Appalachian, (B) Western, (C) Illinois Basin, (D) Gulf Coast, (E) Great Plains. Production data from EIA (2011a) and Milici (1997). Production profiles from regions A, C, D, and E have been in a declining trend since 1990, 1984, 1990, and 1994 respectively. Region B is the only region in the US that is increasing production. The best fit multi-cycle logistic models are shown for each region, giving 1988, 2009, 1988, 1996, and 1996 as the years of peak production for regions A, B, C, D, and E respectively. Other fits of lower quality biased for finding differing values of the year of peak production are shown.

2009, 2010). Though year to year fluctuations do occur, these states have contributed to US production at substantial and increasing levels since 1972 and at an accelerated rate since the combined production of the remaining 23 US states peaked in 1990. From 1990 to 2008, US production excluding Wyoming and Montana has declined by 18%, from 800 to 650 million short tons per year, or by about 8 million short tons per year per year. For the US production to even remain constant in the next 20 years, Wyoming and Montana will have to increase production by 32%, over their 2008 levels, to compensate this decline in the rest of the US. These two states already account for 44% of total coal production. For them to increase production to 58% of the US total from such high levels is a daunting challenge likely to remain unmet. A similar conclusion about the future of Wyoming and Montana coal production was reached by Höök and Aleklett (2009, 2010). Thus our analysis by individual states is consistent with the picture of peak in US coal production in the next decade at the latest, if not earlier.

From our model predictions, along with the detailed analysis by energy content, rank and regional distribution, has emerged a consistent picture that US total coal production and energy produced from coal are at their maximum or near maximum and will go into permanent geological decline in the next 10 years or so. No inconsistencies in the analysis have emerged. We now turn our attention to the validity and accuracy of the model predictions. To assess the uncertainties that may arise in the model predictions we have performed several sensitivity tests which we address next.

3.2. Sensitivity tests for year of peak production

Of the 12 coal regions exhibiting a complete production cycle, the UK total coal and Pennsylvania anthracite coal production were chosen to validate the logistic fitting procedure. Several reasons underlie these two choices. The best fit URR of the UK, 32 billion short tons, is comparable to the best fit URR of individual regions of the US, 65, 10, 2, 1.4, and 29 billion short tons for the Appalachian, Illinois Basin, Gulf Coast, Great Plains, and Western coal-producing regions, respectively. The Pennsylvania data give an analysis for only a specific rank of coal, namely anthracite. This helps us ascertain our model predictions for the production peaks and URR of the four individual ranks of coal. Also, both of these production profiles, the UK total coal and Pennsylvania anthracite, have essentially gone through a complete mining production cycle. In each case, production increased exponentially, reached a maximum, and then decreased. By purposefully restricting analyses to varying degrees of incomplete data from these complete datasets, i.e. by using early portions of the total production profile as the input data for the fitting procedure, we can assess how well the fitted models match up to both the complete production data and the best model fit performed on the entire dataset.

The results for the sensitivity and validation test of the logistic model fitting procedure are given in Fig. 4. Fig. 4 shows the UK coal production from 1830 to 2008. The production data show a virtually complete logistic production cycle showing the initial ascent in production followed by a maximum and then a continuous decline. The maximum production of coal occurred in the year 1913 at 292 million metric tons per year. The best fit logistic model using the entire dataset gives a year of peak production at 1924, and a maximum production of 280.5 million metric tons per year. Also shown are best fit single cycle logistic models fitted using only production data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit curve, giving peak years of 1931, 1915, 1916, and 1919 respectively. The maximum production levels, for the logistic models using data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit model are 405, 242, 228, and 256 million metric tons per year respectively.

The results of the second sensitivity and validation test are given in Fig. 5. Shown is the Pennsylvania anthracite coal production from 1800 to 2008. The production data show a virtually complete logistic production cycle, similar to the UK data. The actual production peaked

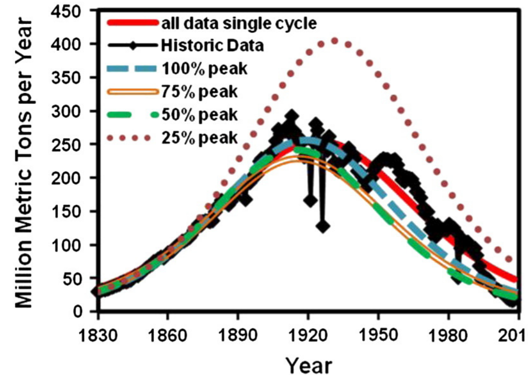

Fig. 4. United Kingdom (UK) coal production from 1830 to 2008. Production data from BP (2010) and Mitchell (1988). The data show a virtually complete logistic production cycle showing the initial ascent in production followed by a maximum and then a continuous decline. A single cycle logistic model, fitted using the entire production dataset, is shown, illustrating an excellent fit. Single cycle logistic models fitted using only production data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit curve are shown. These fits demonstrate the accuracy of prediction of peak year of production once 50% of the peak production corresponding to exhaustion of approximately 14% of total reserves has occurred.

in the year 1917, at 99.6 million short tons per year. The best fit logistic model using the entire dataset gives a year of peak production at 1917, and a maximum production of 85 million short tons per year. Also shown are best fit single cycle logistic models fitted using only production data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit curve, giving peak years of 1905, 1907, 1905, and 1924 respectively. The maximum production levels, for the logistic models using data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit model are 87, 66, 62, and 97 million short tons per year respectively.

For the UK, various fits performed on incomplete data predicted the year of peak production to within ± 9 years of the year of peak production obtained from the best fit using the entire dataset. For the Pennsylvania anthracite, the fits performed predicted the year of peak production to within ± 12 years of the peak production of the best fit model using the entire dataset. In both regions, the model had reduced accuracy when the production profile was far earlier from the actual peak in production. However, once the production profile approached its maximum the accuracy improved. The UK predicted peak production

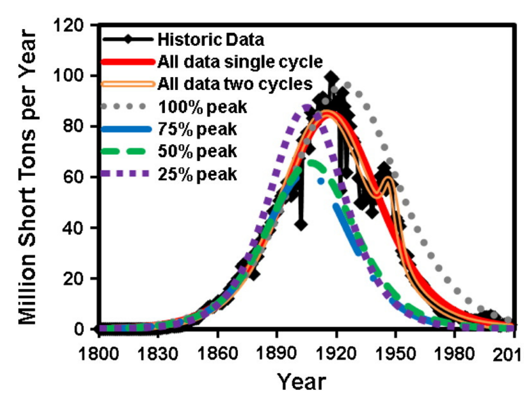

Fig. 5. Pennsylvania anthracite coal production from 1800 to 2008. Production data from EIA (2011a) and Milici (1997). Pennsylvania anthracite coal has the highest energy content of coals in the US. Production of anthracite has followed logistic production cycle in spite of large reported reserves. Single and two-cycle logistic models, fitted using the entire production dataset, are shown, illustrating excellent fits. Single cycle logistic models fitted using only production data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit curve are shown. These fits demonstrate the accuracy of prediction of peak year of production once 50% of the peak production corresponding to exhaustion of approximately 14% of total reserves has occurred.

year went from being 7 years off when using only data prior to 25% of the best fit peak production year, to being 5 years off when using data prior to 100% of the best fit peak production year. For Pennsylvania anthracite, the predicted peak production year went from being 12 years off when using only data prior to 25% of the best fit peak production year, to being 7 years off when using data prior to 100% of the best fit peak production year. This suggests that the fitting procedure is able to predict the future production profile with reasonable accuracy, even when a production profile has only approached 25% of its future maximum production value. This also validates the predictive abilities of the model when it is applied to other regions where the production profiles have not yet reached their peak values. As mentioned earlier in Section 2.5 of the Methods, the results from the other 10 sensitivity test cases show that the results discussed here for the UK and Pennsylvania anthracite, are typical.

The implications for the predictions for the US coal production from these sensitivity tests are unambiguously clear. For the four US regions which have seen their peak production years occur approximately in the mid-1990s, the predictions of our model should be reliable with a high degree of certainly. For the case of the Western region and the US as a whole, it is with high certainty that the peak of production lies in the predicted windows occurring at the latest before 2023. For the rank of coal being produced similar conclusions are in order. We can conclude with certainty that the higher energy content coals, anthracite and bituminous, will continue to decrease in production, while the lower energy coals, sub-bituminous and lignite, will continue to make up a larger portion of the US coal produced. Implications for the near term peak in total energy obtained from coal are obvious. We are at or within a decade of such a peak. Having established a time line for production declines to set in, we may now investigate estimated reserves from our model, and compare with currently reported reserves.

3.3. Coal reserves

The best fit model from Fig. 1 for total US production predicts a URR of 124 billion short tons, with roughly 72 billion short tons already mined, and 52 billion short tons yet to be mined. The remaining coal reserves predicted from the model are 52 billion short tons, which can be extracted at a decreasing rate on average once decline sets in. We now compare these predictions from historically quoted results for reserves, $R(t)$, from Rutledge (2011b) by use of Eq. (5). Fig. 6 shows plots of $\delta URR\%(t)$, for the coal production of the entire United States, the United Kingdom and Pennsylvania anthracite, with its scale on the right axis. It contains for comparison, the historical production data for each of these regions along with the corresponding best fit logistic model with their scales on the left axis. The total reserve base, or URR, of the United States appears to be historically overestimated by as much as 3300% in 1913.

This overestimation has decreased to a level of 170% in 2008. The reserves for the entire US were adjusted to lower levels after each time a local peak in production occurred. These reserve adjustments took place after the peaks in 1918, 1947, and 1956. In more recent years the reserves have again increased, albeit to a much lower level than historical estimates, as seen in panel (B) of Fig. 6.

3.4. Reserves vs. model

To ascertain whether these large deviations occur because the model gives inaccurate predictions for the URR or whether the reserves estimate, $R(t)$, used in Eq. (5) are erroneous, we now analyze the results obtained for our two test cases. Reasons for choosing the UK and Pennsylvania anthracite coal production cycles for our tests have been listed earlier. From Fig. 6 we can see that the total reserve base for the United Kingdom was historically overestimated by as much as 620% in 1913. This high overestimation of reserves occurred in the same year as its maximum production occurred, providing a good example of how the peak in production usually coincides with a maximum in reserve estimates (Jakobsson et al., 2012). The Pennsylvania anthracite reserve base was historically overestimated by as much as 200% in 1964. This overestimation occurred 47 years after the maximum production had occurred in Pennsylvania anthracite mining. In both the UK and Pennsylvania the high overestimations of reserves occurred near the peak in production for the region and persisted until there were significant declines in production, after which, reserve estimates were significantly reduced. In both regions the reserves were adjusted to lower and lower levels, causing the $\delta URR\%(t)$ to approach zero, as production continued to decline to zero.

The $\delta URR\%(t)$ and reserve analysis for the UK and Pennsylvania anthracite suggest that it is typical that the minable reserves for a region, $R(t)$ in Eq. (5), are overestimated, especially before the peak in production occurs. It appears that reserve estimates remain optimistically high even after the peak production occurs, until the decline in production makes it evident that the large reserves are not justified. The UK coal reserves were not significantly adjusted to lower levels until after a smaller secondary peak in production occurred in 1956, as well as, changing economic conditions and environmental regulation which reduced potential reserves. Pennsylvania anthracite reserves were adjusted to lower levels after a secondary peak in production in 1944. This phenomenon of such large overestimations of reserves is well known in oil exploration and has been dubbed the “fallacy of early success” (Jakobsson et al., 2012). It has been shown to come about as a consequence of how the energy exploration process progresses. Though the exact physical processes of oil and coal exploration differ, they both follow the same qualitative exploration pattern, as they are both minable energy sources in discrete deposits of varying quality.

Further evidence for the egregious overestimates of reserves is obtained from current Pennsylvania anthracite reported reserves. The historical production of Pennsylvania anthracite follows the logistic model very well. This is likely because anthracite is the highest energy content, cleanest burning coal, and therefore has been a preferred coal source for several industries, particularly heating, locomotion, and other applications. Additionally, the relatively small geographic distribution of anthracite in Pennsylvania prevented parts of the regions from being economically decoupled from one another, which could have resulted in multiple cycles. Despite large reported reserves and a continuous demand for anthracite due to its high quality, the production of anthracite still declined following the logistic model. The main deviations from the logistic model occurred in 1902, 1922, and 1925 during the anthracite coal strikes, during the Great Depression of the 1930s, and the ramp up in coal production during the second world war. Even with current low production levels, reported “recoverable reserves at producing mines,” “estimated recoverable reserves,” and “demonstrated reserve base” are 6, 35, and 329 times, respectively, what the theoretical remaining recoverable reserves are from the logistic model. It seems unlikely that these reserves estimates will be realized given the current state of anthracite production.

We have observed similar trends in similar post-peak regions such as Belgium, France, Japan, the Netherlands, Portugal, Sweden, and Taiwan. This diversity of countries in which gross and comparable overestimates of reserves occurred shows the generality of the phenomenon and its connection to the “fallacy of early success” discussed in (Jakobsson et al., 2012). The anthracite coal reserve estimates in Pennsylvania confirms that the US reserve estimates are not showing any different trend.

3.5. Major overestimation of US coal reserves

The implications from these sensitivity tests for URR predictions for the US total coal production are clear beyond doubt. The fact that reserves have historically been overestimated and are not adjusted until

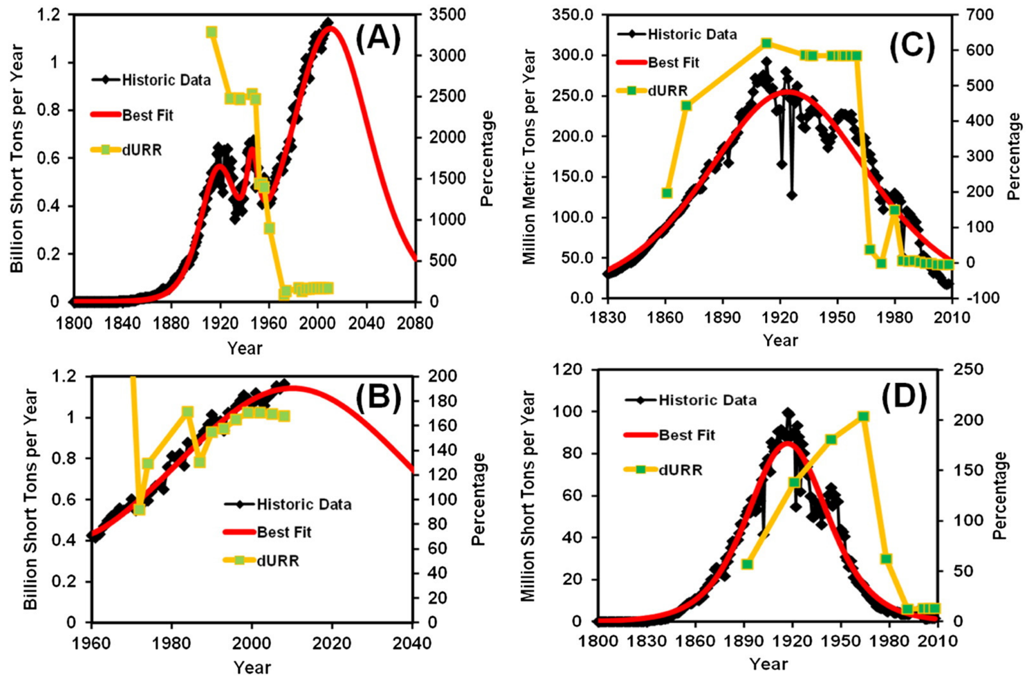

Fig. 6. δURR%(t) for the Unites States (A) and (B, expanded view), the United Kingdom (C), and Pennsylvania anthracite coal production (D); right axis. Coal reserve data used to calculate the δURR%(t) are from Rutledge (2011b). Also displayed are historical production data and best fits as described in Figs. 1, 4, and 5; left axis. δURR%(t) gives an approximate percentage of over- or underestimated reserves as defined by Eq. (5). Both C and D have essentially completed a logistic production cycle allowing δURR%(t) to be directly calculated from historical data, while the δURR%(t) for A is estimated using the best fit model. Panel B shows an expanded view of A so that detail in the δURR%(t) of more recent years can be observed. It can be seen that for C and D that the total reserve base was historically overestimated by as much as 620% in 1913 and 200% in 1964, respectively. These high overestimations in reserves occurred near or after the peak in the production of the coal region, and persisted until there were significant declines in production, after which, reserve estimates were significantly reduced. In both C and D the reserves were adjusted to lower and lower levels, causing the δURR%(t) to approach zero, as production continued to decline to zero. It is shown that it is estimated that A also historically overestimated the total reserve base by as much as 3300% in 1913. As can be seen in B, this overestimation has decreased to a level of 170% by 2008.

peak and then declining production suggests that the current reported US reserve estimates from the EIA of 259 billion short tons (EIA, 2012f) are a gross overestimate. A more reasonable estimate is provided by our best fit model in Fig. 1 of 52 billion short tons yet to be mined. Our result directly contradicts a commonly quoted assertion that there is enough coal supply to last the next 200–250 years. This statement is derived by dividing the reported EIA reserves of 259 billion short tons (EIA, 2012f) by the current production of about 1.1 billion short tons to obtain 235 years. However, such a "reserves-to-production" estimate relies on two assumptions. The first of which is that a high constant production rate can be maintained. Decades of data from real coal production profiles from around the world show that these profiles do resemble in general form, though do not follow exactly, the ideal multi-cyclic logistic type curves of our model. Therefore production goes into decline long before reserves are exhausted or when approximately 50% of the actual reserves have been produced. Thus the first assumption is clearly in error. The second assumption is that the reported reserves are accurate which our sensitivity analysis clearly shows to be false. Thus, our findings not merely echo, but also provide quantitative analysis to confirm, the statements made by the National Research Council in their 2007 report on coal, "However, it is not possible to confirm the often-quoted assertion that there is a sufficient supply of coal for the next 250 years" (NRC, 2007). The summary conclusion of our work is that the US has a reserves-to-production ratio of approximately 47 years and not 200–250 years as often quoted (AP, 2013; CN, 2013; IER, 2013; Katzer et al., 2007; Milici, 1996).

3.6. Comparison to previous results

Our results are comparable to those of prior work on forecasting US coal production that we described in Section 2.1 Forecasting and Prior Work. Here we use the metric units gigatons (Gt), megatons (Mt), and exajoules (EJ), so results can be easily compared between studies. The results of our best fit and lower quality biased fits of the multi-cyclic logistic model fitting process give a range of values for the peak production year, maximum production rate, and URR for both coal raw tonnage and energy.

For coal raw tonnage, these ranges are: 2009–2023 for the peak production year, 1.14–1.28 billion short tons per year, or equivalently, 1035–1163 Mt per year for the maximum production rate, and 124–162 billion short tons, or equivalently, 112–147 Gt for the URR.

For energy from coal, these ranges are: 2003–2018 for the peak production year, 23.1–25.2 quadrillion BTU per year, or equivalently, 24.3–26.6 EJ per year for the maximum production rate, and 2557–3430 quadrillion BTU, or equivalently, 2698–3619 EJ for the URR.

The study by Rutledge provides estimates of the coal tonnage URR for US divided into three regions, Eastern, Western, and Pennsylvania anthracite (Rutledge, 2011a). The estimated URRs for the Eastern, Western, and Pennsylvania anthracite regions are 82 Gt, 45 Gt, and 5.05 Gt, respectively, giving a total US URR of 132.05 Gt. This value is in good agreement with our results as it lies within our estimated range of 112–147 Gt for the US URR.

The study by Patzek and Croft provides estimates for the peak production year, maximum production rate, and URR for energy from US coal (Patzek and Croft, 2010). The values are 2015 for the peak production year, 26.8 EJ per year for the maximum production rate, and 2757 EJ for the URR. These values are in close agreement with our results for energy from US coal. Their peak production year of 2015 and URR of 2757 EJ lie within our estimated ranges of 2003–2018 for the peak production year and 2698–3618 EJ for the URR. Their estimate of the maximum production rate, 26.8 EJ per year, is close to the high side of our estimated range of 24.3–26.6 EJ per year.

The study by Mohr and Evans provides estimates for the peak production year, maximum production rate, and URR for US coal tonnage, using several methods (S. Mohr and Evans, 2009). Here we compare the results of the Hubbert Linearization and Best Guess scenarios in their paper to our results. The results of the Hubbert Linearization give estimates of 2005 for the peak production year, 1232 Mt per year for the maximum production rate, and 171.7 Gt for the URR. Their Best Guess scenario gives 2048 for the peak production year, 1809 Mt per year for the maximum production rate, and 308.1 Gt for the URR. Both of the methods produced URRs and maximum production rates larger than those in our results, which were 112.5–147.4 Gt and 1035–1163 Mt per year, respectively. The Hubbert Linearization used in S. Mohr and Evans (2009) gave a peak production year that is earlier our results, 2005 vs. 2009–2023, while their Best Guess scenario gave a peak production year later than our results, 2048. The results from this study did not align with our results as closely as other studies, however, they still support the common conclusion that the US does not have a 200 or 250 year supply of coal remaining.

The study by the Energy Watch Group provides estimates for the peak production year and maximum production rate for US coal. Their analysis suggests that US coal production by tonnage will peak between the years 2020 and 2030. This range overlaps with our results of US coal production reaching peak between the years 2009 and 2023. The Energy Watch Group study also estimates that the maximum production rate at peak in terms of energy will be at most 20% higher than 2007 production levels. This corresponds to a rate of 27.9 EJ per year, which is close to the high side of our estimated range of 24.3–26.6 EJ per year.

The study by Glustrom concludes that the "planning horizon for moving beyond coal could be as short as 20–30 years" (Glustrom, 2009). This time frame agrees with our results which suggest an imminent peak in US coal tonnage production between 2009 at 2023. The Glustrom study also found that the western states of Wyoming and Montana will dominate future production, similar to our findings.

The studies by Höök and Aleklett and Höök et al. provide estimates several scenarios of future US coal production (Höök and Aleklett, 2009, 2010; Höök et al., 2010). Their analysis found that the US states of Wyoming and Montana will ultimately control the growth and decline of future US production, as we did in our analysis. In each of the studies they suggest that if the large reported reserves of Montana are not fully exploited US production will likely peak before 2050, likely around 2030. Their analysis found that the maximum rate of production of US coal will likely reach 1400 Mt per year and maintain that level until the end of the century if the US's large reported reserves are developed, or slowly decline if the reserves are overestimated. The results from their studies gave later peak years and larger production rates than our results, however, they still support the common conclusion that the US does not have a 200 or 250 year supply of coal remaining.

These studies all used a variety of different analysis and forecasting methods, as described in Section 2.1, and still came to similar conclusions that US coal production will likely be significantly less than what is suggested by the currently reported reserves. Our results agree closely with those of many of the studies, and agree with the common conclusion of a limited US coal supply that all of these studies came to. This agreement lends support to the validity of our results.

3.7. Ancillary evidence of peak production

It is clear from the data presented on individual regions and states that the Western region, particularly Wyoming and Montana, will determine when the entire US will reach peak production. Furthermore, to compensate for the decline in combined production from the other 23 states, these two states have to increase their production rate in the future. Ancillary data about (i) stripping ratio (BLM, 2013; Glustrom, 2009), (ii) US coal mine-worker productivity (EIA, 2012c) and (iii) energy returned on energy invested data (EROEI) (Cleveland, 1992; Gupta and Hall, 2011; Hall and Cleveland, 1981; Hall et al., 1986) are consistent with our model predictions for a peak of US energy production to be approaching soon, i.e. within a decade or earlier. We briefly discuss each of these here.

(i) The majority of the large producing mines in these two states are surface mines located within the Powder River Basin (EIA, 2012g; USGS, 2013). For surface mines a measure known as the stripping ratio is important for determining the economics and feasibility of mining. The stripping ratio is the amount of overburden (i.e. the rock or soil above the coal) that needs to be removed to obtain an amount of coal. Larger stripping ratios may make surface mining uneconomical, as the costs to remove the excess overburden can become too large to make the operation profitable. The stripping of waste rock and soil make up a significant portion of the cost of production for a mine (Thompson, 2005). Additionally, larger stripping ratios do not increase productions costs linearly, but rather exponentially (Shafiee et al., 2009). This means a small increase in stripping ratio can quickly make mining uneconomical. The current producing mines in the Powder River Basin are on the edges of the basin where the overburden is thinnest (DOE, 2007; Glustrom, 2009; USGS, 2013). The USGS has significantly reduced the size of the estimated recoverable reserves in the Powder River Basin in part due to much of the coal having large stripping ratios (Glustrom, 2009; Luppens et al., 2008). As the coal with low stripping ratio is depleted, the coal remaining has a higher stripping ratio. Future production will come from higher stripping ratio mines leading to less net energy obtained from the coal.

(ii) The worker productivity of a coal mine is an important measure for its profitability and will reflect the cost of coal produced at the mine. The more short tons of coal that can be mined per employee hour the more profitable the mine can be. As mines deplete (e.g. thinner coal seams), or the coal becomes harder to access (e.g. larger strip ratios), less coal can be produced for the same amount of time and effort. The overall average mine productivity of the US is therefore an indicator for the state of depletion of US coal resources and the quality of remaining coal resources. US mine productivity increased from approximately 2 short tons per employee hour in the year 1980 to a peak of 7 short tons per employee hour in the year 2000, coinciding with major increases in production from primarily surface mining in the Western region, particularly Wyoming. Since then the average coal mine productivity has been in a decreasing trend and has dropped to a level of 6 short tons per employee hour by 2008, a decrease of 15%. The mine productively in terms of energy from coal shows a more pronounced decrease in productivity since the peak in 2000. Mine productivity has gone from 147 million BTU per employee hour in 2000 to 121 million BTU per employee hour in 2008, a decrease of 18%. This is due to the continuous decline in the energy content of US coals, as was also found in (Höök and Aleklett, 2009; Zittel and Schindler, 2007), as well as, supports our findings that the US will reach peak in energy in coal before tonnage from coal. The timing of this peak in productivity in the year 2000 mirrors the timing of the US reaching a plateau in energy production from coal in 1997.

(iii) EROEI is a form of energy balance of an energy resource. It represents the amount of energy that is obtained for every unit of energy invested in producing that energy source. The higher the EROEI of an energy resource, the greater net energy the source can provide to run the economy and society at large. This means that the EROEI is a measure of a type of quality for an energy resource (Lambert et al., 2014). The EROEI of coal in the US has been calculated in several studies (Cleveland, 1992; Gupta and Hall, 2011; Hall and Cleveland, 1981; Hall et al., 1986). The EROEI for coal increased in the 1960s, decreased to a lower level in the 1970s, and then increased until the late 1980s. The increase in the 1960s is generally attributed to a move to production of western surface coal, while the decrease in the 1970s is attributed to lower energy quality coals beginning to make a larger portion of production (Gupta and Hall, 2011). This pattern appears to be mirrored in the US coal mine productivity discussed in (ii). It is important to note that these western lower energy quality coals are in many cases currently less expensive to utilize than higher energy eastern coals since the western coals do not require the capture of sulfur emissions to comply with regulations, as is the case with the high sulfur eastern coals. (Hall et al., 2014) perform a meta-analysis on estimates of the EROEI of coal. Their work suggests that the EROEI of underground eastern US coal mines had decreased significantly enough by the 1970s to in part prompt more surface production from western coals, along with increased sulfur emissions restrictions. The EROEI of US coal then increased due to the major increases in lower energy intensive surface coal mining since that the 1970s. (Hall et al., 2014) presents data suggesting the EROEI of US coal has been in an increasing trend since the 1980s, however this trend has reversed in the early 2000s. This trend reversal timing matches with that of the plateau in US energy production from coal, the increase in stripping ratio of western mines, and with the peak in US mine productivity. The number of EROEI estimates in this trend is limited so one should be cautious making definitive statements from these data. However, the potential decrease in EROEI from US coal agrees with the many other observed factors associated with a peak in US coal production. Typically, higher ranked coals have greater EROEIs or lower energy intensities than lower ranked ones as was shown by in life-cycle analysis studies by (Lenzen, 2008). Lenzen (2008) performs a life cycle analysis on brown (i.e. lower energy sub-bituminous and lignite coals) and black (i.e. higher energy bituminous coals) coal power generation plants and produces a range of energy intensities. Brown coal power plants have higher energy intensities than black coals power plants and therefore, have lower EROEIs. Based on the factors discussed in (i) and (ii), along with the fact that sub-bituminous coal in the Western region will form a larger percentage of US energy production replacing higher ranked bituminous coal from other regions it is likely that the EROEI of US coal is decreasing.

Thus we observe that these three supplementary indicators support our earlier model results about near term year for maximum production for US energy from coal and the resulting low URR estimates.

4. Conclusions

Over the course of this study we analyzed the current state of US coal production and forecasted likely future production scenarios. For this task multi-cyclic logistic model was fit to historical production datasets of raw tonnage and energy from coal for the entire US. The raw tonnage logistic model indicates that the year of peak production will occur between 2009 and 2023, with 2010 as the most probable year for the maximum. The logistic model applied to the energy production data indicates that the year of peak production will occur between 2003 and 2018, with 2006 as the most likely year for the maximum. These fits used data excluding any recent coal production disruptions due to the rise in shale gas production and the global economic crisis, and therefore are free from potential bias from recent production declines due to these factors. Additionally, the US was also subdivided into five coal-producing regions and the multi-cyclic logistic model was applied to each. This analysis showed that four out of the five coal-producing regions are in post-peak decline, similar to (Glustrom, 2009; Höök and Aleklett, 2009, 2010), with the Western region expected to reach its peak production between 2007 and 2012. The overlap of the peak production time frames, 2010–2023, for the total US, and 2007–2012 for the Western region, are consistent with the data showing the Western region's production will control the direction of future US production. The estimated US coal energy URR from the logistic model is 2750 quadrillion BTU (2900 EJ), with roughly 1680 quadrillion BTU (1770 EJ) already extracted and 1070 quadrillion BTU (1130 EJ) yet to be mined, while the estimated raw tonnage URR is 124 billion short tons (112 Gt), with roughly 72 billion short tons (65 Gt) already mined, and 52 billion short tons (47 Gt) yet to be mined. The estimate of 52 billion short tons yet to be mined is not in agreement with the EIA's reported 259 billion short tons (235 Gt) of estimated recoverable reserves.

Two classes of tests were performed to validate the peak production years and remaining reserve estimates that resulted from the model. The tests used production data from several regions that have completed a full production cycle. Of these two typical cases namely the UK and Pennsylvania's anthracite mines were discussed in depth as examples. The results from the first test showed that the multi-cyclic logistic model was able to predict the production peak year to within ± 9 years for the UK, and ± 12 years for Pennsylvania anthracite using limited pre-peak segments of the respective complete datasets. The second test showed that URR, which reflect reserve estimates, were grossly overestimated by as much as 620% and 200%, for the UK and Pennsylvania anthracite respectively. This is especially the case before the peak in production occurs, but, estimates remain optimistically high even after the peak production occurs, until the decline in production makes it evident that the large reserves are not justified. Additionally, we find that our results agree with those of previous analysis of US coal production. Our findings suggest that the US coal supply has been largely overstated, and that energy policy based on these overstatements should be revised.

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Appendix A

In addition to the peak year sensitivity analysis highlighted for UK and Pennsylvania anthracite coal production, we include figure of the analysis for France, Japan, and Sweden. These regions' historical peak in production occurred later in the production cycle due to the asymmetry of the production profile. To further illustrate the concept of historical gross overestimation of URR and reserves, we also include figures for the δURR%(t) analysis for these three regions.

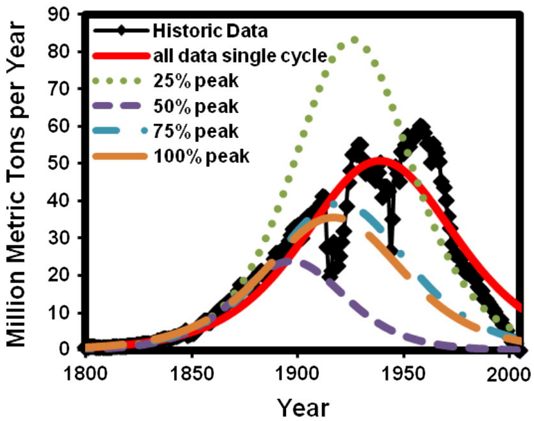

Fig. A1. French coal production from 1787 to 2006. Production data from S.H. Mohr and Evans (2009). The data show a virtually complete production cycle. A single cycle logistic model, fitted using the entire production dataset, is shown. Single cycle logistic models fitted using only production data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit curve are shown.

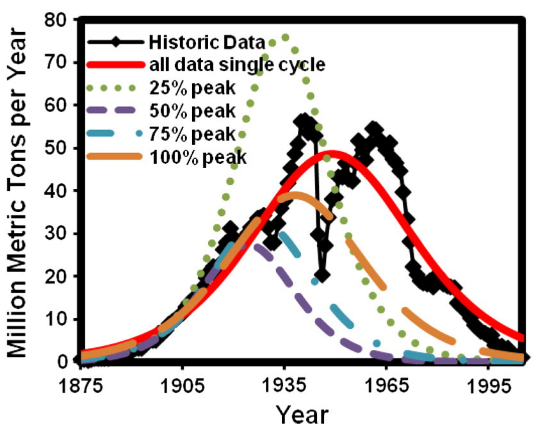

Fig. A2. Japanese coal production from 1874 to 2006. Production data from S.H. Mohr and Evans (2009). The data show a virtually complete production cycle. A single cycle logistic model, fitted using the entire production dataset, is shown. Single cycle logistic models fitted using only production data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit curve are shown.

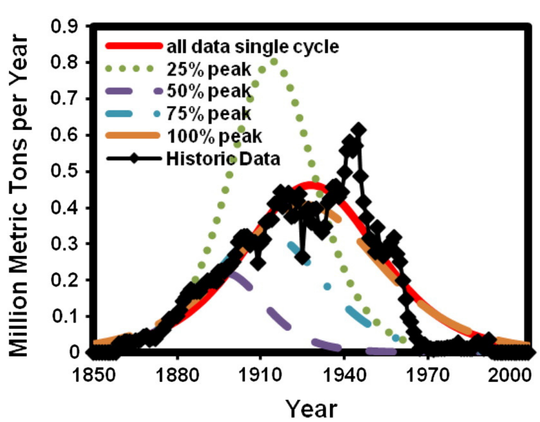

Fig. A3. Swedish coal production from 1850 to 2006. Production data from S.H. Mohr and Evans, 2009). The data show a virtually complete production cycle. A single cycle logistic model, fitted using the entire production dataset, is shown. Single cycle logistic models fitted using only production data prior to 25%, 50%, 75%, and 100% of the peak value of the best fit curve are shown.

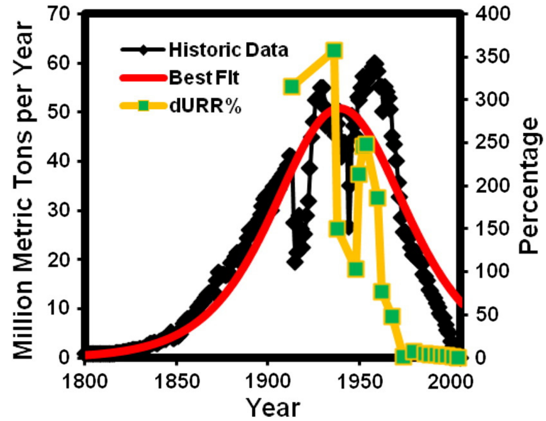

Fig. A4. δURR%(t) for France; right axis. Coal reserve data used to calculate the δURR%(t) are from Rutledge (2011b). Also displayed are historical production data and best fits; left axis. δURR%(t) gives an approximate percentage of over- or underestimated reserves as defined by Eq. (5). France has essentially completed a logistic production cycle allowing δURR%(t) to be directly calculated from historical data. It can be seen that the total reserve base was historically overestimated by as much as 360% in 1936. These high overestimations in reserves occurred near or after the peak in the production of the coal region, and persisted until there were significant declines in production, after which, reserve estimates were significantly reduced. The reserves were adjusted to lower and lower levels, causing the δURR%(t) to approach zero, as production continued to decline to zero.

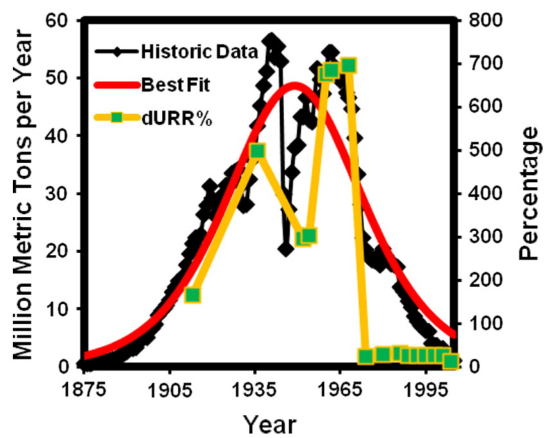

Fig. A5. δURR%(t) for Japan; right axis. Coal reserve data used to calculate the δURR%(t) are from Rutledge (2011b). Also displayed are historical production data and best fits; left axis. δURR%(t) gives an approximate percentage of over- or underestimated reserves as defined by Eq. (5). Japan has essentially completed a logistic production cycle allowing δURR%(t) to be directly calculated from historical data. It can be seen that the total reserve base was historically overestimated by as much as 700% in 1968. These high overestimations in reserves occurred near or after the peak in the production of the coal region, and persisted until there were significant declines in production, after which, reserve estimates were significantly reduced. The reserves were adjusted to lower and lower levels, causing the δURR%(t) to approach zero, as production continued to decline to zero.

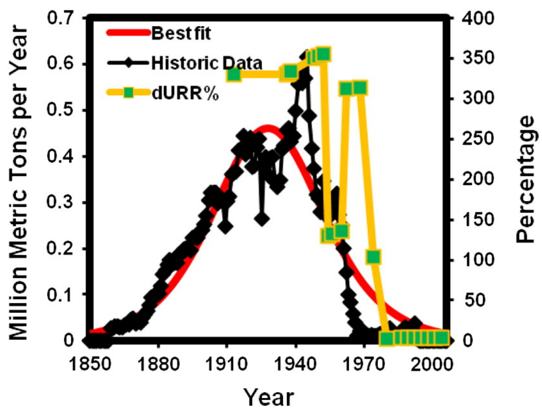

Fig. A6. δURR%(t) for Sweden; right axis. Coal reserve data used to calculate the δURR%(t) are from Rutledge (2011b). Also displayed are historical production data and best fits; left axis. δURR%(t) gives an approximate percentage of over- or underestimated reserves as defined by Eq. (5). Sweden has essentially completed a logistic production cycle allowing δURR%(t) to be directly calculated from historical data. It can be seen that the total reserve base was historically overestimated by as much as 360% in 1952. These high overestimations in reserves occurred near or after the peak in the production of the coal region, and persisted until there were significant declines in production, after which, reserve estimates were significantly reduced. The reserves were adjusted to lower and lower levels, causing the δURR%(t) to approach zero, as production continued to decline to zero.

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