Projection of long-term paths for Australian coal production – comparisons of four models

Steve Mohr+, Mikael Höök*, Gavin Mudd¤, Geoffrey Evans+

Contact e-mail: Mikael.Hook@fysast.uu.se

+ School of Engineering, The University of Newcastle, Callaghan, NSW, 2308, Australia

* Global Energy Systems, Department of physics and astronomy, Uppsala University, Box 535, SE-751 21, Uppsala, Sweden, Telephone: +46 18-471 7643, Fax: +46 18-471 3513, web: http://www.fysast.uu.se/ges/

¤ Institute of Environmental Studies, University of New South Wales, Kensington, NSW 2052, Australia / Monash University, Department of Civil Engineering, Faculty of Engineering, Wellington Road, Clayton, Vic. 3800, Australia

Abstract
Coal exports are an important source of revenue for Australia and for this reason Australian coal production and resources have been examined in detail and two recoverable resource estimates determined namely Standard and High. The Standard case calculated the likely recoverable coal resources in Australia to be 317 Gt, whereas the High scenario determined the maximal amount of recoverable coal resources at 367 Gt. Different modelling approaches (Logistic, Gompertz, Static and Dynamic supply and demand models) were used to project fossil fuel production and the projections of the relative approaches were compared. Good agreement was found between the Logistic, Static and Dynamic supply and demand models with production peaking in 2119±6 at between 1.9 and 3.3 Gt/y. Contrasting these projections the Gompertz curves peak in 2084±5 at 1–1.1 Gt/y. It was argued that the Logistic, Static and Dynamic models are more likely to produce accurate projections than the Gompertz curve. The production forecast is based on existing technology and constraints and a qualitative discussion is presented on possible influences on future production, namely: export capacity, climate change, overburden management, environmental and social impacts and export market issues.

Key words: Australia, coal reserves, coal production, peak coal, modelling
1. Introduction

Coal is a widely utilised material, accounting for 25 percent of the world’s primary energy supply and 41 percent of electricity production (IEA, 2009). It is also used in iron / steelmaking and chemicals manufacturing industries. Between 80-90 percent of world coal resources and reserves are concentrated in just 6 countries, namely: USA, Russia, China, Australia, India and South Africa (WEC, 2007; BGR, 2009; BP, 2010). Coal production is a similar, with China alone accounting for nearly 50 percent of world coal production.

In 2008, Australia produced approximately 7 percent of total world output of saleable coal at 430 million metric tons (Mt) (ABARE, 2009). Production was concentrated amongst the eastern states of Australia, namely New South Wales, Queensland and Victoria. Production was mostly bituminous coal but with substantial amounts of lignite and some sub-bituminous coal as well. Exported coal volume was 252 Mt in 2007-2008 (World Coal Institute, 2009), making Australia the world’s largest coal exporter. Most of these exports are distributed throughout the Asian region, to Japan, China and Korea (Australian Coal Association, 2010). In 2008-2009, export volumes increased to 262 Mt, comprising 135 Mt of metallurgical and 126 Mt of thermal coal (ABARE, 2009). These tonnages correspond to nearly 60 and 20 percent of global metallurgical and thermal coal exports, respectively. Unsurprisingly, coal is the largest export commodity by value for the Australian economy.

Australia is particularly reliant on coal exports both for current and future wealth. For this reason, it is important to have a good understanding of what future demand might be and likely production rates based on known coal reserves. While there have been a number of studies carried out to predict coal production both globally (e.g. Mohr and Evans, 2009; Höök et al., 2010) and for the largest producers like the USA and China (e.g. Tao and Li, 2007; Höök and Aleklett, 2009a, 2009b; Lin and Liu, 2010), similar analysis has not been carried out for Australia and its coal producing states. This study is aimed at addressing that gap in the knowledge. However, before doing so it is important to understand the underlying assumptions that underpin the different modelling approaches reported in the literature.

Hubbert (1956) was one of the first attempts at modelling future production from finite resources. He assumed that production levels begin at zero, before the production has started, and ends at zero, when the resource has been exhausted. In between, the production curve passes through one or several maxima. The actual shape of the production curve may be arbitrary, but ultimately constrained by the recoverable amounts. Hubbert (1956) originally proposed a bell-shaped curve for idealized production, but later (Hubbert, 1959) adopted a generalised logistic curve. The advantage in using logistic similarly-shaped Gaussian curves is that they are simple to work with and for this reason are widely used (e.g. Bartlett, 2000; Laherrere, 2006; Patzek, 2008, Höök and Aleklett, 2009a, 2009b; Patzek and Croft, 2010).

There are a number of studies that indicate future resource production is not necessarily limited to symmetrically-shaped curves (e.g. Bardi, 2005; Mohr and Evans, 2008a; Caithamer, 2008; Höök et al., 2011). In practice, any form of mathematically tractable curve can be used. For example, Feng et al. (2008) has used the HCZ-model (Hu et al., 1995) for petroleum forecasts in China; while Caithamer (2008) introduced a family of exponential power functions with flexible growth rates in both the pre-peak and post-peak regions of the production life cycle. Gompertz curves, which are asymmetric in shape, have also been used for analyzing supply patterns for oil and other exhaustible natural resources (e.g. Moore, 1966; Fitzpatrick et al., 1973). Finally, the supply-demand model by Mohr and Evans (2008b, 2009) attempts to directly model production from individual mines that can be either brought on- or off-line or upgraded depending of the relative difference between inferred demand and supply capacity. Outside factors such as wars, economic recessions or international crises can also be included in the analysis.
The aim of this study was to make a comparison of future coal production in Australia using four different approaches. These included: (1) Logistic curve, representing a symmetrical production profile; (2) Gompertz curve, representing an asymmetrical production profile; (3) Supply-demand interaction model, without interaction; and (4) Supply-demand, with interaction. For the Logistic and Gompertz curves a depletion rate constraint (see Höök, 2009) is applied to reflect the impacts of dwindling reserves. Two URR estimates denoted standard and high are determined for each coal-producing state, based on a review of Australian coal resources and their distribution. The two URR estimates will then be used as a consistent input to all four models. Coal production methodologies are also incorporated into the analysis. Finally, factors such as global warming, overburden management, environmental and social impacts, and export markets that may affect future production are discussed.

2. **Australian coal geology, resources and production**

2.1 **Coal geology**
Australian coals are of Paleozoic, Mesozoic, and Tertiary age. The majority of the coal resources are located in the eastern part of Australia, with smaller deposits occurring in Western Australia and Tasmania. The entire spectrum of coal ranks and types are well represented (Suggate, 1998). Studies of coals and their depositional environment have been made by Crossdale (2004). A location map of the main coal basins is displayed in Figure 1.

![Figure 1. Location of major black coal basins in Australia. Adapted from ABARE (2010) and Mudd (2009). Note: The Cooper Basin is a deep sedimentary basin and primarily a major oil-gas producer. Although it contains substantial high quality coal, the extreme depth of 2-3 km has prevented any extraction to date.](image-url)
Victoria is the principal region for Tertiary coals, primarily high volatile lignite with low ash and sulphur content. Very thick deposits are present and the principal seams can reach a thickness of up to 300 m (Thomas, 2002). The coal seams are shallow and flat-lying, which has helped exploitation. This region is developed in a number of coal fields (Figure 2), where the most important is Latrobe Valley. More extensive description of the Latrobe Valley has been made by Barton et al. (1993), while a review of Tertiary coal deposits in Australia has been done by Holdgate and Clarke (2000).

Figure 2. Brown coal basins in Victoria. Adapted from Mudd (2009)

Queensland and New South Wales contain some Mesozoic coal accumulations. The Brisbane area contains sub-bituminous deposits, but those have not been extensively worked. Additional details on some important basins in this area have been compiled by Hamilton (1991) and Othman and Ward (2002).

The Paleozoic coals have been generated in a number of basins located all over Australia and Tasmania. The principal ones are the Bowen, Galilee and Cooper Basins in Queensland, the Sydney Basin in New South Wales and the Collie and Fitzroy Basins in Western Australia. Closer description of those basins has been made by Evans (1980), Beeston (1986), Hunt (1989), Herbert (1995), Michaelsen and Henderson (2000) and Crosdale (2004).

The Bowen Basin has been explored extensively and its geological history has allowed preservation of shallow and undisturbed flat-lying coals. Seams can reach thicknesses up to 30 m and generally has low ash and sulphur along with good coking properties. However, seam splitting is frequent and igneous intrusions have affected the western part of the basin. The Bowen Basin has generally been developed by large open cut operations. In comparison,
the Galilee and Cooper Basins contain large reserves that are yet to be developed due to remoteness and/or extreme depth (see Figure 1).

The Collie Basin of Western Australia contains structurally undisturbed coal seams with thickness of 1.5 to 11.2 m (Thomas, 2002). The coal ranks as sub-bituminous coal with low ash and sulphur content. Exploitation of the coal deposits has been undertaken in Cardiff and Muja areas. In comparison, the Fitzroy Basin has yet to be developed, although coals have been located.

The Sydney Basin in New South Wales is the most important coal-producing region. This basin is known for its little structural disturbance and has been described by Mayne et al. (1974). Coal seams in the Sydney Basin can reach thicknesses of 10 m and contain high volatile bituminous coal with variable ash and low sulphur content, where some parts even have good coking qualities.

2.2 Coal resources

The definition of a mineral resource as ‘economic’ is addressed through convention or formal codes of practice. In Australia, this is through the Joint Ore Reserves Committee (or JORC) Code (AusIMM et al., 2004), which covers the definitions and standards required to report a mineral deposit as a potentially economic resource. The JORC Code is statutory for all companies listed on the Australian Stock Exchange (ASX) which report mineral resources, of which coal is a major component of ASX-listed mining companies. Under the JORC Code, there are two broad categories of resources (AusIMM et al., 2004):

- **Ore reserves** – assessments demonstrate at the time of reporting that economic extraction could reasonably be justified. Ore Reserves are sub-divided in order of increasing confidence into Probable Ore Reserves and Proved Ore Reserves. Ore reserves have had appropriate assessments and studies carried out, and include consideration of, and modification by, realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors (the ‘modifying factors”).

- **Mineral resources** – the location, quantity, grade, geological characteristics and continuity of a Mineral Resource are known, such that there are reasonable prospects for eventual economic extraction; not all modifying factors have been assessed and hence some uncertainty remains. Mineral Resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories.

Thomas (2002) gave a conceptual picture of the different categories related to coal resources and reserves (Figure 3). Inferred resources generally correspond to no more than 4 km between the measurement points and extrapolation of trends should be no more than 2 km from drill holes. Class 1 indicates continuity of coal seams between measurement points, while Class 2 is more uncertain. Indicated resources have no more than 2 km between measurement points and trends are extrapolated up to 1 km. Finally, measured resources should have no more than 1 km between data points and trends can be extrapolated up to 0.5 km. The level of confidence for measured resources is generally sufficient to allow detailed planning. Reserve estimates are calculated from detailed or conceptual mining plans, as well as suitable recovery factors that depend on the chosen mining method. Marketable reserves (also called saleable) include losses from coal washing and other forms of treatment prior to reaching consumers.
A common problem in coal mining is the extent of geologically known coal resources versus those which are recoverable resources (i.e. mineable). This may be due to incomplete mining methods (e.g. board and pillar methods), thin seams making mining impracticable and/or uneconomic, poor coal quality (rank, sulphur, ash, etc.), land use constraints (e.g. national parks, local communities), and so on. To address this issue, an addendum was recently published specifically for reporting in situ versus recoverable coal resources (CGCNSW & QMC, 2003).

Australia’s coal resources are assessed annually by Geoscience Australia (GA, various). Although GA’s assessments are based on the broad concepts from the JORC Code, they use the categories of economic and sub-economic demonstrated resources plus inferred resources (with each showing less economic and geologic confidence, respectively).

Economic coal resources over time in Australia are shown in Figure 4, and all GA categories in Figure 5. Australia coal reserves and resources are also shown in Table 1 from various WEC and BGR reports. Over time, total estimated resources have been relatively stable, although individual categories have changed as further drilling and studies have been completed. From 1975 to the end of 2009, total production of raw black and brown coal was 7.94 and 1.75 Gt, respectively (data updated from Mudd, 2009) – compared to economic resources in 2009 of 43.8 and 37.1 Gt, respectively. Although total resources have been relatively stable in the past few decades, the years remaining has been declining due to rapidly growing production, and Australia now has less than a century of economic coal resources remaining (assuming constant production).

There are regions of Australia which are known to contain coal, but given factors such as their extreme depth (e.g. Cooper Basin at 2-3 km) or lack of exploration and associated studies to date (such as the Fitzroy Sub-basin of the Canning Basin), they are not included as resources at present. Future exploration programs and new studies can change the picture, but it is reasonable to state that the greatest part of the Australian coal endowment is relatively well known.
Figure 4. Australia’s economic black coal resources and Resources-to-Production ratio. Data sources: GA (1999-2010) and Mudd (2009)

Figure 5. Black coal and lignite recoverable resources
Table 1. WEC and BGR coal resource and reserve estimates for Australia. Data source: Höök et al. (2010) and references within

<table>
<thead>
<tr>
<th>Year</th>
<th>Resources [Gt]</th>
<th>Reserves [Gt]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WEC</td>
<td>BGR</td>
</tr>
<tr>
<td>1924</td>
<td>166</td>
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</tr>
<tr>
<td>1929</td>
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<td>359</td>
<td>77</td>
</tr>
<tr>
<td>2008</td>
<td>393</td>
<td>359</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td>76</td>
</tr>
</tbody>
</table>

* indicates estimates given in tons of coal equivalents (1 tce = 29.3 GJ).

Data from the World Energy Council (WEC) and the German Federal Institute for Geosciences and Natural Resources (BGR) gives additional data over time that can be used for comparison (WEC, various; BGR, various). Coal resources for Australia increased over time to a maximum of 860 Gt in the 1980’s. Since then Australia’s coal resources have been declining and are now estimated to be around 400 Gt. Australian coal reserves have been more variable with WEC statistics showing a 16% decline in the last 15 years compared with a 28% decline in BGR reserves in the last 5 years. Both the BGR and WEC reserve estimates are considerably lower than current recoverable resource estimates shown in Figure 5.

WEC primarily refers to the Geoscience Australia as their primary source of information. WEC also highlights that for “a variety of reasons (e.g. environmental restrictions, government policies, military lands), not all of the tonnages classified as Economic Demonstrated Reserves (EDR) are currently accessible”. Consequently, a 15% reduction of the EDR is presented by the WEC as the actual coal reserves.

The BGR use a range of cut-off parameters that can differ from the methodology used by WEC to estimate coal reserves and resources. Important factors include coal thickness, depth, energy, barren partings and ash content, rank (measured as vitrinite reflectance), and volatile matter content. Depending on the national limits for the workability of the coal thickness concerned, total resources usually refer to thicknesses starting at 60 cm and down to
a maximum depth of 1800 m. Finally, BGR is taking into account the current world market prices for coal in combination with known production costs, coal deposits developed at the moment and producing at prices below US$50/t count as reserves (Thielemann et al., 2007). Also here, economic and social parameters are believed to be the key factor behind the recent changes and the difference from the EDR estimate provided by Geoscience Australia.

A key parameter in projecting future production of a finite resource is the ‘ultimate recoverable resource’ or URR – simply the cumulative production plus remaining recoverable resources. The URR figures for Australia’s coal endowment are based on data presented in Figure 5 and Table 1.

2.3 Coal production

Australian coal production started in the late 18th century near Newcastle, NSW. Production volumes were small and insignificant until after the 1950s. New South Wales was the dominant coal region until the 1950s when other states began to develop coal industries, especially Queensland. Since coal extraction started, NSW has been and remains an important producer, together with Queensland (Figure 6). Victoria currently only produces lignite for domestic use. Other regions of Australia have low production levels, as their discovered reserves are yet to be worked or the resources have not been appealing for commercial development. Some major trends in production include (Mudd, 2009):

- **Open cut mining** – due to the growing scale of excavating machinery and haul truck technology, there has been a major shift since 1945 from underground to open cut mining (Figure 7).
- **Overburden ratios** – in parallel with open cut mining, the ratio of overburden (or waste rock) to coal has been steadily increasing, and now averages about 5 m³/t raw coal. Individual mines can now reach ratios up to 11 (or higher) as shown in Figure 7.
- **Longwall mining** – most underground mines now use longwall extraction techniques.
- **Raw to Saleable ratios** – the ratio of raw to saleable coal has been gradually increasing since the 1960’s, and now averages 1.29, see Figure 8.

Although it is difficult to predict with confidence likely future trends in these aspects of coal mining, and especially how these trends could relate to future conditions for assessing economic coal resources, it is clear that they will present an on-going challenge to coal mining. Major community concerns have been expressed about the increasing scale of coal mining in existing provinces such as the Hunter Valley and Bowen Basin and the complex issues of cumulative environmental and social impacts – providing a catalyst for significant community concerns regarding potential new mines in greenfields provinces such as the northern Sydney (Gunnedah) Basin in NSW and elsewhere in Australia (see ECARC, 2009).

The Bowen and Sydney Basins have dominated historical production due largely to the lack of structural disturbances that has made exploitation easier. Another parameter is the closeness to the coast and export harbours as well as major population centres (see Figure 1).
Figure 6. Australian coal production 1830-2008. (top) by state: (bottom) mass by coal rank

Figure 7. Open-cut production by (a) proportion (b) overburden ratio. Overburden ratios were mostly not available from 1970-1990
Modelling Approach

Four modelling approaches, namely: Logistic and Gompertz curves and supply-demand models both without and with interaction, were used to predict future coal production. Each of these approaches is described below. Also included is a summary of chosen URR values (standard and high), which were applied to each of the production models.

3.1 Constrained Logistic and Gompertz Curves Models

Verhulst (1838) reasoned that any growing system would ultimately reach a saturation level characterized by the environment, i.e. a limit to growth imposed by nature. This resulted in the development of the logistic model, one of the first members of the sigmoid family of curves. The Gompertz curve is derived from the limiting case of a generalized logistic differential equation and also belongs to the sigmoid curves (Winsor, 1932). Over time, other scientists have adopted a similar thinking that has resulted in the development of numerous mathematical models capable of handling growth subjected to inherent limits (Tsoularis and Wallace, 2002).

The Logistic curve was first used to model fossil fuels by Hubbert (1959), and since then it has been widely used to model fossil fuels (e.g. Bartlett, 2000; Laherrere, 2006; Patzek, 2008, Höök and Aleklett, 2009a, 2009b; Patzek and Croft, 2010). The Logistic equation creates a symmetrical bell-shape production profile, and mathematically is defined as:

\[
Q_L(t) = Q_T \left( \frac{1}{\exp \left( -r_L (t - t_p) \right) + 1} \right)
\]

where \(Q_L(t)\) is the cumulative production for the logistic curve, \(Q_T\) is the URR, \(t_p\) is the peak year and \(r_L\) is the rate constant.
The Gompertz curve has also been used to model fossil fuels (e.g. Moore, 1966; Fitzpatrick et al., 1973). Similar to the Logistic equation, the Gompertz curve is also bell-shaped but without the constraint of being symmetrical. Mathematically, the Gompertz equation is defined as:

\[ Q_G(t) = Q_T \exp \left( - \exp \left( r_G(t - t_p) \right) \right) \] (2)

The rate constants, \( r_L \) and \( r_G \), for the Logistic and Gompertz curves, respectively, are typically determined by fitting the curves to historical production data. The disadvantage with this approach, however, is that in some instances unrealistically high depletion rates for future production are obtained. The depletion rate of remaining recoverable resources, \( d_\delta(t) \), is defined as the ratio of the annual production, \( P(t) \), for the year to the amount of remaining reserves, \( Q_T - Q(t) \), i.e.

\[ d_\delta(t) = \frac{P(t)}{Q_T - Q(t)} \] (3)

The depletion rate is governed by physical factors of operation, including infrastructure development, transport, etc; and for American coal production was found to be a maximum of 3 percent (Höök and Aleklett, 2009b). The same limit was applied in this study when determining the rate constants, \( r_L \) and \( r_G \), for future coal production for the Logistic and Gompertz curve projections.

3.2 Supply-Demand model

The Supply-Demand model is described previously (Mohr and Evans, 2009). Briefly, the model is based on having a number of idealised mines, with each having a mine life, \( L \), and annual mine production rate \( P \). Mines can be either brought on-line or taken off-line depending on production requirements. Production begins in year, \( T_0 \), and the rate at which new mines are placed on-line is controlled by the production rate constant, \( r \). The number of mines a region has is determined by the assumed URR value. The model has two key options: (1) Static where supply and demand do not interact; and (2) Dynamic where both supply and demand are influenced by each other.

For this study, the model was commenced in 1880 and demand was assumed to start at 1 Mt in 1880 and increase by 4.8% per annum. In the dynamic case the percentage increase for a given year was dependent on the difference between the supply and demand. The production rate constants for each state and coal type were obtained from historical production data and applying the same analysis as used by Mohr and Evans (2009). The resultant values are listed in Table 2.
Table 2. Production rate constants used in Supply-Demand Model

<table>
<thead>
<tr>
<th>State</th>
<th>Coal type</th>
<th>$T_0$</th>
<th>$L$  (y)</th>
<th>$P$ (Mt/y)</th>
<th>$r$ (1/y)</th>
</tr>
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<td>NSW</td>
<td>Bituminous</td>
<td>1880</td>
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<td>1</td>
<td>2.9</td>
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<tr>
<td>NSW</td>
<td>Sub-bituminous</td>
<td>1940</td>
<td>10</td>
<td>0.014</td>
<td>3</td>
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<tr>
<td>Vic</td>
<td>Bituminous</td>
<td>1890</td>
<td>30</td>
<td>0.1</td>
<td>3.5</td>
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<tr>
<td>Vic</td>
<td>Lignite</td>
<td>1915</td>
<td>80</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Qld</td>
<td>Semi-anthracite $^b$</td>
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<td>20</td>
<td>0.05</td>
<td>3</td>
</tr>
<tr>
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<td></td>
<td>1995</td>
<td>45</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
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<td>1948</td>
<td>55</td>
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<td>4.9</td>
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<tr>
<td>Qld</td>
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<td>1979</td>
<td>40</td>
<td>1.5</td>
<td>$(High)$ 6.22</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(Standard)$ 6.25</td>
</tr>
<tr>
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<td>Sub-bituminous</td>
<td>1957</td>
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<td>90</td>
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<td>2050</td>
<td>70</td>
<td>5</td>
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<tr>
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<td>Semi Anthracite</td>
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<td>2050</td>
<td>70</td>
<td>0.5</td>
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</tr>
</tbody>
</table>

$^a$ Disruption has been included to account for decline in coal production during the great depression.

$^b$ URR of 1.27 Mt for 1950-1995. From 1995, URR of 2092 Mt (Standard case) and 2754 Mt (High case).

3.3 Standard and High URR estimates

A standard estimate was assumed based on the authors’ critical assessment of published and recorded information. A high estimate, taken to be the maximum upper bound on the extractable coal in Australia, was also included in the analysis to provide a most optimistic production estimate. The standard URR estimates were selected from recoverable resource estimated from Sait (2009) instead of from reserve estimates. Reserve estimates of mature regions such as the UK and Germany, have been found in the past to be too optimistic, with WEC (var.) indicating substantial decreases in reserve estimates in recent years. This argument could be used to apply only reserve estimates to Australia as an over-estimate, however as Australia is still rapidly increasing coal production, and with key basins such as the Gunnedah portion of the Sydney-Gunnedah basin currently being underdeveloped. It is believed that reserve estimates would under estimate the URR hence the recoverable resource estimates were used instead. The URR for the standard and high estimates for black and brown coal below are summarised in Table 3.

A standard black coal URR was taken to be the sum of cumulative production to date (7,400 Mt) and the recoverable resources reported by Sait (2009). Black coal was differentiated into the following types based on current production data:

1. Tasmania and NSW were assumed to be 100% bituminous.
2. South and Western Australian coal were assumed to be 100% sub-bituminous.
3. Queensland was 80% bituminous, 15% sub-bituminous, 5% semi-anthracite.

A high estimate for black coal URR was obtained by adding 7,400 Mt of cumulative production to in-situ resources which are reduced appropriately. In particular:
1. 200,000 Mt of in-situ resources are recoverable (see Figure 5a)
2. Resources were reduced based on a Raw-to-Saleable Coal ratio of 1.3 from Figure 8 to obtain ~153,000 Mt of saleable resources.
3. Cumulative production of 7,400 Mt added to obtain a URR of 160,000 Mt

Similarly for lignite, a standard URR was taken to be the sum of cumulative production to date of 2.2 Mt and the recoverable resources reported by Sait (2009). As shown in Figure 5(d), resources and recoverable resources for lignite have been stable for at least the past 10 years. The stable resource and recoverable resources estimates reflect a high degree of knowledge of the deposits. For this reason the brown coal URR is unlikely to increase in the future. A high estimate for lignite URR was obtained by rounding upward all standard URR estimates.

Table 3. Standard and High URR model inputs.

<table>
<thead>
<tr>
<th>State</th>
<th>Black Coal (Mt)</th>
<th>Lignite (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bituminous</td>
<td>Semi-Anthracite</td>
</tr>
<tr>
<td></td>
<td>Standard</td>
<td>High</td>
</tr>
<tr>
<td>NSW</td>
<td>55,004</td>
<td>72,385</td>
</tr>
<tr>
<td>Vic</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Qld</td>
<td>34,962</td>
<td>46,010</td>
</tr>
<tr>
<td>SA</td>
<td>18,323</td>
<td>24,115</td>
</tr>
<tr>
<td>WA</td>
<td>4,590</td>
<td>6,040</td>
</tr>
<tr>
<td>Tas</td>
<td>279</td>
<td>370</td>
</tr>
<tr>
<td>Australia</td>
<td>Black Coal (Mt)</td>
<td>Lignite (Mt)</td>
</tr>
<tr>
<td></td>
<td>121,581</td>
<td>195,523</td>
</tr>
<tr>
<td></td>
<td>160,000</td>
<td>207,150</td>
</tr>
</tbody>
</table>

4. Modelling predictions

4.1. Annual production

Projections of annual production for the four models are shown in Figures 10-13 for the standard and high URR scenarios. There are several interesting points to highlight. First, the Gompertz curve peaks at a lower rate than the other three models and subsequently also declines at a slower rate. The Dynamic model peaks quickly at a high rate and subsequently declines rapidly when compared to the Logistic and Static models. The Static models have a 120 year period of steady coal production between 2060 and 2140, with the High URR scenario showing a plateau at 21 Gt/y and the Standard URR scenario showing a very modest increase from 1.7 Gt/y in 2060 to 1.9 Gt/y in 2140.

The comparison of different modelling approaches highlights that there are only small differences between the projections of the Logistic, Static and Dynamic models. Conversely, there are significant differences between these three models and the Gompertz projections due to the difference in the depletion rate and how fast the recoverable resources can be extracted in the various approaches (Figure 9). In all cases, small differences are seen between the standard and high cases. The Dynamic model extracts the highest percentage of the remaining recoverable resources annually, while the Gompertz model gives the lowest depletion rates. This also explains why quite different production levels can be reached from the same URR in future production levels.
Figure 9. Depletion rate of remaining recoverable resources for Australia (four models)

Figure 10. Projected production: Constrained Logistic curves

Figure 11. Projected production: Constrained Gompertz curves
4.2 Peak production and year

Australian coal production in for the Logistic, Static, and dynamic models for both the standard and high URR estimates is anticipated to peak in 2119±6. The Gompertz curve by contrast anticipates that Australian coal production will peak in 2079 and 2088 respectively for the standard and high URR estimates. The peak production rate is more variable with estimates of 953, 1890, 2067, and 2912 for the Gompertz, Static, Logistic and Dynamic models respectively when using the standard URR and 1134, 2138, 2401 and 3341 when applying the high URR estimates.

Peak production and year are reported in Figure 14. It can be seen that the Logistic and Static models are in agreement, with peak years being less than 15 years of each other while the difference in peak productions is less than 15 percent. The only anomaly is with rest production with the Static model peaking 35-36 years earlier and 28-36 Mt/y lower than the Logistic models for the Standard and High scenarios respectively. The Dynamic and Static model peak years are with 15 years of each other. However, the peak rates for the Dynamic model are more than double the Static estimate for South Australia’s sub-bituminous coal, and 50% higher for Victorian lignite. Both of these differences combine to cause the Dynamic model peak rate for Australia to be 54% and 56% higher than the Static models.
The Gompertz curve is variable, NSW and Queensland bituminous peak year estimates are within 15 years of the Logistic peak year values, however they are 67-69 years later for Victorian lignite and 100-113 years later for South Australian bituminous for the Standard and High URR estimates respectively. Conversely the Gompertz curve projects the peak year to be 42 and 25 years earlier than the logistic projection. The Gompertz curves peak production rate is between 24 and 72% lower than the Logistic peak rates.

To determine which outlook that is most reasonable, it is essential to properly justify the choice of models. The logistic curve has been examined by Höök et al. (2010) by comparing the logistic curve to the production profiles of mature and depleted regions such as Germany, the UK and Japan. Other studies have also pointed to the good empirical agreement with historical production patterns and logistic curves (Rutledge, 2011). This serves as a justification for expecting logistic behaviour from future production. Therefore, the logistic model is deemed a reasonable accurate tool for long-term outlooks, provided that the URR estimate is reliable.

Similarly, the Static and Dynamic model has been justified by examining NSW coal production by mine to ensure the underlying logic is correct and reasonable constants are applied (Mohr, 2010). This model is built on mine-behaviour and real world mineral exploitation, so it is appears that outlooks generated by this models are feasible. The dynamic model reaches high depletion rates and surpasses many historical examples, but this is not impossible if the market is allowed to freely exploit resources. The Static model is in good agreement with the logistic curve, further explaining why the projections are similar.

In contrast, the Gompertz curve gives a very different outlook with a much lower depletion of the recoverable resources. This does not necessarily make it unrealistic as a model and Gompertz curves have been found to have good agreement with historical production patterns (Moore, 1966; Fitzpatrick et al., 1973, Höök and Aleklett, 2009b). The low depletion rate is likely something that must be forced by political decisions or regulations.
as we see it. Unless the current coal production regulations change significantly in Australia, such as by the introduction of production quotas or political limits on development, we can rule out the Gompertz projection as inconsistent with current socioeconomic conditions and likely developments. Consequently, it is reasonable to assume that the other three models more adequately project coal production.

For simple curve fitting models, it should be specifically noted that the shape of the curve will have a major impact on the outcome. As a result, it is vital to justify the chosen curve rigorously so it agrees with historical and expected future outcomes. The agreement between the logistic curve model and the Static/Dynamic models indicates that the logistic curve can be used as a crude approximation for real world mineral exploitation. This may also serve as an explanation why simple curve fits, constrained by good estimates of the recoverable resources, have been rather successful in projecting production trends. This should be more comprehensively studied, but this is work for another study.

Holistic treatment of future production quickly becomes a complex situation, as many elements affect future coal mining. The models used here aim to provide insight into the general long-term development, while perturbations caused by sudden and unforeseen near-term economic or political changes cannot be predicted. Therefore, this long-term life-cycle projections should not be used as a substitute for meticulous economic studies to forecast perturbations in coal production over the next few years or decades (Milici and Campbell, 1997).

5 Influencing factors
The model projections highlight the future production potential for Australian coal. They show that production is likely to increase to 1.0-3.3 Gt/y around 2120, which is comparable to current output from the world’s largest producer, China, of about 2.9 Gt/y. None of the models used in this study include the effect of external influences on production. Some of these possible influences are discussed below:

5.1 Export capacity
There are many coal export terminals in Australia including Newcastle and Wollongong, in NSW, and Brisbane, Gladstone, Hay Point, Dalrymple Bay and Abbott Point in Queensland. The coal export terminal at Newcastle, NSW, is the largest facility of its type in the world. The present capacity is about 113 Mt/y, and is undergoing rapid expansion to reach ~180 Mt/y by 2013 (NCIG, 2010). By 2009, Australia’s total export capacity had reached ~330 Mt/y (ABARE, 2010). Based on reported coal resources, the various coal regions of Australia could readily supply this quantity of coal for export (which excludes all coals consumed locally of ~135 Mt/y). By analogy with iron ore exports, which reached ~360 Mt/y in 2009 almost entirely from the Pilbara region of Western Australia alone, Australia could even boost coal exports further subject to local port and rail corridor factors in each coal province.

5.2 Climate change
At present, Australia has no national legislation in place to reduce greenhouse gas emissions—although debate over such proposals has generated intense political controversy in recent years. The Australian Government proposed the Carbon Pollution Reduction Scheme (CPRS) as an emissions trading scheme in December 2008, though it failed to pass through the both houses of the Australian Parliament in 2009 and was subsequently delayed in early 2010.

In 2008, Australia’s official greenhouse gas (GHG) emissions inventory was 576 Mt CO₂-e/y, of which stationary energy was responsible for 53.6% (DCCEE, 2010a). Australia’s
electricity grid is predominantly generated by coal-fired power stations. By convention in carbon accounting, GHG emissions are counted in the country from which they originate. Accordingly, Australia’s coal exports count in their destination and not for Australia. In 2009, Australia exported some 274.5 Mt of coal, and based on standard GHG emissions factors (see DCC, 2010b), would lead to cumulative GHG emissions of about 693 Mt CO$_2$e/y. This is more than Australia’s total emissions for 2008, highlighting Australia’s vulnerability to global positioning around reducing GHG emissions to address climate change risks.

There are various technology options available to significantly reduce CO$_2$e emissions from coal-fired power stations. One option is to capture the CO$_2$e emissions and pump them underground. Another option is to develop more efficient forms ways to generate electricity from coal production such as Integrated Gasification Combined Cycle (IGCC). The issues of climate change are likely to make it difficult to remain confident that Australia could reach the projected peaks in coal production; unless clean coal technology is researched and implemented.

5.3 Overburden management
There has been a relatively steady growth in the overburden-to-coal ratio in open cut mining since the 1950s, reaching an average of ~6 m$^3$/t by 2009. If this trend is linearly extrapolated to the approximate peak year of 2100 using all data from Figure 7 ($R^2$ of 71.1%), an overburden-to-coal ratio of ~13.7 is obtained. Assuming peak production ranges from 1 to 3 Gt/y and that 80% is still derived by open cut mining, this leads to peak overburden of 11 to 41 Gm$^3$/y—an order of magnitude increase and representing faster growth than coal production. Whether or not this leads to a long-term decline in open-cut coal mining and a resurgence in underground extraction techniques, or possibly a shift to coal seam gas extraction, is difficult to project. Assuming mining continues to be dominated by open-cut, then the increasing overburden ratio would cause the net energy produced to decrease as more waste material is handled. These challenges require more careful research into the efficient extraction of coal resources.

5.4 Environmental and social impacts
Coal mining in Australia has many environmental and social issues. Typical environmental issues include: competitive land use for open cut mining or for keeping the land for farming, (e.g. Bowen Basin, see Miles and Kinnear, 2008; Murray-Darling Basin, see ECARC, 2009). Coal mining can also impact on water quality and flows and can cause damage to aquifers, contaminate groundwater and cause land subsidence resulting in rivers to flow underwater or not at all (e.g. Diega Creek; Cronshaw, 2010; NSW GDP, 2005). Some social issues include coal dust, for instance Camberwell in the Hunter Valley has dust levels exceeding the 50 µg/m$^3$ limit between 10 and 30 days a year (Environ Australia, 2009). Noise pollution is another issue both from mining operations (blasting, etc.) and from the transport of coal trucks and trains through towns and villages. These issues are likely to become more significant and challenging in Australia as more mines are brought online and it is plausible that these issues may reduce the amount of coal recovered in Australia.

5.5 Export markets
Coal exports in 2009 were valued at $39.6 billion, making it Australia’s biggest export commodity. Much of the exported coal is used in coal-fired power stations or in steel production. Many nations are now moving towards renewable energy options and away from fossil fuels, in order to ensure national energy security. This trend can only reduce the overseas demand for Australian coal. Such a trend would likely see coal prices fall resulting
in a reduction in coal exports. For this reason the projection of Australian coal production could be too optimistic if these events were to occur.

6. Conclusions
Coal is an important commodity in Australia as coal is the biggest export by value. Australia is also the largest exporter of coal in the world. For these reasons coal production in Australia were projected using two different URR estimates, Standard and High. The URR for Australia was estimated to be 317 Gt for the standard case and a high case of 367 Gt. The high case represents an upper bound on the URR for Australia. Logistic, Gompertz, Static and Dynamic supply and demand modeling techniques were applied using the Standard and High URR estimates. There was considerable agreement between the Logistic, Static and Dynamic supply and demand models, for all projections except Victorian lignite. Gompertz curves were found to produce vastly different projections compared to the other three predictions. All projections indicate a peak in 2100±25 at a maximum production rate of 1-3.3 Gt/y. However, when excluding the Gompertz projections the projections indicate a peak in 2119±6 at 1.9-3.3 Gt/y. Comparisons between the different models indicates that the Logistic, Static and Dynamic models more likely to produce accurate projections than the Gompertz curve. A variety of issues including climate change, overburden issues, environmental, social and government policy issues are not accounted for in the modeling approach and may result in the projections over estimating the long term coal production.

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Appendix

Table A1. Projected Peak Year estimates

<table>
<thead>
<tr>
<th></th>
<th>Static Low Year</th>
<th>Static High Year</th>
<th>Dynamic Low Year</th>
<th>Dynamic High Year</th>
<th>Logistic Low Year</th>
<th>Logistic High Year</th>
<th>Gompertz Low Year</th>
<th>Gompertz High Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mt/yr</td>
<td>Mt/yr</td>
<td>Mt/yr</td>
<td>Mt/yr</td>
<td>Mt/yr</td>
<td>Mt/yr</td>
<td>Mt/yr</td>
<td>Mt/yr</td>
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<tr>
<td>NSW Bit.</td>
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<td>569</td>
<td>2078</td>
<td>750</td>
<td>2076</td>
<td>572</td>
<td>2083</td>
<td>754</td>
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<td>2057</td>
<td>644</td>
<td>2052</td>
<td>490</td>
<td>2057</td>
<td>644</td>
</tr>
<tr>
<td>SA Sub-bit</td>
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<td>168</td>
<td>2155</td>
<td>220</td>
<td>2137</td>
<td>367</td>
<td>2144</td>
<td>510</td>
</tr>
<tr>
<td>Vic. Lignite</td>
<td>2139</td>
<td>1505</td>
<td>2141</td>
<td>1591</td>
<td>2127</td>
<td>2240</td>
<td>2127</td>
<td>2421</td>
</tr>
<tr>
<td>Rest</td>
<td>2041</td>
<td>196</td>
<td>2046</td>
<td>250</td>
<td>2041</td>
<td>196</td>
<td>2046</td>
<td>249</td>
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<tr>
<td>Aus.</td>
<td>2125</td>
<td>1890</td>
<td>2119</td>
<td>2138</td>
<td>2125</td>
<td>2912</td>
<td>2125</td>
<td>3341</td>
</tr>
</tbody>
</table>

The projections have been compared to the production curves of various countries over a normalised plot, shown in Figure A1. In the discussion the authors have ignored the projection of the Gompertz curve due to its coal production being significantly different to the other three methods. Although the Gompertz curves increase to the peak production in a similar fashion to Belgium, the rate of decline in the Gompertz curve is considerably slower than other nations that have past peak production. The Dynamic and Logistic projections, however, do match well with various profiles of countries. Both the Dynamic and Logistic projections closely match Belgium up to peak production and the Logistic curve declines in a similar way to the UK production declines. Although the dynamic curve remains at a high production level slightly longer than historic countries do, when it begins to decline its profile is similar to that of countries such as France, Belgium, Poland and Germany. The Static projection does not match the production profiles due to the black and brown coal production peaking at different time intervals (~2060 for black) and (2150 for brown). However, both the black and brown production curves have a similar shape to the Logistic curve and therefore likely to be a valid projection. Whilst making long term projections are always difficult the production profiles of the Dynamic and Logistic models do match reasonably well with historic production profiles (Figure A2).
Figure A1. Model projections compared to historic countries. Projections and statistics are normalised so that the peak production reached is 1 in year 0.

Figure A2. Logistic and Dynamic projections compared to historic countries. Projections and statistics are normalised so that the peak production reached is 1 in year 0.