Coal reserves in a carbon constrained future

Author: Paul Baruya

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IEA Clean Coal Centre
Park House
14 Northfields
London SW18 1DD
United Kingdom

Telephone: +44(0)20 8877 6280

www.iea-coal.org

Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International EnergyAgency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, Canada, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

Energy reserves are quite well understood and have been recorded for many decades with varying degrees of accuracy. It appears that global reserves of coal could last in excess of 100 years, but this cannot be stated with absolute confidence. The life of coal reserves could face depletion in some parts of the world where production rates are high. Elsewhere, carbon constraining legislation could depress demand, which could greatly extend the life of world coal reserves. Either way, the concept of supply and demand peaking will impact all coal producing and using countries eventually, but timing and extent of these peaks will differ. This report revisits analyses on fossil fuel depletion, and how various approaches to peak analysis and projections can impact the understanding of coal reserves.

Acronyms and abbreviations

°C	degrees centigrade ([°C x 1.8]+32 = Fahrenheit)
ADB	Asian Development Bank
AfDB	African Development Bank
A-USC	advanced ultra-supercritical
ASTM	American Society for Testing and Materials
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) or Federal Institute for Geosciences and Natural Resources
billion m^3	billion cubic metres of natural gas
BOF	basic oxygen furnace
BRIC	Brazil, Russia, India, and China
CAPP	Central Appalachia
CBM	coal bed methane
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CDM	clean development mechanism
CHP	combined heat and power (cogeneration)
CMM	coal mine methane
CSAPR	Cross-state Air Pollution Rule
CTL	coal-to-liquids
CV	calorific value (heating value)
EAF	electric arc furnace
EIA	Energy Information Administration (US Department of Energy)
ESP	electrostatic precipitator
EU	European Union
FGD	flue gas desulphurisation
FIT	feed-in tariffs
FOB	free on board
ft	feet (= 0.3048 metres)
GJ	gigajoules
Gt	gigatonne = 1000 million tonnes
Gtce	gigatonnes of coal equivalent (= 0.697 Mtoe)
GWe	gigawatt (electrical output)
HELE	high efficiency and low emissions
IEA	International Energy Agency (Paris)
IEA WEO	IEA World Energy Outlook
IEACCC	IEA Clean Coal Centre (London)
IGCC	integrated gasification in combined cycle
IPCC	Intergovernmental Panel on Climate Change
JORC	Joint Ore and Resource Committee
kcal/kg	kilocalorie per kg
km	kilometres
lbs/MBtu	pounds of sulphur per million Btu
m	metric metre
MPa	mega Pascal
MATS	Mercury and Air Toxic Standards (US)
Mt	million metric tonnes
Mtoe	million tonnes of oil equivalent (= 1.434 Mtce)

MWe	megawatt (electrical)
NSW	New South Wales
OECD	Organisation for Economic Cooperation and Development
PCI	pulverised coal injection
QLD	Queensland
R/P	reserves to production ratio
SO_2 (SO_x)	sulphur dioxide (sulphur oxides)
SRES	Special Report on Emission Scenarios
st	short tonne (approx 0.9 metric tonnes)
t	metric tonnes (1.1023 short tons or 0.984 long tons)
tcf	trillion cubic feet
TFC	total final consumption
Tt	terra tonnes (1000 Gt)
TWh	terrawatt hour (1000 GWh)
UCG	underground coal gasification
UNFC	United Nations Framework Classification
URR	ultimate recoverable reserves
USC	ultra-supercritical
USGS	US Geological Survey
WCA	World Coal Association
WEC	World Energy Council
WEO	World Energy Outlook (IEA, Paris)

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1 Introduction

In 2009, IEA CCC published a report entitled *Future coal supply prospects* to examine the world's coal reserves data, which discussed the various definitions of reserves and the issues that affect the accuracy of the published statistics (Minchener, 2009). Some of the conclusions highlighted concerns for the depletion of coal reserves in areas of high or rapidly growing production, not least countries like China and Indonesia. Between 2001 and 2011, the global demand for coal increased by as much as all the other sources of primary energy combined (in energy terms). With such a massive rise in demand, and barely any change in the reported level of global reserves, it seemed as though less coal is available in the world than first anticipated. Other research suggested that the reserves of cheap coal have been used, and only higher cost coal will be available in the future.

All of these conclusions are logical, and deserve more research and effort to establish a more accurate assessment of the world's reserves, and also the prospects of shortening the life of current reserves given the rise in demand for coal in recent years.

Generally, the coal industry seems optimistic about reserves, but localised depletion of economically recoverable reserves is a concern, although this can be alleviated by increasing imports. However, interest in peak coal (akin to peak oil) has grown in importance where forecasting demand and production over the long term has implications for rising greenhouse gas emissions. Such forecasts are essential to climate change scenarios, which are also central to regional and global energy policies. However, analyses on coal reserve depletion often ignore the wide variation in coal qualities and rank. Statistical analysis of coal reserves, such as peak coal, often treats coal as a homogenous commodity for simplicity. Peak production may therefore occur for one type of coal, but not for another.

As a result, this report aims build on the previous work done on coal reserves, and attempt to draw out further detail from the existing plethora of reserves data. The added detail may help to better understand how much coal exists for each major end user market, namely:

- high rank steam coal for heat raising for power generation and industrial boilers;
- high rank coking coal for coke production and steel manufacture;
- low rank steam coal for heat raising for power generation and industrial boilers.

For all types of coal, future policy scenarios may illustrate a sweeping change to the way the world uses coal, either by replacing it with alternative fuels or introducing technologies to reduce coal use and hence emissions (combustion and process).

Replacing old plants with high efficiency technologies will logically reduce the future demand on global coal reserves, while the fitting of carbon capture processes may see either no change or an increase in coal demand (while eliminating 90% of the greenhouse gases from such plants). However in the absence of such lower carbon scenarios, coal demand could continue to increase, and from (CO_2) unabated coal-fired power stations.

This report intends to see what further information can be gleaned from past research and use available data from the mining industry to get a clearer picture of coal reserves and resources, the implications of disaggregating coal reserves based on their qualities, and the link with future demand scenarios. The report attempts to cover the following areas:

- a refresher on the various terms and conventions that define reserves and resources;
- understand the different broad coal types, with emphasis on understanding global coking coal reserves and the share they take of (often quoted) hard coal reserves;
- review the concept of peak coal production, and determine when peak coal might occur;
- in conjunction with the previous point, determine peak demand as a result of environmental policies;
- consider demand scenarios for hard and lignite steam coal for power generation, where demand destruction through higher efficiency technologies could reduce coal consumption;
- consider the possible effects of fitting *carbon capture and storage* (CCS) to new power plants;
- consider the impact on coking reserves due to future trends in coking coal use in steel production;
- extending coal reserves through better mining practices, particularly from room and pillar mining;
- the potential for unconventional energy reserves associated with coal seams, such as coal bed methane and underground coal gasification.

2 Defining resources and reserves

The terms reserves and resources are often mistaken for each other, making the world's availability of fossil fuels difficult to understand for the casual reader. Minchener (2009) explained the general definitions applied to these based on the concept of the certainty of the fossil fuel 'residing' in the ground, which more or less determines its existence in a geological structure.

Whether the coal can be extracted in commercial quantities using current technology then determines its techno-economic feasibility. The ease of access to the coal, the depth of the reserve, the continuity of any single seam affected by geological disturbance, and the location of the deposits all influence the potential to economically mine coal.

Coal can be mined at depths of 2 km, but the deeper mines are hazardous and dangerous workplaces, as well as operating at high temperatures. As a comparison, the deepest mine is the TauTona gold mine in South Africa at 3.9 km, where temperatures can reach 50°C. Deep coal reserves can be mined easily given the right geological conditions, either by longwall or room and pillar methods using subterranean shearing and transportation systems designed for underground workings (WCA, 2013). Only the coal is extracted from these deposits, surrounding rock blasting and tunnelling is kept to a safe minimum to ensure ease of access and safety for the workforce.

Even easier to mine are deposits closer to the surface, but theses often require an initial stage of soil and rock removal, otherwise known as overburden. Terrestrial trucks and digging equipment are used for the coal extraction, and this method is commonly known as opencast. Typically blasting, dragline (for overburden removal), and hydraulic/electric shovels are used to mine the coal. Deep mines tend to use conveyor belts for transporting coals over longer distances throughout the mine, while opencast mines use trucks.

Even opencast mining, with its simpler mining methods, can prove costly if the geology is complex. Tight folding and faulting can lead to steeply dipping seams, making access to such seams almost like mining on a steep staircase with the use of benches that are carved or compacted out of the surrounding overburden immediately adjacent to the coal face. If the deposition of the original material was sporadic or there was a massive amount of movement over time, the coal seams can be thin or heavily fragmented with coal sometimes occurring in thicknesses of just centimetres.

2.1 Understanding the differences between resources and reserves

Here the confusion can be compounded when discussing where coal is found. Academic papers and commercial literature can refer to coal formations, coalfields, coal blocks, coal seams, coal structures, and so on; when found and measured, coal structures will then be classified as a reserve or a resource. The reserve can refer to a local measure of coal on a fixed area of land allocated to a mining company intent on extracting the coal. A reserve in the context of this report will also refer to the total amount of coal that will exist within a country's boundary that is known to exist in sufficient quantity and accessible using current commercially available mining methods.

Error! Reference source not found. illustrates the simple concept of the reserve and resource and, not too unlike the *Joint Ore Reserves Committee* (JORC), offers a clearer explanation of the existence of coal in the ground and the degree of certainty or uncertainty that surrounds the quantification of that coal. Coil and others (2012) provides one of the most concise yet detailed explanations of reserves and resources which are discussed in the next section.

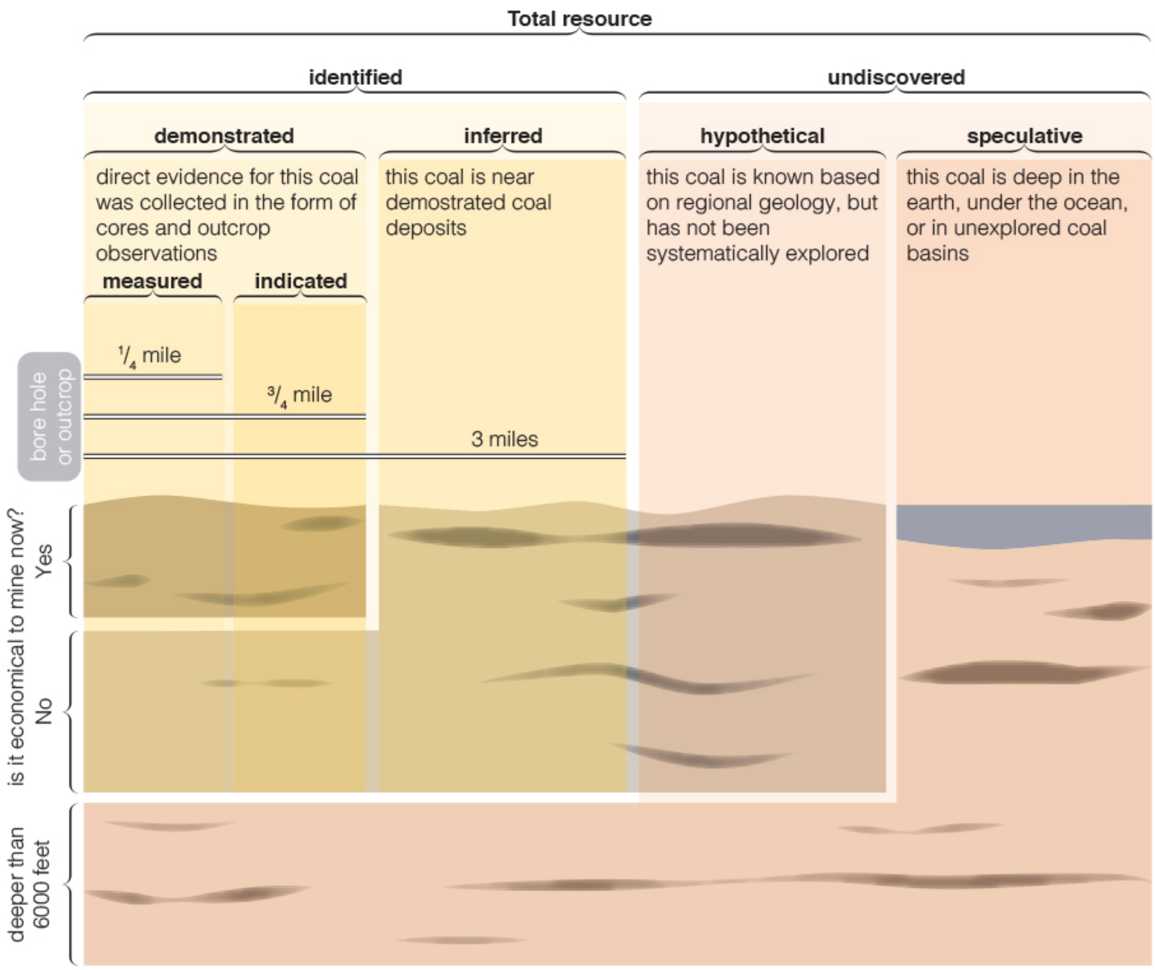

Figure 1 – Resources to reserves (Coil and others, 2012)

2.2 Resources

The term resource is far broader than reserve, and encompassing the amount of coal in the ground with varying levels of certainty, sometimes based on the best judgements on geology by appropriate experts, but without any firm evidence from drilling or outcrops. The various terms are described as follows:

- measured – the amount of coal based on closely spaced, direct measurements such as visual confirmation on the surface, boreholes, or actual mines. Often includes information on coal rank and quality of coal as well. The specifications for this spacing and quality of measurements vary by country and between US states;

- indicated – the amount of coal based on a combination of direct measurements and reasonable geologic assumptions made with high confidence;
- demonstrated – a combination of measured and indicated resource as described above (therefore can be broadly considered as Measured + Indicated);
- inferred – a resource based on the assumed continuity of coal beds, both downwards into the earth and across the landscape from points of direct measurement. In the US a limit of 1830 m (6000 ft) deep is placed on inferred coal beds. For reference, strip mining is limited to extracting coal up to a few hundred feet and underground mining is currently limited to around 1070 m (3500 ft);
- identified – This term refers to the combination of inferred and demonstrated resources as described above;
- hypothetical – this term refers to resources that are present in known but incompletely explored or unmapped coal beds, also limited to 1830 m (6000 ft) of depth and in the US, more than 4.8 km (3 miles) from a measurement point. Additional exploration and measurements in a given area would move hypothetical coal to identified coal as appropriate;
- speculative – this term refers to coal outside all of the above categories and is rarely used in discussions of coal resources. Speculative resource would include coal deeper than 1830 m (6000 ft) or present on the continental shelf;
- total resource – this term includes all of the categories above. Sometimes also called resource base.

2.3 Reserves (resources with more certainty)

Coil and others (2012) explain how a *reserve base* refers to coal which is both *demonstrated* and is deemed to be economically and technologically mineable at any given time. As a generality, reserves occur with more certainty, and with better potential for mining than resources. The coal has been measured or surveyed geologically with a high degree of certainty of its existence and volume. In practice this often means only the shallower, thicker coal beds. It also varies by coal type, for example a seam of lower rank coal has to be thicker than a seam of high-quality coal to be counted in the reserve base, because it is less economically feasible to extract the lower rank coal. Therefore some of the demonstrated coal resource is counted as the reserve base, and some is considered uneconomic. As described below, the definition of reserve base can also vary significantly by country.

The most useful measure is the *recoverable reserve*. This term refers to the amount of the reserve base that might reasonably be expected to be actually mined and used. The *recoverability* factor of coal depends on a number of factors such as the method of coal mining used, but in general is considered to be about 50% of the reserve base. Sometimes also called *proved reserve* or *proven reserve*.

2.4 Unifying the definition of coal reserves/resources

Because some 80–85% of the coal that is mined globally is used inside the country of origin, different classification systems have been developed over time in the major coal-producing countries. Smaller coal producing countries often adopt the conventions used by others.

Different systems were developed in Australia, China, Germany, Russia, the UK and the USA (*see also* Section 2.7). Similarly, many coal experts developed an in-depth knowledge and understanding of their own coals and of their geological settings, but had relatively limited knowledge of the coals which occurred in other places (Couch, 2006).

The various definitions of coal used around the world all have some common basis from which the UN has attempted to unify the various approaches. The *United Nations Framework Classification* (UNFC) for Energy and Mineral Resources is a universally applicable scheme for classifying and evaluating reserves and resources. The system uses a three digit code indicating the essential characteristics of extractable energy commodities (and minerals), these are based on:

- economic and commercial viability (E);
- field project status and feasibility (F);
- geological knowledge (G).

The three digit codes refer to the degree of certainty in the various criteria shown in Figure 2 based on the grid letters E, F, and G.

1 Mineral reserves including:
   - proved mineral reserves: code 111
   - probable mineral reserves: codes 121 + 122

2 Mineral Resources (Additional or Remaining Resources) including:
   - feasibility mineral resources: code 211
   - pre-feasibility mineral resources: codes 221+222
   - measured mineral resources: code 331
   - indicated mineral resources: code 332
   - inferred mineral resources: code 333
   - reconnaissance mineral resources: code 334

Proved mineral reserves are the quantities defined by code 111.

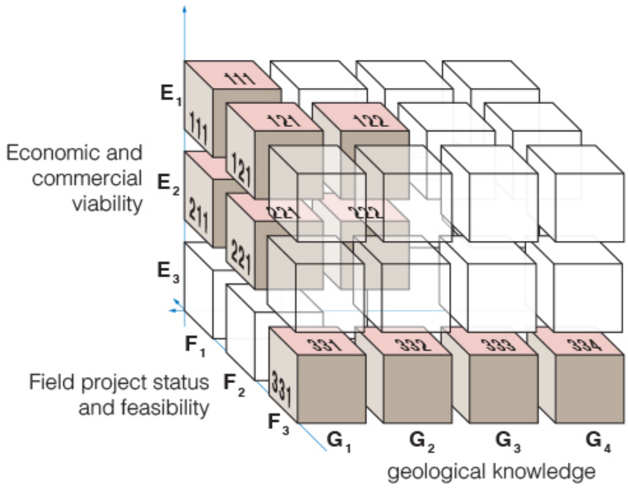

Figure 2 – Coal resource and reserve classification (UNFC, 2009)

Using the UN, this method defines a proved mineral reserve as the economically mineable part of a recoverable quantity assessed by a feasibility study or actual mining activity usually in areas where detailed exploration (measured recoverable quantity).

The 111 code provides coal reserves assessments to a high degree of confidence. It includes diluting materials and allowances for losses which may occur when material is mined and milled. Further assessments are made for the marketing of the coal products, environmental impact assessments and all the associated administration and legal requirements needed to license a mining facility and produce coal. The code 111 therefore applies to the reserves where mining is almost imminent and planned by a mine operator. The code system is explained in detail in the UN document published in 2009 and available at the following website: http://www.unece.org/fileadmin/DAM/ie/se/pdfs/UNFC/UNFCemr.pdf and http://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/unfc2009/UNFC2009_ES39_e.pdf

According to the UN system, the attempt to unify reserves assessment was done to support the rational use of resources, improve efficiency management and enhance the security of energy supplies and of the associated financial resources. The classification unifies petroleum resource and uranium resource classification.

In Australia, the JORC Code defines standards needed to report a mineral deposit as an economic resource. JORC code is statutory for all companies listed on the *Australian stock exchange* (ASX) of listed companies but is also a benchmark for many emerging economies estimating coal reserves for the purposes of coal exports.

The US Geological Survey carried out a comprehensive global survey of coal qualities based on 1580 samples from 57 countries between the period 1995 and 2006. A database was created of ultimate analysis of coal samples, and the testing was carried out by a variety of collaborators around the world. Some variation was noted in the quality of testing but the overall results do not necessarily define a single set of definitions for coal, but provides a useful basis for quality comparisons. What the database does not do is define reserves; rather it is s single source for coal qualities for specific samples from specific coalfields from around the world.

2.5 Determining reserves with higher certainty

Unlike the more general explanation given by most analysts, a more specific example of determining reserves is given by Thomas (2002) to better explain the ground level estimation that determines the extent of coal required in any structure to be a reserve or resource for the intention of developing as a mine operation (*see also* 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 a 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.
- *Measured resources* have no more than 1 km between data points and trends can be extrapolated up to 0.5 km. the level of confidence of a measured resource should be high enough to determine detailed planning.

Reserve estimates are calculated from these plans and could include recovery factors depending on the mining methods that are chosen. Gaining accurate figures for mineable coal reserves is a common problem as incomplete mining methods (for example room and pillar mining) and thin seams can make mining impractical, or the` coal is of sufficiently low quality (rank, sulphur content, ash etc), land use constraints (national parks and local communities) and so on. While these issues are important, a great deal more research is needed in this area, but are mentioned throughout this report where applicable.

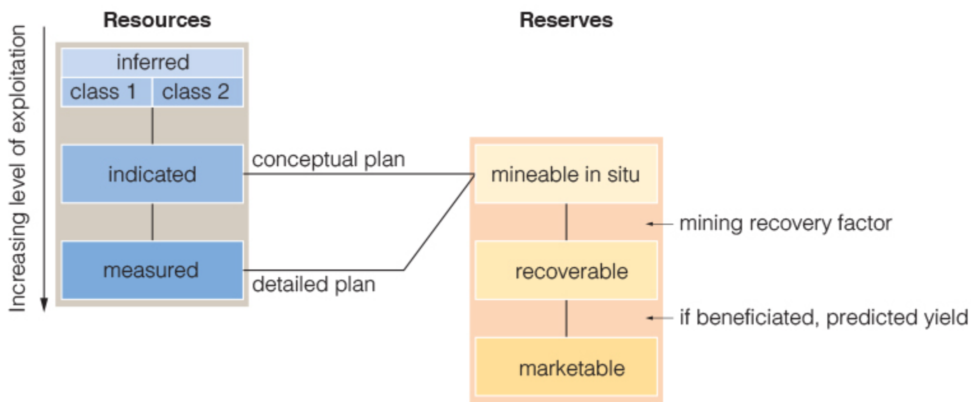

Figure 3 – Australian coal resource classification (Thomas, 2002)

Finding reserves and refining those assessments to reserves is a process of surveying and measurements and eventually mine development. Mine companies either employ contractors or use in-house expertise to carry out surface geological studies, such as mapping, geophysical mapping, environmental studies, and drilling. The various results are analysed using computer modelling to build a picture of the coal location and estimated amount in place. This would normally determine the *resource*. Within this, the depth, geology, and local topography will determine the access to and design of the mine for a particular location, then turning an amorphous mass of coal below ground into a discrete mining block for commercial exploitation. Unless the coal extraction method is a longwall system, with its defined limits of operation based on the shearing equipment, coal is not always extracted in a geometric block. The coal extraction tends to start geometrically and then fan out safely to the marginal coal where possible. Assessing this total feasible extraction provides a mine company with its reserve. The mine company will then continue to analyse planned extraction rates and productivity based on the local geology and manpower, but for this report, it is the level of total reserves that is of most interest.

2.6 Assessment of total coal reserves

Table 1 lists the world's known coal reserves disaggregated into hard steam coal, coking coal and lignite (steam) coal. The data are adapted from two key sources, the *German Federal Institute for Geosciences and Natural Resources* (BGR) and the *World Energy Council* (WEC) which list data for anthracite, bituminous, subbituminous and lignite. Steam coals can be any rank, but only higher rank coals with particular coking properties can be classed as coking coals. Further discussion on coal rank and qualities is found in Chapter 9.

While at the mine level, detailed surveys, computer modelling, and laboratory analysis means accurate volumes and qualities (using ultimate or proximate analysis) can be calculated. At a national level, determining reserves to the same level of accuracy is not as straightforward.

However, getting a better understanding of the world's reserves is essential. The bulk of the future demand for coal will be for hard steam coals, yet much of the new development in mining capacity around the world (especially for export coal in frontier countries such as Mongolia and Mozambique) is geared towards coking coal production. Although steam coal is often associated with these new operations, they are often secondary products. So the question arises, are there enough reserves of the right coal to meet future demand. A shortage of one type of coal will mean certain markets will see an increase in coal costs. Conversely, an abundance will lower the costs of certain coal products.

In Table 1, coking reserves are estimated from a wide range of published materials from company data and associations, which is then subtracted from the *hard* coal reserves to derive *hard steam* coal reserves. Coking and metallurgical coals are discussed in more detail in Chapter 9, but for now they provide the context for determining hard steam coal data. The purpose of defining steam coal is to understand the impact of this particular sector of the coal market (power generation) on the world's *hard* coal reserves. Other markets such as coking coal and lignite will have their own impacts on their respective reserves base of that particular coal type. Chapter 9 examines the impact that future coking coal and lignite could have on reserves, but a bulk of this report focuses on the largest coal market, hard steam coal.

Many countries have already identified their coal reserves in accordance to steam and coking characteristics (Russia, USA, Canada, OECD Europe), but there is currently no single information source that collates the global reserve for each country. This report attempts to do this, with the view that a great deal more research will be required to refine and improve the data.

According to Parijat (2007), world coking coal reserves amounted to 430 Gt of proven reserves, although Table 1 shows a more conservative 200.6 Gt. This is an important number, as much of the remaining non-coking reserves will be steam coal (comprising anthracite, bituminous, subbituminous and lignite coals). For this reason, this report assumes that the quantity of coal that is proven to be of coking quality will determine the reserve of steam coal that is suitable for power generation. At best, only conservative estimates for coking and steam coal reserves can be obtained (*see* Figure 4 and Table 1). Some countries are likely to be underestimated while a few will be overestimated.

For example, some Southern and Central African countries have yet to be fully explored, yet are known to have coal bearing strata, and so the reserves for such countries can only refer to those found in specific coal blocks that are currently under development, even though coal is found widely across the country.

Table 1 shows Indonesia having a reserve of 21 Gt, but more recent data suggest that reserves could range 5.5 Gt to 28 Gt. The lowest figure of 5.5 Gt is extremely close to the 4.3 Gt of reported mineable reserves belonging to the top five producers in Indonesia alone (Baruya, 2006; BP, 2013; MEMR, 2013). As such, it is unlikely just a handful of coal operations in Eastern and Southern Kalimantan have access 80% of the nation's coal reserves. Other parts of Kalimantan and South Sumatra could yield a great deal more coal, and so reserves in excess of 20 Gt could be more realistic.

Mongolian reserve statistics show total reserves estimated at 20 Gt proven and 150 Gt of resources found, but only 10 Gt are shown in Table 1 as recoverable. Similar to Indonesia, Mongolia holds potential that has not yet been realised.

This report describes throughout how reserves estimation is at best based on measurement and survey, but once the mine is operating and detailed production designs are in place, losses can trim the reserve figures further. A great deal more research needs to be carried out on coking coal reserves in order to provide a more accurate set of data as shown here, but for the purposes of this report, a reasonable indication is sufficient.

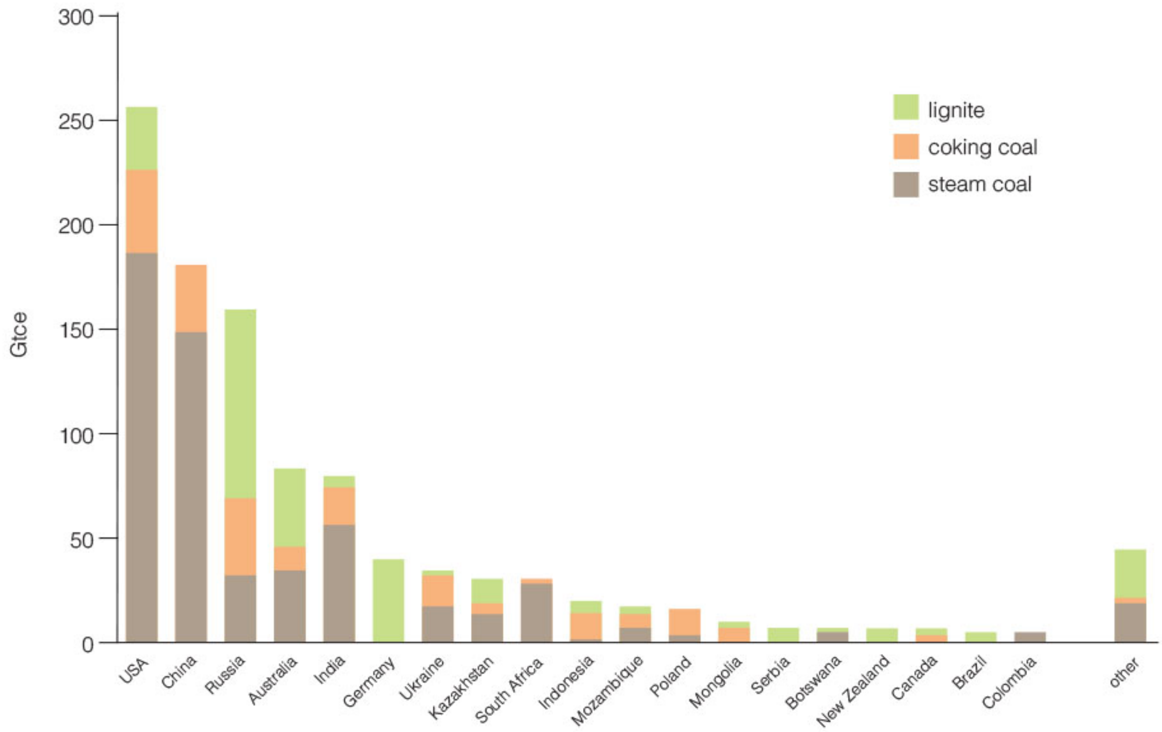

Figure 4 – Global coal reserves split by coal type (BGR, 2011; WEC, 2010; author's estimates)

Table 1 – Global coal reserves split by coal type, Mt (BGR, 2011; WEC, 2010; and author's estimates)

Country	Hard coal			Total	Per cent of global reserves
	Steam coal	Coking coal	Lignite		
USA	186.8	39.0	30.8	256.6	24.6
China	148.7	31.9		180.6	17.3
Russia	32.8	35.9	91.4	160.0	15.3
Australia	34.3	11.6	37.2	83.1	8.0
India	56.7	17.9	4.9	79.5	7.6
Germany			40.5	40.5	3.9
Ukraine	18.4	13.6	2.3	34.4	3.3
Kazakhstan	13.8	5.0	12.1	30.9	3.0
South Africa	28.4	1.8		30.2	2.9
Indonesia	2.3	12.6	6.1	21.0	2.0
Poland	7.3	5.8	4.6	17.6	1.7
Mozambique	4.0	12.0		16.0	1.5
Mongolia		8.0	2.0	10.0	1.0
Serbia			7.1	7.1	0.7
Botswana	7.0	0.1		7.1	0.7
New Zealand	0.2		6.8	7.1	0.7
Canada	0.9	3.5	2.2	6.6	0.6
Brazil			5.0	5.0	0.5
Colombia	4.9			4.9	0.5
Pakistan	2.1		2.9	4.9	0.5
France	4.4		0.2	4.6	0.4
Greece			2.9	2.9	0.3
Hungary			2.6	2.6	0.3
Belgium	2.6			2.6	0.2
Bosnia			2.4	2.4	0.2
Czech Republic			2.3	2.3	0.2
Turkey	0.5		1.8	2.3	0.2
Bulgaria			2.2	2.2	0.2
Zimbabwe		2.0		2.0	0.2
Uzbekistan	1.4			1.4	0.1
Mexico	0.9		0.4	1.2	0.1
Iran	1.2			1.2	0.1
Chile	1.2			1.2	0.1
Korean Republic	0.3		0.8	1.1	0.1
Thailand			1.1	1.1	0.1
Slovakia			0.9	0.9	0.1
Venezuela	0.9			0.9	0.1
Spain	0.5		0.3	0.8	0.1
Kyrgyzstan			0.8	0.8	0.1
Netherlands	0.6			0.6	0.1
Albania			0.5	0.5	0.1
Argentina	0.5			0.5	0.05
Laos			0.5	0.5	0.05
UK	0.4			0.4	0.04
Japan	0.3			0.3	0.03
Philippines	0.2		0.1	0.3	0.03
Bangladesh	0.3			0.3	0.03
Romania			0.3	0.3	0.03
Vietnam	0.2			0.2	0.02
Swaziland	0.2			0.2	0.02
Taiwan	0.2			0.2	0.02
Tanzania	0.2			0.2	0.02
Denmark			0.1	0.1	0.01
Niger	0.1			0.1	0.01
Peru	0.1			0.1	0.01
Zaire	0.1			0.1	0.01
Congo	0.1			0.1	0.01
Afghanistan	0.1			0.1	0.01
Algeria	0.1			0.1	0.01
Global economy. rec reserves	566.1	200.6	276.0	1042.8	

Figure 4 and Table 1 show the dominance of hard steam coal in the global reserve base. Perhaps this is why coal is treated as a homogeneous fuel in academic papers. Steam coal exists in the form of both hard and lignite, both of which are widely distributed. Coking quality reserves are also widely distributed but much of it seems to be found in some BRIC countries (Brazil, Russia, India, and China) and emerging coal producers like Mozambique and Mongolia. It is worth reiterating that this distribution of coking coal is only based on limited data from existing mine operations and developments where the data are available.

The USA, China, and India appear to have the largest steam coal reserves, while Russia has an immense quantity of lignite. Australia has almost as much lignite as it has all other types of coal. It is worth highlighting that these reserves have been assessed on the basis of tonnes of coal equivalent so the lower heating values of some coals have been accounted for. Germany also has a large quantity of lignite; coking coal is found mainly in the USA and Russia.

Most of Russia's coking reserves are concentrated in the Kuznetz Basin (80%) located deep inland in the southern central part of Russia; the rest is found in the South Yakut Basin in the far east of the country. In the USA, coking coal is found all across the USA, in the Appalachian, Illinois, and Central US basins, as well as elsewhere in North America in the western provinces of Canada.

Coking coal mining is driven primarily by steel markets and demand for coke, a high carbon content coal that has had most of the volatiles and organic matter driven off during a coking process. These are high quality products with low ash contents. Global steel markets usually rely on imported coking coals due to the location of these specific coalfields being some distance from the markets for coking coal.

Lignite coals are mined very close to the power station or market. Without upgrading or pre-drying, lignite can contain more than 50% moisture, so transporting lignite products is limited to shorter distances.

Across all these reserves is the potential for coal seams to be a store for methane associated with the coal, also known as *coal bed methane* (CBM) and is discussed in detail by Sloss (2005). Other aspects of coal reserves and resources include gasification in situ of the coal seam. Some coals have the propensity to self-combust but under controlled conditions, this underground process of gasifying coal can yield useful hydrogen and a concentrated stream of CO_2 for storage, *underground coal gasification* (UCG) is discussed in detail by Couch (2009). UCG could open up a considerable resource that is otherwise unobtainable by conventional mining methods. Both CBM and UCG are discussed later in this report.

2.7 Reserves in China – impacts on the global market

Perhaps the most important market of all is that of China. The availability of economically recoverable coal in this country will determine the domestic industry's capability to supply China. The implications of this are that the domestic industry determines whether over the long term China is a net exporter of coal or a net importer. This has major implications on the dynamics of the world seaborne trade and the repercussions on global pricing. Since 2004, China has been an importer. Furthermore, the degree of the shortfall between demand and local supply determines the draw on the international seaborne market, and therefore has a significant influence on prices.

China's recoverable reserves are difficult to pinpoint, but range 114–180 Gt (WEC, 2010; BGR, 2011). At the most optimistic resources level of 5 Tt (terra tonnes or trillion tonnes), recoverable reserves are less than 4% of the potential resource. This staggering difference between resource and reserves provides considerable potential for China to boost its reserves, a feature that is common worldwide as seen in Figure 5. In China especially there are a number of impediments that prevent this. Much of the resource might exist at depths below 1000 m, where current average depths of reserves is around 600 m and more than half of the reserves are already at around 1000 m (Heping and others, 2013). The geology of existing reserves may well push underground mining to the limits of safety. Elsewhere, exploration for coal in the farthest west province of Xinjiang could yield more proven recoverable reserves, but the remote location close to the Kazakhstan border could pose difficulties. As Table 1 shows, China possesses roughly 17% of world recoverable reserves; the USA is by far the most endowed coal bearing nation possessing almost a quarter of the world's reserves. Russia has 15% with its vast quantities of coking coal. The top six countries have 75% of the world's reserves; the top twenty countries have more than 95% of the world's reserves.

Table 1 shows only a list of reserves, while resources show a much greater level of availability. According to the BGR, the world could have 18 Tt of hard coal and 4 Tt of lignite. These resources occur in the same countries with the same distribution as that of reserves.

2.7.1 Emerging coal regions of China

Large coal reserves will continue to be found in the western provinces such as Xinjiang, Shaanxi, Gangsu and Qinghai. Production focus is in Shanxi, Inner Mongolia and Shaanxi Provinces, where Inner Mongolia is one of the most richly abundant coal reserves in China.

The region with the most interesting prospects for new coal developments in China is the province of Xinjiang. The region is considered to be so well endowed that production could reach an estimated 160 Mt of coal in 2013. The region consumes some 50–60 Mt/y but a plethora of coal investments and plans including coal gasification plants, power transmission lines, gas pipelines and coal railways are being constructed. Much of the investment is for exporting energy to surrounding regions including a 30 GWe power transmission line (Collins and Erickson, 2012). Xinjiang is developing its coalfields to rail coal to the rest of China. One of the most exciting developments is the discovery of the Hoxtolgay coalfield that is predicted to contain 81 Gt of steam coal. The proportion that is economically mineable is not yet confirmed, but the region is known for its shallow thick deposits, a feature uncommon amongst most of the country's reserves. Xinjiang has possibly the largest reserve of coal lying at depths of less than 1000 m.

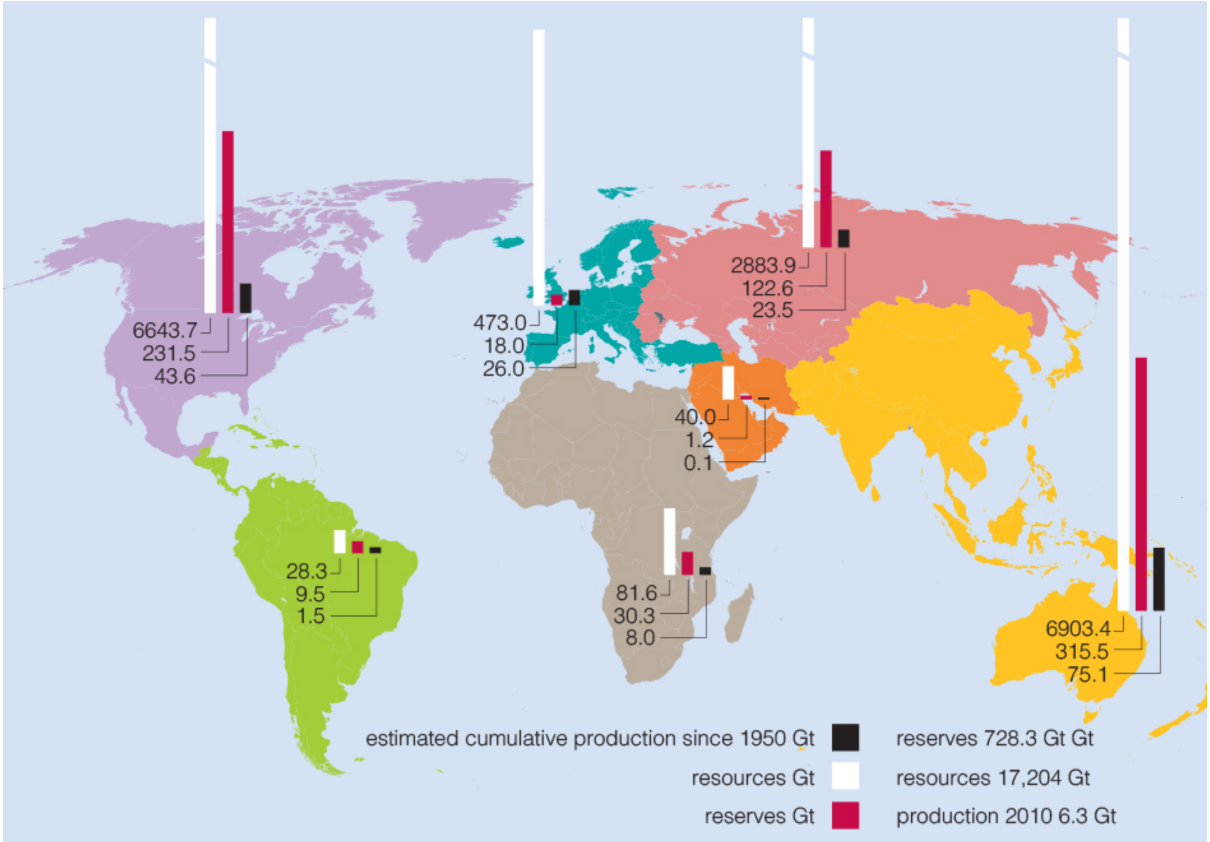

Figure 5 – Regional distribution of reserves, resources, and cumulative production in 1950–2007 (BGR, 2011)

2.8 Disparities in national reserves reporting

Official estimates of coal reserves have changed over time, sometimes upwards and occasionally downwards. An extreme example of a change in coal reserves occurred in Germany in 2004. At that time the government downgraded the size of their 'proven reserve' from 23 billion tonnes to 0.183 billion tonnes, a reduction of over 99%. This was because a large proportion of the reserves were reclassified as speculated reserves, and therefore had less geological certainty than measured reserves.

In 2007, Poland redefined its reserve base to only include developed deposits, thereby removing over 6 Gt from their reserve base. These uncertainties also have an effect on the investment climate relating to new coal power projects. Additionally, in almost all these calculations coal is treated as a single entity, when in fact coal varies widely in quality, primarily heat content and sulphur content. The issues of coal type and reporting reserves are discussed later in the report.

Over the years different coal producing regions adopted a range of specific definitions of coal qualities and reserve definitions based on their own domestic needs, where local power, industrial and coking consumers were the key markets for the coal. As such, the country's own definitions were quite sufficient. In addition, quantifying reserves was also in accordance to that country's practice.

Mohr (2011) identified different approaches made by publishers when reporting reserves data. For example, when reporting Australia's national coal reserves, the WEC use data from the Geoscience

Australia department of the Australian government. Their data are adjusted to account for environmental restrictions, government policies, military land, and so on. Consequently not all the *economically demonstrated reserves* (EDR) are accessible, thus reducing the EDR by 15% to arrive at the actual coal reserve figure. This could explain the low reserve level of Indonesia (5.5 Gt), whereby much of Indonesia is forested and poses a major restriction on accessibility to its coal reserves.

Similar to WEC data, BGR also has limiting parameters including consideration of coal thickness, seam depth, energy content, barren partings, and certain coal qualities such as ash content, rank (measured as vitrinite reflectance), and volatile matter content. Total resources usually refer to thicknesses of 60 m and a maximum depth of 1800 m. BGR also accounts for world market prices in combination with production costs where known, coal deposits developed today, and producing at prices below 50 US$/t count as reserves (Thielemann and others, 2007).

While different reporting agencies might use slightly different criteria, all organisations still rely on the accuracy and openness of the official geological or coal associations and mining corporations around the world that submit these data. Two countries in particular reported their coal reserves using slightly different definitions: Russia and China. In Russia, there are two broad categories, *balance reserves* and *industrial reserves*.

- balance reserves can be developed economically but is equivalent to the term 'resources' as used in western coal industries;
- industrial reserves are those balance reserves to be extracted according to the development plan and are calculated by subtracting project losses from the balance reserves. This term is probably equivalent to 'saleable/marketable reserves'.

2.8.1 Russian definitions

Russia's coal market, industry and reserves are discussed by Crocker and Kovalchuk (2008). Broad classifications for reserves based on geological certainty are described only briefly here for comparative purposes; further subdivisions are not discussed in this report. Reserves of all natural resources in Russia are classified into four categories A, B, C1 and C2 described as follows:

- *Class A* reserves that have been explored and studied to the extent that guarantees a detailed knowledge of the deposit, the formation and the body of the natural resource as well as its quality and technical condition. This is the most accurate of all the categories;
- *Class B* is reserves that have been explored and studied whose quality has been measured from individual samples;
- *Class C1* and *C2* include reserves that have been explored and studied to the extent of establishing a general understanding of the deposit conditions, the shape, formation and quality of the resource body and its technical conditions.

2.8.2 Chinese definitions

In China, resources are classified on the basis of geological knowledge, project economics and the project feasibility. The old Chinese system of classification was derived from the former Soviet system and has been gradually phased out since 1999. The current system uses the UN-based 3D matrix based on degrees of confidence in economic, feasibility, and geological evaluations. Resource estimates and feasibility studies that were carried out on projects prior to 1999 continue to use the old Soviet system, and so both old and new codes might exist for a single resource base. (*see* Figure 6)

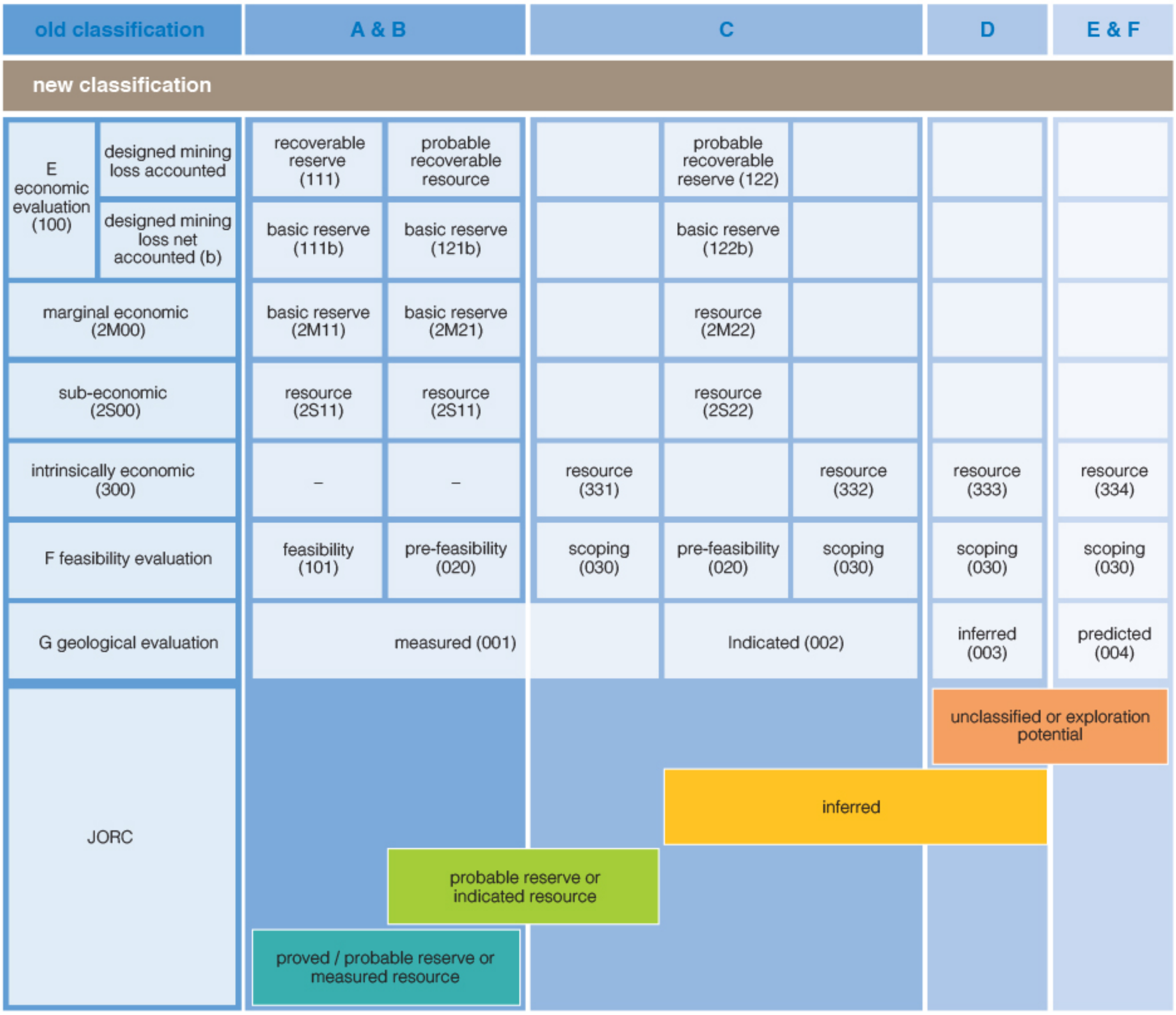

Figure 6 – Comparison between reserve classification in China and JORC (SRK, 2013)

3 Estimating the life of coal reserves

Probably the simplest representation of reserve analysis that most people are familiar with is the *reserves to production ratio* provided by some of the most widely quoted sources of reserve data, which includes the aforementioned data publications, as follows:

- *BP Statistical Review of World Energy*: coals are split into two groups, bituminous (including anthracite) and lignite. Reserves data for 40 countries are listed annually;
- *WEC Survey of Energy Resources* (which supplies the BP statistics) lists bituminous (including anthracite), subbituminous and lignite data for almost 80 countries, published every few years;
- *BGR Annual Report on Reserves, Resources and availability of Energy Resources*; hard coal and lignite reserves data for more than 80 countries.

The preparation of these databases relies heavily on contributions by companies operating in those countries, or member government organisations. The most important data are the economically recoverable reserves. These refer to coals that can be mined using all economic and commercial techniques available to the mining industry today. This chapter discusses the headline figures, but does not discriminate for coal types. Table 2 shows how the R/P ratio of coal is almost double that of gas and more than double oil.

Table 2 – Fossil fuel reserves and resources by region and type (based on BGR data)
(World Energy Outlook 2012; IEA, 2012)

	Coal*(billion tonnes)		Natural gas (trillion m^3)		Oil (billion barrels)	
	Proven reserves	Recoverable resources	Proven reserves	Recoverable resources	Proven reserves	Recoverable resources
OECD	427	10,657	28	193	244	2,345
Non-OECD	576	10,551	205	597	1,450	3,526
World	**1,004**	**21,208**	**232**	**790**	**1,694**	**5,871**
Share of non-OECD, %	57	50	88	76	86	60
R/P ratio (years)	132	2,780	71	241	55	189

For coal, the data are for 2010 and may differ from other coal data sources. Notes: R/P ratio = reserves-to-production ration based on 2011 levels of production. Resources are remaining technically recoverable resources

Table 2 shows global proven reserves of coal being 1004 Gt, and potential recoverable resources more than twenty times this. If the most optimistic value was considered, this would equate to a reserve life of 2780 years. Half of this coal exists in non-OECD countries although some of this reserve might be licensed to mining corporations based in the OECD. Coal reserves that are found in OECD countries are concentrated in North America and Australia, but parts of Europe still maintain a large reserve of low rank coals. **Error! Reference source not found.** shows the overall reserves figures for all major coal producers in the world as published by BP (2013). There is no discrimination for coal type or usage, and so all coals are assumed to be the same. The top ten countries account for 90% of the world's coal reserves. ***The USA, Russia, China, Australia, and India possess 78% of global bituminous and anthracite coal reserves, and 75% of global subbituminous and lignite reserves.*** Coal is plentiful in Russia and the USA, each having 471 years and 239 years of coal left respectively (as of 2011). Ukraine and Kazakhstan have high R/P ratios. Clearly the central Asian region is endowed with vast reserves that could yield a long future of coal production.

Coal production in Japan is extremely low, but the cost of production is extremely high. This is an example where the life of reserves may be high, but the likelihood of these reserves being fully exploited remains remote. A surprising statistic is the quantity of lignite that exists in Germany, giving the country more than 200 years of lignite mining that could feasibly continue long after the closure of the country's remaining hard coal mines. Lignite mining is not subsidised and is a cost-effective fuel, but burning the fuel remains subject to emission standards for all pollutants and CO_2. Following close behind in terms of R/P ratio are Hungary and Zimbabwe which as they also have such low production, the resulting high ratios could misrepresent actual reserves in some countries.

One of the most immediate concerns is the life of reserves located in Indonesia. With just 16 years left at current production rates, the Indonesian coal industry either has to find and prove more economically recoverable reserves, or cut back on production. The country has an estimated 5.5 Gt of economically recoverable reserves (BP, 2013). With production levels reaching 353 Mt in 2011, the reserves are reducing fast. However, the Indonesian Ministry of Mines and Minerals lists a total coal reserve of 28 Gt, of which the recoverable proportion remains uncertain, but given the current ease at which coal is extracted in vast quantities around the country, the likelihood is that Indonesia could realise a great deal more than 5.5 Gt of recoverable reserves in the near future. The challenge for the coal industry is that some coal reserves may lie below forest or at greater depth than they are mining at present, and so costs and ecological matters may hinder the production viability of some reserves and is an area that needs a great deal more research.

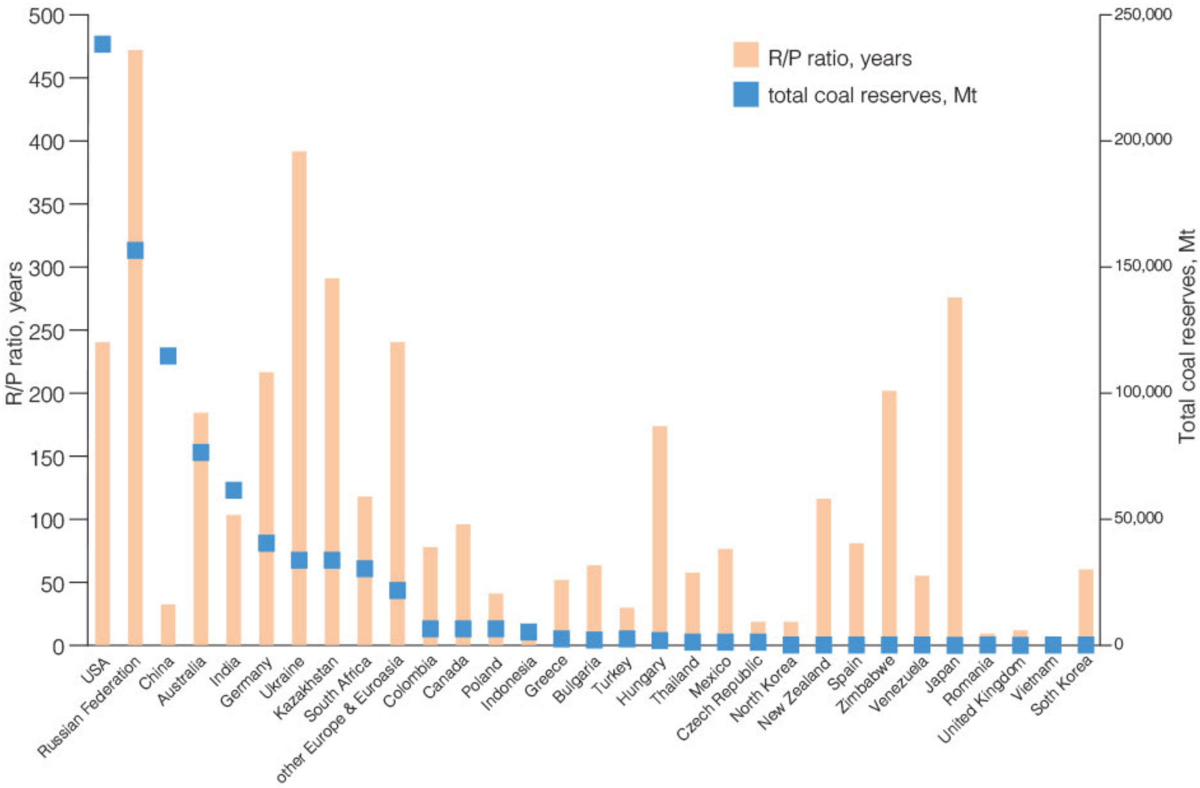

Figure 7 – Headline figures for al coal reserves and the R/P ratios (BP, 2013)

3.1 Long term trends in coal reserves

Like BP, most analyses do not examine coal reserves in their disaggregated form as hard steam coal, coking, or lignite. Nevertheless, research has been carried out on the long term trends for coal production. Höök (2010) compared data for coal resources published as far back as 1924 to see how reported reserves changed over time up until 2007/08.

The WEC showed a decline in global reserves since the 1980s while BGR did not. However, in some regions, resources increased. The addition of reported reserves in China and Russia was explained by the inclusion of 'unaccounted prognostic resources' in 2006. This led to a rise in resource from 6039 Gt to 9554 Gt between 2005 and 2006. Another upward trend occurred in 2007 increasing world hard coal resources by 68% and lignite 36% due to new coal resources being identified in Alaska by the US Geological Survey (Flores, 2004). Much of the new resource is still uncertain, and not confirmed recoverable.

A great deal of variation occurs in reporting hard coal and lignite reserves, whereby the BGR Annual Report 2011 states a global resource equivalent to 21358 Gt and a reserve of 1004 Gt. Clearly with more exploration, surveying, and further advancements in mining technology the potential to expand reserves is immense. The difference in reserves and resources of hard coal alone show the massive potential for converting resources into reserves if the economic conditions are favourable (*see* Figure 5). The WEC reserves figure for all coal stands at 860 Gt, 15% below the BGR figure, but whichever number is used, there appears to be enough coal to supply the world into the 22nd Century.

3.2 The end of cheap coal?

Coal is similar to all mineral extraction; the cheapest and easiest to mine is usually exploited first. Less cheap, but not necessarily uneconomic coal is usually left unmined until the market and regulatory conditions are right. Sometimes, the conditions are irreversibly poor for coal mining. Poor geology and high costs can end coal industries, as is being seen in Japan, Germany, Spain, especially for underground hard coal production.

'The end of cheap coal' is a quote that was published by a number of media reports based on the views of Heinberg and Fridley (2010), as well as echoing the study by Haftendorn and others (2012). These are important as they attempt to look objectively at the quoted figures of coal reserves, and in common with most extractive industries, tend to overestimate the economically recoverable portion of the reserve base. The authors do not claim that the coal is scarce, rather, if the rate of extraction for some countries such as China increases, the lowest cost mines could disappear in coming decades, and therefore coal prices must rise to improve the viability of higher cost operations. This probably explains China's interest in overseas coal developments in neighbouring countries such as Mongolia, along with other countries in Southern Africa.

In response to much of the analysis that has covered supply depletion, Haftendorn and others (2012) asks whether a paper published in Nature entitled 'the End of Cheap Coal' is valid when the analysis is based purely on the depletion of coal reserves using Hubbert logistic curves. A great deal of reserve depletion analyses for coal is based on broad assumptions on the growth of coal production, based on demand and the broad assumption that production continues to grow with little constraint.

The idea of the end of cheap coal should extend to the end of cheap energy worldwide as all energy source face reserve and land use constraints. Haftendorn and others (2012) attempted to increase the understanding of exploiting coal reserves over a period of time, typically over the life of the mine, and of the additional mine capacity that may come online over many decades to serve both a global and a national market. The end of cheap coal may be valid even if there is an abundance of coal due to a lack of transport creating supply bottlenecks and infrastructure limitations of rail and port capacity which is probably the most pressing issue for the next 20 years. These issues are occasionally omitted from coal reserves research, but nevertheless much of this research provides a platform from which a greater understanding can be built of the world's coal reserves.

4 Peak coal supply

The analysis of peak coal is well researched; one of the most detailed studies of its type was done by Mohr (2009) in an attempt to forecast world coal production for the 21st century to the year 2100. Modelling techniques attempted to determine the *ultimately recoverable resources* (URR) based on earlier work done on oil reserve depletion. In 1956, Hubbert made predictions that oil production in the USA would peak between the late 1960s and the early 1970s, after which there would be decline (Lin and Liu, 2010). The concept of the bell curve was proposed, a trajectory that oil production would take over the lives of then known finite reserves.

4.1 Hubbert logistic curves

Later, Hubbert (1959) used the bell shaped logistics curves to simulate historical oil data and further revisions were made in 1974.The prediction of the bell curve is a common method, and a logical approach to establishing future production, although the bell curve will not always be symmetrical as Brandt (2007) and Bardi (2005) state. If the rate of new oil discovery does not match the high production rates, then the steep decline in reserves leads to an apparent catastrophic depletion of global reserves, a notion that has proved popular amongst some commentators of fossil fuel resources.

By 1976, Hubbert applied the bell-shaped curve to global coal production. This was later refined by Liu and Liu (2010) who used the method to calculate a global production peak of 10–24 Gt/y in 2100-2200. At a current global production of just 7.8 Gt/y these figures are not implausible. Estimates of future coal production were based the pattern of coal depletion in maturing coal operations, but this often gave rise to overestimated trajectories for future coal production. Yet, Rogner (1997) stated that 'the sheer size of the fossil fuel resource base makes fossil source an energy supply option for many centuries to come', provided the economics and technological progress are favourable.

4.2 The difficulty in predicting long-term coal supply

Projecting coal supply to 2100 can be straightforward provided the location and quantity of the coal reserve can be ascertained, there is an assurance that the coal is economically mineable, and that the environmental and legal regulations permit the exploration of these coal reserves. If local reserves are exhausted, then access to more distant coal supplies (often from other countries) will be determined by the availability of transportation. International trade may therefore play an important role, although for convenience, some analysts treat different producers as independent of each other and ignore the role of coal export countries. While internationally traded coal is not considered in detail in this report, it is still recognised as a feature of world markets that might need more attention.

The rise in import markets into some of the largest consumers in Asia is discussed in Baruya (2012), but since international trade only covers 17–20% of global coal supply there may be some merit in the independence of some local markets for coal.

A more fundamental and important aspect is that in China, market and price deregulation, rail constraints, and an increasing role of imported coals can put upper limits on production, yet many analysts simplify the problem by assuming that the supply peak is a phenomenon of physical coal reserve depletion.

Past production only indicates the economic and regulatory conditions of the past. The Hubbert model could fail to integrate paradigm shifts that will affect future production such as regulated carbon constraints.

4.3 Projecting coal production

Geological reserve depletion is not always the cause of rising prices, at least not in the short to medium term. Shortages of temporary coal stocks or shipping and rail costs are often the cause of price hikes. This is an issue that is reflected by most mining industry professionals who produce and trade coal on a daily basis. However, long term increases in production include a slow expansion of mine capacity and infrastructure.

Research suggests that by 2025-30, some 3.0–4.7% of demand will not be met, and 16.3–18.0% of reserves will be depleted by 2030. This is not due to a loss of coal from the earth, but more due to lack of investment to supply the coal. Between $85 billion and $125 billion are required to boost production capacity depending on the scenario of growth, and between $2.4 and 6.6 billion are required to boost port capacity for the rising demand for export coal (Haftendorn and others, 2012). Future resource consumption is dependent on future prices and future mining techs capable of mining resources, but increasingly changes in regulations and business confidence will be crucial and is discussed in more details later in this report.

Höök (2011) states that the geological availability and quality of coals are regarded as 'non-interesting or solvable' aspects of coal reserves. This is an interesting point but could be subject to debate. Rising prices 'automagically' creates an increased availability of coal reserves, although this assumption is also true of uranium and perhaps oil and gas. Rising oil prices also raises the possibilities of coal to liquids and other unconventional forms of liquid fuel production from coal and shales. Höök (2011) examines a wide range of scenarios, up to 40 variations. For simplicity just four scenarios (A1, A2, B1, and B2) are shown in this report, although 17 sub-scenarios also exist within these. The plethora of scenarios shows how production forecasts can take any pathway depending on the future policy and market conditions.

China was expected to account for 46% of global production over the next 90 years, but the *Special Report on Emission Scenarios* (SRES) is underpinned by a paradigm of perpetual growth and technological optimism based on old and outdated resource estimates:

- A1 rapid economic growth, low population growth, rapid advance in energy efficiency;
- A2 high population growth. Growth is regional, with regional identity, remains strong, technology change is fragmented as individual regions pursue self-serving policies;

- B1 a convergent world, with the same low population growth, rapid transition to service and information development and clean and resource-efficient technologies; environmental objectives worldwide are unified, global solutions to economy, social and environmental sustainability; better equity but no further climate initiatives; and
- B2 local solutions to economic social and environmental sustainability. Moderate population growth, more adverse technological changes than B1 and A1.

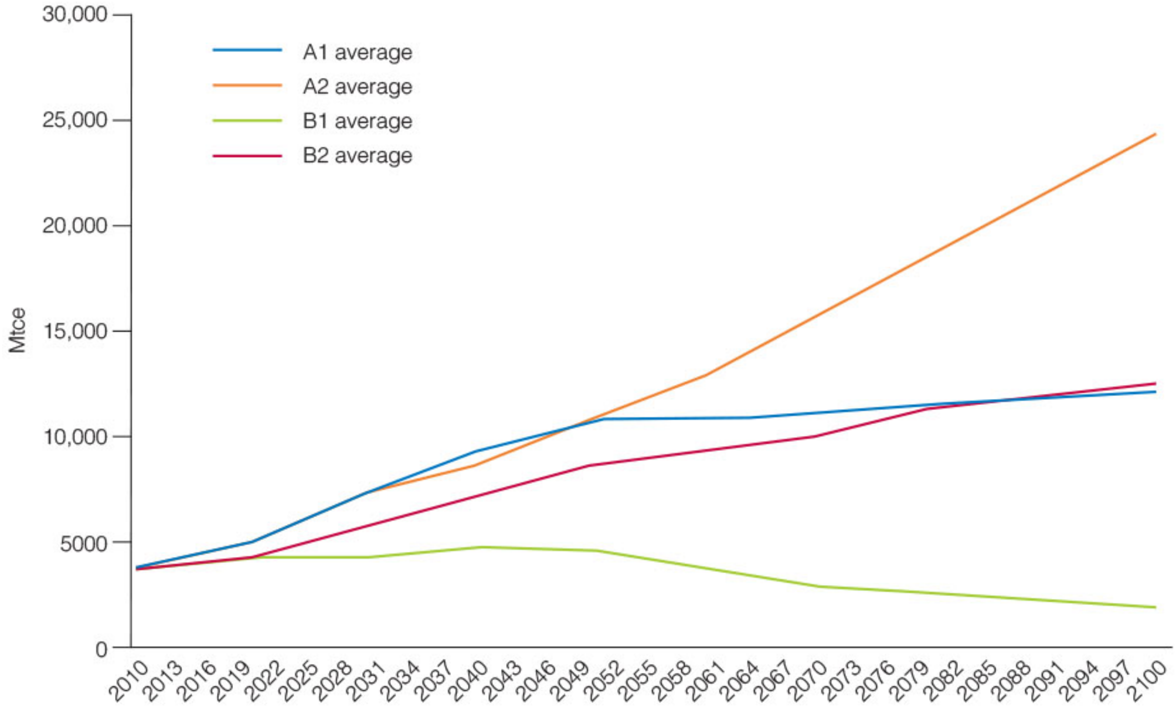

Figure 8 – Very long-term scenarios for coal production, *see also* **Appendix Table 7** (Höök, 2011)

Since 1860, the cumulative world production of coal amounted to 235 Gtce (165 Gtoe); where 74 Gtce (52 Gtoe) was produced in the last 20 years (Ion, 1974, 1979; Jenkins, 1989; Mitchell, 2003; BP, 2010). The A2 family of scenarios assumes that the cumulative production by 2100 will be many times the total historical output. Höök (2011) asks whether this is achievable in terms of necessary investments, equipment, miners, permits and other things required to extract the coal.

The A2 scenario average shows how production in world coal increases from 3570 Mtce (2500 Mtoe), to almost 24,284 Mtce (17,000 Mtoe). A comparison of the *averages* of the four sample scenarios shows a wide variation in potential coal production trajectories based on various production scenarios. Three of the four scenarios suggest that with a given reserve base of 1039 Gtce of coal in the world, there should be enough coal to match the potential increase in production, one way or another (*see* Appendix – Table 7). The lower growth production scenarios are in fact more plausible and based on more conservative assumptions that supress growth. The life of reserves under these circumstances is good, but is still complicated by the fact that demand scenarios come in so many variations.

On the supply risks, Höök goes further and discusses the issues that impact future production. Easy coal is always accessed, first leaving more difficult to mine coal in reserve, either to be exploited at a later date if costs allow, or sterilised and potentially lost forever. Future coal extraction is not entirely determined by geological availability, but by what fraction is recoverable and how much is needed. The impact of coal production scenarios on reserves based on different coal types is discussed later in this report.

4.4 Limits to growth in production

Global production is dominated by China, currently accounting for 50% of world output and demand. Detailed studies on China and the USA (two largest producers) suggest a low rate of increase compared to previous years; in recent years. For example, the USA has seen a decline, indeed a massive contraction in certain producing states. Many scenarios may contain extreme growth projections, and policymakers assign equal probability to all scenarios (Höök, 2011). Many scenarios are improbable and extreme, but necessary to gain an understanding of outcomes from different energy market and policy paths. However, assigning equal probability to outcomes such as zero coal production to a scenario showing a tenfold increase compared to current levels are extreme and perhaps not within the current and economic boundaries of existing markets.

A high importance seemingly assigned to *coal to liquids technology* (CTL) in the SRES (2000) outlook is unsound based on the current state of cost effectiveness of the process. The B2 MESSAGE scenario suggests a 32 million barrels per day of CTL production as vital for meeting future supplies by 2100; this is equivalent to more than a third of current global crude production. Such CTL capacity would exceed world consumption of all coal today.

The concept of perpetual growth may need to be reconsidered as models suggest that reserves will deplete sooner, and peak demand is inevitable within the next century. Clues as to when peaking occurs are not always clear, or which of the peak theories is correct.

Based on an analysis of the SRES scenarios, the B1 set of scenarios is the only group that imposes constraints on future coal production that shows a less optimistic trajectory based on mathematical geology and historical time series evidence. As a consequence, the optimistic trend in future coal production and demand has the same over-estimation of CO_2 emissions.

Future coal production projections in SRES (2000) are exaggerated states Höök (2011) and so are the CO_2 emissions, and more attention is needed to be paid to the fossil fuels assumptions being fed into climate models. So, scenario analysis with regards to coal production is fraught with uncertainty, and offers no constraint to forecast rising demand.

4.5 Peak coal in selected coal producing countries

Major coal producing countries are facing peak coal demand challenges as they embrace the policies that are intent on reducing CO_2 emissions from power stations, but also peak supply appears to be occurring in regions within these countries. For example, in the USA peak coal has already occurred in the Central

Appalachian coal region, although other regions possess cheap and abundant coal. Peaking may be due to external influences such as cost, environment, regulation, but not necessarily the depletion of coal.

China could face peak coal for the same reasons, but these are difficult to understand fully. Coal production is based more or less on market principles, when the market price increases (due to international coal prices), production increases to meet the demand. In times of surplus, coal prices drop, and so the incentive to explore further fields and discover new reserves may drop.

4.6 Peak coal in the USA

In the USA, the state of Virginia contains the Appalachian coalfields where the region's mines were already reaching post-peak production in the 1990s (Milici and Campbell, 1997). Production models predicted Appalachian production would decline to 200 Mt/y or less by the year 2150 (Milici, 2000).

Much of the production in the USA in east of the Mississippi has undergone a winding down of production, with the possible exception of the Illinois coal region, which also reached a peak coal stage in the 1990s (Lin and Liu, 2010).

Much of the growth in production has been in the western coalfields, but Appalachian basin production has dropped considerably. Coal production underwent a number of economic cycles, two of these cycles were a result of the massive drive in heavy industry during the two World Wars and the third based upon the massive drive towards coal-fired power post 1960s.

Sulphur emission legislation in the USA played a major role in the subsequent shift away from Eastern coalfields to the Western coalfields where production in and around the Powder River Basin flourished. Coal sulphur content in the USA is classified in lbs/MBtu, with:

- low sulphur <0.6;
- medium sulphur 1.68;
- high sulphur 1.2.

The Northern Appalachian basin has a near absence of compliance coal, almost all the low sulphur coals are in the Central Appalachian basin in eastern Kentucky, southern West Virginia, and Virginia.

4.7 Peak coal in China

China consumes almost half the world's hard coal, yet has just 14% of the world's reserves. China will reach its peak production level within 5–15 years given reserves of 114.5 Gt. Kavalov and Peteves (2007) concluded a similar peak for China. Any artificial restriction on future production could relieve the country of depleting reserves.

In 2010, the National Energy Administration (NEA) announced that production output could be restricted to 3.8 Gt under the 2012-16 Five-Year Plan. Such a plan has yet to take shape and does not appear to be part of the current plan (12th), but could take some form in future plans.

The demand for coal in China is considered unsustainable, and if the trend continue, coal production could peak and domestic supplies could cease in 21–38 years. The impact on both domestic production and import demand is immense. As of 2013, some 106 GWe of new coal-fired capacity was under construction. Assuming more than 90% is supercritical and high in efficiency, coal demand could be boosted by almost 250 Mt (assuming a 6000 kcal/kg coal and an efficiency of 43% net).

With coal demand in 2012 reaching an estimated 3500 Mt/y, demand could reach 3750 Mt/y within a few years as new power station capacity is commissioned (and assuming no closures). In China, peak coal has been reached in some provinces such as the Shandong province which peaked in 2003.

Nationwide, China could have an emissions target during the 13th Five-Year Plan which would mean 15% of power could come from nuclear and renewables by 2020. If successful, this plan could slow down coal demand considerably. Seven Chinese cities are planning to enact a carbon trading programme and a moratorium on coal-fired station building around some of the most densely populated metropolitan areas has been imposed to encourage greater use of gas-fired power. Steam coal demand might not peak before 2030. China's shale gas reserves could come online, but slowly, and most coal reduction schemes will be around larger cities such as Beijing and Shanghai.

IEA (2012) scenarios for projected energy demand in China assume a real growth rate of 5.7%/y for the period 2010-35 compared to the global average of 3.5%/y (EU 1.8% and USA 2.4%). Cumulative production between 2005 and 2025 of 87 Gt could use almost half the 189 Gt of reserves in China; this infers that coal will peak around 2025 even with a declining rate of growth which could peak at 4 Gt/y (Shealy and Dorian, 2010; Tao and Li, 2007). One drawback from analyses using logistic growth and Gaussian methods is that the methods often ignore factors such as coal price in the forecasts (*see earlier*). Nevertheless, these methods are described as follows:

- logistic curves follow an S-curve trajectory, such as those seen for population growth. The initial stage of growth is low, and then rises exponentially. As saturation begins, growth slows and at maturity, growth stops and flattens, effectively levelling off at the top of the slope. A decline follows, mirroring the upward slope leading to the familiar bell curve;
- the Gaussian method looks the same as the logistic bell curve, but slightly flatter. With algorithms to assess future coal consumption and limits to production based on reserve depletion, the gap will determine a (net) import/export forecast. This is sensitive to the ultimate recoverable reserves, and the assumption of economic and population growth.

4.8 Peak production for a coal exporter – Australia and Indonesia

While Australia appears to have good prospects for coal production and export in coming years, long term trends are harder to establish. Many factors lead to a slowdown and decline of production in fossil fuels. For oil this is dependent on the pressure reduction in a given oil well, the number of wells per field, and the ability to enhance recovery, perhaps through the pumping of pressurised CO_2. For coal, the depletion will arise due to the increased depth of reserves, increasing geological difficulty of accessing and extracting seams, such as thinner seams, decrease in quality, or the location being under environmentally sensitive land (or even sea). Diminishing productivity and reserves on a global scale however might lead to supply cost inflation, and if the demand for coal remains strong, an upward pressure on long term prices. This in turn could lead to stimulation in coal exploration.

Australia is an example where the demand from countries in and around the Asia-Pacific region has perpetuated a continuing demand for good quality Australian coal products for both steam and coking quality coals.

Coal production in Australia started in the late 18th century in New South Wales (NSW), and then followed by Queensland (QLD) in the 1950s while lignite extraction in Victoria was reserved for domestic consumption only. Today, a mixture of opencast and deep mines operates in NSW and QLD, and overburden ratios for opencast mines are increasing. Most underground mines use longwall techniques. Future production is based almost entirely on export demand and the demand from Japan, Korea, Taiwan and China. However, environmental and social impacts may restrict greenfield developments in the long term.

The Bowen (QLD) and Sydney (NSW) basins dominate production. These regions are not tectonically active and so the coal seams are undisturbed and also well connected to the coast by dedicated rail links and coal export port terminals along the Australian coastline.

Research suggests that production is expected to peak between 2079 and 2119 depending on the method of measuring the ultimate recoverable reserves or URR (Höök, 2010; Rutledge, 2011). The higher depletion rates assume that there is less stringency in terms of mineral resource regulations or environmental constraints, but land use conflicts sometimes occur with the agricultural industry/farming sectors.

Political intervention can slow depletion rates, especially if the mining companies decide to produce less coal in favour of other commodities or government policy mandates production caps on domestic output (domestic market obligations). Other factors might include restrictions on export capacity and intervention due to climate change initiatives in countries importing coal from Australia, or indeed the rest of Asia.

Current production of Australian coal (with no discrimination for quality or rank) is roughly 420 Mt/y. Reserves are roughly 76–80 Gt providing a simple R/P ratio of 180 years so peak production might not be expected this century at current extraction rates. Other estimates show similar figures but use much higher production rates from a much larger resource base. The URR for Australia is estimated to be 317–376 Gt. All projections indicate a peak in 2100 (–/+25) at a maximum production rate of 1.0–3.3 Gt/y (Mohr and others, 2011).

A rather different outcome is expected for another major exporter, and that is Indonesia. Indonesian coal and infrastructure industry has propelled the country to become the leading exporter of steam coal in the world. Based on current production of around 400 Mt/y, the reserves of 21,000 Mt provides the country with a coal reserve for more than fifty years. Yet, much more conservative reserve data suggest that the life of the country's reserves could be closer to 15 years (BP, 2013).

Much of the country's coal is low in rank (subbituminous and lignite) and easily mined in two major regions, Kalimantan (Indonesian Borneo) and Sumatra. Both regions have challenges, not least the rainforest that covers much of the region. Other challenges remain the rapid rise in demand for coal from its expanding fleet of coal-fired generating capacity, as well as demand from the Asia-Pacific region. Indonesian export coals are also some of the lowest cost in the world and reserves are close to the coast and easily transported and loaded for shipping to the rest of Asia. Despite export taxes and domestic market obligations, Indonesian coal exports remain a major source of coal for countries which are facing their own supply issues. Indonesia will remain a major supplier of export coal but because of uncertainties in the true level of reserves, it is difficult to assess the impact on reserves from rising production. The impact of future export trends on coal reserves in exporting countries is discussed in more detail in Chapter 7.

5 Steam coal demand scenarios for the power sector

There has been a great deal of research into peak supply from different analysis groups, based on a variety of growth curves and reserve depletion methods using various statistical methods. It is assumed that production growth curves follow historical trends and production and demand follow the same trajectory. As a concept, this is reasonable, but aspects of peaking are also being applied to demand by a range of international groups. Demand peaking assumes supply is fixed and freely available but depletion varies based on factors that can affect the end users of coal. These may be due to either a rise in demand from the emergence of coal-fired power in non-OECD economies, or a massive reduction in demand as OECD nations garner efforts to switch away from coal (without CCS).

Demand destruction is a concept where energy consumption is reduced by either market or regulated means, or a combination of the two. The global coal-fired fleet could look very different to how it is today and this chapter considers the impacts on future coal demand, with further discussion on scenario options in Chapter 6 and the key drivers to reduce unabated coal combustion are discussed in Chapter 8.

5.1 Steam coal demand trends in the power sector

Figure 9 (and Appendix Table 8) shows some comparable trends for steam coal demand from the world power sector, the single largest market for coal, all converted to million tonnes of coal equivalent (Mtce). The units are expressed in energy terms where a tonne of coal equivalent is equal to 29.3 GJ. Most forecast data are published in oil equivalent (41.9 GJ). For simplicity, all Mtoe data are divided by 0.7 to standardise to Mtce.

The most notable trend is the apparent peaking of steam coal demand from four sample projections from the IEA, IEA CCC, BP, and Exxon. Other sources such as Shell Scenarios and the Institute of Energy Economics of Japan were used for comparison purposes only and showed similar outcomes for projections of total primary energy. As the graph shows, the IEA power trend (New Policies scenario) is an approximately median trend compared with Exxon and BP.

Data published by the IEA CCC covers a number of coal producing countries, of which four are selected (China, India, USA, and South Africa); these cover 75% of the world's demand for steam coal. For this reason, the data trends are consistently below those of all other projections. Figure 9 shows what appears to be agreement amongst numerous projections published by various analytical groups.

Future growth is expected to be lower than that seen in previous decades with demand peaking around the period 2020-40. Whether the peak demand occurs early on in this period or later is uncertain, but the key factors influencing this are discussed later. The chief determinants of coal demand over a period of time include:

- the size of the coal-fired fleet;
- performance of the fleet;
- technology deployed;

- the average utilisation/load of the fleet

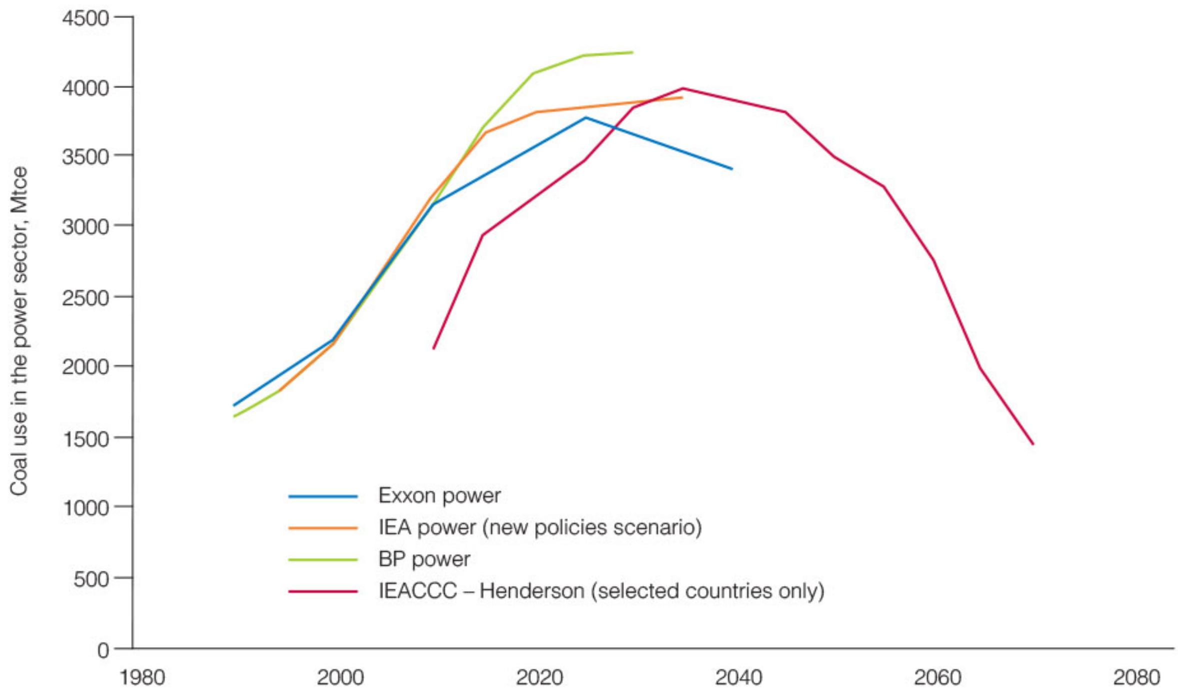

Figure 9 – Long term coal demand scenarios in the power sector, *see also* **Appendix Table 8** (various sources)

5.2 Replace ageing stations and the impact on coal demand

Henderson and Baruya (2012) determined the potential savings of CO_2 from a shift towards high efficiency coal technologies, if cost was not a factor. The research was a technical analysis of the effect of deploying wide scale *ultra-supercritical* (USC) steam technology across the world and the fitting of CCS to examine the CO_2 savings on coal-fired power plants compared with a baseline of existing plants.

In the various scenarios, ageing power stations (mostly subcritical) are closed at the end of their operating life and inefficient plants become a much smaller proportion of the fleet in favour of replacements with USC. USC offers a commercially available method of reducing CO_2 emissions for countries which have few alternatives to coal for bulk power production.

Installation rates for various carbon capture technologies were simulated in a model for roughly 70% of the world's coal-fired fleet. The most appropriate technology advances were considered for reducing CO_2 through the upgrading of subcritical units, these include:

- replacement of *subcritical* (SC) pulverised fuel units with supercritical or USC;
- some replacement with *integrated gasification and combined cycle* (IGCC).

The operating efficiencies of stations were assessed carefully, taking into account losses due to age over the forecast period, and hard coal and lignite were treated separately. The impact of burning high ash coals, reduced efficiency in hot climates and lower efficiencies for lignite stations compared with hard coal stations of similar capacity were all considered. Representative load factors were considered to reflect the actual operating conditions for that particular country. CCS causes an unavoidable reduction in power station efficiency, but is unlikely to ever be fitted to stations with subcritical steam conditions unless efficiency penalties can be reduced significantly. The effects of efficiency reductions on coal demand are researched by Vidal and Jowit (2009) and are discussed later. Ideally, CCS will be fitted to new stations with a high efficiency of operation, even though the increased system losses will bring the efficiency down to that of subcritical plant without CCS (achieving perhaps 35–39% efficiency).

5.3 Results from a IEA CCC high efficiency coal-power scenario

The drop in future coal demand exhibited by Henderson and Baruya (2012) shows plants built between 2000-10 to be decommissioned or idled around the period 2050-60, based on a 50-year plant life. All other scenarios (IEA, Exxon, and BP) appear to see an earlier drop off in demand in around 2035-40. As an example, the IEA WEO (2012) scenario shows total generating output from the world's coal-fired plants rising 37% between 2010 and 2035 (*see* Table 3). This increase occurs in non-OECD nations particularly in Asia where capacity (net) growth in GWe increases by a considerable 41%, indicating a boom period for the boiler and equipment manufacturing industries of the Far East.

The need for coal-fired power is great but in time, the average plant utilisation is expected to drop from more than 60% to 58%, indicating a greater role as a *load follower* to renewable and gas-fired capacity. Of those coal-fired stations that will still be operating in 2035, the technology advancements and replacement of old plants means that the global fleet efficiency increases from 39% to 42%. CCS could be installed in perhaps 60–70 GWe worldwide as the technology remains in the early stages of commercialisation. The resulting emission performance of the global fleet improves gradually from 1041 gCO_2/kWh to roughly 890 g as a consequence of replacing old stations and fitting CCS to a small proportion of the world's coal stations.

Table 3 – Projected world coal-fired generation to 2035, New Policies scenario (Henderson and Baruya, 2012)

	1990	2010	2015	2020	2025	2030	2035
TWh	4426	8687	10242	10897	11212	11565	
GW		1649	2012	2119	2171	2250	
Calculated utilisation, %		60.1	58.1	58.7	59.0	58.7	
Total CO_2, Mt	8335	13105	14901	15350	15391	15360	
Power CO_2, Mt	4918	9040	10253	10643	10684	10664	
TFC CO_2, Mt	3278	3769	4308	4362	4361	4351	
gCO_2/kWh	1111	1041	1001	977	953	922	

5.4 CCS and coal-fired generation

On a plant by plant basis, CCS has great potential to reduce 90% of the CO_2 from the flue gas of fossil fuelled installations before it reaches the atmosphere. However, the lack of support for CCS means progress to achieve these reductions is slower than needed, and the technology remains in development. The current scale of CCS is small, at most 300 MWe, and the operation for all the additional CO_2 reduction equipment imposes a penalty on the overall station efficiency.

Based on current designs, the installation of CCS equipment can pare back the station's overall efficiency by up to 8 percentage points. This is a large penalty on power stations operating at 35–45% efficiency. Nevertheless, the development of high efficiency power stations can help counter the effects of this loss; such stations could reach 50% efficiency, but are currently in the development and component testing stage. Adding CCS onto combined heat and power plants will have a much smaller impact where the system efficiency is in excess of 90%. Elsewhere, power stations using ultra-supercritical steam systems are reaching 45% net efficiency. The installation of CCS and resulting efficiency penalty would pull efficiencies down to 37%, equivalent to that of a modern subcritical plant. Nevertheless, the 90% reduction in CO_2 emissions will prove a necessary incentive in a carbon constrained future.

The IEA identified some 3000 industrial installations where CCS could be fitted over the long term, creating a potential market for 150 Gt of captured and stored CO_2. This level of CCS goes beyond decarbonising coal-fired power, which might only account for 19% of CCS-related CO_2 reductions. Interestingly, the 450 ppm scenario of the WEO (2012) considers a wide suite of decarbonising measures, but only part of the world's coal fleet is expected to be equipped with CCS. Some 80% of the CO_2 reduction associated with CCS projects could be attributed to non-coal plants; natural (including unconventional) gas CCGT, biomass power generators, and industrial process plants could all benefit from CCS (Lipponen, 2012).

From a coal demand and production perspective, even high efficiency plants equipped with CCS could continue to produce the same electrical output and burn fuel at the same rate as a subcritical plant, but with just 10% of the CO_2 emissions. This could be a boon for the mining industry that has yet to be realised by most in the coal business.

Attempts to quantify the impact on coal demand as a result of efficiency losses due to the parasitic nature of CCS was done for the UK fleet using a large efficiency drop of 12% points. As a result, CCS fitted onto a subcritical coal-fired power station could increase the coal demand by 37–47%; other estimates suggested the increase could be as much as 57%. Of this, an estimated 26% rise would be due to the capture system alone, but the balance would be attributed to a number of additional 'loads' due to the transport and permanent storage of CO_2 (Vidal and Jowit, 2009; Owens and others, 2010).

Given the pipeline transportation and storage of CO_2 is offsite from the coal-fired station, the power demand for the downstream processes would come from the public grid and could overestimate the amount of coal actually needed to deliver the necessary power. It is more likely that the extra load would be supplied by a mix rich in renewables, gas-fired, and nuclear power. The analysis also assumes a subcritical power station operating at 36% efficiency, dropping to 24% efficiency after a 12% point drop in efficiency, and does not consider that generating companies are more likely to fit CCS to high efficiency plants, which will make CCS more cost effective when hosting a CCS plant.

Another similar technical analysis went further to estimate the impact of CCS on global coal demand over a forecast period 2010 and 2031. The most extreme scenario assumed a 100% take-up of CCS in the entire world's coal-fired fleet (Owens and others, 2010). The broad results are as follows:

- *without CCS* peak coal production would be reached in 2033-48 at 7.9–9.9 Gt/y; for simplicity, we can say roughly 9 Gt/y by 2040. A depletion of almost all current recoverable reserves would occur after the year 2165;
- *with CCS* peak production rises to 9.95–12.5 Gt/y (averaging 11.7 Gt/y). This rise is equivalent to China's current coal production. After 2050, production declines and global reserves face 98% depletion by 2115 (with CCS). Reserve depletion *with* CCS would occur 50 years earlier than a scenario *without* CCS.

The modelling is simple and elegant, and looks primarily at historical trends as an indicator of future trends which is logical. However, coal reserves appear to be ample enough to cope with any rise in coal usage due to CCS over the coming decades.

6 Demand destruction – bringing forward the peak demand, less pressure on peak production

Most projections anticipate a reduction in coal demand arising from competition from other non-coal sources and more stringent environmental regulations. However, CCS could bring about a rise in coal demand to 10 Gt/y after 2033. Furthermore, one of the chief tenets of the concept of peak coal assumes coal production declines as the cheapest coal reserves are depleted and the coal mine faces enter more difficult and costly seams. So peak coal can occur from both a demand and a supply perspective. If both affect the coal markets simultaneously, then peak coal can be accelerated. Before that occurs, demand growth may falter due to market and regulatory pressures, the latter often influencing the former in the short to medium term. Over the long term these effects will drive a need for technology advancement and a shift to higher efficiency and cleaner methods of generation, as discussed in previous chapters.

6.1 Drivers of demand destruction – China and USA

Incentives to promote the rise in low carbon technologies could halt the growth in coal demand in coming years, especially in OECD countries. Drivers of demand 'destruction' of coal come about by a number of means at different levels of the energy economy. However, governments do not dictate markets, but can be instrumental in steering them strongly towards a single or small group of fuels and sources. Emission regulations often steer utilities to building gas-fired stations. Such emission limits might include limits on CO_2 per kWh of generation basis, where a coal station must perform as well as a CCGT gas plant (which is half that of coal), therefore exempting gas plants from emission constraints but effectively placing a moratorium on coal plants. Some of the main drivers to encourage decarbonisation of the power station fleet might include:

- *renewable feed in tariffs* (FITs): without FITs, or an appropriate tax to internalise CO_2 into fossil fuel costs, renewable energy is uneconomic; and
- other tariff agreements to ensure an adequate return on investment such as contracts for differences for nuclear power; and
- flexible mechanisms such as carbon trading operating under a CO_2 cap, but allows different renewable, nuclear and fossil fuel assets to operate in tandem to reduce the overall CO_2 emissions.

All of the above drivers work in combination with carbon reduction schemes, whether on a national or an international level.

6.2 Milestones in CO_2 agreements

Some of the milestones for carbon reduction policies to affect coal demand, notably in the OECD, are as follows (Rutledge, 2013):

- 1997 Kyoto Agreement to reduce CO_2 emissions by 2012 – North America shows the least or no commitment to cap or reduce carbon emissions, and Taiwan (did not sign);

- 1998 UN IPCC (Inter-Governmental Panel on Climate Change) Special Report on Emissions Scenarios (SRES) — 40 scenarios for making projections that are business-as-usual with respect to climate change;
- 2007 UN IPCC (Inter-Governmental Panel on Climate Change) publishes its 4th Assessment Report – main conclusions continue to support the scientific evidence that climate change is evident through changes in glacial and weather related phenomenon;
- 2009 G8 at L'Aquila, Italy, sets a goal of reducing fossil-fuel CO_2 emissions 80% (below 1990 levels) by 2050 – a suite of measures including energy efficiency, renewable and nuclear are highlighted;
- 2009 UN Copenhagen Accord (COP15) sets a goal of limiting the temperature rise to 2°C above pre-industrial levels;
- 2012 UN Doha (COP 18) extension of Kyoto Protocol to 2020 and commitment to climate adaptation funding;
- 2013 UN IPCC 5th Assessment report – states that scientists are 95% certain that humans are the 'dominant cause' of global warming since the 1950s.

6.3 Adoption of new regulations

Two of the world's largest coal markets are the USA and China, and both are implementing, or have introduced air pollution regulations that will severely limit emissions from coal-fired power stations, but are moving forward with legislation that could set national carbon caps or CO_2 standards on future generation. Carbon taxation and trading is already being supported by successive governments in Australia. In China and USA, regional carbon trading is underway and national schemes are being considered. China's economic stability may be dependent on the carbon trading scheme. The most financially powerful provinces have already benefited from the boost that coal-fired power can afford local economies, but some more rural and/or inland provinces may well be looking to enhance power supplies to local communities in the future, but if it's done under a carbon constrained market, the options may be limited. Despite this, carbon reduction will have a multitude of benefits.

A total emission control scheme is being considered for the 2016-20 Five-Year Plan in China. One of the major hurdles is the development of accurate carbon emission inventories for some provinces. Liquidity in the carbon market is limited, with no forward contracting and China is also in receipt of CDM credits, meaning some Chinese projects could receive double credits unless they are properly accounted for (World Coal, 2013).

6.4 US air pollution regulations

In the USA, the *Mercury and Air Toxics Standards* (MATS) on coal and oil-fired plants will impose restrictions on emissions in 2015. The legislation follows the Clean Air Act 1990 and has created a great deal more regulatory risk associated with coal-fired stations so improving the chances of utilities building gas plants. The MATS poses major challenges for the competitiveness of coal-fired power. The *Cross-state Air Pollution Rule* (CSAPR) works alongside MATS to reduce SO_2 and NO_x emissions by 71% and 52% (on

2005 levels) respectively. The CSAPR will require a number of measures which will require coal-fired plants to fit control equipment, not least FGD.

Mercury can be controlled using similar equipment for SO_x control, but mercury can also vary in coal usually present with pyrite, an inorganic sulphur compound that is often found in the ash of coal after combustion. Low-chlorine content coals can be a problem, because without the promotion of oxidation (of mercury) by chlorine, more mercury is left in the elemental vapour phase. Such low-chlorine coals include the PRB coals, which are extremely popular for their low-sulphur content. High-sulphur coals are also afflicted, not just with higher demands on SO_2 control systems, but also the fact that SO_3 derived from SO_2 during combustion (and can also be added to enhance ESP performance) can reduce the performance of mercury absorbing sorbents.

There is no surprise that power utilities may switch to gas given the technical considerations needed to run coal-fired plants under ever stricter regulations. Carbon limits will be set on new coal-fired plants in the USA, possibly setting a moratorium on any new coal build that does not have CCS. The CO_2 limits would be set to that equivalent to a gas-fired plant at 1000 lbs CO_2/MWh) (Volcovici, 2013). The best performing coal plant emits at a rate of 1800 lbs CO_2/MWh thus making new plants impossible to build without CCS.

Carbon trading schemes are only as effective as the strictness of the carbon allocation. A generous allocation might well be issued in the first round of any national scheme, almost as a business as usual case, but stringency could be introduced early, raising the price of CO_2 and severely curtailing coal fired generation. The premature closure of coal plants and limits to new build as a result of new regulations will affect projected coal demand as well as add extra levels of risk to the operation of power stations.

6.5 Impact of US regulations

The EIA projected a reduction in the role of coal-fired power in the USA, with total coal-fired generating capacity falling from 318 GWe in 2011 to 278 GWe in 2040 (EIA, 2013). This reduction of 40 GWe is equivalent to a 15% reduction in capacity. Other reports estimate a closure of 59–77 GWe (Power, 2012). The oldest and most polluting plants would be at most risk, but with the US fleet comprising of around 104 GWe of plants that were built before 1970 (Platt's, 2013), the potential closure programme is immense. In 2016, the year that MATS is implemented, coal-fired output could be affected by the boost in natural gas-fired generation. Increased generation from renewable energy, excluding hydropower, could account for 32% *of overall growth* in electricity generation from 2011 to 2040. Federal tax credits, state-level policies, and federal requirements to use more biomass-based transportation fuels would be major incentives for investment in the renewable sector. Growth in renewable generation is supported by public funds, as well as new regulations on CO_2 emissions in California. The share of US electricity generation coming from renewable fuels (including conventional hydropower) could grow from 13% in 2011 to 16% in 2040.

Aside from emissions regulations, competition from natural gas is intensifying in the US, with the massive drive towards unconventional gas production from chiefly shale gas (in addition to shale oil, tight gas and so on). Regulatory incentives were introduced in 2005 when shale gas facilities became exempt from various environmental regulations, creating a massive boom in production. The reduction in CO_2 emissions in the US is only partly explained by the shift to shale gas, but the incentives for natural gas have resulted in a market shift to cheaper gas at the expense of coal.

The previous examples have offered just a few ways large coal consuming countries are looking to tackle carbon emissions by reducing incentives for coal demand and boosting incentives for renewables. This does not necessarily mean eliminating coal from the power generating mix, but with the adoption of high efficiency coal power and CCS, it can be part of the solution of decarbonising the electricity generating market.

Low carbon scenarios all form a part of the work in projecting the future energy trends, while business as usual is often the ignored scenario by the wider popular media. Neither is irrelevant, but all scenarios are plausible pathways, regardless of the economic or environmental cost associated with it.

Error! Reference source not found. shows the coal demand scenarios from the IEA WEO (2012). The particular coal demand trends are for global power generation. The key assumptions behind the scenarios are explained in detail in the WEO (2012), needless to say, the most severe scenario is the 450 policy which drives coal out of the market using a variety of government regulations to promote energy efficiency and renewable energy, but an equal commitment to promote CCS for many remaining fossil fuelled plants and industrial facilities.

A significant amount of investment is essential to follow the 450 path. Under this scenario, the price of CO_2 reaches 120 $/t in 2035, versus 45 $/t in the other scenarios. All countries, including the USA and BRIC countries engage in carbon trading in the New Policies and 450 ppm scenario. In addition, subsidies are withdrawn from the fossil fuel pricing system, although a vast proportion of this is geared towards making oil products cheaper in Asia and the Middle East. Regarding a low carbon technology roadmap for all fossil-fuelled power, CCS on power stations and industrial facilities using coal, oil and gas account for just 12% of the CO_2 savings. The vast bulk of the CO_2 cuts are made through government and market led initiatives to promote end user efficiency (50%) and renewable power (21%).

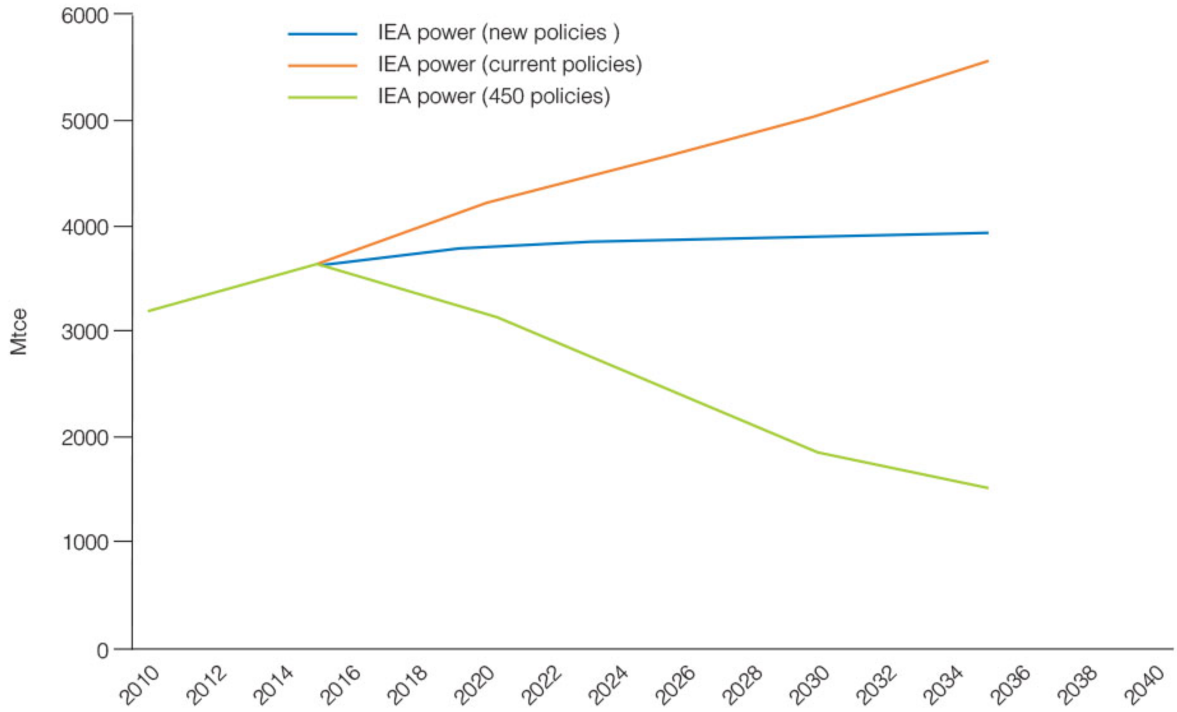

Figure 10 – Coal demand scenario analysis, Mtce (IEA, 2012)

6.6 High efficiency coal power and CCS – no change in coal demand

As already mentioned, a CCS equipped USC coal plant may result in coal consumption equivalent to a non-CCS subcritical plant (at 36–39% net). The gains in fuel efficiency from building a USC plant will be neutralised by the energy penalty of operating a post combustion or oxyfuel CCS plant. However, this effect is likely to be an acceptable penalty in order to achieve a near-zero emissions coal plant.

Coal plants with CCS might therefore maintain the current rate of depletion of existing reserves. IGCC might not suffer from such high efficiencies penalties. Nevertheless, developments in the various power technologies should reduce the efficiency losses in the future.

IEA WEO coal demand scenarios are heavily dependent on economic growth, fuel prices, and strategic decisions such as moratoria on nuclear plants and coal plants unable to meet emission limits. The pace of development will be critical in the prospects for CCS especially for coal, gas and heavy industry. Public acceptance to burn fossil fuels with CCS is essential but cost reductions, storage sites, transport routes and the reliability and scaling of CCS to power station level are critical.

6.7 The erosion of coal competing in the power markets

As a generality, most energy forecast models rely on population and economic growth trends. These macroeconomic drivers tend to determine growth in primary energy and electricity demand. Fuel prices will determine the growth, where high prices might subdue growth. At the same time, different prices will give one fuel an advantage over another (in the case of renewable, feed-in-tariffs), and if switching is possible, coal could lose ground to cleaner and more economic fuels.

Regulations often offer a blunt instrument in attempting to achieve low-carbon targets, and in Germany, this has been partially successful. Most capital projects, whether they are coal or otherwise are still market led. However, regulations can impair the decision for building new coal-fired stations, all of which can lead to further repercussions on future long term coal demand, as follows:

- financial institutions stop funding coal-fired power – banks are developing policies that recognise public perception, weighs against coal;
- financial risk could be eased for non-coal alternatives such as from low gas prices and unconventional gas production;
- inflate construction costs for coal;
- remove subsidies or state influence on pricing;
- air pollution and CO_2 price floor is introduced and set at a high level – closure of old plants is accelerated, new plant moratorium especially without CCS;
- uncertainties in CCS policies – either restricting storage or lack of regulatory and financial incentives for the CCS chain;
- above all, and possibly encompasses all of the other issues, is the full incorporation of environmental externalities and withdrawal of state aid in the form of tax relief or direct subsidy.

The timing of the demand peak is less critical in terms of reserve depletion; there seems to be no shortage of coal worldwide. However, the timing is critical for the deployment of *high efficiency and low emissions* (HELE) and CCS equipped power plants, without which achieving CO_2 targets will be prohibitively more expensive, possibly making CO_2 targets unattainable. Similar peaking trends are expected from industrial coal demand as facilities shift to natural gas and electricity based steel production.

6.8 Penalty approach to CCS investment

According to Froggat (2011), a number of CO_2 reduction regulations or proposals are aimed squarely at discouraging investments and the operation of fossil fuelled stations. Some are based on performance standards of CO_2 emissions measured on a gramme per kWh bases (gCO_2/kWh):

- Emission performance standards on CO_2: USA, Canada (375 gCO_2/kWh for all fossil fuelled stations by 2015); exemption could apply for plants equipped with CCS;
- EU proposals for emission limit values (ELV) of 450 gCO_2/kWh applicable to new fossil-fuelled plants; exemptions could apply for CCS plants, or cofiring biomass, while new gas CCGT plants will perform at or below this level;
- Vattenfall-NUON committed to limit CO_2 for new plants at Eemshaven to the level of CCGT (360 gCO_2/kWh);
- HSBC bank will not support units exceeding 850 gCO_2/kWh in developing countries and 550 g in developed countries. Plans might include CCS, biomass and CHP;
- BNP Paribas had similar standards of 550 g in developed countries, but 650 g for developing countries.

It is likely these will only measure CO_2 for simplicity, but other greenhouse gases should be included in future. They also propose to set efficiency standards of at least 43% net in developed countries or 38% net developing countries. Other banks to consider this have included WestLB and Societe Generale. Given the current state of technology, there is little or no risk reduction strategy than can adequately hedge against CO_2 regulations in the EU. However, most international financial institutions have guidance to promote the best available technology (BAT) for fossil fuelled stations. In the cases of institutions that have supported developing nations in the past, such as the World Bank, the Asian Development Bank (ADB), and the African Development Bank (AfDB), the best technology has been sub-critical. However, attitudes to supporting coal-fired stations have changed, and in some cases, financial institutions such as the European Bank of Reconstruction and Development (EBRD), World Bank as well as government bodies like the UK Department of Energy and Climate Change (DECC) have pledged to avoid funding all coal projects where possible. Support for CCS equipped coal plants will probably not be affected by this pledge.

7 Implications of demand scenarios for coal reserve depletion

Given the considerable growth in the demand for coal, we can now apply the various growth scenarios to a comparison with the remaining reserves and get an understanding of the level of depletion. Four global demand scenarios for steam coal used for power generation are shown in Figure 11 as published by Exxon, IEA (Paris), BP, and the IEA CCC.

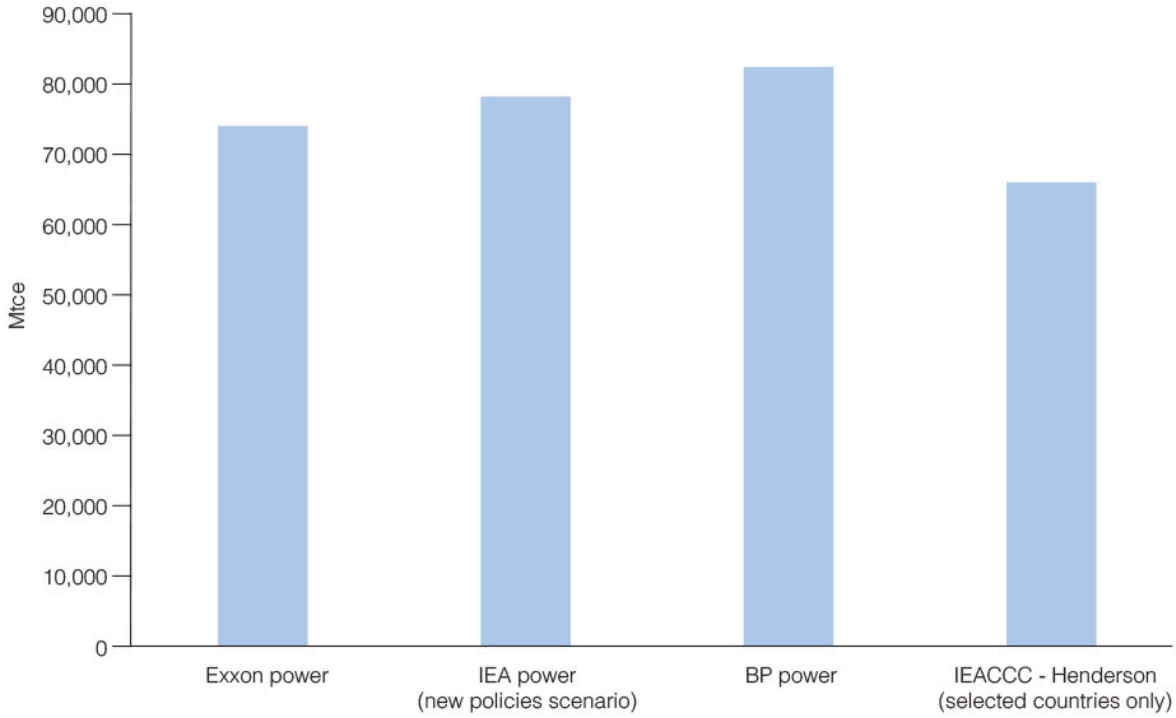

Figure 11 – Cumulative coal demand for the world's power sector in the period 2010-30

Assuming all other factors remain the same, the demand projections are assumed to mirror the total cumulative level of production in the same period 2010-30. The long-term projections are published in intervals of five to ten years. These data are converted to annual series, and so linear interpolating equations are used to calculate the demand in the interim years. In the 20-year period between 2010 and 2030, the total amount of coal that will be consumed in the world power sector could be between 65 and 82 Gtce. For scale, the total global demand for steam coal in 2011 used solely in the power generating sector was 3.2 Gtce (IEA, 2013).

The projection shown as *IEACCC – Henderson* illustrates the same figure for a small sample of countries, chiefly the USA, China, India and South Africa. The blue demand columns do not account for industry, which could be as much as 50% over the power demand (*see later*).

BP (2013) states that the world's proven recoverable reserves amount to 860.9 Gt. The IEA shows a proven reserve level of 1004 Gt. Compared with the cumulative demand in the power sector reaching 65–82 Gtce over 20 years, there appears to be little danger of depleting proven reserves. Based on these peak coal scenarios, just 10% of the global coal reserves will have been used by the period 2030-35. The cumulative demand for (hard and lignite) steam coal demand in the power sector is 92 Gt in the 20 year scenario period between 2010 and 2030 (*see* Figure 10 on page 49). Power generation accounts for 65% of the world's coal demand. When adding all other sectors, the total cumulative demand increases to around 140 Gt accounting for 16% of global recoverable reserves.

7.1 Impacts of exports on producer countries' reserves

Some countries such as Australia, Indonesia, Russia and South Africa are important exporters of coal to the international market and therefore produce greater volumes of coal than their respective markets consume. This added 'demand' for export coal therefore enhances the depletion rate for these countries and adds another dimension of error and uncertainty.

Steam coal exports are expected to rise from 833 Mtce in 2010 to 1095 Mtce in 2020, and 1122 Mtce by 2035 (IEA WEO, 2012). This demonstrates a rise of 35% on 2010 levels, although in tonnage terms the volumes could be much greater if lower calorific value coals are exported such as subbituminous coals from Indonesia or the US Powder River Basin.

According to some projections, global demand for coal could peak around 2030-40; logically international coal trade may well reach a peak also. Another possibility is that those countries specialising in coal exports may have a comparative advantage over many domestic mines elsewhere around the world, and so countries like Australia may well continue to grow their export business.

For the purposes of this analysis a projected coal export target has been used to understand what impact this rise in seaborne trade could have on coal reserves. For Australia, exports of hard steam coal reached 170 Mt in 2012 (SSY, 2013). A possible growth in investment in mine, infrastructure and port facilities could increase exports to more than 200 Mt/y from Queensland alone (QG, 2010). As an estimate, export levels of 250 Mt/y may not be unreasonable for 2070.

Elsewhere, in South Africa exports of steam coal were 77 Mt steam coal in 2012. Expansion plans for infrastructure have been slow over the years, but target capacity for exports of 100 Mt/y by 2070 should not be insurmountable. Growth in exports from Mozambique and Botswana could also follow.

The USA has boosted coal exports in response to domestic market issues, thus seeing exports exceed 100 Mt. The closure of some mines and opposition to coal export facilities proposed for the US west coast continue, but exports of 100 Mt/y are well within current trends and could continue through to 2070.

China and India are net coal importers, at least for now. There's little evidence to show that China will return to its role as an exporter. However, China's coal strategy could switch to support local producers if domestic demand slows down, yet this remains a major uncertainty over the long term. A buoyant trade in seaborne traded coal could see demand for export coal increasing by 450 Mt/y from Australia, South Africa and the USA from a current export tonnage of more than 1200 Mt/y.

Figure 12 illustrates the remaining reserves for a sample of countries for the period between 2013 and 2070 after 50-60 years of coal use in power stations based on a high efficiency scenario in Henderson and Baruya (2012). The bars in the chart indicate the following:

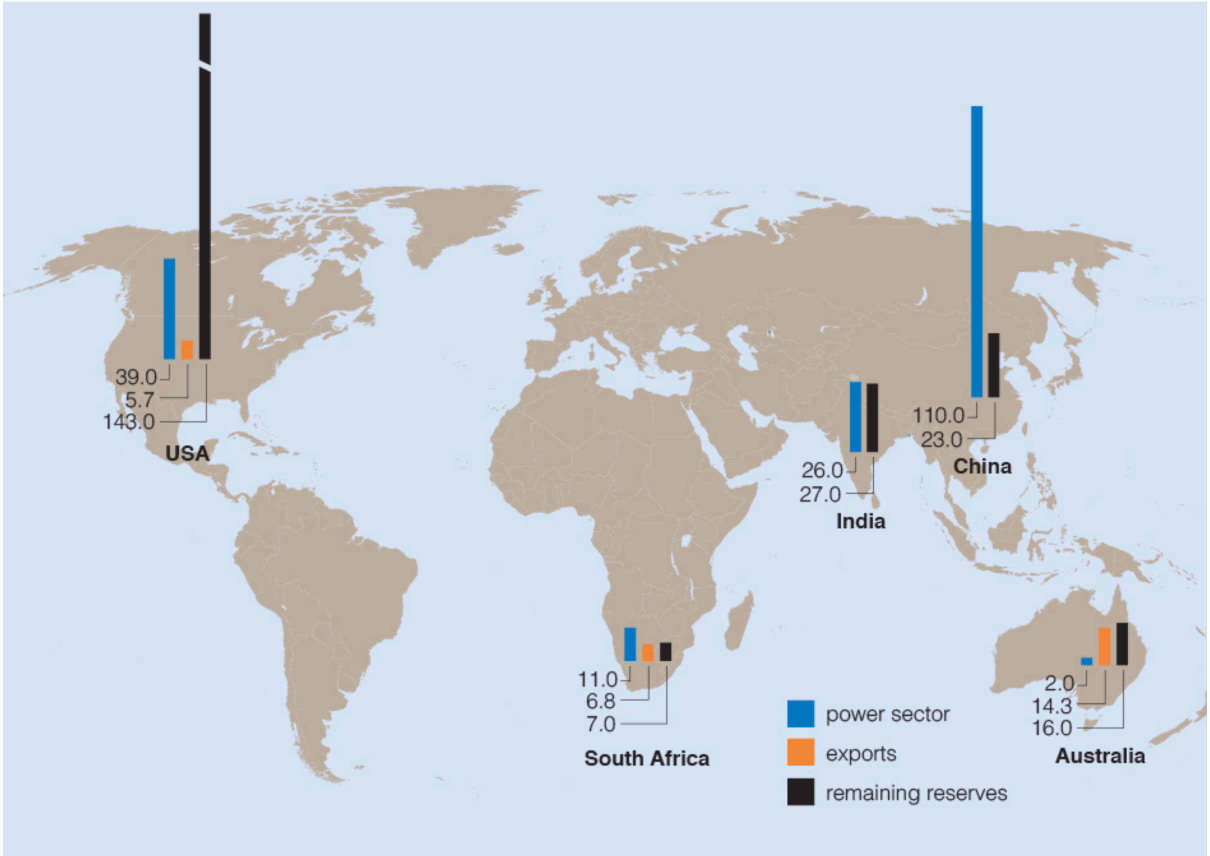

Figure 12 – Remaining global coal reserves in 2070 due to the accumulated demand from the power sector, Gtce (IEA CCC, 2013)

- the black bar indicates the remaining reserves in the year 2070 (total current economically recoverable reserves *less* cumulative power sector coal demand (hard coal only) and cumulative exports of steam coal;
- the blue bar – cumulative demand for hard steam coal from the power sector; and
- the orange bar – cumulative steam coal exports.

The results show that for countries like the USA and Australia, there is little danger of depletion of hard steam coal reserves by 2070, but South Africa, India, and China will have mined half of their recoverable reserves (of that coal that is surveyed and reported today). Resources that have yet to be surveyed and converted into reserves may well change this situation for these countries, along with better techniques for both utilising and mining coal.

Australia and the USA appear to have a much higher ceiling for their domestic and export coal businesses, South Africa on the other hand has a lower reserve. Similarly the South African Witbank fields are approaching depletion but Waterberg and exports from other Southern African countries like

Mozambique could boost exports from the region if sufficient infrastructure capacity can be made available.

The USA appears to have a wealth of hard steam coal reserves but mines in areas like Central Appalachia are facing closure, despite the qualities of the coal being very good by world standards. Low-sulphur CAPP coal is also expensive to produce, and so the export potential is limited. Any gaps left in the market by CAPP producers could be filled by Northern Appalachian, Illinois Basin, and PRB coals. However, the closure of CAPP mines potentially sterilises a considerable amount of reserves lying in this region.

8 Releasing carbon locked in coal reserves – the energy dilemma

This chapter discusses the concept of how coal reserves can be viewed as stored carbon, and the combustion of which will release that carbon into the atmosphere unless power stations can be equipped with CCS.

Low carbon scenarios offer a very different view of the world that we see today, and could offer a much lower energy demand path, which could have two positive impacts: one is a lower carbon future, and therefore helping towards climate targets, second is the preservation of earth's coal reserves for a longer and more sustainable future.

Energy scenarios are different for different economies, but some common threads seem to arise as follow:

- OECD will probably focus more on decarbonisation and energy security;
- non-OECD will be based on economic empowerment and greater parity with OECD nations in terms of GDP, wealth, political and trade influence;
- all countries will be maintaining momentum in wealth creation in order to maintain tax revenues to fund various areas of government and services, chiefly health, education, welfare, defence and so on.

8.1 Carbon in energy reserves

The exploitation of fossil fuels has enabled the electrification of millions of the world's poor and aided economic growth in many parts of the world in a way that few other energy sources can. Inevitably, the use of coal leaves a CO_2 footprint that lasts for many years, and without CCS, it is argued these fuels should be left in the reserves.

To reduce the probability of an average global temperature rise exceeding 2°C, CO_2 emissions from fossil fuels and land use change in 2000-50 must not exceed 1440 Gt (Meinshausen and others (2009). In the first 10 years (2000-11), the world's economies emitted 420 Gt (Oliver, Janssens-Maenhout and Peters, 2012). The budget for 2011 onwards was therefore reduced to 1020 Gt. A further deduction for non-energy related emissions of 136 Gt leaves a ***fossil fuel budget of 884 GtCO₂***. The world has therefore used almost half its carbon budget up to 2050.

More recent reports have come to similar conclusions, stating that global emissions of GHGs should be no more than 820–1445 $GtCO_2$ equivalent. If global emissions are roughly 50 $GtCO_2$/y, then the budget could be exhausted within 15–25 years (Harvey, 2013). This remaining 884 Gt is the total amount of fossil fuels that is permitted to be burned by all sectors of the economy; the most heavily penalised is usually the power generation sector.

The world's fossil fuel reserves contain 2860 Gt of potential locked CO_2 if burned using current technologies.

Two thirds of the CO_2 related reserves are in N America, the Middle East, China and Russia. Africa contains 83 Gt of carbon reserves. Some 53% of these reserves in energy equivalent terms belong to coal.

Without CCS, more than two-thirds of the current fossil fuel reserves cannot be commercialised in a 2°C scenario before 2050 (IEA WEO, 2012).

Coal forms the bulk of the carbon locked in reserves, partly because of the higher emission factor (68% more CO_2 than natural gas), but also because of the larger quantity of reserves compared with gas or oil.

Coal could contain 1800 Gt CO_2 of locked in carbon, compared with just over 600 Gt for oil and 400 Gt for gas.

In 2004, the Intergovernmental Panel on Climate Change concluded that:

Absolute fossil fuel scarcity at the global level is not a significant factor in considering climate change mitigation. Conventional oil production will eventually peak, but it is uncertain exactly when and what the repercussions will be. The energy in conventional natural gas is more abundant that in conventional oil, like oil, is not evenly distributed across the globe. In the future, lack of security of oil and gas supplies for consuming nations may drive a shift to coal, nuclear, and/or renewable energy. There is also a trend towards more efficient and convenient energy carriers (electricity, and liquid and gaseous fuels) instead of solids (high agreement, much evidence). The IPCC maximum scenario depends on an ultimate coal usage (past production plus projected future production) of 3400 Gt compared to 663 Gt projected by the analysis.

According to the IPCC, there are a number of mitigation technologies whose potential is dependent on the price of CO_2. The cheapest (<20 US$/t$CO_2$) include fuel switching and plant efficiency, nuclear and renewable energy leading to a reduction potential of 3.9 Gt CO_2. CCS on coal plants becomes cost-effective at a CO_2 price of 20–50 US$/t$CO_2$. CCS will only be effective if alternatives are costly or not widely available at reasonable cost. It is widely believed that a suitable CO_2 price is necessary to encourage the deployment of low carbon technologies. This level of CO_2 price could have major impacts on the future demand trends for coal and the implications on reserves as discussed in the previous chapters.

9 Metallurgical and low-rank (steam) coals

9.1 Coal reserves defined by use

In mass terms, more hard steam coal is produced every year than any other type of coal (5770 Mt), accounting for 75% of global production. A remaining 1900 Mt is split between coking coal and lignite. The respective impacts on steam and coking coal reserves are therefore different. Table 1 lists the world's reserves. Much of the analysis so far has looked at the impact of the power sector on hard steam coal reserves. Initially, current levels of production were considered unsustainable, but scenario analysis considered the positive impact of peak demand that might occur due to carbon constraining policies that promote new clean coal technologies alongside cleaner alternatives. This chapter shifts the focus to the other coals, coking coal and lignite (steam).

As this report has already mentioned, published reserves data comprise a range of coal groups, the broadest being:

- hard coals comprising of anthracite and bituminous, and
- subbituminous and lignite.

In general, these categories are separated by the (total) moisture content, where anthracite and bituminous coals have low moisture, and subbituminous and lignite have high moisture within the coal. Other characteristics are also included, but for simplicity, moisture content is probably the easiest way to identify these broad types of coal. Moisture content is different from the commonly used term 'dry' when examining a coal's quality for the purposes of pricing where this refers to the absence of all moisture as though it is to be fired into a power station boiler or similar, and so may be dry for testing purposes. According to the World Coal Association, coal rank and quality is determined by:

- varying types of vegetation from which the coal originated;
- depths of burial;
- temperatures and pressures at those depths;
- length of time the coal has been forming in the deposit.

Over time, the degree of change in the coal determines its rank, gradually maturing from peat to the highest rank coal, anthracite. This change is known as coalification. Ranking is determined by the degree of transformation of the original plant material to carbon. The ranks of coals, from those with the least carbon to those with the most carbon, are lignite, subbituminous, bituminous and anthracite. The order of rank is also similar to the order of moisture content.

Figure 13 illustrates the range of coals that exist and the various applications associated with that coal type, and also the minor differences in coal definitions in different parts of the world. It is worth noting that while power generation applications can use lignite, subbituminous and bituminous coals (and occasionally anthracite), often these coals cannot be interchanged, and power stations are designed to use one or other of the fuel types due to specific characteristics and design criteria peculiar to that coal. One exception is the subbituminous coal, whose characteristics make it suitable for blending and in some cases replacement for bituminous coals without too much modification to the power station. Power stations designed for lignite rarely burn other coals as the stations are usually minemouth to lignite mines and substitution is not practical.

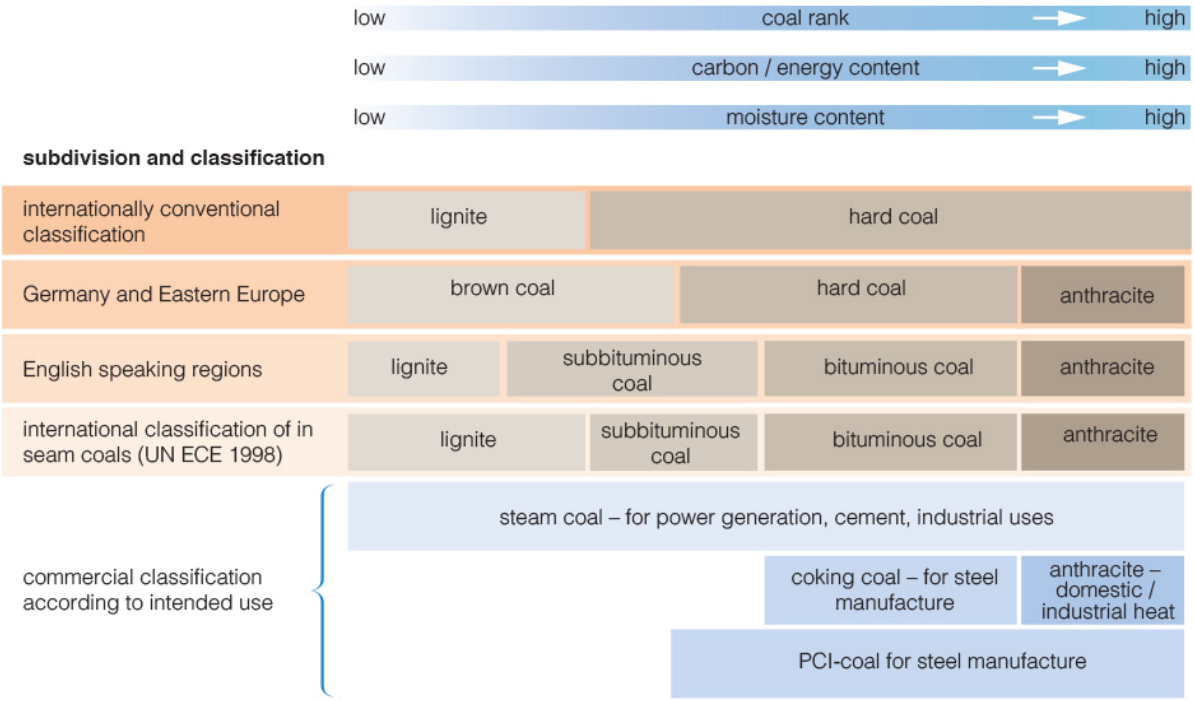

Figure 13 – Coal types, key characteristics, and applications (WCA, 2013)

There are a few specific uses for certain coals, these coals are uncommonly interchangeable and will be discussed later. The system of coal classification devised by the *United Nations Economic Commission for Europe* (UNECE) and described in Chapter 2 is based partly on the British National Coal Board Code system and partly upon the ASTM coal classification. The parameters that separate hard steam coal from hard coking coals are the caking and coking properties of coals that typically contain less than 33% volatile matter; a steam coal's key characteristic is calorific value for coals with more than 33% volatile matter (for anthracite, bituminous, and lignite coals). Low volatiles contents can still be found amongst bituminous coals and anthracites; these coals either need to be burned in specially designed boilers, or are suitable as metallurgical coals. Other parameters are used to characterise the caking properties of hard coals, namely, the thickness of the plastic layer (y), the free swelling index (SI), and the Roga index (RI).

Most coking coals are traded by seaborne dry bulk vessels; steel producers therefore rely on the international export market for their supplies. The quality control and criteria for coking coals are often strict, undergoing washing and preparation prior to shipment. Coking coals therefore command higher prices.

9.2 The coking coal market

Consumption of coking coal (and to a lesser extent pulverised coal injection) amounts to 600 Mt, at least 12% of coal consumption. Although coking coal is a minority product in the global coal market compared to steam coal, the value of coking coal is significant, being priced at roughly double that of steam coal. Its financial appeal to coal producers is therefore very attractive t times of higher prices.

Global inventories of coking reserves are difficult to assess due to a relative lack of publicly available data. In Chapter 2, world coal reserves show the various coal types, but deriving this on a wider global scale is challenging. Tables 4 and 5 summarise the results from Table 1 showing reserves of hard steam coal, hard coking coal, and lignite (brown coal). Subbituminous coals are unusual, in that they can be high moisture and low heating value, but often the qualities straddle hard steam coals and lignite. For convenience, subbituminous coals are included in the hard coal category as subbituminous and bituminous coals are commonly blended, but lignite is rarely burned with any other types of coal.

As Table 6 shows, global coal reserves consist predominantly of hard steam coal (bituminous coals and anthracite) which accounts for more than half of the recoverable global reserves, amounting to 562 Mtce. Coking coal accounts for 18% of global reserves, equivalent to 187 Mtce, while lignite accounts for a sizeable 27% of known recoverable reserves (276 Mtce). According to the data, there appears to be more lignite in the world's reserves than coking coal, therefore, the abundance of lignite may well prove to be a more valuable energy reserve than perhaps initially thought.

Table 4 – Cumulative coal production projections (IEA, 2012; IEA CCC, 2013)

	Global reserves, Gtce	Production, Gtce	R/P ratio	Cumulative production 2012-35, Gtce	Remaining reserves in 2035, Gtce
	2012	2012	2012	2012-35	2035
Hard steam coal	562	4.2	135	109	453
Coking coal	187	0.8	234	19	168
Lignite	276	0.3	935	6	270
Total	1025	503	195	134	892

This is evident in the R/P ratio in Table 4, where lignite reserves have enough tonnage to last more than 900 years. Coking coal has 234 years but hard steam coal has the least at, a still impressive, R/P ratio of 135 years based on IEA figures, which may differ from other data quoted throughout this report. Based on the IEA WEO (2012) projections for coal production to 2035, hard steam coal will have amounted to more than 109 Gtce, coking coal 19 Gtce, and lignite 6 Gtce. Figure 14 illustrates the extraction to reserve after 23 years of continued production between 2012 and 2035 under the New Policies scenario. In almost all cases, demand peaking (and production) occurs towards the end of the projection period, and as such, barely half of the world's coal reserves will have been extracted at this point, leaving two major conclusions, either

- a vast quantity of coal is left in the ground potentially as stranded assets in the event of demand side peaking; or
- a vast quantity of energy assets remains in the ground, providing many years of future fossil fuel supply to the world.

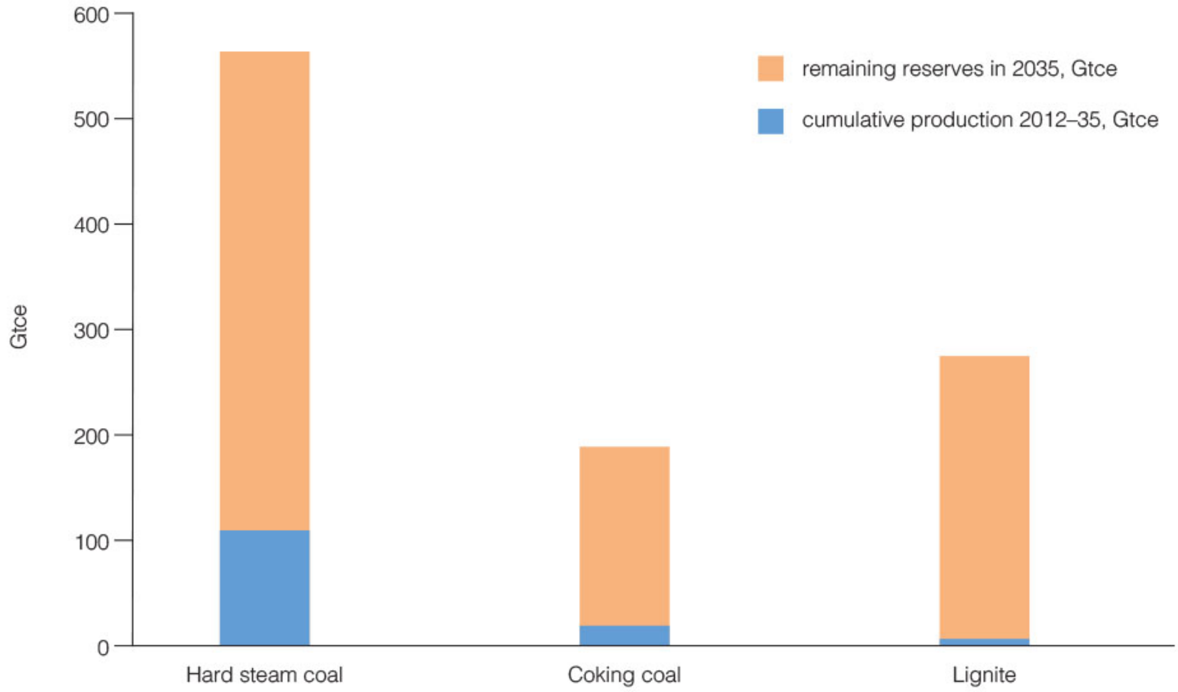

Figure 14 – Cumulative production in 2012-35 (IEA WEO, 2012)

Even under a Current Policy scenario where demand and production grow at higher rates, the increase in total coal production over the forecast period is 19 Gtce, a small proportion of the 1025 Gtce that exist. Conversely, the 450 scenario sees demand reduced by 30.4 Gtce in the period 2013-35 compared with the New Policies scenario.

9.3 Coking coal and lignite production

Coking coal only accounts for 16% of world coal production, lignite is even less. However, unlike the massive variation in demand/production scenarios for hard steam coal, coking coal and lignite seem less sensitive to competitive pressures than hard steam coal markets are subject to (*see* Figure 15). Nevertheless, the share of lignite production compared with other coals falls (*see* Appendix Table 9). Lignite production is strongly correlated to the demand from local markets. The costs of transportation resulting from the low heating values and high moisture contents of the fuel means it cannot be transported by rail or shipped over long distances. Consequently, lignite exports are limited to short distance rail shipments between neighbouring countries in parts of Central and Eastern Europe, chiefly the Czech Republic and the Slovak Republic. However, the future of lignite production is particularly unclear. Methods of coal upgrading could improve the prospect of lignite production and utilisation if they become commercial and are discussed in Dong (2012). These technologies have reached either pilot scale or commercial demonstration scale with projects undertaken in Indonesia, the USA and China.

Low rank coals are already being readily exported, with low heating values of less than 5000 kcal/kg being quite normal for Indonesia, compared with South African exports of 6000 kcal/kg, and Australian exports of more 6300–6700 kcal/kg. Despite a threat of banning low-rank coal imports into China in 2014, the demand for such fuels in the rest of Asia could remain strong

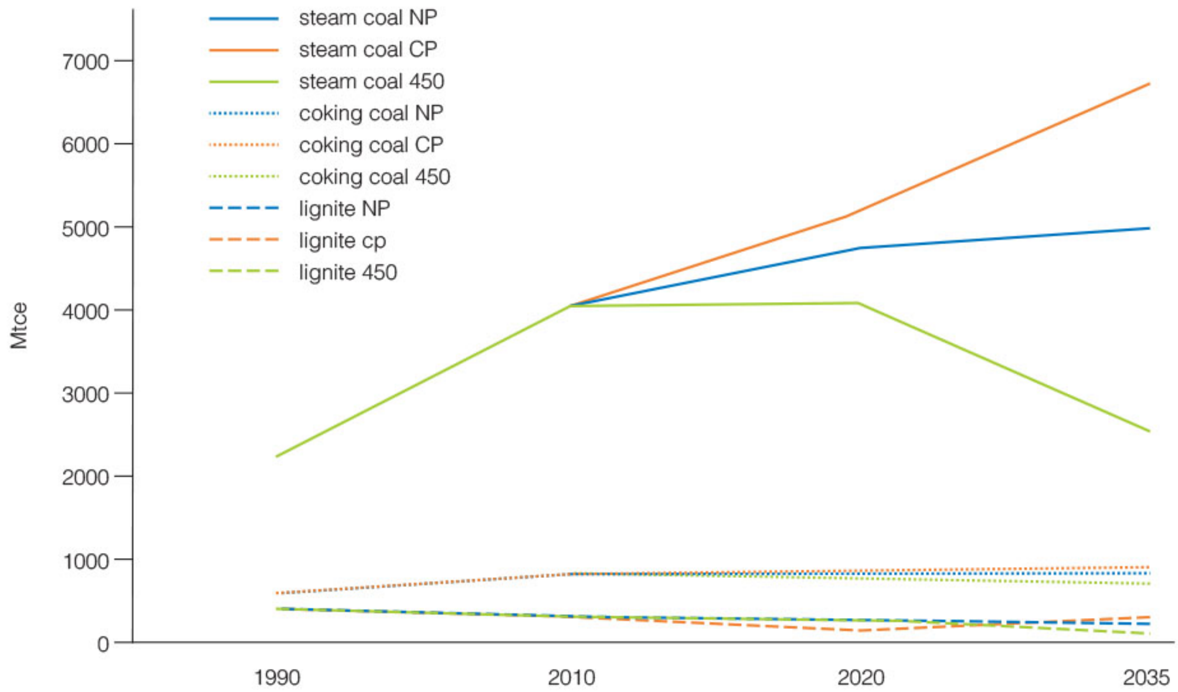

Figure 15 – Current (CP), New Policies (NP), and 450 ppm scenarios for hard steam, coking and lignite coal demand between 1990 and 2035 (IEA WEO, 2012)

9.4 Drivers of coking coal markets

Coking coal prospects are tied closely to steel production which requires coke, a high carbon content product derived from coking coal. The *basic oxygen furnace* (BOF) steel production process uses about 450 kg of coke to produce a tonne of steel (Parums, 2012). The coke is converted from around 500 kg of coking coal in ovens. Coking coal is converted to coke by driving off impurities to leave almost pure carbon. The physical properties of coking coal cause the coal to soften, liquefy, and then solidify into hard but porous lumps when heated in the absence of air. Coking coal must also have low sulphur and phosphorous contents. Almost all metallurgical coal is used in coke ovens.

Efficiency gains in coke making and shifts to other methods is a key determinant in the demand for coking coal, which in turn is determined by the demand for steel and steel products. According to Parums (2012), BOF steel production that is coke intensive will continue to increase between 2011 and 2013, but at a slower pace compared to the production of finished steel products. The emergence of alternative methods which are less carbon intensive, chiefly the electric arc furnace method, will make up the difference.

Even within the world's BOF production capacity, the amount of coke use will decline from around 450 kg/t steel, to less than 420 kg. While these efficiencies occur, the rate of pulverised coal injection will increase from around 110 kg/t steel to 150 kg, giving rise to a fuel termed PCI coal. These are typically coal products which are much cheaper than coking coal, but priced above normal steam coal. The quality of the product reflects this price position, yet it's good enough to be injected in small amounts to supplement the coke in a blast furnace process.

The BOF process can also use around 30% scrap recycled steel, but the *electric arc furnace* (EAF) process, which is a purely electricity based process as the name implies can use 100% recycled scrap. The energy intensity is still large consuming vast amounts of electricity, and without access to hydroelectricity, EAF steel production can still lead to round 150 kg/t steel of coal consumption where coal-fired power is prevalent (WCA, 2013b).

9.5 Coking coal reserves

Figure 15 shows the IEA WEO (2012) projections for the three main coal types and the three main scenarios. What is clear is how the variation in total projected coal demand will be almost entirely dependent on the scenarios for (hard) steam coal demand for power generation. This is due to the policy driven scenarios determined by national and international regulation to reduce greenhouse gas emissions in addition to stricter emissions of SOx, NOx, and particulates. In part, the same regulations apply to the coking coal and lignite markets where CO_2 legislation is no less important, although these sources are relatively small compared to the power sector.

The projections for demand are more or less the same for each scenario shown in Figure 15, and the future demand for lignite and coking coal shows a fairly flat trend, with some minor reductions in lignite. Reserves will therefore be unaffected by whichever policy scenario the trends for coal demand follow. Comparing the cumulative demand (ultimate rate of recovery) with reserve data for coking coal in Table 4, reserve depletion can be assessed after any given period.

This report has already discussed the life of coking coal reserves. This section looks in a little more detail about where these reserves are found, for the key hard coal producing countries in the world, that have a high coking coal production (*see* Table 5).

Table 5 – Coking coal reserves (IEA CCC, 2013)		
Country	Reserve/ resource, Gt	Coking R/P
World	430	
China	31.9	63.3
Australia (QLD)	10.0	
Australia (NSW)	1.6	79.3
Russia	35.9	460.0
Canada	6.6	227.6
USA	39.0	475.8
Poland	5.8	522.8
Ukraine	13.6	679.9
Kazak	5.0	384.6
Mongolia	8.3	416.5
SA	1.8	596.6
Mozambique	11.0	
Zimbabwe	2.0	
India	17.9	512.4
Subtotal	190.4	201.3

9.5.1 China

China could have more than 30 Gt of coking coal, and with high rates of production, the R/P ratio of these coals is 63 years, one of the lower ratios seen in the list. Yet, China has the third largest reserves after Russia and the USA. In China, coking coal is most abundant in a few a provinces, mainly in Shanxi, but the reserves are not found in shallow seams. At depths of 800–1200 m there are large amounts of 'fat' coal and coking coal with good 'caking' characteristics. Fat coal and coking coal are just two terms for coals suitable for coking; an estimated 56% of coking coal resources are found in Shanxi.

9.5.2 Canada and the USA

Canada has just 6.6 Gt of coking coal, but at current extraction rates the life of reserves is 227 years. Most of Canada`s metallurgical coal deposits are located in the Rocky Mountain Ranges of south-eastern British Columbia and south-western Alberta, and in the Inner Foothills Belt of north-eastern British Columbia and west central Alberta. Most of Canada`s thermal coal deposits are located in the Interior Plains of Alberta and Saskatchewan, and in the Outer Foothills Belt of Alberta. Other major thermal coal resources occur in the coastal and intermontane regions of British Columbia, and in Northern Canada.

The key area for coking coal mining is the region labelled medium-low volatile bituminous coal, a long thin field from lower (west) Alberta to the northeast of British Columbia. This is part of the largest coal bearing field that starts in southern Saskatchewan and Alberta and lies south of the Canada/USA border. While a majority of coal is low sulphur, the coal rank in this region is highest towards the Pacific coast, while the rank lessens towards the interior to lignites in Saskatchewan. Eastern coast coalfields are higher rank bituminous with coking quality coals but also higher in sulphur content. The northern field, chiefly the Yukon Territory contains high, medium, and low volatile content bituminous coals although some smaller coalfields are present in the Yukon Territory.

In the USA, there could be the largest reserves of coking coal in the world at 39 Gt, with an impressive R/P ratio of 475 years. The largest reserves of coking coal in the US exist as low volatile, low sulphur coals in Central Pennsylvania and West Virginia. While coking coal and lignite form much smaller proportions of total coal production, it is important to understand the cumulative effect of continuous production of coking and lignite coals as these fuels are vastly different from each other.

9.5.3 Russia

Table 5 shows a conservative reserve base of 36 Gt, but beyond this, Russia could have one of the largest coal resources in the world with forecast resources of 3928 Gt. Coal deposits recorded in the Russian state balance are those most promising for development which amount to 192.3 Gt with a further 75.8 Gt in category C2; the potential is therefore immense (Crocker and Kovalchuk, 2008). Some 80% of the explored reserves of coking coal in Russia are concentrated in the Kuznetsk Basin. Coking coal reserves are also found in the Far East Federal District South Yakut Basin and in the North-Western District Pechora Basin. The realisation of Russia's reserve potential appears to be as in need of greater research than almost any coal producing country in the world.

9.5.4 Emerging producers – Mozambique and Mongolia

Emerging coal producers include Mozambique and Mongolia. These countries each have attracted a great deal of foreign interest in coal mine operation. Mozambique could have a reserve base of 11 Gt, while Mongolia could have 8 Gt. These countries are in the early stages of development and have been targeted as potential export producers to the Asian market.

Key target markets include India which itself has 17.9 Gt of coking reserves, but Mongolia and Mozambique could rival Australia in terms of total coking reserves. Each of these new producing countries will also have associated steam coal production, but their industries are in their infancy and the true potential could well exceed that of almost any other exporting country.

Mozambique benefits from having several export ports and rail infrastructure projects are being developed to exploit these. Mongolia is currently discovering the potential to use Russian rail infrastructure as well as Black Sea routes to transport coal to Eastern Europe. A great deal more research is needed to monitor these countries as the coal industries develop.

10 Extending coal reserves – or slow the closure

10.1 Risks of reserves sterilisation – US case study

The assessment of mineral reserves is based on detailed surveys that determine the quantity and aspect of coal that lies below the ground. However, once the mine is designed and in operation, not all of the coal can be exploited. For this reason corrections are made to the reserves to ensure there is an accurate measure.

A good example where constant assessments and data gathering are made of the country's resources is the USA. The recoverable reserves of existing mines are tracked every year by the US Energy Information Administration (EIA). An extremely interesting outcome is that the number of producing mines in 2011 dropped to levels equivalent to that of 2003 with 1296 mines operating (*see* Table 6). This level could fall further in 2012 and 2013 as operations in Central Appalachia idle and shut also; production nationwide has also dropped to 1.09 Gt (short).

Reserves reported by the US coal industry have increased over time, yet paradoxically more coal seems to exist in fewer mines. Clearly, the closure of mines has opened up opportunities for the existing mines to fill the gap left in the market with further exploration and coalfield development. Yet the closed mines may or may not be reported. It therefore raises the question, whether reserves become 'sterilised' after the closure of a mine, and what proportion of the world's reserves would be subject to this.

Demand and supply peaking may well lead to many mines becoming uneconomic, but mines that have been subject to flooding, catastrophic mine fatalities, or permanent closure will mean all reserves linked to these coal seams could lie abandoned. It is difficult to properly assess this as the resources that are yet to be proven economically recoverable could compensate for the sterilisation of closed mines. In India, a number of reports have expressed concern regarding these issues. The reality of the correct reporting of coal reserve, but also the restrictions that could face future development, is well documented.

Table 6 – Annual recoverable reserves and production reporting in the USA (EIA, 2013)				
Year	Recoverable reserves at producing mines, Gt, short*	Coal production, Gt, short*	Number of producing mines*	Net change in number of producing mines from the previous year*
2003	18.0	1.07	1294	
2004	18.1	1.11	1357	+63
2005	18.9	1.13	1398	+41
2006	18.9	1.16	1424	+26
2007	18.6	1.15	1358	–66
2008	17.9	1.17	1435	+77
2009	17.5	1.07	1375	–60
2010	17.9	1.08	1257	–118
2011	19.2	1.09	1296	+39
*reserve, production, and mines do not include refuse recovery				

10.2 Losses of reserves during mining

Despite the best efforts of the mine planner and the accuracy of the reserve data, production and extraction techniques can lead to the reserves being underexploited. These losses can occur in both underground and opencast mines. Losses at the mine occur due to the incomplete extraction of the seam or leaving coal in the ground (Baruya, 2012). Intentional losses such as the coal left in the supports for room-and-pillar mining can be substantial, in extreme cases up to 90% of a coal reserve, but typically more like 40%, but retreat mining can utilise some of this. Under these circumstances, coal reserve data should take these losses into account.

In India, some coking coal reserves are in danger of being sterilised. Most of Indian coal production is from opencast mines, but from underground mines, for every 10–30 t of coal extracted, 90–70 t is not being recovered. Much of this coal is left in the ground to ensure the integrity of pillar supports for ongoing extraction. A significant amount of coking coal is burnt inside the mines of the Jharia basin alone. Over the last century, a large number of mines have been closed with no appropriate mine closure method.

India's total coking coal reserves available up to a depth of 1200m appear to be based on ***virgin reserves alone***. Reserve and resource assessment ***does not take into account the coal that is locked in pillars of the closed and abandoned mines*** and excludes seams of ≤0.5m thickness from the coal inventory. These losses are an example of coal that is intentionally left in the coal mine. It consists of potentially marketable coal but inaccessible using the current means of extraction. This does not necessarily deem these as inaccessible using future means of production, perhaps through underground coal gasification.

The importance of opencast mining and longwall extraction is increasing for high productivity mines, but bord and pillar is still a method used widely across the world.

10.3 Intended losses in bord and pillar mining

Bord and pillar mining offers the flexibility to extract coal from thinner or narrower seams where longwall is less suitable or uneconomic. Pillars are essential in cases where localised load bearing permits workings to occur in the vicinity of the pillar safely (Wagner, 1980). Pillars can be dug out under safe conditions to maximise the reserve, but often the pillar protects surface ground support, to prevent subsidence. As such, the coal reserves lost to the pillars must be accounted for when assessing coal reserves.

Coal pillars should be as small as possible to minimise losses in the reserves, but the loading condition can be complex given the nature of the coal seam and the surrounding rock. With large pillars, if there is no scope to recovery the coal from these pillars due to safety, there's a risk much of the reserves will be sterilised. There is no amount of surveying or accurate reserves assessment than can compensate if the recovery of the total reserve is low due to large pillar design.

Room and pillar mining can leave 50–60% of the coal in place to support the mine roof, so this potential reserve could be exploited safely if the geology allows. If the overburden subsidence permits excavation, support pillars can be mined out in a process called retreat mining in the mine's last phase of coal extraction. Temporary support pillars such as mobile roof supports relieve the pressure of the overburden. This is often planned as part of the whole mine development over the life of the mine. So the retreat mining does not suddenly boost coal reserves, but it does minimise sterilisation of the reserves. Retreat mining starts at the back of the mine at the furthest coal face, and mines towards to the entrance, allowing the mine to collapse in a controlled fashion after the equipment and personnel have been evacuated.

10.4 Thin coal seams

Aside from pillars and residual coal, thin coal seams can exist which are less accessible by large mechanised means. In China, mineable thin coal seams can account for 20% of the total resources and as much as 10% of total production (Wang and others, 2012). Thin coal seams may be identified as less than 1.3 m; while in the USA thin coal seams might be less than 2 m. In China, mineable thin coal reserves amount to 6.1 Gt. Given the warning of peak coal in China in coming years, accessing these seams could be a more common feature of the industry.

Thin seams face a limited degree of automation, low advance rates in mixed coal/rock ground, and require a larger number of mine personnel to extract each tonne of coal. Mechanisation in underground mining technology has improved rapidly with the use of advanced shearers, ploughs and auger mining methods. Thin seams can contain hard stone bands that contain pyrite, and so blasting may be necessary. Blasting methods can greatly enhance the extraction rates, by loosening the coal seam making extraction easier but clearly carries a higher risk of loss if done incorrectly.

10.5 Opencast seam losses

In an Australian study in the mid-1990s, 94% of the mines surveyed considered that losses might occur in two ways (Scott and Wedmaier, 1995):

- incomplete extraction thus leaving good coal in the ground; and
- full extraction which leads to surrounding rock entering the coal feed, therefore diluting the coal and lessening the coal's product value.

Where overburden was subject to loosening by explosive blasting too close to the coal seam, and then removed using a dragline, the top of the coal seam itself might be mixed and lost during the overburden removal process. This loss is often the cause of large scale removal of the overburden, operator error, or poor visibility during operating hours. These are just a few factors, but a more detailed analysis of all the loss and dilution problems of coal mining can be found in Baruya (2012). Loss analysis of a variety of mines in Australia showed that 7% of the mineable (in situ) coal was lost during opencast mining, with losses greater in New South Wales (8.5%) than in Queensland (6.5%). Losses were lower for underground mines where the coal extraction was more selective and care in avoiding cutting into the surrounding rock was paramount. This was not only to ensure a better quality product with little dilution, but avoiding hard material reduces wear on the cutting teeth and therefore reduces costs and maintenance downtimes.

10.6 Utilisation of fines and minimising losses

Lewitt (2011) and Baruya (2013) discuss the potential for the utilisation of coal that is otherwise lost from settlement ponds resulting from the coal fines from washery plants. The fines have a heating value and are otherwise difficult to handle using conventional transportation measures, such as rail and truck. Fines could yield 10–20% of material that is otherwise lost, but recovery is possible.

10.7 Mine closure in China

Mine closures are difficult to assess and could create a great deal of uncertainty in the assessment of reserves. For example, mine closure due to accident or flooding could threaten the sterilisation of that particular seam or reserves. The dangers may be too great to rework the coal face therefore creating a very uncertain future for that mine and cause a loss of reserve.

Mine closures due to inefficiency and poor working and safety practices could potentially be reworked. The spate of closures occurring in 2011-12 is based on a threshold of mine capacity, where small mines are associated with high accident rates and poor working conditions. Coal mines with an annual production capacity of less than 90,000 tonnes as well as those that do not meet safety standards.

In China, safety problems and accidents are a serious concern and being addressed quickly leading to a considerable reduction in fatalities. However, of these closures, the implications of cessation of production on reserves sterilisation are not yet fully understood. Mining technology has improved greatly in 622 mines, and 388 mines were merged with other operations. China is planning to close a further

5000 small mines in 2013, and 2000 mines before 2015. Areas that accelerate mine closures or succeed in shutting more mines will be provided with more financial aid. Coal regions would also be encouraged to develop alternative industries and improve infrastructure. (Qing K, 2013)

These mergers and closures of the smallest mines had an impact on almost 100 Mt/y of production, yet output from the industry continued to grow, even creating stock surpluses in 2013. Clearly ongoing analysis of the Chinese market is essential as structural changes can bring about closure of some facilities, but mergers and expansion of others.

11 Unconventional coal resources

One of the most pressing issues of recent years has been the impact of unconventional sources of fossil fuels, most notable shale gas and shale oil. The impacts on the global coal market are still yet to be fully felt outside of the USA, but interest in shale deposits is attracting a great deal of investment and policy debates in countries across the world. The major sources of unconventional energy from coal involve a whole suite of potential products that can be manufactured from coal. These include *coal-to-liquids* (CTL), coal gasification above ground for power generation and industrial chemicals, *coal bed methane* (CBM), and *underground coal gasification* (UCG). The first two approaches are more related to coal utilisation, while CBM and UCG are both related to the exploitation of in situ coal reserves.

11.1 Underground coal gasification

UCG is being looked at particularly for utilising unmineable coal deposits and deeper seams which are not included in the proved reserves figures (Couch, 2009). The amount of work carried out in deep seams is very limited. It can potentially be used in steeply dipping seams and in coal deposits where the ash content is so high that it precludes conventional extraction. Nobody is currently looking at UCG in preference to conventional mining where the coal can be extracted economically using well proven methods, but if the technology becomes established, that situation might change.

Early studies suggest that the use of UCG could potentially increase world's coal reserves by as much as 600 Gt (World Energy Council, 2007), which represents a 70% increase. As discussed in this report, UCG is not easy to carry out without environmental impacts, and the inability to manage these acceptably would reduce the amount of coal which can be utilised by this method. However, even an increase of 60 Gt (based on a conservative assumption that just 10% of the potential can be realised) would provide a significant amount of additional energy.

Coal deposits located at or near the surface can be extracted by open pit methods at depths down to 100 or 200 m. Underground mining of the deeper seams is possible at depths down to a little over 1000 m, although it gets increasingly expensive to ventilate and cool the deeper mines. Extraction costs increase at greater depths, and are proportionately higher for mining thinner seams.

Only a fraction of the energy can be recovered by conventional mining, some is recoverable in the form of CBM extraction, and considerably more would be recoverable if UCG is developed into a commercial-scale process. The order of magnitude of the different approaches is illustrated in Figure 16. Figure 16 is based on a typical coal deposit in the Surat basin in Queensland, Australia. The average seam thickness there is 7 m. The deposit is in an area comprising some 12 km^2 and lies almost horizontally. Not all deposits can be mined conventionally, and any comparison is 'coal deposit specific', nonetheless the diagram illustrates the potential for energy recovery using UCG and provides an indication of the orders of magnitude involved. Underground gasification would therefore pose as an opportunity to exploit reserves that would otherwise be unattainable using conventional means. However, theoretically all coals could be obtained using UGC, but it would be uneconomic to do so for coals that could be extracted using opencast or longwall/bord and pillar methods.

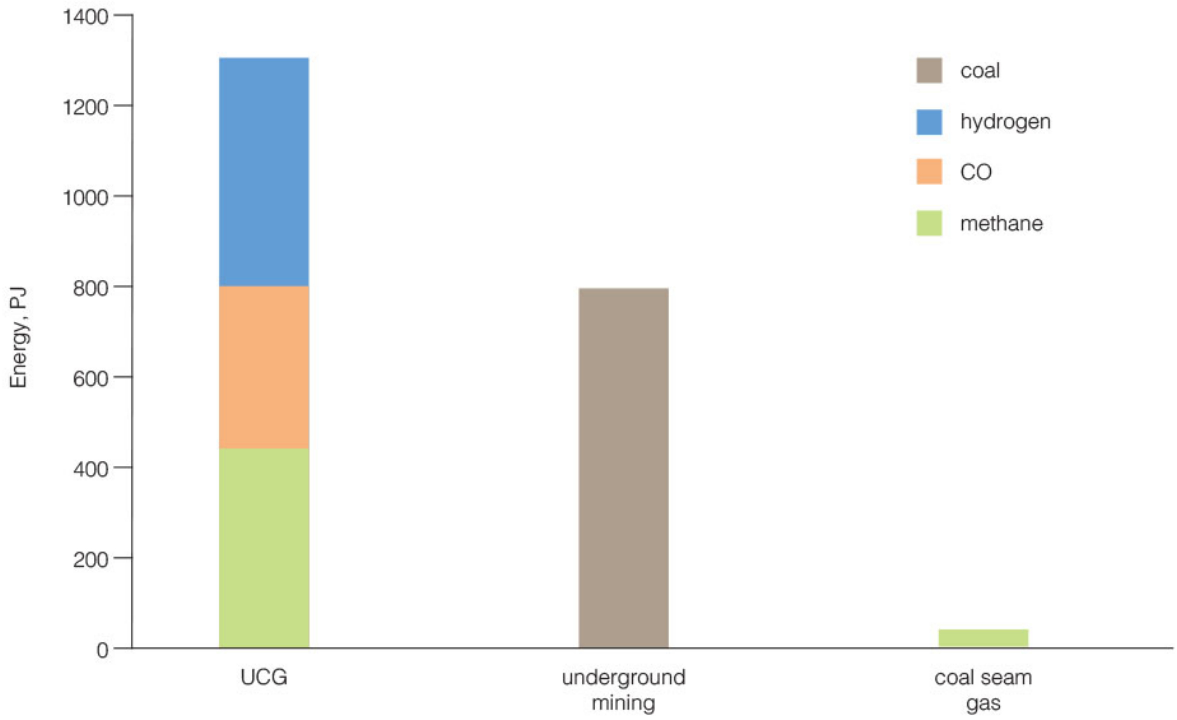

Figure 16 – Potential energy recovery comparison from different methods of energy extraction from coal seams (Mallett, 2008)

11.2 Coal bed/mine methane (CBM/CMM)

Coal bed methane (CBM) is a generic term for gas that is stored within coal pore and fissure structure, and might refer to gasses that have been released during mine operations, and/or remain in situ in unworked seams. CBM is becoming an attractive option to enhance natural gas reserves for some countries, but also to avoid the uncontrolled emissions of methane, a potent greenhouse gas. By capturing and combusting the CH_4 methane, the greenhouse gas impact is lessened.

Coal mine methane (CMM) specifically refers to gasses released from the coal and surrounding rock strata of a mine facility. In underground mines, methane poses a hazard to coal miners, so it is removed through ventilation systems. Some underground mines are sufficiently 'gassy' to use enhanced ventilation systems using degasification (drainage) systems. In abandoned mines and surface mines, methane escapes through natural fissures. CMM is an incredibly important resource, which if uncontrolled, and not utilised, contributes to 8% of total global anthropogenic methane emissions (WEC, 2010). Methane from existing underground mines is one of the major sources of these emissions.

CBM utilisation started in the USA in the 1980s, where detection and extraction methods were rapidly developed. Advances in basin modelling, seismic techniques, horizontal-well drilling and hydraulic fracturing have reduced the uncertainties relates to reserves assessments; these are all methods common to fracking.

Global CBM resources are found in Russia, Canada, China, Australia and the USA. In 2006, global resources of CBM ranged 73–184 Gtce (143 trillion m^3), while only 1 trillion was exploited (Ojha and others, 2011; CBM Asia, 2013). Studies of major coal-bearing basins in the world suggest that more than 50% of the estimated in situ CBM resources are found in coals at depths below 1500 m (Thomas L, 2002). The USA produces around 72 tce (56 billion m^3/y) while Canada produces 12 tce (9 billion m^3/y). In Australia, CBM represents 21% of Australian domestic gas supplies. CBM accounts for 40% of Australia's onshore gas reserves. India is encouraging CBM with new areas being licenced to operators. Production started at 0.3 ktce/d (0.2 million m^3/d) in 2011-12, and could rise to 5 ktce/d (4 million m^3/d).

China has enormous potential given the coal reserves with 48 Gtce (37 trillion m^3) at depths below 2000 m. Production is around 11 Mtce (8.6 billion m^3) and there are aims to double this to more than 26 Mtce (20 billion m^3) by 2015 based on the 12th Five-Year National Plan. Shale gas remains the main area of interest regarding unconventional gas reserves. However, the potential yield from CBM could be immense.

CBM is a complex issue when extraction is involved. The porosity of the coal, whether the gas resides as a dry gas within pores making it a more useful reservoir, or whether most is dissolved in water within the coal pores making extraction far more limited. In abandoned, mines, CBM can effectively extend the life of the energy reserves associated with the former coal operation. In which case CBM does not replace coal production or sterilise reserves, rather the gas extraction process enhances it. CBM drainage can therefore be successful and have a twofold effect:

- support gas supplies with methane from coal that cannot be mined economically using conventional methods (depending on the prevailing market price);
- supply gas prior to coal extraction therefore extending the business plan to a gas and coal operation over the longer term.

12 Conclusions

Coal reserves are probably the most abundant source of fossil fuel in the world today. With more than 100 years of coal, the expectation of depletion is far off into the future, but with coal use declining in some regions and accelerating in others, the implications of depleting reserves differ around the world.

Perhaps due to its abundance, accuracy in measuring coal reserves is not seen as necessary. Nevertheless, getting a better understanding of reserves and resources has several important and disparate implications:

- to provide an advance warning of reserve depletion in parts of the world that have high coal extraction rates;
- assess the potential depletion of coal over the long term (up to the years 2070-2100) under different coal demand scenarios and adapting the concept of peak oil to coal reserves (which could feasibly occur as soon as 2020-35);
- differentiate metallurgical coal reserves from thermal coal reserves, and the different ranks to see whether this creates a squeeze on the types of coal that will be in most demand in the future;
- determine how a global shift in coal technology such as CCS could impact coal demand;
- measure the potential stored carbon that could be released as CO_2 into the atmosphere from unabated coal combustion, this is critical for feeding future CO_2 emission data into a climate change models;
- consider the factors that will lead to a more sustainable use of a limited resources, such as demand destruction and a careful extraction of coal leading to a much more efficient coal supply chain;
- and alternative and unconventional methods of energy extraction from coal reserves (such as UCG and CBM).

As a definition, the most meaningful measure of a coal reserve is that that is economically recoverable. Although a great deal more of the coal could be technically recovered, the coal could reside in seams that are difficult and expensive to mine using current methods.

Before the emergence of a large market for seaborne traded coal, a great majority of the world's coal supply was for use within the country borders of where it was mined. This resulted in the major coal markets in the US, Russia, and Europe adopting their own methods of reserves evaluation.

The UN has developed a general coding system that determines coal reserves with a higher degree of confidence, which also includes losses that might occur during the mining process. This is as close to a mine operator's evaluation of a coal reserve and a method adopted by the Chinese coal industry. This might mean a downgrading of some reserves, but there still appears to be no danger of the world depleting its coal reserves.

China remains one of the most interesting debates regarding coal reserve assessments. Its access to domestic coal reserves may or may not diminish depending on the rate of extraction and the abundance of coal that it has. To date, exploration of the country's coal is ongoing with new reserves being exploited in some of the westernmost provinces.

There is almost no publicly available data quantifying the world's reserve of coking coal. Yet, many of the new virgin coal developments in countries such as Mongolia and Southern Africa have an initial focus on high quality metallurgical coal, chiefly coking coal. At best, the coking coal measured in economically recoverable reserves can be found, but what exists beyond this is largely unknown.

Global coal reserves vary from different sources and date of publication, but an amalgamation of these sources suggest world reserves could be 1042 Gt, comprising 566 Gt hard steam coal, 201 Gt of hard coking coal, and 276 Gt of lignite (brown coal). Steam coal and lignite are both thermal coals for power generation and heat raising; neither is directly substitutable, although some subbituminous coals might be considered hard coal if the blending properties are acceptable.

Coking coal is rarely mixed with thermal coals. For this reason, we see that 54% of the world's reserves are available for power stations designed for hard steam coal, 26% is for use in the much smaller fleet of power stations designed for lignite, while 20% is for the steel industry. These proportions are at best a gross estimate, and a great deal more research is needed.

With a small proportion of this reserve base being currently exploited, the debate of reserve depletion continues. China uses half the world's coal, but only has 14% of the world's reserves. Peak coal has been reached in some provinces, and could peak nationally in 5–15 years, but new reserves in the western most regions and Mongolia are being discovered and developed. Foreign companies are obtaining a stake in these regions to develop new reserves which are as yet not fully explored and could yield a great deal more coal.

Coal reserves could be depleted, not because of the exhaustion of physical reserves, but the inability for transport infrastructure to however extract and transport the coal to the market. Some analysis suggests that production could peak at levels higher than today (10 Gt/y) after the year 2100, but this assumes no other constraints on transport infrastructure or limits to demand.

While there is a great deal of analysis on coal production, demand-side peaking could happen much sooner. Ironically, coal demand peaking could have a positive feedback by stemming the demand for coal and therefore reducing the pressure to convert resources to reserves.

The cumulative demand for coal between 2010 and 2030 could be roughly 70–80 Gtce, from the power sector alone. This therefore puts the emphasis on hard steam coal, although a small amount of this will be lignite and will not affect lignite reserves to any extent. Reserve depletion will accelerate in countries where export led growth is strong, particularly in countries such as Australia and South Africa, but there appear to be ample reserves to cope with the growth.

Emission regulations for both air pollution and greenhouse gases internalise the costs of environmental and climate damage into the cost of using coal. As yet, a number of scenarios see coal demand worldwide peaking between 2020-35, provided certain regulations are in place to cause this massive shift away from coal-fired power. This peaking could be concurrent with policies to adopt higher efficiency and CCS, so the market for coal technology could be enhanced, therefore preserving a longer term and more sustainable future for the global coal industry.

CCS has almost no impact on today's coal demand (from a predominantly subcritical fleet) if it is assumed that CCS is fitted to only high efficiency coal plants such as USC or A-USC. Any efficiency reduction arising from CCS should be countered by the massive efficiency gains achieved by these newer technologies.

In the short to medium term, existing coal reserves may not be fully exploited under certain conditions. The measured reserves must therefore take into account the amount of coal that can be extracted using the equipment and manpower that is available at any time. Geologically complex seams can make some of the reserves less profitable. Consequently, the production plan for a particular coal face may differ from the true quantity of coal that exists. This is the case in particular with bord and pillar mining where up to 60% of the coal can be locked in pillars to support the overburden. With the use of retreat mining, a reasonable percentage of this coal could provide a greater yield from the in situ reserve.

Novel extraction techniques might be commercialised and adopted opening up new business opportunities where previously there was none. Underground coal gasification and coal bed methane extraction are two such examples where existing coal beds might offer a new source of energy that cannot be exploited using traditional mining techniques. While underground coal gasification is being developed, coal bed methane holds more promise in the immediate future and is abundant worldwide. Apart from utilising a valuable energy source, successful and safe extraction also avoids the leakage and escape of methane, as well as greatly boosting natural gas reserves in countries.

Clearly coal reserves and resources require a great deal more analysis and understanding with more research and exploration. Most reserves are well understood but the potential to extend these could yield a greater level of energy security for many parts of the world. Coal reserves depletion does not appear to be critical except for a few countries, but even so, demand side management and low carbon power technologies could provide the world's coal with a much more sustainable future than appears today.

13 Appendix

Table 7 – Cumulative world coal production based on Höök (2011)						
			A1 average	A2 average	B1 average	B2 average
Total cumulative production	1990-2100	Gtoe	652.1	851.1	276.9	579.7
Total cumulative production		Gtce	936	1221	397	832
Estimated cumulative production		Gtce	862	1159	322	774
Global reserves		Gtce	1039	1039	1039	1039
Remaining reserves in 2100			176	–120	717	265

Table 8 – Long term coal demand scenarios in the power sector (Various sources)									
	1990	2010	2015	2020	2025	2030	2035	2040	2070
IEA Power – new policies	1751	3213	3664	3813	3856	3904	3940	0	0
IEA Power – current policies	1751	3213	3664	4216	4636	5056	5566	0	0
IEA Power (450 policies)	1751	3213	3664	3189	2519	1849	1527	0	0
Exxon power	1728	3168	3372	3576	3780	3660	3540	3420	0
BP Power	1654	3140	3683	4096	4228	4243	0	0	0
IEA CCC – Henderson	0	2141	2918	3191	3483	3854	3981	3893	1451

Table 9 – Coal production scenarios by coal type (IEA, 2012)								
			New Policies		Current policies		450 Scenario	
	1990	2010	2020	2035	2020	2035	2020	2035
OECD	1533	1406	1403	1259	1516	1689	1203	690
Steam coal	986	930	962	855	1048	1202	804	423
Coking coal	282	278	270	289	279	321	248	226
Lignite	265	198	171	115	188	166	151	41
Non-OECD	1668	3718	4428	4767	4794	6200	3895	2649
Steam coal	1250	3101	3762	4128	4114	5493	3273	2129
Coking coal	290	517	554	539	565	582	528	470
Lignite	129	100	112	100	115	125	95	51
World	3201	5124	5831	6026	6309	7889	5098	3339
Steam coal share, %	70	79	81	83	82	85	80	76
Coking coal share, %	18	16	14	14	13	11	15	21
Lignite share, %	12	6	5	4	5	4	5	3

Note: Lignite, predominantly used for power generation, also includes peat

14 References

Bardi U (2005) The mineral economy: a model for the shape of oil production curves. *Energy Policy*, 33, 53-61 (2005)

Baruya P (2012) *Losses in the coal supply chain*. CCC/212, London, UK, IEA Clean Coal Centre, 66 pp (Dec 2012)

Brandt A R (2007) Testing Hubbert. *Energy Policy*, 35, 3074-3088 (2007)

Bucci l A (2006) *JORC and the Chinese Resource Classification Scheme – An SRK View*. Available at: http://www.srk.co.uk/en/newsletter/jorc-and-chinese-resource-classification-system-srk-view

CBM Asia (2013) *CBM around the world*. Available at: http://www.cbmasia.ca/CBM-Around-The-World (2013)

CoalPlan 2030 (2010) *Coal Plan 2030*. Queensland Government, Australia. Available at: http://www.dsdip.qld.gov.au/resources/plan/cg/coal-plan-2030.pdf 48 pp (Nov 2010)

Coil D, MKittrick E, Higman B (2012) *Coal terminology: resource & reserve*. 25 Sep 2012 update Available at: http://www.groundtruthtrekking.org/Issues/AlaskaCoal/CoalTerminology.html (25 Sep 2012)

Collins G, Erickson A (2012) Xinjiang poised to become China's largest coal producer: will move global coal, natural gas and crude oil markets. *China Signpost*. Available at: http://www.chinasignpost.com/2012/09/xinjiang-poised-to-become-chinas-largest-coal-producer-will-move-global-coal-natural-gas-and-crude-oil-markets/ (Sep 2012)

Couch G R (2009) *Underground coal utilisation*. CCC/151, London, UK, IEA Clean Coal Centre, 129 pp (Jul 2009)

Couch G R (2006) *Ash management in coal-fired power plants*. CCC/118, London, UK, IEA Clean Coal Centre, 69 pp (Oct 2006)

Crocker G, Kovalchuck A (2008) *Prospects for coal and clean coal technologies in Russia*. CCC/138, London, UK, IEA Clean Coal Centre, pp 56 (Oct 2008)

EIA (2013) *Annual Energy Outlook 2013 with projections to 2040*. US Energy Information Administration, DOE/EIA-0383; 244pp (April 2013)

Froggatt A (2011) *Coal financing in Europe: the banker's dilemma.* Chatham House 24pp (Feb 2011)

Haftendorn C, Holz F, Hirschhausen C(2012) The end of cheap coal? A techno-economic analysis until 2030 using COALMOD-World model. *Fuel,* 102; 305-325 (2012)

Harvey F (2013) 'Carbon budget' talks urgent, warns Lord Stern. *The Guardian*. Available at: http://www.theguardian.com/environment/2013/sep/29/carbon-budget-talks-urgent-ipcc-lord-stern (29 Sep 2013)

Heping X, Hong L, Gang W (2013) China's coal industry must follow the path of sustainable production capacity. *Cornerstone,* Beijing, China. Available at: http://cornerstonemag.net/chinas-coal-industry-must-follow-the-path-of-sustainable-production-capacity/ (24 Jul 2013)

Hőők M (2011) Future coal production outlooks in the IPCC emissions scenarios: are they plausible? *Energy & Environment*, v22 (7), 837-858 (Oct 2011)

Huang W, Zhang K, Tang X, Zhao Z, Wan, H (2010) Coking coals potential resources prediction in deep coal beds in Northern China. *Energy Exploration & Exploitation*. v28 (4); p 313-324 (2 Jul 2010).

Hubbert M K (1956) Nuclear energy and the fossil fuels. In: *Drilling and production practice first.* The American Petroleum Institute, New York, pp 7-25

Hubbert M K (1959) Techniques of prediction with application to the petroleum industry. In: *44th Annual Meeting of the American Association of Petroleum Geologists*. Shell Development Company, Dallas, Texas, USA, pp 43

Hudecek V, Stonis M (2011) Methods of drilling of coal pillar. *Journal of Mining Science*; v47(3) 367-375

IEA (2012) *Medium term market report 2012*. Market trends and projections to 2017. IEA/OECD, Paris, France, 143 pp (2012)

Lin B, Liu J (2010) Estimating coal production peak and trends of coal imports in a China. *Energy Policy*, 38; p 512-518 (2010)

Liponnen J (2012) Do we allow a role for CCS in our long-term future? Presented at: *APEC EGCFE workshop*, Gold Coast, Australia, 22 Feb 2012; 17 pp (22 Feb 2012)

Mark R, Mallett C (2008) Wyoming UCG trials at Hanna. A template for commercial scale UCG in Queensland. In: *Proceedings of the conference on clean coal technologies Queensland and Wyoming – the case for cooperation.* Brisbane, Qld, Australia, 10-11 Apr 2008, Brisbane, Qld, Australia, University of Queensland, 14 pp (2008)

Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, Frame DJ and Allen MR (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. Available from: http://www.nature.com/nature/journal/v458/n7242/full/nature08017.html. *Nature*, 458, 1158-1162 (30 April 2009)

MEMR (2013) *2012 Handbook of energy & economic statistics of Indonesia.* Ministry of Energy and Mineral Resources, Jakarta, Indonesia. Available at: http://prokum.esdm.go.id/Publikasi/Handbook%20of%20Energy%20&%20Economic%20Statistics%20of%20Indonesia%20/Handbook%20of%20Energy%20&%20Economic%20Statistics%20ind%202012.pdf; 126 pp (27 Feb 2013)

Minchener A (2009) *Future coal supply prospects*. CCC/146, London, UK, IEA Clean Coal Centre, 59 pp (Mar 2009)

Mohr S, Höök M, Mudd G, Evans G (2011) Projections of long-term path for Australian coal production-Comparisons of four models. *International Journal of Coal Geology*, 86;p 329-341 (2011)

Ojha K, Karmakar B, Mandal A, Pathak AK (2011) Coal bed methane in India: difficulties and prospects. *Interntional Journal of Chmeical Engineering*; 2 (4); 5 pp (Aug 2011)

Oliver J, Janssens-Maenhout G, Peters J (2012) *Trends in global CO_2 emissions*. Available from: http://edgar.jrc.ec.europa.eu/CO2REPORT2012.pdf. 42 pp (2012)

Owens E H , Chapman S, Allan P (2010) The impact of carbon capture and storage on coal resource depletion. *Energy & Environment*: 21(8); 925-936

Parijat (2007) Trends in global coking coal markets. Presented at: *65th session of the OECD Steel Committee and the joint OECD/Malaysia/World Steel Association workshop on steel & related raw materials*, Kuala Lumpur, Malaysia; Available at: http://search.oecd.org/officialdocuments/displaydocumentpdf/?cote=DSTI/SU/SC(2008)54&docLanguage=En; 20 pp (15 Dec 2008)

Parums (2012) Long term outlook for metallurgical coal. Presented at: *Mozambique Coal Conference*, Maputo, July 2012. 31 pp (Jul 2012)

Patzek TW and Croft GD (2010) A global coal production forecast with multi-Hubbert cycle analysis. *Energy 2012*; 35(8); 3109-22 (2010

Power (2012) Brattle report projects doubled coal retirement estimates ascribed to low gas prices. *Powernews* (10 Apr 2012)

Qing K (2013) China to shut 2,000 small coal mines by end of 2015. Reuters, Beijing, China. Available at: http://www.reuters.com/article/2013/10/12/china-coal-closure-idUSL4N0I208A20131012 (Oct 2013)

Rutledge D (2010) Estimating long-term world coal production with logit and probit transforms. *International Journal of Coal Geology*; 85(2011); p 23-33 (21 Jul 2010)

Rutledge D (2013) *Energy Supplies and Climate*. California Institute of Technology, USA. Available at: http://rutledge.caltech.edu/ (Jan 2013)

Scott A, Wedmaier R was ACARP (1995) *The Assessment and Control of Coal Damage and Loss – Final report C3017*. Available at: http://www.acarp.com.au/abstracts.aspx?repId=C3017. Australian Coal Association Research Program (ACARP), Brisbane, Australia; 93 pp (Sep 1995)

Sloss L (2005) *Coalbed methane emissions – capture and utilisation*. CCC/104, London, UK, IEA Clean Coal Centre, 56 pp (1 Nov 2005)

SRK (2013) *JORC and the Chinese resource classification system – an SRK view*. Available at: http://www.srk.com/en/newsletter/jorc-and-chinese-resource-classification-system-srk-view (2013)

SSY (2013) *Monthly shipping review.* SSY Consultancy & Research (19 Sept 2013)

Thomas L (2002) *Coal Geology*. John Wiley & Sons Ltd, Chichester, UK; 384 pp (Sep 2002)

UNFC (2009) United Nations Framework Classification for Fossil Energy and Mineral Resources. Available at: http://www.unece.org/fileadmin/DAM/ie/se/pdfs/UNFC/UNFCemr.pdf (2009)

Vidal J, Jowit J (2009) Ed Miliband promises new era of clean coal – but who will pay? *The Guardian*. Available at: http://www.guardian.co.uk/environment/2009/apr/24/energy-coal-carbon-capture-environment (2009)

Volcovici V (2013) US sets first curbs on power plant carbon emissions. *Reuters*. Available at: http://www.reuters.com/article/2013/09/20/us-usa-energy-emissions-idUSBRE98J03A20130920 (Sep 2013)

Wagner H (1980) Pillar design in coal mines. Journal of the South African Institute of Mining and Metallurgy (Jan 1980)

Wang F, Tu S, Bai Q (2012) Practice and prospects of fully mechanized mining technology for thin coal seams in China. *The Journal of the Southern African Institute of Mining and Metallurgy*. 112(2), p 161-170 (2012)

WCA (2013) Uses of coal. *World Coal Association*, London, UK. Available at: http://www.worldcoal.org/coal/uses-of-coal/coal-steel/ (downloaded in 2013)

World Coal (2013) Regional trials could see national carbon trading scheme by end of the decade. *World Coal*, 22 (9), p 12 (Sept 2013)