Low quality coals – key commercial, environmental and plant considerations

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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 Energy Agency (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, China, the European Commission, Germany, India, Italy, Japan, Poland, 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

Around half of the world's estimated recoverable coal reserves comprise coals of low quality and value. These are predominantly subbituminous and high-ash bituminous coals, and various grades of lignite. All are important for power generation and/or cogeneration, by far their biggest market. However, on a more localised basis, some are also used for various residential, commercial and industrial applications. Each coal type brings its own combination of advantages and disadvantages. Despite the latter, a number of countries have turned increasingly to the use of such coals.

The use of low quality coals was last examined in detail by the Clean Coal Centre in 2011. The international supply and demand situation for these types of coal has evolved since. In some parts of the world, there has been a significant increase in the amount used as utilities have switched to lower quality sources, largely for commercial reasons. In the last decade, subbituminous coals and coals with higher ash content have been introduced into the market and traded in increasing quantities. As reserves of some better quality export coals have been depleted, there has been a shift towards the greater use of variants of lower quality. Often, the motive has been cost saving measures instigated by utilities. However, switching can, potentially, reduce power plant efficiency, increase emissions, and escalate plant maintenance requirements.

A number of major economies rely heavily on indigenous resources of lower quality coals, particularly for power generation. In some cases, these comprise the only significant energy resource available. Such coals are often mined relatively inexpensively via large-scale opencast techniques. They are of strategic importance, providing a secure source of energy and helping minimise dependence on imported supplies.

This report examines the current production and use of these three categories of coal and discusses what the future may hold. For each, the situation in the biggest coal producers and/or users is examined. Despite moves away from coal in some economies, on a global basis, all three are expected to continue to play a major role in energy production for some time.

Acronyms and abbreviations

ASTM	American Society for Testing and Materials
BFBC	bubbling fluidised bed combustion
BHEL	Bharat Heavy Electricals
CBM	coalbed methane
CCC	[IEA] Clean Coal Centre
CCGT	combined cycle gas turbine
CCT	clean coal technology
CCS	carbon capture and storage
CFBC	circulating fluidised bed combustion
CIL	Coal India Ltd
CTL	coal-to-liquids
CV	calorific value
DRI	direct reduction of iron process
DRB	demonstrated reserve base
ECBM	enhanced coalbed methane recovery
EIA	Energy Information Administration (USA)
EOR	enhanced oil recovery
EPA	Environmental Protection Agency (USA)
EROI	energy return on investment
ESP	electrostatic precipitator
ETS	Emissions Trading Scheme (EU)
EU	European Union
FBC	fluidised bed combustion
FEED	front end engineering design
FGD	flue gas desulphurisation
GAD	gross, air-dried
GHG	greenhouse gas
IEA	International Energy Agency
IED	Industrial Emissions Directive (EU)
IGCC	integrated gasification combined cycle
KBR	Kellogg, Brown and Root Ltd
LCPD	Large Combustion Plant Directive (EU)
LHV	lower heating value
MoU	Memorandum of Understanding
MPa	megapascals
NDRC	National Development and Reform Commission (China)
NGCC	natural gas combined cycle
NLC	Neyveli Lignite Corporation
NTPC	National Thermal Power Corporation (India)
OECD	Organisation for Economic Cooperation and Development
PCC	pulverised coal combustion
PCI	pulverised coal injection
PPC	Public Power Corporation (Greece)
PRB	Powder River Basin
ROM	run-of-mine
SANEDI	South African National Energy Development Institute
SC	supercritical

SCR	selective catalytic reduction
SNG	synthetic natural gas
UMPP	Ultra Mega Power Project (India)
USC	ultrasupercritical
VC	volatile content
VIU	value-in-use
WEC	World Energy Council

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1 Introduction

Around half of the world's estimated recoverable coal reserves are made up of coals of low quality/value. These comprise predominantly subbituminous and high-ash bituminous coals, and various grades of lignite. By rank (on a tonnage basis) anthracite and bituminous coals account for 51% of the world's reserves, subbituminous coal 32%, and lignite 18%. All three types are of particular importance for power generation and/or cogeneration, by far their greatest market. However, on a more localised basis, in some countries, their use is also important in a number of residential, commercial and industrial sectors. Each type of coal brings its own combination of advantages and disadvantages, but despite the latter, many countries have turned increasingly to the use of coals of lower quality. Based on International Energy Agency (IEA) data, in 2014, global production comprised 80% bituminous coal, 9% subbituminous coal, 10% lignite, and 1% anthracite (IEA, 2015a). Some 45% of production was made up of high rank coals, with the balance comprising coals of lower rank.

In recent years, the world's demand for coal, particularly for power generation applications, has increased. Although environmental concerns have seen markets decline in some developed economies, the global market for coal has grown significantly. Much of this growth has been centred on a number of Asian countries, particularly China and India. However, the quality and types of coals traded and utilised has been changing. A decade ago, the breadth of coal qualities available in the seaborne market was relatively narrow. Since then, subbituminous coals and coals with higher ash content have been introduced into the market and traded in increasing quantities. As reserves of some better quality export coals have been depleted, there has been a shift towards the greater use of coals of lower quality.

For some decades, many coal-producing countries have witnessed a steady decline in the quality of the coal they produce. Particularly in those with a long history of coal mining, reserves of better quality coals have been exhausted. The result has been a shift towards the greater use of coals with lower heat content or other undesirable properties (such as high-ash content). In some cases, this trend has been evident as far back as the 1950s or earlier (for example, with US coals). Thus, in many coal-exporting countries, production capacity has been increasingly replaced or augmented with coals of lower heat content. As recently as 2000, the bulk of seaborne coal trade was for coals with heat content of 25 MJ/kg (as-received) or greater. More recently, lower heat content variants have been entering the market, most notably low rank Indonesian coals of less than 21 MJ/kg. Globally, the general trend towards the greater use of lower quality coal is expected to continue.

This trend has not been limited to the seaborne trade. Despite their potential drawbacks, many countries rely heavily on indigenous resources of lower quality, particularly for power generation. In some cases, these comprise the only significant energy resource available. Such coals are often mined relatively inexpensively via large-scale opencast techniques. They provide a secure source of energy and help minimise dependence on imported supplies, some of which would otherwise be sourced from politically unstable parts of the world. It has become increasingly apparent that the long-term future of coal-derived energy supplies will include the greater use of low rank and low value coals, a trend that is already evident in various markets around the world.

In the coming years, the global coal industry is expected to see significant changes. Some of this will reflect a move away from Chinese-led demand growth. The bulk of the world's proven coal reserves are in the USA, Russia, China, Australia, India and Germany. The major producers are China, the USA, India, Australia, Indonesia and Russia – combined, these account for >80% of global production. In the period up to 2020, these rankings are expected to remain the same (Smee, 2016). Currently, the two largest consumers of coal, China and the USA, are attempting to curtail coal use – this was a contributing factor in 2014's decrease in global coal consumption. However, in the period up to 2020, global coal production is forecast to increase moderately to 8.6 Gt/y. As in recent years, this growth will be driven mainly by developing Asian countries, predominately India.

In the following chapters, the production and consumption of the three main categories of low quality coals is considered on a country by country basis. Their current level of use and possible future developments are considered for the biggest individual coal-consuming economies.

2 Classification – what constitutes a ‘low grade’ or ‘low quality’ coal?

The degree of alteration that occurs as coal matures from peat to anthracite is referred to as its rank. Low rank coals include lignites and subbituminous coals. As they contain less carbon, they have lower energy content than coals of higher rank. However, when issues associated with low grade coals are considered, rank becomes less important. There is no single universally accepted definition of low grade or low value coal. However, a coal that has only limited use because of undesirable characteristics, such as high mineral matter content, can be so termed.

All low rank coals (subbituminous coals and lignites) are generally categorised as ‘low grade’ because of characteristics such as high moisture content and low heating value. Such coals often require the application of specific technologies for their successful use in power generation and other industrial processes. Anthracites and semi-anthracites are also sometimes classified as low grade as a result of ignition and burnout problems. However, for bituminous coal, it can sometimes be difficult to classify which coals are low or high grade, although it can generally be stated that bituminous coals with one or more of the following troublesome properties can be classified as ‘low grade/quality’:

- low heating value, implying low efficiency;
- high moisture content, which also translates into low efficiency;
- low volatile matter content, related to flame stability;
- high ash content, causing ash-related problems and reducing efficiency;
- high sulphur content, implying high SO_2 emissions and/or high control costs;
- low ash fusibility, having potential for slagging;
- high alkali/alkaline content, having potential for slagging, fouling or corrosion; and
- low Hardgrove Grindability Index, implying high milling power consumption.

In summary, a coal is categorised as ‘low grade’ or ‘low quality’ if it has one or more troublesome properties related to use, particularly in power plants. A significant proportion of low grade coals are used in plants that have been designed specifically to operate on these particular types of coal.

Coals are often categorised in a variety of other ways; some of these may be applied internationally, whereas the use of others may be restricted to a particular market or country. Such is the case with the loosely applied term ‘steam coal’. Confusingly, this can cover a range of coal types and qualities. In some situations, steam coals can encompass various combinations of bituminous and subbituminous coals and lignite. The properties of a particular coal can sometimes overlap several different categories. For example, it is not unusual for the properties of some lignites to overlap with those of poorer quality subbituminous coals. The situation can be complicated further – some subbituminous coals can have a moisture content of between 10% and 35%, and others can have a CV similar to some bituminous coals. Lignites generally have a moisture content of between 35% and 70% and a CV of less than 15 MJ/kg. Export coals often border on low-mid rank subbituminous although some have heating values of

~21 MJ/kg (similar to some Indonesian lignites). At times, some higher grade subbituminous coals are identified as bituminous. Thus, some coals may fall into different classifications, making it difficult to reconcile reserve and production figures cited. As a result, statistics cited by some national authorities may not necessarily agree with those from other organisations. Thus, in reality, the term 'steam coal' can cover a range of coal types.

The categorisation of coal by type can be further complicated as there is no classification system that is adopted universally. For example, under the Chinese classification system, some types (such as some lignite and subbituminous coals) are categorised differently to other systems. The Chinese system recognises three main categories of coal, namely low rank, coking, and high rank. Low rank coals comprise several lignite variants, plus low rank bituminous (subbituminous) coals. The latter comprise a number of types that include long flame (CY), non-caking (BN), and weakly caking (RN). Typically, BN and RN have average ash contents of between 10% and 11%, and sulphur contents of between 0.75% and 0.87% (Sijian, 2010). Similarly, Russia adopts its own classification system. Under this, there are three grades of lignite/brown coal (1B, 2B and 3B) – under the ASTM categorisation, 1B equates with lignite A and B; 2B equates with subbituminous C; and 3B overlaps with subbituminous B. Russian 'long flame' D overlaps with subbituminous A. Russian brown coal grades have different moisture contents (1B has moisture >40%, 2B has 30–40%, and 3B is <30%) (Crocker and Kovalchuk, 2008).

The various factors noted above can sometimes make it difficult to reconcile figures produced by different organisations for coal reserves, production and consumption.

3 Global coal reserves

Low value coals make up around half of the world's estimated recoverable coal reserves. Depending on the source, estimates can vary. However, US Energy Information Administration (EIA) data suggest that by rank (on a tonnage basis) anthracite and bituminous coals account for 47% of the total, subbituminous coal for 30%, and lignite 23% (US EIA, 2013). Recent years have seen these figures change slightly from previous EIA estimates (51%, 32% and 18% respectively). The World Energy Council (WEC) suggests that bituminous coals account for 45.2% of proved reserves, subbituminous coals 32.2%, and lignites 22.5%. Based on the latest IEA estimates, global economically recoverable coal reserves amount to ~968 Gt (Table 1).

Table 1 Proved recoverable coal reserves (IEA, 2015a)

Region	Proved recoverable reserves, Mt		
	Hard coal	Soft brown coal*	Total
OECD Europe	19,421	56,279	75,700
OECD Americas	230,122	32,842	262,964
OECD Asia Oceania	63,586	50,924	114,510
OECD Total	312,190	140,045	453,174
Non-OECD Europe and Eurasia	131,110	107,314	238,424
Of which: Russian Federation	69,634	90,730	160,364
China	120,697	7350	128,047
Asia excluding China	101,157	19,917	121,074
Of which: India	81,897	4755	86,652
Non-OECD Americas	7945	5073	13,018
Of which: Colombia	4881	–	4881
Africa and Middle East	14,420	66	14,486
WORLD	688,456	279,762	968,220

* classified as lignite with a CV of less than 16.5 MJ/kg

Although coal deposits are distributed widely, as noted, around 80% of the world's recoverable reserves are located in five regions, namely the USA (27%), the Russian Federation (18%), China (13%), non-OECD Europe and Eurasia outside of Russia (11%), and Australia/New Zealand (9%) (US EIA, 2013). Proved reserves for the top six individual coal-producing countries are estimated at more than 100 Gt of hard coal and nearly 100 Gt of lignite.

The latest estimates (based on 2009 data) from the US EIA provide a breakdown of coal types and the location of the largest individual deposits. Generally, these agree reasonably well with other data (for example, from the World Energy Council). Although there are some individual disparities, most are relatively small and result from differences in classification. Furthermore, recent additions have increased some categories. WEC estimates suggest that the total global reserves of bituminous coal + anthracite are 403 Gt, plus 287 Gt of subbituminous coal and 201 Gt of lignite (WEC, 2013).

3.1 Coal reserves – the top ten

Low quality coals are used in many countries although levels of production and consumption vary enormously. The biggest individual coal-consuming economies are summarised in Table 2.

Table 2 Top ten coal producing/consuming countries

	Reserves (Gt)	Status
USA	~235	Reserves distributed widely, with the bulk in Montana, Wyoming, Illinois, western Kentucky, West Virginia, Pennsylvania, Ohio and Texas. The USA is the world's second largest producer and consumer of coal.
Russian Federation	157	Reserves comprise various bituminous and subbituminous coals and lignite. Russia is the world's sixth largest producer and the fifth largest consumer of coal.
China	>114	China is the world's biggest producer and consumer of coal. Around 80% of China's electricity generation is coal-based. In 2012, the country also imported 289 Mt of coal, becoming the biggest global coal importer.
Australia	~76	Bituminous coal is concentrated mostly in New South Wales and Queensland, which together account for >95% of the country's output of black coal. Victoria hosts ~96% of the country's lignite reserves. Australia is the fifth largest coal producer – around 90% of output is exported, making it the world's second biggest coal exporter after Indonesia.
India	~61	Major hard coal deposits are located in the eastern parts of the country. The southern state of Tamil Nadu has most of the country's lignite deposits (Figure 1). India is the third biggest coal producer after China and the USA. More than two-thirds of India's electricity generation is coal-based.
Germany	41	The Rhineland region holds the country's largest lignite deposits. The country is the eighth biggest coal producer. It is the largest lignite producer in the world – most is used for power generation (Figure 2).
Ukraine	~34	Most reserves comprise steam and coking coals that are located in the Donetsk Basin.
Kazakhstan	~33.6	Annual production of >120 Mt. Karaganda and Ekibastuz are the country's two major coal producing basins. Lignite reserves are mainly in the Turgay, Nizhne-Iliyskiy and Maikuben regions.
Colombia	~6.7	The country produces mainly steam coal and is a major exporter.
Canada	~6.6	More than 90% of reserves are located in sedimentary basins in the western part of the country. Most coal output is from opencast mines.

Despite projected declines in OECD countries and efforts to rein in growing coal demand in others, some industry sources suggest that global coal use could increase by more than 50% in the period up to 2030. Developing countries will be responsible for most of this increase, primarily to meet improved electrification rates (WEC, 2013). However, in light of proposed changes and a general move towards a more diversified energy mix in some economies, the suggested 50% increase could prove over-optimistic. For example, the USA is reducing its reliance on coal, India aims to greatly increase its uptake of solar power, and China is significantly increasing the deployment of wind power. Developments such as these could influence the scale of future increases in demand. However, a significant increase in global coal demand remains a possibility.

Figure 1 The 250 MW CFBC power plant of Neyveli Lignite Corporation (NLC) in Tamil Nadu (photograph courtesy of NLC)

Figure 2 RWE's 3.68 GW lignite-fired Niederaussem power plant in Germany (photograph courtesy of RWE)

3.2 Declining coal quality and global markets

For decades, many coal-producing countries have witnessed a steady decline in the quality of the coal they produce. Often, this reflects the increasing exhaustion of reserves of higher grade coals and a growing reliance on those of lower quality. This trend is particularly apparent in many of the long-industrialised nations where significant coal production may have been taking place for two centuries or more. For instance, this overall downward trend in quality has been evident in the USA since the 1950s. Partly, this has resulted from the exhaustion of some higher grade sources, most notably in the Appalachian region, and the subsequent increased production of subbituminous coal that started in the 1970s. However, there has been a reduction in calorific value (CV) across all ranks of US coals – this appears to have peaked in 1998. Indeed, the decline in the quality of the country's energy supply in general (largely fossil fuels, including coal) has been cited as a contributing factor in the recent US recession. Studies undertaken by the University of Texas have identified similar falls in the periods before major recessions of the 1970s and 80s (King, 2010).

In many European and some Asian coal-producing countries, overall quality has also declined through a combination of unfavourable geology and the depletion of better quality reserves. These problems have been replicated in many places around the world, where exhaustion of good quality and/or easily accessible reserves has forced increasing reliance on lower quality deposits. In some economies, these comprise the only economically-viable bulk source of energy. Where countries depend predominantly on imported coal, there has been a significant increase in the seaborne trade and market acceptance of coals of lower quality and/or energy content.

For the first time in a number of years, on a global basis, 2014 witnessed a fall in the total amount of coal produced. In 2013, overall output was 8075 Mt, falling to 8022 Mt in 2014 – a reduction of nearly 53 Mt (IEA, 2015a). This reduction was due mainly to reduced production in China (-96.1 Mt), the Ukraine (-4.1 Mt), Indonesia (-16.9 Mt), and Serbia (-10.4 Mt). During this period, demand for coking coal increased, whereas that for steam coal and lignite decreased. However, in 2014, total coal production still exceeded 8 Gt (Table 3).

Table 3 Total world coal production 2014 (Mt) (IEA, 2015a)

	2012	2013	2014
Steam coal	5900.6	6201.1	6147.2
Coking coal	976.1	1037.6	1064.8
Lignite	887.2	834.7	810.5
TOTAL	7763.9	8075.5	8022.5

Much of the global increase in coal production and consumption in recent years has been directly attributable to economic activity in China and India. Since 2000, OECD coal production declined by 0.1%, whereas that of China increased by nearly 177%. In the rest of the world, the increase was 78.4%. The world's biggest coal producers (all types) are shown in Table 4.

Table 4 Major coal producers (Mt) (IEA, 2015a)

	2013	2014
China	3843.6	3747.5
USA	903.7	916.2
India	610.0	668.4
Australia	458.9	491.2
Indonesia	487.7	470.8
Russian Federation	326.0	334.1
South Africa	256.3	253.2
Germany	191.0	186.5
Poland	142.9	137.1
Kazakhstan	119.6	115.5
Colombia	85.5	88.6
Canada	68.9	69.0
Turkey	60.4	64.1
Greece	53.9	48.0
Czech Republic	49.1	46.9
Ukraine	68.8	44.7
Other	349.2	340.8
WORLD	**8075.5**	**8022.5**

Although some of the economies noted in Table 4 use predominantly higher quality bituminous coals, others rely on a range of lower qualities that encompass lignite, subbituminous, and high ash bituminous coals. In some cases, combinations of these are used, mostly for power and/or cogeneration purposes. With a number of countries, the bulk of national production is supplied entirely to domestic markets, whereas in others, much is exported. Historically, higher quality bituminous coals have dominated the export trade, although in recent years, the amount of subbituminous coal exported has grown significantly. For obvious reasons, there is relatively little seaborne trade in lignite, although a growing amount is transported both within and between various countries (*see* Section 6.1.6).

In 2014, global steam coal production amounted to 6147.2 Mt (Table 3) (IEA, 2015a). The biggest individual producers were China, the USA, India, Indonesia, South Africa and Australia. As noted, much is used internally although some is directed to export markets. China is responsible for >50% of the world's steam coal production (although this figure includes lignite). India is the second largest non-OECD coal producer. On a global basis, it is the third largest – in 2014, steam coal production increased by >10%, reaching nearly 570 Mt. Most Indian reserves comprise high ash bituminous coals although in some parts of the country, lignite is also of importance.

Indonesia is the world's fourth largest coal producer, with a sizable proportion of its output destined for export to countries such as China. In 2014, decreased demand from the latter contributed towards a reduction in Indonesian output – production fell by ~16 Mt to 468 Mt. South African steam coal production remained at 250.6 Mt, down slightly from the previous year. Australian output was nearly 246 Mt.

3.3 Future coal supply

The amount of coal available for international export markets varies widely between individual countries. In some cases, the level is influenced by the domestic demand at the time – the split between export and domestic consumption can vary significantly between individual economies. For example, Indonesia has major lignite and subbituminous coal deposits on the islands of Kalimantan and Sumatra. In 2014, overall coal production was 471 Mt, of which, 411 Mt was exported (87%). Kalimantan is the main hub of production for coals of internationally tradeable quality whereas those from Sumatra tend to be of lower rank and higher moisture – these are directed mainly to domestic markets. However, in the longer term, the country's plan to significantly increase its coal-fired power generation sector could affect the amount sent to overseas markets. A similar level of exports (on a percentage basis) is found in Colombia – in 2014, production was 88.6 Mt with some 78.8 Mt exported (89%). However, the situation in South Africa, for example, is somewhat different. Here, production amounted to 253 Mt, of which, 76.4 Mt was exported (30%), the remainder used mainly for domestic power generation.

Major coal exporting countries are summarised in Table 5. Since 2011, Indonesia has been the world's biggest individual coal exporter. In 2014, the amount exported by some of the biggest players (such as the USA and Indonesia) declined, whereas that from Australia and the Russia Federation increased (Table 5).

In 2014, world coal imports amounted to 1423.6 Mt, a 2.3% increase over the preceding year. The biggest individual increase was recorded by India (+50.6 Mt). However, China's imports decreased by 35.6 Mt to a total of 291.6 Mt. This fall in demand impacted mainly on Indonesia, South Africa, Vietnam and the USA, who lost 19.4 Mt, 7 Mt, 6.3 Mt and 5.2 Mt respectively.

Table 5 Major coal exports (Mt) (IEA, 2015a)

	2013	2014
Indonesia	427.9	410.9
Australia	336.1	375.0
Russian Federation	140.8	155.5
USA	106.7	88.3
Colombia	80.2	80.3
South Africa	74.6	76.4
Netherlands	31.9	38.7
Canada	39.1	34.5
Kazakhstan	33.8	28.9
Mongolia	18.4	19.3
South Korea	16.7	15.6
Vietnam	12.8	9.9
Other	55.7	50.3
WORLD	1374.7	1383.6

Much of the preceding decade was marked by a sustained increase in global coal demand (although it has since fallen slightly). To meet this and the additional demand expected in the future, various mining operations around the world were slated for near-term expansion (Table 6). Output of coals with a CV of less than 21 MJ/kg was expected to increase significantly. However, for several years, the market has seen periods of oversupply and depressed coal prices. This has impacted on the scale and timing of some proposed projects. At the moment, investors have become more cautious than in the past and worldwide, a number of projects have been cancelled or at least deferred (IEA, 2015b). For example, in the USA, Arch Coal, the country's second largest coal company (currently in bankruptcy) has blamed the current state of the coal market for the cancellation of the proposed Otter Creek Valley mine in southeastern Montana's portion of the Powder River Basin – this contains 1.4 Gt of coal. This was the largest proposed coal mine in the country. A hoped-for switch towards overseas export markets (via a new rail link to proposed coal export terminals in the Pacific Northwest) has yet to materialise.

However, on a global basis, in the longer term, considerable expansion could still be achieved, with some sources suggesting that coal demand could be met by a production increase of up to 100 Mt/y. Some opine that should market conditions dictate it, additions of up to 400 Mt/y could be made available. However, because of current low prices and the over-supply situation, some major producers are now focusing on minimising losses from their respective mining businesses although in the longer term, expansions to some mining operations are expected to resume. As noted, there are many projects at different phases of development ready to start or ramp up production, although most of them are unlikely to do so at current prices (IEA, 2014).

Table 6 Major steam coal mine developments (Ewart and Oommen, 2010, plus recent updates)				
Mine	**Location**	**Type (Surface or Underground)**	**As-received heat content (MJ/kg)**	**Ultimate export capacity (Mt/y)**
Alpha	Queensland, Australia	S	21–25	30
Muara Wahua	Indonesia	S	<21	30
Waratah	Queensland, Australia	S	21–25	30
Wara	Indonesia	S	<21	25
East Kutai	Indonesia	S	21–25	20
Cleremont	Queensland, Australia	S	>25	12.2
Pakar	Indonesia	S	<21	10
Moolarben	NSW, Australia	S/UG	>25	8
Mangoola	NSW, Australia	S	>25	7
Caroona	NSW, Australia	UG	>25	6
Oaklands	NSW, Australia	S	<21	6
Signal Peak	USA	UG	21–25	6
Las Cuevas	Colombia	S	21–25	4.5
Naudesbank	South Africa	S/UG	21–25	4.5
Zondagsfontein	South Africa	S/UG	>25	3.5
Leandra	South Africa	S/UG	21–25	2

Over the next 5–10 years, although China will remain a major coal consumer, the biggest growth in coal demand is expected to be India. Other potential growth countries are Russia and several of the former Soviet Union states. Recently, the Russian government announced plans to increase the use of coal as one of its primary energy sources from 25% (in 2014) to 27% in 2020 (Smee, 2016). In contrast, few of the previously announced new large-scale projects in the USA, Australia and Indonesia seem likely to proceed during the next five years. However, some new projects continue to make progress. For instance, in Indonesia, the Electricity Generating Authority of Thailand (EGAT) is in the process of buying into a significant Indonesian mining operation in Kalimantan, Borneo, with a production capacity of 50 Mt/y of subbituminous coal.

To date, the pace of development of the various proposed projects has varied. Some have been delayed through changes in local circumstances whereas others have been affected by the depressed state of international coal markets. Important developments have included China's recent restrictions on the importation of certain lower quality coals, and major changes taking place within the US coal market. As a result, some earlier predictions of possible mine expansions and increased coal production have proved to be over-optimistic. For example, it was originally suggested that by 2015, the Muara Wahua project in Indonesia would be producing an additional 7.5 Mt/y of export coal. This has yet to be achieved although progress is being made with land acquisition and development of appropriate transport infrastructure. Recent estimates by project developer PT Bhakti Energi Persada (BEP) suggest a resource of more than

9 Gt with a low average CV (14.1 MJ/kg). This type of coal is already familiar and accepted by overseas customers such as India. BEP envisages a 30-year production window. When operational, production is expected to be 1 Mt/y in Year 1, increasing to 8 Mt/y in Year 3, and possibly up to 50 Mt/y from Year 12 onwards (BEP, 2012). Similarly, in the USA, it was previously suggested that further developments at the Signal Peak mine in Montana would result in the production of an additional 6 Mt/y of coal by 2015. In reality, approval for the project was not obtained until March 2014. Furthermore, proposed legislative and other changes taking place in the country are also having major impacts on the scale and viability of coal mining in a number of states, and many proposed major coal mining projects now seem unlikely to materialise. Even US projects that have been in development for some time continue to face difficulties. For example, a proposal by Cloud Peak Energy to expand its Spring Creek operation in Montana by 117 Mt (of PRB coal) is being contested in the courts by environmental groups. This proposed expansion would keep the mine open until at least 2022. In 2014, the mine produced 17.4 Mt of coal from the Anderson-Dietz seam. Cancellation of the project could result in closure.

A complicating factor is that in some locations, newer reserves are more remote or less accessible than those previously exploited, making mining and transport more problematic. For obvious reasons, there has been a tendency to mine reserves that lie close to existing major users and benefit from established transport infrastructure. Inevitably, accessing more remote reserves can entail significant capital expenditure, often needed long before any income starts to be generated. Access can involve the construction of new haul roads and/or rail links to move the coal to market. For example, the Alpha Coal Project in Queensland, Australia, comprises an opencast mine and railway. This is being developed at a cost of A$6.9 billion. Granted in 2012, the mine is the first in the Galilee Basin to be approved for development by both the Government of Queensland and the Federal Government. It is expected to have a lifetime of 30 years and is claimed to be the first fully integrated project of this type to be built in Australia. Coal produced will have a CV of between 21 and 25 MJ/kg and will be directed to export markets. To get the coal to a new port facility at Abbott Point will entail a 495 km rail journey. The new rail link will cost A$4 billion, expenditure that will need to be factored into the final selling price, as will ongoing daily transport costs.

Elsewhere, producers intend to rely on road transport; for example (as noted above), in Indonesia, the proposed Muara Wahau coal project is located in the East Kutai Regency, East Kalimantan. Deposits are approximately 130 km from the coast where deep water access is available relatively close to the shore. Apart from exploration activities, mining in this region is largely undeveloped. Coal produced will be moved to the coast by a new haul road, the land for which is currently being acquired. Fortuitously, these substantial untapped deposits have low sulphur and ash contents and are present in thick seams with low stripping ratio (BEP, 2012). Thus, the low mining costs will work in their favour.

Summary

Around half of the world's estimated recoverable reserves comprise coals of low quality/value (primarily lignite, subbituminous and high-ash bituminous coals). Despite some inherent disadvantages, all are used widely for power generation/cogeneration. In recent years, as the quality of many major coal reserves has declined progressively, there has been a shift towards the greater use of coals of lower quality. In some cases, the motive has been economic, whereas in others, supplies of better quality coals have been exhausted.

Increasingly, subbituminous coals and coals with higher ash content have been introduced into the market and traded internationally in increasing quantities. However, this increased use has not been limited to the seaborne trade – a number of major economies rely heavily on indigenous lower quality coal resources, particularly for power generation. Despite efforts to reduce reliance on coal, in some countries, low quality reserves comprise the only significant energy resource available. As such, they are often of strategic importance, providing a secure source of energy and helping minimise dependence on imported supplies.

A significant part of the global economy continues to rely on coal. Although use in some countries is declining, overall, coals of lower quality will continue to provide much of the world's electricity and heat for some considerable time.

4 Advantages and disadvantages of using low quality coals

Each type of coal brings its own combination of properties. Some are beneficial whereas others can be more problematic. The advantages and disadvantages are discussed below.

4.1 Advantages

Depending on the individual circumstances, there are various reasons cited for using either low rank or low quality coals. Many are self-evident and focus on access to an affordable, secure source of energy for power generation and other industrial and commercial uses. They include:

- Security of supply. Some low quality coal output is used close to the point of production. There is limited international trade of some types (such as lignite), hence much is sourced from indigenous deposits and used locally. Despite the current global fall in the price of competing fossil fuels, the cost of producing such coals usually remains relatively unaffected by market and other outside forces. This imparts a stabilising effect on the price of electricity and helps keep its cost low.
- In a number of countries, low quality coals represent the only major indigenous resource – there may be few (if any) economically viable alternatives. Their utilisation helps reduce the level of imported energy, decreasing reliance on outside sources. This has a positive impact on national trade balance. For instance, for an annual lignite production of 50 Mt, Greece avoids the import of ~36 million barrels (bbl) of oil. Based on a nominal price of 43 US$/bbl, the estimated saving is US$1.55 billion per year. Similarly, indigenous lignite is also a major strategic energy resource in Turkey.
- The use of large-scale surface mining techniques means that extraction costs are often low. Some lignites, subbituminous coals and high ash bituminous coals represent the world's cheapest fossil fuel-based sources of energy. For example, a number of large Indian opencast mines produce coal for <15 US$/t (compared to >150 US$/t for small underground mines).
- The maintenance of a national mining industry and attendant power generation sector is often an important local factor as they provide many long-term jobs. For instance, the state-owned Coal India Ltd has >333,000 employees. Worldwide, coal provides an estimated 7 million jobs.
- Some higher grade bituminous coals have high sulphur content. From an environmental standpoint, this may require the application of often-expensive control equipment such as FGD. Even though a subbituminous coal may have a lower energy content (hence, more must be burned to produce the equivalent amount of energy), it may contain less sulphur – thus, in some circumstances it can prove cheaper to switch to a lower grade coal than to apply expensive back-end SO_2 clean-up measures.
- Even though some coals have high ash content, they may have advantages in other areas. For example, Indian coals are generally low in sulphur, chlorine, mercury and arsenic. Most ash produced is refractory in nature and has a higher ash fusion temperature and lower iron content. This reduces slagging/fouling potential.

Many of the reasons cited for using low quality coals focus directly or indirectly on energy security, an issue often associated with developing economies. However, it also remains a major consideration in more developed counterparts. For example, energy security is taken seriously by the EU. The EU currently imports over half of the energy it consumes. The external energy bill is >€1 billion per day (a total of €443 billion in 2014) – energy imports make up more than a quarter of total EU imports. The most pressing energy security issue is the strong dependence of six Member States on natural gas from a single external supplier. Coal has a significant advantage in that it can be stockpiled easily; thus, a few million tonnes of stockpiled coal (at a mine, port or power plant) can often secure a Member State's electricity supply for some months.

At current rates of extraction, the EU has proven coal and lignite reserves that will last for 130 years. Six Member States mine hard coal and nine produce lignite as a competitive fuel for power generation (Bulgaria, the Czech Republic, Germany, Greece, Hungary, Poland, Slovakia, Slovenia and Romania). Turkey and several countries in South East Europe are also major lignite producers. In 2014, the EU produced 401 Mt of lignite, 106 Mt of hard coal, and imported a further 205 Mt of hard coal. After China, the USA and India, the EU is the world's fourth largest consumer of coal. Despite current efforts to diversify (mainly on environmental grounds) coal is expected to remain one of the most reliable and affordable energy resources in Europe for several decades (Fornea and Eisenvortová, 2015). The annual value of EU coal production exceeds €25 billion. Replacing this with imported gas would cost almost €60 billion per year. Indigenous hard coal and lignite account for 88% of EU energy reserves – as elsewhere, they reduce energy import dependency and energy costs, and help moderate energy prices.

4.2 Disadvantages

However, there can be some less positive aspects to using low quality coals that should be considered:

- In the case of lignite, extraction costs in some countries are likely to increase as more easily accessible sources become exhausted and deeper reserves are tapped. Thus, future production may become more difficult and associated costs increase. Even where produced by opencast mining, accessing deeper reserves entails the removal of greater volumes of overburden. The thickness of this can vary enormously and in many locations, is increasing.
- The general decline in CV being experienced effectively means that a greater volume of lower quality coal will need to be mined (and probably overburden moved) in order to supply the equivalent amount of energy available from a smaller quantity of higher quality coal. When burned, more ash may also be produced and there may be other environmental consequences associated with increased mining activity.
- The long distance transport of high ash/moisture coals reduces profitability and increases overall environmental impacts. For instance, in India, although coal is used in all states, it is produced in only nine. Thus, long distance transportation is common. Some 70% of thermal coals are transported more than 400 km to the end user. In 2002, in an effort to minimise the associated drawbacks, the movement of coal with an ash level >34% was banned. This has helped reduce costs and minimise transport bottlenecks. Because some power plants are now obliged to use only cleaned coals, they

produce less ash and generate less CO_2. Assuming that, as predicted, the country's coal demand continues to increase, this will become increasingly important.

- Coals/lignites can have high moisture and ash contents, and a low CV. When upgraded, there will be associated costs. Moisture may need reducing via a drying technique, and ash removed through some form of coal cleaning process. All such upgrading invariably increases process complexity and impacts on overall production costs. It will reduce the final amount of coal produced, and upgrading plants (washery or drying units) will generally generate emissions, effluents or tailings for disposal. The amounts of the latter can be considerable. For example, South Africa generates ~65 Mt/y of discards from the washing of export coals. An estimated >1 Gt has so far been stockpiled. This could have doubled by 2020.
- Mineral matter present in some high-ash coals can be highly abrasive and cause erosion of power plant components. For example, some Indian coals contain high levels of quartz (Muthukrishnan, 2016).
- Where low rank coals are upgraded, there may be an increased tendency for spontaneous combustion to occur during storage and transport (Okoh and Dodoo, 2005). Some low rank coals are more susceptible than bituminous coals. In extreme situations, fires may start. To reduce this risk, stockpiles may need to be mechanically compacted and circulated. To obviate the problem, most lignite mined goes directly to the power plant with a minimum of intermediate storage/stocking (Sloss, 2015). The amount held as a buffer in hoppers can amount to just a few hours of plant operation. In the case of a plant shut-down, hoppers may need to be inerted (with nitrogen or CO_2) or emptied (Couch, 2004). This clearly adds a degree of complexity and cost, when using such coals.
- In some cases, coals/lignites can have a low ash fusion temperature (resulting from the presence of alkali metals such as potassium and sodium, or a high base:acid ratio). Fusion temperatures are indicative of the temperature range over which portions of the ash will be in a molten fluid or semi-molten plastic state. High fusion temperatures mean that ash in the furnace will cool quickly to a non-sticky state, minimising the potential for slagging. Conversely, with low fusion temperatures, ash will remain in a molten or plastic state longer, exposing more of the furnace to potential deposition. Alkali metals (sodium and potassium) are associated with ash fouling.
- Where high ash coals are used (unwashed) directly in power plants, considerable quantities of ash can be produced and require disposal in an environmentally-acceptable way or utilised to serve some useful purpose.
- Some lower quality coals can degrade quickly, generating excessive fines. For example, once US Powder River Basin (PRB) subbituminous coals are exposed by mining, degradation begins – this can occur within a few days. The degree of degradation depends largely on the distance to the plant from the mine – effectively, how long the coal is exposed to the atmosphere during transportation. Other factors can include the rate of moisture loss from the coal, and the type of crushing and handling processes adopted.
- The characteristics of different lignite reserves can show considerable variation (even within the same deposit) and this must be taken into consideration. Some (such as Australian) can have high

moisture content. Others (such as those from Greece, Romania and Turkey) may contain >35% moisture, but also have >25% ash. Some may have a very low sulphur content (such as some Indonesian sources), whereas others may be much higher (such as those from Bulgaria and Thailand) (Couch, 2004). Globally, lignites with heating values in the range from 5 to >16 MJ/kg are both mined and used. For instance, the energy content of Canadian lignite can be three times that of a Greek one.

- Emissions of CO_2 are likely to be higher than when using higher grade bituminous coal. The lower CV coupled with other issues means that a greater volume of low grade coal needs to be burned to provide the same amount of energy as a smaller amount of higher quality coal. Depending on the individual circumstances, combustion efficiency can be lower, resulting in an overall increase in CO_2 emitted per MWh of electricity generated.

New projects can face a combination of problems or issues that need to be resolved. For example, developers of new Indian lignite mines have faced a number of constraints (Joshi, 2014). These have included excessive transport distance, risk of spontaneous combustion, lack of a local guaranteed market for electricity, limited proven reserves (at economically recoverable depth) in some areas, thin seams and variable properties, hydrogeological problems, issues of land acquisition, and difficulties in obtaining official clearance for projects.

Summary

Depending on the individual circumstances, there may be various reasons for using low quality/value coals. Many are self-evident and focus on access to an affordable, secure source of energy for power generation and other uses. When using indigenous resources, reasons include security of supply, reduced energy imports, and inexpensive electricity generation.

However, there can be some less positive aspects to consider. For example, poorer, less accessible sources are now being tapped meaning that the quality of many coal reserves is declining. As a result, greater volumes need mining, transporting, and treating. Inevitably, there are economic and environmental consequences. Inappropriate use in power plants can reduce efficiency and cause operational problems. Plant maintenance requirements may also increase. Ideally, appropriate features will be incorporated into a plant at the design stage. However, circumstances can change and access to a plant's 'design' coal may no longer be possible.

5 Application of Clean Coal Technologies (CCTs) to low quality coals

Various types of low quality coals have been confirmed as suitable for use in a range of applications more often associated with coals of higher quality. Although the biggest global use remains combustion in power stations using conventional pulverised coal combustion (PCC) technology (often with subcritical steam conditions) there are numerous situations where low quality coals and lignites form economic and viable sources of energy. Emissions of SO_2, NOx and particulates can be controlled successfully through the use of modern emission control systems, although as with all types of fossil fuel-fired power plant, CO_2 produced remains an issue of concern. Because lower grade coals/lignites contain less energy than higher grade equivalents, a greater amount has to be burned in order to provide the equivalent amount of energy.

The first stage in the chain where improvements have the potential to be made comes immediately after coal production. There are a number of commercially available systems designed to improve the properties of the raw coal, either through removal of water and/or mineral matter present. However, the additional costs involved in upgrading need to be factored in – the end-product must still have a cost advantage over competing fuels. Although the past few years have seen the price of higher rank thermal coals decrease significantly, in some economies, there is continuing interest in low quality coals for securing long-term fuel cost reductions. Use of indigenous resources can help save foreign exchange and conserve high rank coal reserves.

There are large amounts of lower quality coals in Australasia, South Asia and South East Asia, much of which have the potential for upgrading to increase energy content, improve transportability, and increase market value. During periods of high thermal coal prices, as a fuel cost reduction measure, many coal users have looked at replacing higher rank thermal coal with lower rank subbituminous coal and/or lignite. When replacing a high rank coal with one of lower quality, there are likely to be operational challenges that must be addressed. However, by suitably upgrading, it may be possible to overcome them.

5.1 Improving the properties of low quality coals

From a purely technical standpoint, the upgrading of lignites and subbituminous coals is possible via a number of techniques. Upgrading can increase their value and options for utilisation. However, the characteristics of the upgraded fuel must be well understood in terms of its suitability for specific coal-to-electricity (or other options) conversion technologies. If the total fuel costs (for mining + upgrading) are favourable, and the fuel is compatible with the particular technology and logistics, a positive result can be attained (Clarke, 2013). Currently, over a third of the world's coal production is cleaned or upgraded in various ways. Estimates suggest that there are around 3000 coal cleaning plants operational around the world, and new capacity continues to be added.

Coal properties can play a major role in the overall effectiveness of coal-fired processes. This is particularly true for power generation where they can impact on many operational aspects. The choice of coal type can be critical in the development of a successful and economically-viable project. For both new-build and existing plant, coal properties can influence numerous aspects of plant design and operation (Table 7).

Table 7 Possible impacts of coal quality variation on power plants (Saxena, 2013; Sharma, 2015)

Property	New plant	Existing plant
High moisture content	Bigger boiler and pulveriser needed High power availability Lower boiler efficiency and higher fuel requirement per MW of output	Difficulty in maintaining steam and reheat temperatures Reduced boiler efficiency Reduced pulveriser capacity Reduced outlet temperature
High ash content	Increased boiler and pulveriser size Higher power requirement May require more support oil Higher fuel requirement per MW of output Large amount of ash for disposal	Increased erosion and/or slagging and fouling of pressure parts and draught fans May require more support oil Reduced ESP performance Overloading of draught fans Large amount of ash for disposal
Volatile matter (VM) content	Low VM content may require special boiler design (down-shot) Impact on boiler turndown ratio and fuel residence time in boiler	VM helps combustion – a sudden reduction can affect flame stability, requiring secondary fuel oil support to manage part-load operations
Calorific value (CV)	Low CV can impact on size and design of boiler, mills, ESP, draught fans, air and flue gas ducts, fuel handling system, and auxiliary power consumption	Lower CV means that a greater volume of coal will be needed, as will higher heat transfer into convective surfaces. Increased de-superheating spray will be required to maintain main steam temperature. Lower efficiency of boiler, mills, and ESP
Hardgrove Grindability Index (HGI)	Mills must be designed to accommodate extreme values, resulting in high equipment costs	Coal fineness affected if HGI is less than design value. Increased mill maintenance and downtime Reduced boiler efficiency and performance
Impacts of fuel constituents		
C, H, S and N content	Change in fuel composition can affect combustion process May be an increase in some emissions	
Cl content	Increased risk of corrosion	
Impact on emission control systems		
Particulates	Selection of control equipment affected by fuel characteristics, boiler type, ash properties, plus particle loading and size. High ash level can impair effective ESP operation	
NOx	Thermal NOx control possible by reducing combustion zone temperature Fuel containing less nitrogen will generate less overall NOx	
SO_2	Can be controlled by switching to low sulphur coal or deploying post-combustion systems such as FGD	

5.1.1 Drying

Upgrading can take a number of forms, some commercially more developed than others. For many applications, drying is of particular importance as the use of low quality coals can be constrained by their high moisture content – this can fall between 30% and 70% (as-received). Without pre-combustion drying, up to ~25% of the coal's energy may be expended in evaporating the water present. This reduces thermal efficiency and increases emissions of CO_2 per unit of useful energy output. However, it can be difficult to effectively dry some low rank coals. With bituminous coals, most of the moisture ('free moisture') is present on the surface; low rank coals differ in that a considerable proportion of the moisture is held in capillary pores, hence is more difficult to remove.

Recent years have seen a number of drying projects and techniques proposed or developed. Much of this effort has been concentrated in Australia, Germany, the USA, and to a lesser extent, Japan and Indonesia. The main technological focus has been on evaporative drying processes. This is a natural extension of conventional evaporative drying techniques (such as flash mill or steam tube drying) that are now used widely in power plants and coal briquetting facilities (Dong, 2011). In evaporative drying, moisture is removed in vapour form by applying heat, either directly or indirectly. As there is no heat recovery from most such processes, the energy requirement is in the range 3.0–4.5 MJ/kg of water removed. Several evaporative drying processes (such as WTA and DryFining™) have attained large-scale demonstration. For example, in the USA, DryFining has been demonstrated at Great River Energy's lignite-fired Coal Creek Station. The system was subsequently installed on both of the plant's two units – it was confirmed that emissions were reduced and plant efficiency increased.

There are also a number of alternative processes that have been developed but have not yet been demonstrated at large scale such as the LLD drying process, Coldry™, Drycol™, DevourX mill, LamiFlo™, Alligrator mill, and superheated steam drying. Under the appropriate conditions, most have shown potential for improving the properties of low rank/grade coals, making them more amenable for transport and improving combustion efficiency.

As an alternative to evaporative drying, there are also a number of non-evaporative techniques. These have emerged primarily as they have lower energy consumption per unit of water removed. However, all such processes come with an (often costly) requirement to treat the contaminated wastewater produced. Both evaporative and non-evaporative drying concepts were examined comprehensively by Dong (2011).

Although drying is an important upgrading option, there are also other technologies dedicated to transforming low quality/rank coals into high-value, stable and transportable fuels. These generally incorporate drying as one component of the system. Thus, drying can be combined with processes such as briquetting or pelletising, or mineral matter removal via a suitable coal cleaning process. Some briquetting/pelletisation processes take raw coal and agglomerate it (either with or without washing) and generate a dewatered product with reduced sodium, potassium and chlorine content; this can help reduce issues of low ash fusion temperatures and corrosion respectively (Clarke, 2013).

An interesting variant that is reaching commercial deployment is the Clean Coal Technologies Inc. (CCTI) *Pristine-M* process. This was developed as a means of dewatering coals with moisture contents of up to 60%, but where a reduction in the level of volatile matter was not needed or where remaining levels would inhibit combustion in PCC boilers. Patented technology extracts the volatiles and moisture from the coal in liquid form. Via an adsorption process, the liquid volatiles are then used to coat the coal particles and fill in the pores – this is claimed to result in a stable, dehydrated product.

Some drying processes present a number of challenges: dried coal can gradually reabsorb moisture, it can be friable and easily degraded, and the risk of spontaneous combustion can be increased. Clearly, the process must also be cost-effective. The Pristine-M process claims to have overcome these problems. Thus, the feed coal is not pulverised and suffers little degradation, obviating the need for briquetting or pelletising. The process operates on a continuous basis and comprises three main components. The first is a devolatiliser used to produce gases (for process heat and to stabilise the dry coal) – only a small portion of the feed coal (typically <7%) is devolatilised. The second component is a dryer that operates at ~120°C – this can reduce inherent moisture to 5%. In the third stage ('stabilisation/vapour phase deposition'), volatile matter present is absorbed into the pores of coal from which the moisture has been driven off. Fines generated during processing are removed at various stages and can be used for combustion (process heat) purposes. Treated coals are claimed to be impermeable, the structural integrity is maintained, and the CV can be increased beyond what would be obtained by moisture removal alone. Particles do not tend to break in transport and also have a long outdoor shelf life. In January 2016, a 40 t/d demonstration plant began operation at AES's Shady Point power plant in Oklahoma, USA. Jindal Steel & Power Ltd of India (the country's third largest steel producer and coal miner) has licensed the Pristine-M technology for 25 years and is planning to build a 1 Mt/y plant, following process validation later in 2016.

5.1.2 Upgrading

Clearly, upgrading processes add complexity and cost – the overriding factor will be the total relative cost of upgraded coal versus the cost of available higher rank coal. Put simply, the upgraded product must be an economically viable option to alternatives sources of fuel. To succeed, it must be acceptable in the marketplace, have adequate energy content, have chemical and physical stability, a secure supply must be available, prices must be stable, it should be suitable for blending, and it should have an overall price advantage (Clarke, 2013). Around the world, a number of upgrading processes are either available commercially or have been tested at least to pilot scale. Some recent examples are given in Table 8. In the case of some low quality coals, although technically feasible, process economics are often the overriding factor.

Table 8 Examples of low rank coal and lignite upgrading processes and their status (Clarke, 2013)

Process name	Developer	Country of origin	Input raw fuel	Status
Coal Plus	Jatenergy Ltd (Australia)	China	Lignite and some subbituminous coals	Operational plants
CCT Pristine	Clean Coal Technologies Inc	USA	Lignite, subbituminous coals	Pilot plant
CCT Pristine-M	Clean Coal Technologies Inc	USA	Lignite, subbituminous coals	Pilot and demonstration plants
Continuous Hydrothermal De-watering	B Exergen Pty Ltd	Australia	Lignite and some subbituminous coals	Pilot plant
Binderless briquetting	White Energy Ltd	Australia	Subbituminous coals and some lignites	Operational plant
Coldry	Environmentally Clean Technologies Ltd (ECT)	Australia	Lignite and some subbituminous coals	Pilot plant
ZEMAG	Clean Energy Technology GmbH	Germany and China	Lignites, brown coals	Operational plants

Lignite and lower rank subbituminous coals can be useful as blending fuels (*see* Section 5.2.1) when added to more expensive coals of higher rank. However, excessive addition can increase the propensity for spontaneous combustion and overall moisture content of the blend. Because of the former, low quality coals and lignites are often restricted to local use, and are not transported for long distances. The risk of spontaneous combustion can be reduced by briquetting or pelletising. Potentially, through the application of such processes, some Australian and various Asian low rank coals and lignites (not currently exportable) have the potential to be transformed into export quality. Their properties could be suitably enhanced by moisture reduction and associated improvements in chemical and physical stability.

Interest in improving the properties of low quality coals has not been limited to global export markets. In some situations, the particular coal may represent the only major national energy resource, and hence be of significant economic and strategic importance. For example, the booming Turkish economy relies on the use of indigenous lignite for a significant proportion of its power supply. Many Turkish lignites have high ash contents, although once washed, some (such as those from Tunçbilek and Soma) can compete with imported coals. Not all production is washed, although a growing amount is treated in order to increase CV and minimise combustion- and environmental-related issues. As the amount of lignite used in Turkey has grown, so the deployment of washeries has increased. Currently, around half of the country's production is washed, mainly using dense medium separation techniques. The advantages accrued have been shown to outweigh the increased costs (Mills, 2014).

Some high ash bituminous coals are also cleaned in order to reduce their ash content. For example, many Indian coals contain high levels of mineral matter – coking coals can contain 30–40%, and thermal coals, 30–>50% (Sinha and others, 2015; Muthukrishnan, 2016). In this case, ash removal can be difficult. The majority of the ash is 'inherent' ash – this comprises small particles of mineral matter embedded in the combustible part of the coal. The composition of a typical Indian coal is given in Table 9.

Table 9 Composition of 'typical' Indian coal (Muthukrishnan, 2016)

Property	Unit	Average	Range
Total moisture	wt%	12	10–17
Ash	wt%	35	25–45
Volatile matter	wt%	22	19–23
Fixed carbon	wt%	26	20–32
HHV	MJ/kg	14.7	11.7–18.8

Unlike 'free' ash (mineral impurities associated with the mining process) inherent ash cannot be removed easily from the coal (IEA India Energy Outlook, 2015; Muthukrishnan, 2016). Inorganic impurities present are mixed intimately within the coal matrix making such coals difficult to wash (Kumari and others, 2015). However, reducing the level of ash has been found to benefit power plants through increased boiler efficiency, reduced auxiliary power requirements, minimised operation and maintenance (O&M) requirements, and decreased emissions to land and air. Studies and practical experience have confirmed that on a cost-benefit basis, the cost of the coal washing process is usually outweighed by the benefits generated. As elsewhere, savings may be made at various stages although it is generally at the transportation stage that some of the biggest direct savings can be made. Indian coal washeries are based mainly on systems using cyclones, barrels, baths and jigs. Total thermal coal washing capacity exceeds 70 Mt/y and more is being added. For example, in February 2016, Adani Enterprises announced the creation of a new coal washing arm (a wholly owned subsidiary – Korba Clean Coal Pvt Ltd). This was set against a background of increased washing; between April and December 2015, the company had extracted and washed 3.7 Mt of coal, up from 2.1 Mt in the previous corresponding period. Other companies have reported similar increases.

In September 2015, the Indian energy minister announced that state-owned Coal India Ltd (CIL) aims to produce 1 Gt of coal by 2020, and that the government was committed to setting up washeries capable of treating a further 250 Mt/y of coal within the next three years. Furthermore, third-party sampling to check coal quality has been adopted – reportedly, this has significantly reduced quality problems at power plants. Under the 12th Five-year Plan (2012-17), CIL envisages setting up 15 new washeries (via various subsidiary companies) to meet the increased requirements. These will have a total capacity of ~93 Mt/y. Six new washeries (capacity of 19.6 Mt/y) will be for coking coal, and nine for thermal coal (capacity 74.5 Mt/y). Coking coal washery capacity will increase from 24.9 Mt/y to ~43.5 Mt/y and that of thermal coal washeries, from 14.5 Mt/y to ~89 Mt/y (Sinha and others, 2015). Subsidiaries of CIL also plan to increase washing capacity. For example, Western Coalfields Limited (WCL) and Mahagenco are developing a joint venture aimed at setting up four new washeries (at Nagpur, Wani North, Wani and Ballarpur) with a combined capacity of 15–16 Mt/y. As well as environmental advantages accrued by washing, the reduced ash level will mean that the end product will be improved from Grade G9, to G7 or G8, increasing its selling price. Other projects continue to be authorised. For example, Mahanadi

Coalfields Ltd recently received permission to develop a 10 Mt/y washery project in Odisha. Usefully, rejected coal is to be used for power generation via a joint venture with National Thermal Power Corporation (NTPC). This will help minimise any associated environmental impacts.

High ash bituminous coal is also washed in large quantities in South Africa, although here, cleaned coals are often directed to export markets. Although relatively low in sulphur (<2%), South African coal is generally considered to be low grade by international standards, typically having an ash content in the range of 20–30%. However, ash contents of 30–40% have become more common, with values as high as 65% having been reported in run-of-mine (ROM) coal from the Waterberg region. Coking coals and export grade coals require washing to reduce ash content and increase the CV. Historically, CVs of between 26 and 27.5 MJ/kg have been required for export grade coal, although in some cases, average values have declined to less than 25 MJ/kg. Coal with a CV as low as 23 MJ/kg have proved acceptable for the Indian market.

Steam coals directed to South African markets tend to have higher ash content and lower CV and for some applications, are used unwashed. Some supplies to local power plants (and Sasol's coal-to-liquids, CTL, operations) are produced from the middlings fraction of export coal washing plants. Transport costs generally account for a significant proportion of the delivered product cost, thus, for economic reasons, power plants at some distance from mines are often supplied with washed coal with higher CV (SANEDI, 2011). Generally, between 25% and 30% of South Africa's saleable coal is exported. In 2015, exports from Richards Bay Coal Terminal increased by 5.7% to 75.4 Mt, helped by demand in Africa and India. A similar level is expected for 2016 (Reuters, 2016). The terminal is located on the country's Indian Ocean coast and has a capacity of 91 Mt/y. It ships coal for several large operators that include Glencore and Anglo American.

In China, a wide variety of coals are produced. Some, such as those mined in the southwest part of the country, have high sulphur content (>3%) although their production is now being restricted. Their CV tends to be on the low side but could be improved by washing. At the moment, around 40% of China's thermal coal output is washed, although the government has a goal of increasing this to 70% by 2017 (Cornot, 2014).

5.2 Costs and benefits of improving coal quality

Widespread experience has established that coal cleaning can be vitally important from both economic and environmental perspectives. There can be significant benefits in using cleaned coal in thermal power plants. Some are tangible and easily quantified, although others are less so (Mishra, 2015). However, overall, the use of washed coal can provide many benefits to the power sector.

It is well known that the emissions characteristics of coal combustion are influenced significantly by the type and processing of the coal in question, and that its quality can affect the profitability of a power plant. It can also have a major impact on a plant's ability to meet environmental requirements. As noted above, some of the main variables that influence coal quality are ash and sulphur content. Both have no heating value, hence the higher the ash content, the lower the coal's CV. Clearly, CV will be increased as ash content is reduced. Washing provides directly several benefits that can impact on power plant profitability and emissions, as well as reducing future economic risks. Reducing ash content can increase a coal's CV significantly, meaning that less volume of coal needs to be burned to produce a comparable amount of electricity. A power plant using a higher quality coal will generally have an economic and performance advantage over one using coal of lower quality.

The presence of ash and sulphur species in the boiler can affect plant operability and result in increased maintenance and decreased capacity factor. Downstream, ash and sulphur can cause deposition (slagging and fouling) and corrosion in plant ductwork and other systems, reducing their lifetime. High ash content will also create greater volumes of plant by-products that will require disposal. It can also have a detrimental effect on major components of the coal handling and processing system (conveyors, mills and crushers). Wear will be higher and systems will consume more electricity, reducing the amount available for sale. Thus, improving coal quality by reducing ash and species such as sulphur can be both environmentally and economically beneficial to power plant operation. There can also be positive impacts on the lifetime and operation of emissions control systems. A high percentage of ash passes through the combustion process and is carried in the flue gas for eventual capture in an ESP or fabric filter. A lower initial ash content will reduce the impacts on such systems and may allow the power plant to install smaller emission control systems, reducing both capital expenditure and daily operating costs.

Reducing ash levels is also undeniably beneficial in terms of associated transport costs as it reduces the movement of inert materials with no heat content. This can be of particular importance in economies (such as India and China) where large quantities of high ash coal are transported, sometimes for considerable distances. For example, around 45% of China's rail capacity is directed to moving coal – recent estimates suggest that ~70 Mt/y of dirt and rock are moved along with coal.

Any coal washing process will provide benefits although clearly, there will also be associated costs. Various studies have examined the cost:benefit ratio and concluded that generally, the benefits outweigh the costs. For example, a study (Sharpe, 2011) examined the washing of high ash Indian coal and determined that on average, washed coal was ~10% less expensive than raw coal, even with a calculated washing fee of 2.40 US$/t. This work examined the heating value of coal after different levels of washing and confirmed that, for distances >900 km, the delivered price (on a cost per MJ basis) was lower for washed coal than for raw. The study (and others) also confirmed that coal washing produces additional plant benefits. Within an Indian context, advantages cited include:

- improved plant efficiency due to higher coal heat content;
- improved operation of ash handling system and lower ash disposal costs;
- lower power plant operational and maintenance costs;
- reduced auxiliary power consumption (less draught fan and milling requirements);
- improved ESP performance;
- reduced overall cost of generation;

- reduced congestion of the national rail system;
- savings in freight costs; and
- cost savings – washed coal costs 10–20% less than imported supplies.

In the USA, a number of studies undertaken by EPRI also determined that there can be benefits in using better quality coal. As elsewhere, higher ash levels were found to impact negatively in terms of thermal efficiency, quantity of ash landfilled, annual tube failures, unit availability, and amount of CO_2 emitted. Each one per cent increase in boiler thermal efficiency was found to decrease CO_2 emissions by 2% to 3% (Crossley and Xuan, 2013). Similarly, examination of the Chinese coal-fired power sector also concluded that the use of low quality coals increased environmental damage, added unnecessary expense, and decreased the operating life of power plants (James and Gerhard, 2015). Potentially, a small price increase for better fuel quality could produce more revenue for the power plant through increased availability, and decreased operation and maintenance costs. However, many factors remain highly site-specific.

5.2.1 Coal blending

Coal quality can be improved by the application of various beneficiation methods. Alongside this, there may also be the option of blending. For a number of reasons, in some major economies, the blending of indigenous and imported coals has increased significantly. Reasons cited for blending power plant supplies include increased overall CV, reduced auxiliary power consumption, lower overall ash content, reduced forced boiler outages, improved ESP performance, decreased soot blowing requirement, and reduced maintenance costs (Sharma, 2015).

Historically, blending coals for the power sector was carried out mainly as a cost-saving exercise – the usual aim was to increase the proportion of cheaper coals used. Often, this entailed blending a low quality (often high ash) domestic coal with higher quality imported supplies in such a way that the thermal performance of the plant boiler remained at its optimum level and the cost of electricity was kept as low as possible (Sloss, 2014). For example, coals are blended regularly at the Dandong power plant in China – the main aim is to decrease costs. In this particular case, units burn coal from Inner Mongolia blended with local lignite and (bituminous) coal. There are innumerable other examples around the world.

However, not all blending is focused solely on cost saving – it is also undertaken in order to achieve environmental goals such as lower SO_2 emissions. For some years, a large proportion of the coal imported into China has been blended with domestic coals with this in mind (much imported Indonesian coal has low sulphur content). Thus, the judicious blending of a low-sulphur imported coal with high-sulphur domestic sources has been effective in reducing emissions and in some cases, avoided the need for back-end gas clean-up systems such as FGD. Blending can also be beneficial in others areas of plant operation. For example, problems with slagging and fouling can sometimes be minimised.

Not all blends used in power plants rely solely on imported coals. For example, some plants in the USA burn blends produced from different indigenous coals. For instance, low-sulphur PRB subbituminous coals are sometimes blended with high-sulphur Eastern bituminous coal. This approach has been used to minimise SO_2 emissions, although the exhaustion of some previously used bituminous coal reserves has also been a factor. Blending of several sources of domestic coals is continuing via new projects. For example, at its Oak Creek power plant, We Energies is nearing completion of a new US$62 million project that will enable it to burn more low-sulphur PRB coal. This will be blended with higher-sulphur Appalachian coal and fired in two units (combined capacity of 1230 MW). The utility expects fuel savings of US$31 million per year if burning a 60% PRB blend. At the moment, 20% PRB is used. Oak Creek's two newest units burn ~3.3 Mt/y and its older units, a further 3.1 Mt (Coal Age, 2015).

In theory, blending is a straightforward option. However, in practice, the process can sometimes be more challenging. Depending on the particular plant and its design specification, there is the potential for plant operation and efficiency to be affected when the fuel feed deviates from the design specification. Operational issues can arise when switching from a low grade high-ash coal to one of better quality; clearly, it can also impact in the opposite direction, where higher quality coal is replaced with one of lower quality. There are likely to be instances where a switch to a single alternative supply is not technically feasible, but that a suitable blend of two or more sources (of low and high quality) may be effective.

Coal blending is more significant in some economies than others. In India, for a number of reasons, it has long been of importance. For some power plants, blending is a necessity in order to achieve environmental compliance. More generally, it helps alleviate shortages from domestic coal sources and overcome the progressive reduction in quality occurring with some sources of Indian coal (Arora and Banerjee, 2013). Considerable quantities of coal are imported into India, specifically for blending with high-ash domestic supplies. Pronouncements in 2016 by the Indian Government suggest that within the next 2–3 years, increased domestic production will obviate the need for imports, although most industry observers feel that this is unlikely. The Central Electricity Authority (CEA) has instructed power producers to import a total 73 Mt in 2016 (~35% more than in 2015) for blending purposes. NTPC has been permitted to import 22 Mt, followed by Maharashtra State Power Generation Company (5.2 Mt) and Tangedco (5 Mt). Other companies permitted to import coal include private thermal producers (such as Reliance, Vedanta, and Bajaj Energy) as well as state-owned power generating and distribution companies (Sivakumar, 2015). For the future, the CEA has issued guidelines to all power utilities that new power plants must be capable of using blended coal with a blending ratio of 30:70 (Sharma, 2015). In general, a 10% increase in blend ratio increases the generation cost only slightly (between 3 and 5 Paisa/kWh) (Sharma, 2015).

5.3 Technologies utilising low quality coals

5.3.1 Supercritical (SC)/ultrasupercritical (USC) pulverised coal combustion

Around the world, there are many older subcritical power plants firing lower grade coals. Clearly, it would be beneficial for these to be replaced by units of higher efficiency/lower emissions (Barnes, 2014). A growing number of newer projects are now adopting supercritical (SC) or ultrasupercritical (USC) steam conditions – compared to older subcritical plants, the greater efficiency achieved effectively reduces emissions and fuel use per unit of electricity generated. Some countries have long embraced SC/USC technology based on lower grade fuels. For example, Germany operates a number of highly efficient lignite-fired power plants that include units at Neurath and Niederaussem. Some are based on innovative BoA technology ('lignite-fired power station with optimised plant engineering') that helps boost efficiency to >43% – this significantly reduces levels of classic pollutants and CO_2 emissions per unit of power produced. However, as noted elsewhere in this report, in Germany, even highly efficient units such as these may be relegated to back-up duties (as opposed to base load). Elsewhere in Europe, the use of lignite for base load applications seems likely to continue for some time. For example, a consortium involving Mitsubishi Hitachi Power Systems Europe (MHPS) is building a new 450 MW lignite-fired USC power plant at Turów in Poland. MHPS's proprietary technologies in low grade coal combustion for boilers will be used for the project, scheduled to commence operations in 2019. Similarly, a new USC-based lignite-fired project is under construction in Greece.

In the USA, one of the world's cleanest, most efficient coal-fired power plants (the 600 MW USC John W. Turk, Jr. Plant in Arkansas) relies on subbituminous coal, confirming that with the use of appropriate control systems, environmental issues associated with the use of low quality coals can be largely overcome. The unit came into commercial base load operation in 2012 and uses low-sulphur PRB coal mined in northeastern Wyoming and delivered in 125 car unit trains (each car contains 120 tonnes) – the plant consumes ~310 t/h. NOx emissions are controlled by a combination of SCR, low-NOx burners and overfire air, SO_2 is controlled using a dry FGD system, and particulates via a pulse-jet fabric filter.

The biggest market for SC/USC power plants now lies firmly in the developing economies of Asia. In particular, recent years have seen the widespread adoption of SC/USC systems in the burgeoning economies of China and India. The advantages provided by the technology mean that increasingly, older inefficient units are being closed down and replaced with supercritical capacity. In other cases, new SC/USC capacity continues to be added in order to meet the growing demand for a reliable supply of electricity. For example, India is building numerous power plants, many fired on indigenous high-ash bituminous coal. The concept of SC technology was introduced as a national plan in the Indian Integrated Energy Policy Report of 2006. The 12th Five-Year Plan saw the introduction of SC technology through the development of Ultra Mega Power Projects (UMPPs – capacity of ~4 GW each) and other major undertakings. Although some fire imported bituminous coal, many rely on high-ash domestic supplies, sometimes blended with imports. So far, four UMPPs have been commissioned and other plants are planned or in development. However, a number of major coal-fired projects have recently been cancelled and emphasis switched to solar power. Despite this, poor quality Indian coal continues to make a significant contribution towards providing the country's electricity. For the foreseeable future, coal will remain an important source of energy in India.

There are a number of other Asian economies that have adopted SC/USC technology. For example, in order to meet the growing domestic electricity demand, Indonesia plans to increase its coal-fired generating capacity. As part of this, the country's first SC-based project was undertaken – this was an

815 MW expansion project for PT Paiton Energy. Much of the plant (including the boiler) was supplied by MHI of Japan. This uses steam conditions of 24.4 MPa/538°C/566°C and was designed to fire exclusively domestically produced subbituminous coal. Other similar projects are in development. In Thailand, Marubeni and Alstom have recently been awarded an EPC contract for a new 600 MW USC lignite-fired power plant at Mae Moh. The new unit will replace the site's existing Units 4–7. It is being developed by a consortium comprising Marubeni Corporation, Alstom, and Electricity Generating Authority of Thailand (EGAT). Again, other projects are planned. As well as such combustion-based applications, Mae Moe lignite is also currently being assessed by NEDO in Japan for possible IGCC use.

Elsewhere, the importance of indigenous lignite as a reliable, cost-effective source of energy has long been recognised. For example, both Turkey and Greece rely heavily on lignite to meet much of their electricity demand. With the latter, despite the country's ongoing economic problems, a new 660 MW USC lignite-fired unit (Ptolemais V) is being built by Hitachi Power Europe GmbH for the state-owned Public Power Corporation.

5.3.2 Fluidised bed combustion

Circulating fluidised bed combustion (CFBC) technology has been shown to be well suited to burning low grade and/or difficult to burn fuels. CFBC is an established technology and is used widely – there are now numerous units (mostly using subcritical steam conditions) that fire lignite or low quality subbituminous coals. Although (compared to many PCC stations) most are of relatively low capacity, recent years have witnessed a trend towards larger units. In addition, supercritical steam conditions are now being adopted for some larger projects. SC CFBC boilers with capacities up to 800 MWe are offered commercially (Zhu, 2013).

Fuel flexibility has been a major driving force behind recent major projects, as increasingly deregulated markets have encouraged utilities to seek cheaper sources of fuel – the ability to easily change supply has become more attractive. For example, several US power plants employ CFBC as a means of cofiring locally available opportunity fuels such as petcoke and waste coal. In China, the technology is seen as ideal for firing high-ash anthracite, lignite and waste coal (Lockwood, 2013). In India, an increasing amount of bituminous coal output is now washed before transport and use. Most washeries produce a stream of reject material that can have an ash content of up to 80%. Despite this high level, some is now utilised as a fuel source for CFBC units, used to generate steam and/or electricity (Khumar and Jha, 2015).

Some lower-rank coals and lignites have low ash fusion temperatures, high sodium and/or potassium content and high base:acid ratios. This can create problems of slagging and/or fouling in conventional PCC-based plants. Because of their lower operating temperatures (850–950°C), the use of both bubbling fluidised bed combustion (BFBC) or CFBC technology can avoid some of these problems.

In some countries, local circumstances have meant that CFBC technology has become well established. For example, Turkey relies heavily on indigenous lignite for power generation. This is used to fuel a growing number of CFB-based plants using technology variants from several suppliers. Most are used for power and/or cogeneration applications. Examples are shown in Table 10. As elsewhere, lignite properties can be variable. However, by way of example, lignite supplied to the Göynük power plant has a CV of 9.2–11.7 MJ/kg, moisture content of ~30%, and ash content of 26–31%. The design fuel for the Soma CFBC plant has a CV of 6.77 MJ/kg, moisture content of 23%, and ash content of 43%.

Table 10 Examples of Turkish CFBC power/cogeneration plants in operation or under construction

Plant	Fuel	Comments
Can, Çanakkale	Local high sulphur (>8%) lignite	Efficiency of ~40%
IÇDAŞ Steel Works, Biga, Çanakkale	Lignite and hard coal	3 x 135 MW units
Göynük Power Plant, Bolu	Local lignite	2 x 135 MW units
Yunus Emre Thermal Power Plant, Eskişehir	Washed local lignite	2 x 145 MW units Equipped with FGD
Tufanbeyli Thermal Power Plant, Adana	Local lignite	3 x 150 MW units
Çankiri Orta Thermal Power Plant (the YOTES Project)	Local lignite	3 x 133 MW units
Hidro-Gen Soma Thermal Power Plant, Soma, Manisa	Local lignite	2 x 255 MW units

When it becomes fully operational in 2017, the 2 x 255 MW Hidro-Gen Soma CFBC plant will be the biggest such facility in Turkey. Here, plant emissions will be controlled through the use of CFB scrubbing (CFBS) technology. This multi-pollutant system will remove a range of pollutants from flue gases. In operation, boiler flue gas enters at the bottom of the CFB scrubber's up-flow absorber vessel. The gas mixes with hydrated lime and water injected into the absorber, as well as recirculated solids from the downstream fabric filter. The 'turbulator' wall surface of the absorber causes high turbulent mixing of the flue gas, solids, and water to achieve high capture efficiency of the vapour phase acid gases and metals contained within the flue gas (Pyykkönen and others, 2015). Successful operation may encourage further similar installations to be made within the country.

In the USA, there are several CFBC plants that fire difficult coals; for example, the Alstom-designed 300 MW Units 3 and 4 of East Kentucky Power Cooperatives' Spurlock Power Station in Maysville, Kentucky. An acknowledged advantage of CFBC technology is its fuel flexibility and the Spurlock units were designed with the capability of firing a wide range of coals with up to 20% cofiring of petroleum coke, biomass and tyre-derived fuel. Since coming on line, these units have fired a number of different coals that have included high sulphur (~7%) and high ash bituminous coal from southeastern Ohio. Despite such properties, as a result of its modern design and effective emission control systems, the plant has exhibited high availability, flexible operation, and low emission levels.

In China, a similar 300 MW unit also supplied by Alstom is in operation at the Baima power plant in Sichuan province. Here, the design fuel is a difficult to burn anthracite. Properties are variable – it contains very low levels of volatile matter and has a high ash content (that can include stones). The design ash content is 35%, although levels can be greater. The design sulphur content is 3.54 wt%, although it can also be much higher. During initial operation, a number of operational problems arose, many connected with excessive ash content in the feed coal. However, these were systematically resolved via various modifications and the plant now operates successfully, a testament to the fuel flexibility of the technology and its ability to operate with lower quality coals.

India's pressing need for more energy has meant that some types of fuel (that in other situations would probably be excluded) are used to provide heat and/or power. For example, a CFBC plant (2 x 125 MWe) at Surat is one of several firing 'challenging' high sulphur content lignite. These two units were designed (but subsequently modified) specifically to burn this fuel efficiently. The plant's lignite feed has a moisture content of up to 40%, ash content of 15%, and sulphur content of >13%. Heat content is 12.56 MJ/kg (HHV). Since first coming on line, a number of operational problems have required addressing, including cyclone blockages at very low loads, and heavy/rapid deposit build-up on the flue gas side of the heat transfer tubes in the back pass of the boiler (resolved mainly by improvements in the soot blowing procedures) (Barnes, 2015). The plant now appears to be operating well.

As with Baima and Surat, not all FBC-based projects have been trouble-free during initial operation. Although generally regarded as highly tolerant to high ash loadings, historically, some CFBC units have suffered erosion damage and/or agglomeration. For example, in 2015, the Neyveli Lignite Corporation of India commissioned two 250 MW lignite-fired CFBC units in Tamil Nadu. Reportedly, as a result of repeated failures in boilers plus other issues, this was delayed for six years. The technology supplier (BHEL) delayed commissioning until it had developed improved fluidised bed heat exchange tubes for the units. However, other Indian CFBC-based projects have progressed more smoothly. For example, JSW Energy's 1080 MW Barmer power plant sells its entire output to the Government of Rajasthan. It was commissioned in 2013 and consists of eight CFBC units fired on local lignite supplied from its captive mine at Kapurdi. This has a low CV and high sulphur and moisture contents. Despite this, since start-up, the plant has operated smoothly and has coped with extreme weather conditions, sandstorms and a lack of water (supplied via a dedicated 185 km pipeline from the Indira Gandhi Canal). Generally, teething problems appear to have been overcome through the adoption of improved design and operational practice. Highly reliable operation is now achieved regularly.

New Indian CFBC projects continue to be developed. For example, BHEL is commissioning a new 250 MW unit in Gujarat. This is operated by Bavanger Energy and is fired on local lignite. A second similar unit is also under construction.

5.3.3 Gasification

Around the world, a variety of coals have been gasified – these have included feeds with 6–36% ash, up to 35% moisture, and ash melting points between 1140°C and >1500°C. Different types of low quality coals and lignites have been successfully gasified in commercial operations, producing a number of end-products. Plant size and configuration has varied widely, although some facilities are of considerable scale. Probably the biggest and most well-known is the Great Plains Synfuels Plant near Beulah, North Dakota, USA. This is operated by the Dakota Gasification Company and is the only US-based commercial-scale gasification plant to manufacture synthetic natural gas (plus a range of other products) from local lignite. Gasification is carried out using 14 Lurgi-based gasifiers. The plant consumes 18,000 t/d of lignite sourced from the nearby Freedom Mine. This is gasified to produce ~5.53 million m^3/d of gas. Much of this is piped to Ventura and Harper, Iowa, for distribution in the eastern USA. Raw gas produced is cooled and CO_2 removed via Rectisol™ washing, followed by methanation (using nickel catalyst), drying and compression. The plant also forms part of the world's largest CO_2 capture and storage project. Since 2000, Dakota Gas has been sending CO_2 through a 330 km mile-long pipeline to Saskatchewan, Canada, where oil companies use it for enhanced oil recovery operations/permanent CO_2 geologic storage. Up to 50% of the plant's CO_2 is captured each day (~8000 t/d) – this amounts to ~3 Mt/y.

In terms of number of individual gasification projects, China has the biggest number. Development of the sector continues with the Chinese government supporting a significant number of R&D programmes. Technology has been sourced from international suppliers and also developed within Chinese institutions. At least seven different types of gasifier have been successfully developed and commercialised. These are being used in over 100 individual projects spread across most provinces. Gasification systems sourced from overseas vendors include those from Air Liquide/Lurgi, Environtherm/BGL, Gencorp/Pratt & Whitney, General Electric, KRB, Shell, Siemens, and Synthesis Energy Systems. Shell is the biggest of these suppliers – by 2013, the company had been responsible for at least 36 coal gasifiers for 23 individual projects (US-China Energy Center, 2013). Domestically-developed gasification systems include those from Aerospace Science and Technology Corporation, East China University of Science and Technology, the Institute of Coal Chemistry/Academy of Science, Northwest Research Institute of Coal Chemistry, TPRI, and Tsinghua University of Thermal Engineering. Different technology variants are in operation (entrained flow, fixed bed, slagging, transport, and fluidised bed). Chinese-developed systems include opposed multi-burner gasification and multi-component slurry gasification. Various coal types are gasified to produce a range of products that include ammonia, oxo chemicals, methanol, SNG, CO, hydrogen, propylene, hydrogen, DME, gasoline, LPG, acetic acid, butanol, octanol, urea, methane, and ethylene glycol.

In some cases, low grade coals are used as feedstocks. For example, KRB TRIG technology (advanced, pressurised, circulating fluidised bed gasification) is used by Berun Holding Group's 100 kt/y ethylene glycol project in Inner Mongolia with high-ash lignite as feedstock. The plant has a design capacity of 35,000 m^3/h of syngas. According to the Twelfth Chinese Five-Year plan, at the end of 2015, total annual SNG production capability was between 15 and 18 billion m^3/y. More than ten coal-to-SNG projects have been built or are planned. For example, the Datang Keqi SNG Project came on line in December 2013, supplying gas to Beijing. This is based on fixed bed gasification and is fuelled on lignite. It can produce up to 4 billion m^3/y of SNG. Initial problems of gasifier corrosion have been overcome and the plant is now operating reliably. A Phase II expansion was completed at the end of 2015. The project has been important for demonstrating the technical and economic feasibility of SNG production from low rank fuel, and confirming the reliable, stable operation of lignite-fuelled pulverised coal, pressurised (4 MPa) gasification. A similar project (the Datang Fuxin Project) is also under construction (Chunqi Li, 2014). This will use the same type of gasifier fuelled on lignite.

Other Chinese projects use subbituminous coals for SNG production. For example, the Yima Coal Industry Group Company, Henan Province, operates two 1200 t/d U-gas gasification-based systems for methanol production. The plant was designed to produce 300,000 t/y of methanol from subbituminous coal with 38–45% ash content. The Hai Hua facility in Shandong Province uses a similar U-gas-based system to produce SNG used for producing methanol. Two 400 t/d gasifiers generate 22,000 m^3/h of syngas supplied to a methanol production facility. The plant operates on high ash middlings (55%), run-of-mine bituminous coal, high-ash subbituminous coals, and lignite.

In South Korea, Posco, the country's biggest steelmaker, has established a subsidiary to operate an SNG business. This is developing several coal-to-SNG plants. The technology is being used at the company's Gwangyang complex, where an SNG plant with a capacity of 500 kt/y is being constructed – this will gasify low quality coals. Gas produced will replace expensive imported LNG. Commercial operations are scheduled to begin during 2016. Posco has also agreed with Mongolia's MCS Group to establish a 50:50 joint venture to build an SNG plant in Mongolia. Commercial operation is expected by the end of 2018.

At Angul in India, KBR has been involved in a major project focused on coal gasification for Jindal Steel & Power Ltd. Syngas is produced and used as a reducing gas for the direct reduction of iron (DRI) process. High ash bituminous Angul coal (~40% ash) is gasified to generate 360,000 m^3/h of syngas. Also in India, in 2014, it was reported that the Indian Adani Group planned to invest US$3.75 billion in a coal gasification project to be located in Chhattisgarh state. It will use local high ash coal.

In a number of developing economies, the application of gasification to indigenous coal reserves holds considerable potential for replacing expensive (and sometimes unreliable) imported sources of energy. For example, Ukraine holds substantial reserves of lignite and subbituminous coals. The country's economy is heavily dependent on imported natural gas and oil – in principle, large-scale production of SNG could cut gas costs by 50% (Minchener, 2013). There are plans for the country to replace imported gas with SNG produced from domestic coal. As part of this process, China will design and supply five coal-to-SNG plants in Luhansk, Donetsk and Odessa. These will be built under license and based on Shell gasification technology. The Chinese Development Bank will provide a loan to cover project costs.

In other situations, gasification processes are being co-fuelled with combinations of low quality coal and petcoke. At least four Chinese Shell gasification-based projects currently blend high ash coal with petcoke to promote stable gasification operation and increase syngas output. These plants have shown the longest continuous runs and greatest uptime of all the Shell Coal Gasification Process (SCGP) plants operating in China. Examples of Chinese gasification projects are shown in Table 11 – many utilise coals of lower quality.

Table 11 Examples of Chinese coal gasification projects (Aranda and others, 2014)

Project	Location	Plant output (bm^3/y)	Plant output (GW)	Investment (billion US $)	Start-up date
CPIC/Shandong Xinwen Mining Group	Yili, Xinjiang	6	6.66	4.41	2014
Datang Energy Chemicals Corp.	Fuxin, Liaoning	4	4.44	4.02	2013
Datang Group/Beijing Gas Group/Tianjing Jinneng	Chifeng, Inner Mongolia	4	4.44	4.2	2012
Datang International Power Generation	Kesheketeng Qi, Inner Mongolia	4	4.44	3.76	2012
Huineng Coal Chemical Co.	Ordos, Inner Mongolia	2	2.22	2.21	2013
Shenhua Group	Ordos, Inner Mongolia	2	2.22	2.29	2014
Xinjiang Guanghui Industry Co Ltd	Yiwu County, Xinjiang	0.5	0.55	1.47	2011
CPIC	Yili, Xinjiang	6	6.66	4.57	2012
China Huaneng Group	Changji, Xinjiang	1.3	1.44	1.12	2013
Yili Xintian Coal Chemical Co Ltd	Yili, Xinjiang	2	2.22	1.96	2013
China Guodian Corporation	Xing'an, Inner Mongolia	2	2.22	2.12	2014
Qinghua Group	Yining County, Yili, Xinjiang	1.3	1.44	0.82	2012
Shendong Tinanlong Group	Changji, Xinjiang	1.3	1.44	1.12	2013
China Huadian Corporation	Changji, Xinjiang	4	4.44	4	–
Xinjiang Guanghui Group	Aletai, Xinjiang	4	4.44	3.27	2013
CNOOC, Datong Coal Mine Group	Datong, Shanxi	4	4.44	4.9	2013

5.3.4 Underground coal gasification

The underground gasification of coal deposits that are not currently economically recoverable is being examined in a number of countries. More than 50 individual projects are at various stages in their respective development in Australia, UK, Hungary, Pakistan, Poland, Bulgaria, Canada, US, Chile, China, Indonesia, India, South Africa, and Botswana. In some of these, the focus is on low quality coals or lignites. Thus, although not yet deployed on a commercial basis, the longer-term potential of the technology has been recognised. For example, the Indian government has indicated that the country should explore the use of UCG to increase domestic production of chemicals and petrochemicals. As part of this process, in 2015, the Ministry of Coal formulated a draft UCG policy. A number of lignite and (high ash) bituminous coal blocks have since been identified for UCG purposes.

Around the world, some proposed UCG projects are at relatively early stages, although others have progressed further. In some cases, momentum has been provided by pressing energy shortages, coupled with available coal resources. For instance, in South Africa, Eskom and Sasol formed a joint UCG development programme aimed at the commercialisation of the technology within the country. Eskom had previously undertaken a decade-long test programme that included 66 months of pilot testing, the commissioning of a syngas pipeline, and the cofiring of UCG syngas at the coal-fired Majuba power station. The Eskom work also addressed syngas clean-up issues and water treatment, and included a FEED study for a 140 MW scheme focused on the Majuba plant. However, Sasol is no longer involved and Eskom has since reduced the project's budget. In order to move ahead, Eskom is seeking external partners. Several other South African projects are also being considered or are under development.

5.3.5 Integrated gasification combined cycles (IGCC)

In IGCC, coal is gasified and the gasification products purified to remove pollutants and particulates before entering one or more gas turbines. Heat recovered from the gas turbine exhaust gases is used to generate steam to drive additional steam turbines. IGCC for power generation has been reviewed in a number of Clean Coal Centre reports, most recently by Barnes (2011 and 2015), Fernando (2008) and Henderson (2008).

Around the world, there are several IGCC projects (based on a number of technology variants) that rely on low quality coals as feedstock. The **Puertollano IGCC power station,** located in the central south part of Spain, is fuelled partly on subbituminous coal. It was launched as a demonstration project in 1992 and was selected as a target project by the European Commission under the THERMIE programme to assure reliable clean coal technology for power generation. The 300 MW plant came into commercial operation on syngas in 1998. The gasifier is of the entrained oxygen-blown type (PRENFLO technology), originally developed by Krupp Koppers. It is fuelled on a 50:50 (wt) blend of subbituminous coal and petroleum coke. However, largely for economic reasons, the plant is scheduled for closure.

In China, subbituminous coal is also being utilised in the 250 MW **GreenGen IGCC project** in Tianjin. GreenGen Ltd. Co. China was established by the China Huaneng Group and seven other Chinese state-owned companies in 2006. The consortium was later joined by Peabody Energy. The goal of the programme is to develop a large-scale IGCC + CCS demonstration project (via three phases). Phase I comprised the construction of the 250 MW IGCC plant (completed in 2012). This is based on a 2000 t/d 2-stage dry pulverised coal pressurised gasifier, a proprietary IGCC process design, and a power island with an E-class multi-shaft combined cycle generating unit. Reportedly, during operation, emission rates have been far below those of some of the most advanced coal-fired power stations in China and on a par with advanced gas-fired units. Phase II (2013-17) comprises a pilot project that will supply hydrogen to fuel cells and turbines to produce electricity. Carbon dioxide captured will be utilised for industrial applications; construction began in 2014. During this phase, ~60–100 kt/y of CO_2 will be captured and stored (Xu Shisen, 2014). Phase III (2018-25) will be an 800 MW power plant with full-scale CCS; CO_2 will be stored in underground rock formations, or possibly used for EOR in the Tianjing Dagang oil field. Completion is expected in 2020.

There are several projects in China that utilise TRIG gasification technology fuelled on low quality coals, one of which is the 120 MW **Dongguan IGCC Retrofit Project**. The Beijing Guoneng Yinghui Clean Energy Engineering Company awarded KBR a contract to provide services and proprietary equipment for the implementation of KBR and Southern Company's TRIG technology at the Dongguan Tian Ming Electric Power Company plant in Guandong Province. TRIG technology has been added to an existing gas turbine combined cycle plant, enabling it to use SNG produced from ~1600 t/d of low grade coals – this replaced the use of fuel oil.

In South Korea, the 380 MW **Taean IGCC Project** is being built for Korea Western Power. The plant is based around Shell gasification technology and has a design target of >42% efficiency (net). It will be fired on 2760 t/d of bituminous and subbituminous coals. The first coal firing through the burner system was carried out successfully in September 2015 (Kim, 2015), with commercial operations beginning in August 2016. In December 2015, it was announced that **Alps Energy** was to use Southern Company's TRIG technology for a 1GW power project being developed at the Saemangeum Industry and Research Area in South Korea. The system will be fuelled on low quality coals.

Alongside subbituminous coals, lignite is also used in several IGCC projects. In the Czech Republic, the 400 MW **Vresova IGCC plant** is operated by Sokolov Coal Corporation (SUAS). The plant uses 26 Lurgi-type fixed bed gasifiers that consume 2000 t/d of lignite sourced from SUAS's local mines. A Siemens gasifier has been added to the plant in order to provide additional syngas through the gasification of tars produced by the fixed bed gasifiers.

Since 2002, a small lignite-fuelled IGCC plant has been in operation at the **Sanghi cement plant** in Gujarat, India. This is based on an IGT/Enviropower dry-bottom fluidised bed gasifier, supplied by Ignifluid. The unit was developed by IES and supplies electricity and steam via a 38 MW gas turbine and 26 MW steam turbine (both General Electric units). It uses ~1000 t/d of local lignite. Reputedly, it was the first commercial-scale coal gasification project in the world to use lignite for producing electricity and steam.

In the USA, after a number of delays and cost overruns, Southern Company's **Kemper County IGCC plant** is nearing completion. This 582 MW plant is using TRIG gasification technology and will be fuelled on Mississippi lignite. TRIG was developed at the Power Systems Development Facility (now the National Carbon Capture Center) in Alabama. A unique feature is the high-efficiency design that allows a high rate of lignite-to-gas conversion to take place at a lower temperature, thus reducing plant costs. The plant is located close to an estimated 4 Gt of mineable lignite – which has high moisture and ash content. Southern Energy owns the lignite fields that will supply the Kemper plant. The plant will also incorporate a carbon capture and storage project. Pre-combustion capture (65% capture) will generate a CO_2 stream of 3.5 Mt/y that will be used for onshore EOR. The plant will also emit fewer particulates, NOx, SO_2 and mercury emissions than traditional pulverised coal plants. It is claimed that CO_2 emissions will be on a par with those of similarly sized natural gas-fired power plants. Lignite was adopted as the fuel of choice as it will provide decades of low-cost fuel and avoid large price swings associated with unpredictable fuel markets. It will also help minimise the import of alternative sources of energy.

5.3.6 Coal to liquids (CTL)

CTL is particularly attractive to countries that rely heavily on oil imports but have large domestic coal reserves. Over the past decade, there have been a number of CTL projects proposed. To date, a combination of economic and environmental concerns has meant that most have failed to materialise. However, there are a number of commercial scale CTL plants and projects operating in several parts of the world. The best known is SASOL's operation in South Africa, where, since 1955, indigenous coals have been gasified to produce liquid and other products. SASOL currently has two large indirect coal conversion facilities (SASOL II and III) that generate ~160,000 bbl/d of liquid fuels from ~40 Mt/y of local coals. This equates to nearly a third of the country's total liquid fuel production. SASOL II and III started up in 1974 and were originally based around 80 SASOL-Lurgi fixed bed dry bottom gasifiers; four additional gasifiers have since been added. The feedstock comprises low grade bituminous coals (although sometimes categorised as subbituminous coal), supplemented with natural gas (Tennant, 2014). South African coals are generally low in sulphur but high in ash. The company's original plant (SASOL 1) started up in 1955 and was based around 17 gasifiers. This used low grade bituminous coal with an ash content of between 20 and 40% (in 2005, it was converted from coal gasification to natural gas reforming). SASOL II and III remain in coal-based operation. SASOL-Lurgi gasification technology is considered to have a number of advantages when applied to low rank/grade coals – it can accommodate run-of-mine coals with ash content of up to 50% and can also tolerate significant variations in feedstock properties.

In late 2013, SASOL unveiled plans for an initiative known as *Project 2050*. This will maintain and expand its operations in South Africa until at least the middle of the century. Coal and CTL form integral parts of this long-term plan. Coal will be supplied by group company SASOL Mining – this has already secured the necessary coal reserves to cover this period. The company will supply coal to the synfuels plant at a constant rate of ~40 Mt/y. Four new mining projects are under way (Thubelisha, Impumelelo, Shondoni and Tweedraai) – SASOL Mining intends to replace 60% of its current coal production via these projects. This new capacity will replace some long-standing, but depleting, mines. A main priority will be to provide the correct quality of coal to the synfuels plant at the appropriate cost and in the required volumes. Properly managing coal quality is viewed as crucial. SASOL is a member of South Africa's Centre for Carbon Capture and Storage and has set carbon reduction targets of 15% at existing CTL operations by 2020, and 30% at any new CTL operations by 2030 (Creamer, 2013).

Elsewhere, a number of major CTL projects have been proposed or developed, mostly in China. Historically, more than 100 Chinese coals were evaluated for their suitability for CTL applications. Around 15 (from ten mines) were identified as being suitable. The most appropriate were subbituminous coals with low ash content (Couch, 2008). There are a number of Chinese CTL projects that use several types of low grade coal (Aranda and others, 2014; Cui, 2012; Zhao, 2013). Examples of large-scale projects include:

- **Yitai Yili Energy Company** (Yitai Coal Liquefaction Co. Ltd) 2-stage CTL demonstration plant – output of 30,000 bbl/d of Fischer-Tropsch liquids. The fuel source is a local high sulphur coal, currently discarded during mining operations in Changzhi. Total reserves of this otherwise unusable coal are ~12 Gt. This is processed (in the form of coal-water slurry) using indirect coal liquefaction technology provided by Synfuels China. The plant has been fully operational since June 2010 (Cui, 2012). The main products are diesel, naphtha and LPG;
- **Shenhua Ningmei CTL plant** – output of up to 100,000 bbl/day of liquids. The plant will use up to 4 Mt/y of bituminous and subbituminous coals. It is under construction and due for commissioning in 2016; and
- **Shanxi Lu'an CTL demonstration plant** – output of 160,000 bbl/y (~3200 bbl/d) of Fischer-Tropsch liquids. The plant uses ~1 Mt/y of high sulphur, high ash bituminous coal. Four Shell gasifiers are deployed, each with a 3200t/d dry coal intake capacity. Indirect coal liquefaction technology provided by Synfuels China is deployed.

Although a number of major projects are proceeding or are now operational, the Chinese government recently announced that funding for the development of additional CTL facilities will be reduced, at least for the next few years. The main aims are to reduce national energy consumption and minimise emission levels. Several projects have been cancelled.

Over the past decade, there have also been a number of major CTL projects proposed for different parts of the USA. These encompassed several types of coal and proposed both direct and indirect liquefaction technologies. Major projects involving feasibility studies and/or design stage work, included those of DKRW Advanced Fuels, Rentech, Diversified Energy, and Synfuel Inc. Project capacities ranged from 20,000 to 80,000 bbl/d. To date, none has progressed to commercial operation.

In other parts of the world, CTL projects using low grade coals have been proposed in countries such as Indonesia, India and Mozambique. Some, such as an 80,000 b/d facility proposed by Jindal Steel and Power Ltd. in India (using high ash local coals) have since been abandoned, although reportedly, several others remain in the planning stage. For example, in Indonesia, US-based company Celanese is cooperating with PT Pertamina to develop a (subbituminous) coal gasification project. This proposes the gasification of up to 4 Mt/y of coal, predominantly for the production of 1.3 billion litres of liquid product for use as fuel additive. Should it proceed, it will take around 30 months to build the new facility. As in a number of other economies, the Indonesian government has an objective to make greater use of the country's abundant resources, specifically coals with lower energy content, to drive economic development.

5.3.7 Carbon capture and storage (CCS)

Under some circumstances, subcritical PCC technology has been the focus for CCS-based activities. Currently, there is considerable interest in SaskPower's subcritical Boundary Dam power plant at Estevan, Saskatchewan, Canada. This is hosting the world's largest commercial-scale CCS project of its kind. In 2014, the project came on line as the first post-combustion (amine-based) coal-fired CCS project integrated with a power station. The project centres on a rebuilt lignite-fired generation unit (Unit 3) at the plant. In order to minimise the energy penalty associated with carbon capture, this was rebuilt such that the boiler and turbine steam cycle efficiency was increased. Babcock & Wilcox Power Generation Group Canada designed, supplied and installed the main boiler components. This included new, redesigned superheater and reheater components used to increase steam temperatures to a new steam turbine (from the original 538°C to 566°C) thus improving turbine efficiency. Unit 3 was updated for the long-term production of up to 115°MW of base-load electricity. The carbon capture project will eventually be capable of capturing up to 1°Mt/y of CO_2 from the plant, although during the first year of operation, it was somewhat lower. The captured CO_2 is sold and piped to nearby oil fields in southern Saskatchewan where it is used for EOR.

During the past decade, there have been a significant number of CCS-related projects proposed or undertaken, most of which fell in the small pilot-scale range. Some projects were based on the use of higher grade bituminous coal, whereas others focused on lower grade coals such as lignites and subbituminous coals. For example, there were lignite-based projects in Australia, the Czech Republic, Germany, and the USA. There were also a number that intended to use subbituminous coals. In the USA, these included post-combustion capture projects at power plants firing PRB coals; for example, a 60 MW slipstream project on a 600 MW unit of the WA Parish power plant in Texas, and a proposal for the Tenaska Trailblazer Energy Center, also in Texas. Some CCS-related work is continuing in the USA, focused on the use of PRB coals. For example, in 2015, a new integrated CO_2 research/test centre was established at Basin Electric's Dry Fork power plant in Wyoming. The Dry Fork plant came on line in 2011 and is one of the country's newer coal-fired power stations. Construction of the new test facility is under way, with completion scheduled for 2017. Alongside capture, there will be a strong focus on the utilisation of CO_2. Possible avenues of research include the production of diesel, cement, advanced polymers and graphene. Wyoming (which supplies around 40% of US coal) has pledged US$15 million toward construction of the research centre. Tri-State Generation and Transmission Association Inc. has promised US$5 million, and the National Rural Electric Cooperative Association has pledged US$1 million.

Coal-fired CCS demonstration plants have been examined in several IEA Clean Coal Centre reports, most recently by Mills (2012). This examined the status of projects based on pre-combustion and post-combustion technologies, as well as those based on oxyfuel combustion. However, subsequent shifts in the global economy and market conditions have meant that many proposed projects have failed to materialise or have at least been delayed.

Summary

Low quality coals can be cleaned and upgraded in various ways so as to improve their energy content and other properties. This enables many to compete directly with coals of higher quality. Clearly, the benefits accrued by upgrading must not be outweighed by increased costs.

Such coals can be used in most coal-based processes, including all main forms of clean coal technologies. In some cases, they can be used directly, whereas in others, a degree of pre-treatment is sometimes required. Some are already used widely in considerable quantities and in a number of processes; others hold potential for the future.

6 The use of low quality coal in major economies

The envelope terms 'low quality' or 'low value' when applied to coal generally refer to three main categories: lignite, subbituminous coals, and high-ash bituminous coals. The application and importance of each to major global economies is discussed in the following chapters.

6.1 Low quality coal production and consumption

For countries with **lignite** reserves, a particular advantage of its use as an energy source is that it often offers a high security of supply. No other fossil fuel energy carrier offers lignite's availability with such a degree of certainty. At current rates of consumption, the world has an estimated 200 years of supply remaining. However, in some countries, new reserves continue to be discovered. Global lignite production peaked at 1189 Mt in 1990. Since then, it has fluctuated. However, the overall reduction masks the fact that some economies rely heavily on their reserves of lignite, where they form a strategic asset used extensively for electricity generation.

The world's biggest proved recoverable lignite reserves are in Germany, Australia, the USA, China, Serbia, Kazakhstan, Russia, and Turkey. In 2014, total global production amounted to 810.5 Mt (IEA, 2015a). The biggest individual producer remained Germany, followed successively by China, the USA, the Russian Federation, and Poland (Table 12).

Table 12 Major lignite production and consumption (Mt) (IEA, 2015a)

	Production		Consumption	
	2013	2014	2013	2014
Germany	182.7	178.2	182.5	177.0
China	na	na	na	na
USA	70.1	72.1	69.7	70.1
Russian Federation	73.7	69.6	73.3	69.3
Poland	65.8	63.9	65.9	63.8
Turkey	57.5	61.5	55.3	61.5
Australia	62.8	60.7	62.8	60.7
Greece	53.9	48.1	54.4	47.1
India	44.3	47.2	43.9	47.2
Czech Republic	40.4	38.3	38.9	38.7
Bulgaria	28.6	31.2	28.7	31.2
Serbia	40.3	29.9	40.3	30.2
Romania	24.7	23.6	25.0	23.9
Thailand	17.6	18.0	19.1	18.0
Hungary	9.6	9.6	9.7	9.2
Canada	9.0	8.5	8.9	8.4
Kosovo	8.2	8.2	8.3	8.2
Other	45.5	42.2	36.7	33.3
WORLD	**834.7**	**810.5**	**830.8**	**804.8**

For various reasons, during 2013-14, global lignite production decreased by 8.6%. However, because of different categorisation systems noted, the overall production figure could be significantly higher. This makes it difficult to arrive at an accurate figure for the amount of lignite produced and traded. Depending on the particular system, lignite may be reported as subbituminous coal, or in some cases, 'other' bituminous coal, or sometimes simply referred to as steam coal. For example, currently, some Indonesian lignite is recorded as subbituminous coal. Furthermore, accurate data for Chinese lignite production is not available as under the Chinese categorisation system, it is included under 'other' bituminous coal (along with subbituminous). If appropriately reclassified, both would have major impacts on lignite statistics. For example, China is probably the world's second largest lignite producer – it may even be the largest. Thus, compiling accurate data can be problematic (IEA, 2015a).

With this proviso, in 2014, the global consumption of lignite was reported as having decreased by 25.5 Mt to 804.8 Mt (Table 12). The downturn was attributable to falls of 10.1 Mt in Serbia, 7.3 Mt in Greece, 5.5 Mt in Germany, 4 Mt in the Russian Federation, 2.2 Mt in Australia, and 2.1 Mt in Poland. Germany remained the largest individual producer and consumer of lignite. Increased use was reported for Turkey, India, and the Czech Republic, although consumption decreased in Germany, Australia and Poland. In the case of the Czech Republic, lignite is viewed as of strategic importance and the government has approved a plan to expand production beyond previously set limits in order to access to up to 120 Mt of reserves in the northwest of the country.

Globally, lignite's biggest market is for power generation. There are more than 700 stations (of >100 MW) in operation. Around 10% of these have come on line since 2006. Such plants provide some of the world's lowest cost electricity although, depending on the individual circumstances, emissions can sometimes be high. Many plants are subcritical and are of relatively small capacity, although maximum capacity is increasing year-on-year. Plant capacity of 600 MW is becoming standard (Reid, 2016).

Compared to hard coals, there is limited international trade in lignite. In 2014, only 8 Mt of lignite were recorded as being exported (IEA, 2015a). However, Germany, for example, exports limited amounts, mainly to other EU member states. In 2012, the amount exported grew by nearly 22%, but only increased slightly in 2013 (Appunn, 2015).

In 2013, 122.3 Mt of lignite and subbituminous coals were imported by various countries around the world (but under most categorisation systems, the bulk of this comprised subbituminous coals). By the end of 2014, this had risen to 150 Mt. OECD countries imported 16.7 Mt of this total, and non-OECD countries, 133.6 Mt (non-OECD Asia was responsible for 130 Mt). Only 7.8 Mt was imported to the OECD Americas region, with 5.4 Mt going to OECD Asia Oceania, and 3.6 Mt to OECD Europe. The biggest individual importers of these types of coals were India (111.8 Mt) and Tapei (13.5 Mt). India's imports increased significantly from 90 Mt in 2013.

Most of the 830 Mt of lignite consumed around the world is used for electricity generation and/or heat production, although smaller amounts are also used in various residential, commercial and industrial applications.

As in the case of lignite, the use of **subbituminous coals** is important in a number of major economies. Based on WEC data, subbituminous coals make up 32.2% of the world total (WEC, 2013). These coals generally have characteristics that fall some way between those of lignite and bituminous coals. However, some individual reserves can have properties that overlap with either category. They are used primarily as fuel for power and/or cogeneration and heat plants. Some sources are low in sulphur, hence can be used without recourse to back-end SO_2 control using systems such as FGD. The moisture content of subbituminous coals tends to be lower than that of lignites.

Total proven global reserves of subbituminous coal amount to 287.33 Gt (WEC, 2013). The biggest individual reserves are located in the USA (98.6 Gt), the Russian Federation (97.4 Gt), China (33.7 Gt), Indonesia (28 Gt), and the Ukraine (16.6 Gt). Combined, US and Russian reserves represent nearly 70% of this total. Unlike lignite, there is considerable international trade in certain types of subbituminous coals – currently, the biggest source is Indonesia. Smaller amounts are also sometimes exported from Poland, Canada, the USA, the Russian Federation, and Kazakhstan.

Several major global economies rely heavily on **high-ash bituminous coal**. Despite the associated drawbacks, this type of coal can be of strategic importance and constitutes a major source of energy. Thus, in recent years, high-ash bituminous coal has become of particular importance in the economies of India, China and South Africa.

The application of the different types of low quality coals in individual economies is reviewed in the following sections. Countries are ordered based on the scale of proven reserves of all types of coal that each possesses.

6.1.1 USA

In parts of the USA, **lignite** makes an important contribution to electricity generation. The country has an estimated 30 Gt of recoverable reserves (with a demonstrated reserve base of ~39 Gt) (EIA, 2012). Production is mainly in Texas, North Dakota, Louisiana, Montana and Mississippi (Figure 3). Annually, around 70–72 Mt of lignite is used (IEA, 2015a). The North American Coal Corporation is the biggest individual US lignite producer. A large proportion of lignite output is directed to the power sector although some is also used elsewhere. The US Lignite Energy Council reports that 79% is used to generate electricity, 13.5% in the production of synthetic natural gas, and 7.5% in the manufacture of fertilisers (such as anhydrous ammonia and ammonium sulphate). Small amounts are also used for home heating, as stand-alone fertiliser, and as oil well drilling mud.

Coal reserves in Texas include substantial deposits of lignite that lie in a belt from the far northeast, through central Texas, and to the southwest. In 2012, Texas produced 40 Mt of lignite from surface mining operations. Recent years have seen production increase within the state which is home to five of the 50 largest coal mines in the USA. In 2012, around a third of all electricity generated in Texas was produced from coal-fired power plants (firing lignite and PRB coal) (TMRA, 2014).

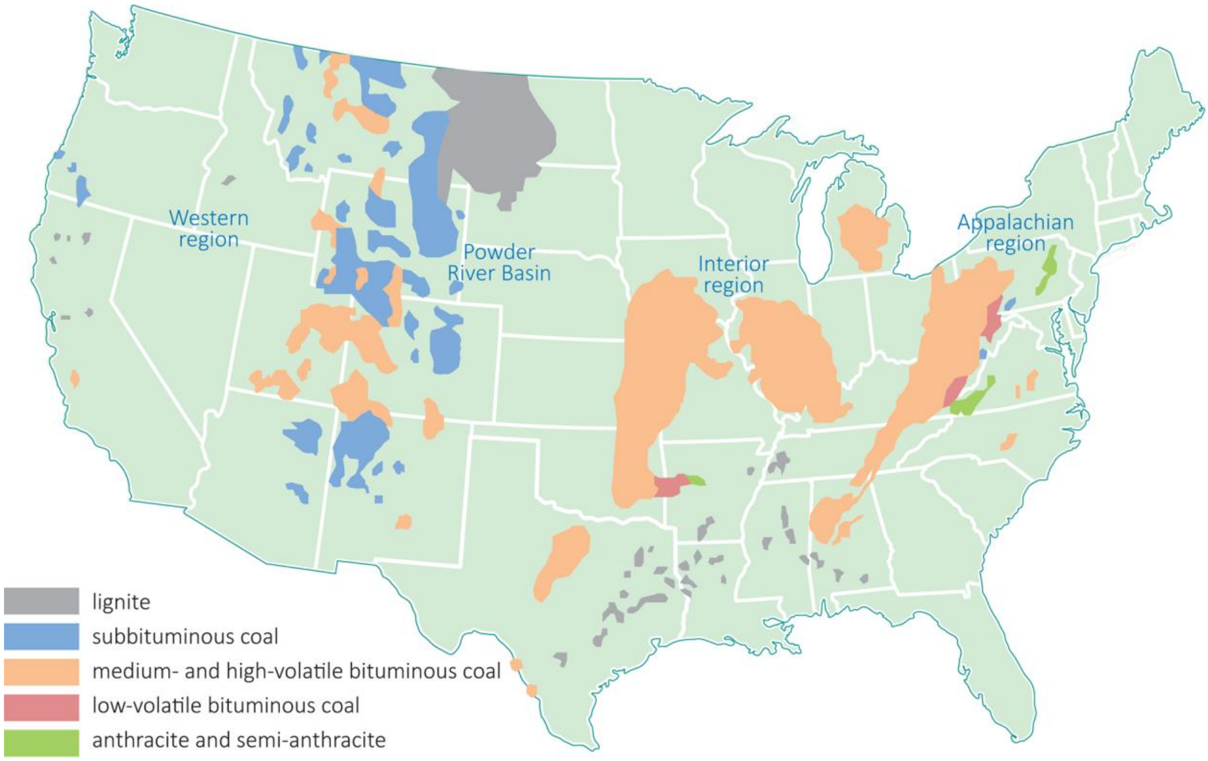

Figure 3 Location of main US coal deposits

For several decades, lignite production from mines in North Dakota has averaged ~30 Mt/y (Figure 4). As elsewhere, most is used to generate electricity. Lignite is supplied from four mines (plus one in eastern Montana) to seven major power plants located in western North Dakota plus one in eastern Montana (Lignite Energy Council, 2015). It is also supplied to the Great Plains Synfuels Plant (*see* Section 4.3.3). In 2014, sales of lignite increased by a million tonnes over the previous year, with the state's four mines either increasing or maintaining sales and production levels.

Within the USA, new environmental legislation is being developed. In particular, more stringent CO_2 emission regulations have been proposed that will impact on future operations of all fossil fuel-fired power plants throughout the country. These EPA regulations are being driven by the Clean Air Act in an effort to reduce the 'pollution-to-power-ratio'. On a state-by-state basis, the EPA is setting goals for CO_2 emission levels based on a national formula, with reference to the state's specific power profile. Under Section 111(d) of the Clean Air Act, the EPA is looking to improve the efficiency of coal-fired power plants, increase the utilisation of existing natural gas-fired power units, and increase input from renewables.

Figure 4 Beulah lignite mine, North Dakota (photograph courtesy of US Lignite Energy Council)

Although some areas have seen lignite production increase during the past few years, there are understandable concerns that the impending legislation will have a major impact on the amount used for power generation. For example, the Electric Reliability Council of Texas (ERCOT) has voiced concerns that the latest version of the Clean Power Plan could see 4 GW of coal-fired capacity shut down (representing ~6% of ERCOT's current installed capacity); potentially, this could begin as soon as 2022. The final version of the Plan calls for 32% CO_2 reductions (compared to 2005 levels) from existing power plants by 2030. Other legislation is also in the pipeline (addressing, for example, regional haze). Modelling undertaken by ERCOT suggests that the cumulative impact of proposed legislation could result in multiple unit retirements within the region in a short timeframe (Cassell, 2015). ERCOT estimates that it would cost ~US$1 per tonne of CO_2 to meet interim 2022 goals, which could increase retail electricity prices by as much as 16% (Penn Energy, 2015).

The lignite-based mining and power sector is of major economic importance in states such as Texas. A study produced by the Center for Economic Development and Research (CEDR) at the University of North Texas concluded that it contributes more than US$7 billion in economic activity to the state, as well as being a major employer. In July 2015, representatives of the Lignite Energy Council and Gulf Coast Lignite Coalition (of lignite producers and consumers) met with the US Office of Management and Budget to discuss the possible impacts of the Clean Power Plan on lignite generation. They requested that lignite-fired plants should be granted a 'categorical exclusion' from the plan, given the significant threat it presents to their industry (Office of Management and Budget, 2015). Part of their argument centred on the fact that many lignite power plants are not very old; many were built in the 1980s, plus some as recently as the 2000s. This makes them recent vintage with decades of remaining useful life. They further noted that the mandatory emission budgets proposed would place lignite operations at a significant economic disadvantage relative to other power generation sources. It was suggested that under the legislation, the industry needed an exclusion, or at least a sub-category for lignite, that would significantly reduce the retirement risk to lignite units and ultimately, risk to local and regional economies.

North Dakota is another of the 16 states that, under EPA rules, will be required to make major cuts in CO_2 emissions from power plants. Under the new standards, the state must cut its emission rate by almost 45% by 2030. Because of its 'unique circumstances' (high lignite dependency) the state (like a number of others) is challenging the new legislation. It intends to ask an appeals court in Washington DC to block the new rules while the lawsuit proceeds. The Lignite Energy Council has pointed out that lignite-based power plants within the state have already invested US$2 billion in technology to control emissions, and utilities with plants in North Dakota are continuing to invest significant amounts in further improvements to emissions control technologies. According to US EPA data, North Dakota is one of only seven states to meet all federal ambient air quality standards (Lignite Energy Council, 2015).

At nearly 99 Gt, the USA has the world's biggest proved reserves of **subbituminous coals**, representing some 37% of the country's demonstrated coal reserve base (DRB). All subbituminous reserves are located south of the Mississippi, mostly in Montana and Wyoming, with the biggest individual component being in the Powder River Basin (PRB). Montana hosts six major coal mines – five produce subbituminous coal (the other produces lignite). The PRB is the largest source of coal mined in the USA and contains one of the largest deposits of coal in the world. In 2013, the USA produced 394 Mt of subbituminous coal, virtually all of which was directed to US power plants (IEA, 2015).

The accessible parts of the PRB cover around 19,500 square miles. The PRB contains the largest resources of low-sulphur, low-ash, subbituminous coal in the country, and is the single most important coal basin in the USA. Recent estimates from the US Geological Survey suggest an original coal resource of about 1.05 trillion tonnes for 47 coal beds within the basin; in-place (remaining) resources are about 1.04 trillion tonnes. Recoverable coal resources (coal reserve base) are estimated at 147 Gt at a 10:1 stripping ratio or less. An estimated 22 Gt of the coal reserve base meets the definition of 'reserves' (resources that can be economically produced at or below the current sales price at the time of the evaluation). The total underground coal resource in coal beds 3–6 metres thick is estimated at 276 Gt (Luppens and others, 2015).

In 2014, PRB mines produced about 346 Mt of coal (US EIA, 2015). The ten biggest individual US mines all produce subbituminous coal and are located in the PRB. The largest and most productive are shown in Table 13. Historically, the three largest PRB coal-producing companies have been Peabody, Arch and Cloud Peak Energy, and the two largest individual mines, Peabody's North Antelope/Rochelle site, and Arch's Black Thunder mine (Figure 5). A typical PRB coal (for example, from Black Thunder) has a low sulphur content and is used mainly as power station fuel without any preparation apart from crushing. Black Thunder coal has a heating value of 20.3 MJ/kg, an ash content of ~5%, and as-received moisture of 25–30%. Peabody owns ~9 Gt of proven and probable coal reserves in the PRB, and Arch has 3.3 Gt of reserves in that region. In 2013, production in the Western Region (that includes Wyoming and Montana) represented nearly 54% of total US coal production.

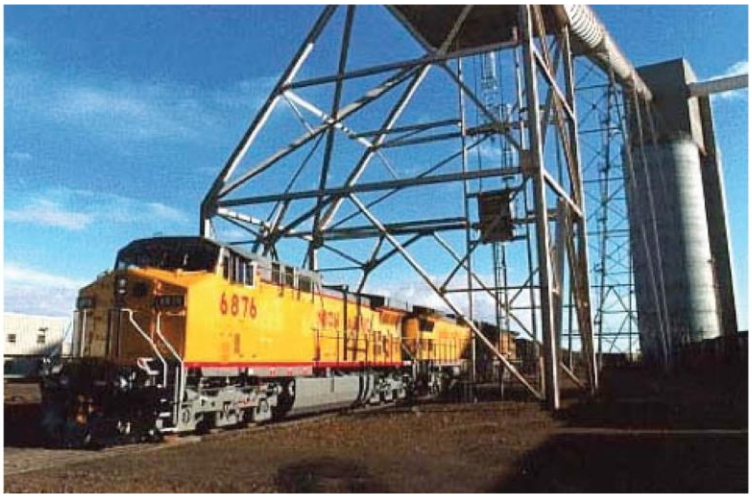

Figure 5 Subbituminous Powder River Basin coal production at Black Thunder Mine in Wyoming, USA (photograph courtesy of Arch Coal Inc)

A significant proportion of the USA's electricity comes from power plants fired on PRB coal. However, ongoing changes taking place within the US power sector meant that in 2013, for the first time in two decades, US coal production fell below a Gigatonne (US EIA, 2015). Within the country as a whole, the number of operational coal mines has since reached a new low. EIA data suggests that in 2013, just over 1000 mines were operating, a decrease from 1400 in 2008 when coal production was at its highest. In 2013, coal companies opened 103 new mines while 271 were idled or closed (a 14% decline in the total number of active mines between 2012 and 2013) (Pandey, 2015).

The changes taking place in the US generation sector are impacting on the amount and types of coals produced by PRB mines noted in Table 13, particularly those that produce coals at the lower end of the heat content spectrum. During 2015, low natural gas prices and other factors reduced PRB coal demand, with increasing cuts affecting lower heat value mines. Most affected were those producing coals with a heat content of 19.5 MJ/kg or less. These included Alpha Natural Resources' Belle Ayr and Eagle Butte mines. Production at the Belle Ayr mine dropped 27.9% in the second quarter of 2015 to 3.4 Mt, compared with first-quarter output. During the first half of 2015, total PRB output amounted to 186 Mt, down from 191 Mt in the same period of 2014. Some lower heat content production from mines operated by Arch, Peabody, Kiewit and Cloud Peak Energy is now also considered to be at risk. An example is the output from Peabody's Rawhide mine which has an average heat content of 19.3 MJ/kg (McDonald and Miller, 2015).

The current reduction in PRB output reflects the wider changes taking place in the USA, where coal demand in general is expected to decrease in the coming years. In the period up to 2019, demand is forecast to fall by 1.7%/y. Increasing shale gas production, climate initiatives, as well as new emissions regulation is already seeing the closure of some coal-fired generating capacity. For example, it was announced in October 2015 that the state of Michigan would retire 25 of its coal-fired plants by 2020, switching mainly to gas-fired capacity; this scenario is being replicated in other states across the region. For the first time, on two occasions during 2015, gas's share of the US energy mix surpassed that of coal.

However, there is still a considerable quantity of low-cost coal in the USA, and >250 GW of coal-fired capacity is expected to remain in use at the end of the present decade (IEA, 2015b).

Table 13 Powder River Basin coal production (2014)

Mine	Operator	Production (Mt)
North Antelope/Rochelle	Peabody	107.0
Black Thunder	Arch	91.6
Cordero-Rojo	Cloud Peak Energy	31.6
Caballo	Peabody	7.2
Belle Ayr	Alpha Natural Resources	14.2
Eagle Butt	Alpha Natural Resources	18.7
Antelope	Cloud Peak Energy	30.5
Buckskin	Kiewit Mining	13.9
Coal Creek	Arch	8.5
Rawhide	Peabody	14.0
Wyodak	Wyodak Resources	3.9
Dry Fork	Western Fuels	4.8
PRB total		345.8

The scenario of a continuing fall in PRB coal output is disputed by some industry observers. Despite the current challenges facing the US coal industry, it has been suggested that in the period to the end of the present decade, the amount of PRB coal burned will remain relatively stable. There may also be potential for increased exports. In contrast, the amount of coal from some other basins, especially Central Appalachia, is expected to decline. With declining production in the basin, high operating costs, increased emissions standards and the low cost of natural gas, the share of Central Appalachian (bituminous) coal in the generation mix will continue to drop – this could fall from 8% in 2014 to 6% in 2020. In parts of the region, much of the better quality coal has already been mined and only thinner and lower-quality seams remain, hence production and productivity are declining (Plumer, 2012). Overall, the amount of coal used by US generators is expected to decrease although compared with that of other basins, PRB's share of the generation market could remain relatively flat. As noted, potentially, it could even increase (Levesque and Greenhalgh, 2015).

In 2014, coal-fired plants accounted for 39% of all US generation; 48% of the coal burned (372 Mt) was PRB coal. If PRB coals retain a degree of attractiveness for power generation, it is suggested that in 2020, coal-fired plants will account for 36% of all US generation, with 54% of the coal burned coming from PRB mines. PRB coals have a major advantage in that production costs are low. For example, in 2015, Cloud Peak Energy had 73 Mt of coal committed for sale, with 65 Mt at a weighted-average price of 11.7 US$/t. For 2016, some 43 Mt has been committed, with 34.5 Mt fixed at a weighted-average price of 12.47 US$/t.

What does the future hold for PRB coals in the US market place? As noted, the US power generation sector is changing, with coal-fired capacity reducing significantly in some areas. Analysis suggests that 75% of the coal supplied to surviving plants will come predominantly from three locations: Powder River Basin, Illinois Basin (ILB), and Northern Appalachia (NAPP) (Christian and Powell, 2015). PRB coal is forecast to continue serving 47% of the surviving fleet (an increase from 44% in 2007). Bituminous coals from ILB and NAPP will see bigger market gains, rising to 13% and >14%, respectively, from 7.9% and 9.7% in 2007. The high-cost Central Appalachia (CAPP) region is forecast to be the biggest loser, with its portion of US power sector coal deliveries possibly falling to ~6% (in 2007, it was >15%) after all announced coal-fired power plant closures and conversions are completed.

Producers of more competitive US coals believe that their market share and overall sales will increase. For example, Peabody (with mines in the PRB and ILB) expects demand for both coals to rebound post-2016. The company anticipates that by 2017, coal's share of US generation will have returned to nearly 40%. It expects combined demand for PRB and ILB coals to increase by between 50 and 70 Mt/y by 2017. However, this forecast could prove to be over-optimistic as, for example, Southern Company has since announced that it intends to retire or convert a significant amount of its coal-fired generating capacity to natural gas – this could limit the PRB's penetration of the southeastern utility market (Christian and Powell, 2015). Despite the PRB's dominant role in US coal markets, a significant amount of generating capacity using PRB coals seems set to close, and this will hit some coal producers harder than others. Several major US coal producers have so far filed for bankruptcy or are in financial difficulties. However, the situation with some companies appears to be improving. For instance, mid-2016, Cloud Peak announced that its mining operation was back in profit.

As some US markets for PRB coals decline, there has been growing interest in directing output to export markets. To date, only modest amounts have been shipped. In 2012, exports from Wyoming and Montana were ~11 Mt, roughly 10% of the total coal exported through US ports. PRB coal export levels are currently limited, not by production capacity, but mainly by handling constraints at accessible ports. The west coast of North America provides the closest geographic location for US exports to China's coast and is also relatively close to some of the largest, cheapest, and lowest sulphur coal deposits in the world. For several years, the focus of PRB coal exports has been primarily to Asian markets, particularly China, but also potentially to India, South Korea, Taiwan, Japan and Vietnam. It is considered that PRB coal would be highly competitive, especially in south eastern Chinese coastal markets. Analysis of the cost of mining an additional 140 Mt of PRB coal and shipping it by rail and ship from proposed new and expanded coal ports on the US and British Columbian west coast determined that coal could be delivered at a lower cost than either domestic Chinese coal or the current major seaborne exporters of coal to that market, Indonesia and Australia. Using conservative assumptions, it is claimed that PRB coal could, if necessary, undersell current suppliers to the south coast of China by as much as 40% (Power and Donovan, 2015).

However, recent moves by China to reduce its coal consumption and restrict the import of some types of coal could impact on the attractiveness of any such operation. In 2014, China's annual coal imports dropped for the first time since 2009, although the country is expected to remain a major player for thermal coal imports (Levesque and Greenhalgh, 2015). Some observers opine that the international demand for PRB coal could increase from 10 Mt in 2014 to 68 Mt in 2020 (Platts, 2015). A proportion of

PRB coal reserves have the advantage of higher heat content. For example, Cloud Peak's Spring Creek complex has been suggested as a strong player in the export market. As well as being closer to coastal export facilities, it is also low in sulphur and has a heat content of 21.7 MJ/kg. However, in February 2016 it was announced that Cloud Peak had made a net loss of nearly US$205 million in the previous year. This was alongside the bankruptcies of mining companies Alpha Natural Resources and Arch Coal. Cloud Peak's sole focus on Wyoming and the relatively easy opencast mining of PRB coal has made it more resilient to some of the changes that have forced other companies into bankruptcy.

Over the past few years, the potential for increased exports of PRB coal has resulted in proposals for new or expanded West coast coal ports. At least five coal export terminals have so far been proposed specifically for exporting PRB coals to Asian markets. These include the Millennium Bulk Logistics Longview Terminal, several sites in Washington state that include the Gateway Pacific Terminal, several Northwest ports (in particular, Oregon), and a number of sites along the Columbia River. Millennium Bulk Terminals has applied for permits for 44 Mt of coal from Wyoming and Montana. The Gateway Pacific Terminal has been proposed for the export of 24 Mt a year.

6.1.2 Russia

The country is estimated to have between 157 and 162 Gt of proven recoverable coal reserves (Table 14). Reserves recorded in the State balance (explored and studied to at least a reasonable degree and the most promising for development) are currently estimated at ~161.5 Gt. A further ~76 Gt is more speculative. Russia has one of the biggest coal resources in the world (>3900 Gt) (Mills, 2011).

Table 14 Russian proven recoverable reserves of coal (Mt) (EMIS, 2013)

Source	Coal type(s)	Reserves (Mt)
World Energy Council (WEC)	Bituminous + anthracite	49,088
	Subbituminous	97,472
	Lignite	10,350
	TOTAL	157,101
International Energy Agency (IEA)	Hard coal	69,946
	Lignite	91,607
	TOTAL	161,553

Coal reserves are dispersed widely, with mining carried out in 25 regions and at least 16 coal basins (Table 15 and Figure 6). In 2015, Russian coal consumption declined by 5.8%. Coal accounted for 12.5% of the country's primary energy consumption (BP, 2015).

Table 15 Main Russian coal basins

Basin	Coal types	Output (Mt, 2012)	Ash content (%)	Sulphur content (%)	CV (MJ/kg)
Kansk-Achinsk	Black, lignite	41.1	6–15	0.3–1	12.6–17.7
Kuznetsk/Kuzbass	Black, lignite	201.5	10–16	0.3–0.8	22.8–29.9
Irkutsk Region	Black, lignite	14.2	7–15	1.5–5	17.6–22.6
Pechora	Black, lignite	13.6	8.5–25	0.5–1	18.1–26.7
Donetsk	Black, lignite	4.7	10.5–29	1.8–4.2	18.5–20.1
South Yakutia	Black, lignite	9.2	10–18	0.3–0.5	22–37.4
MINUSA (Khakassia)	Black, lignite	12.3	6.6–29.7	0.5–0.6	18–32

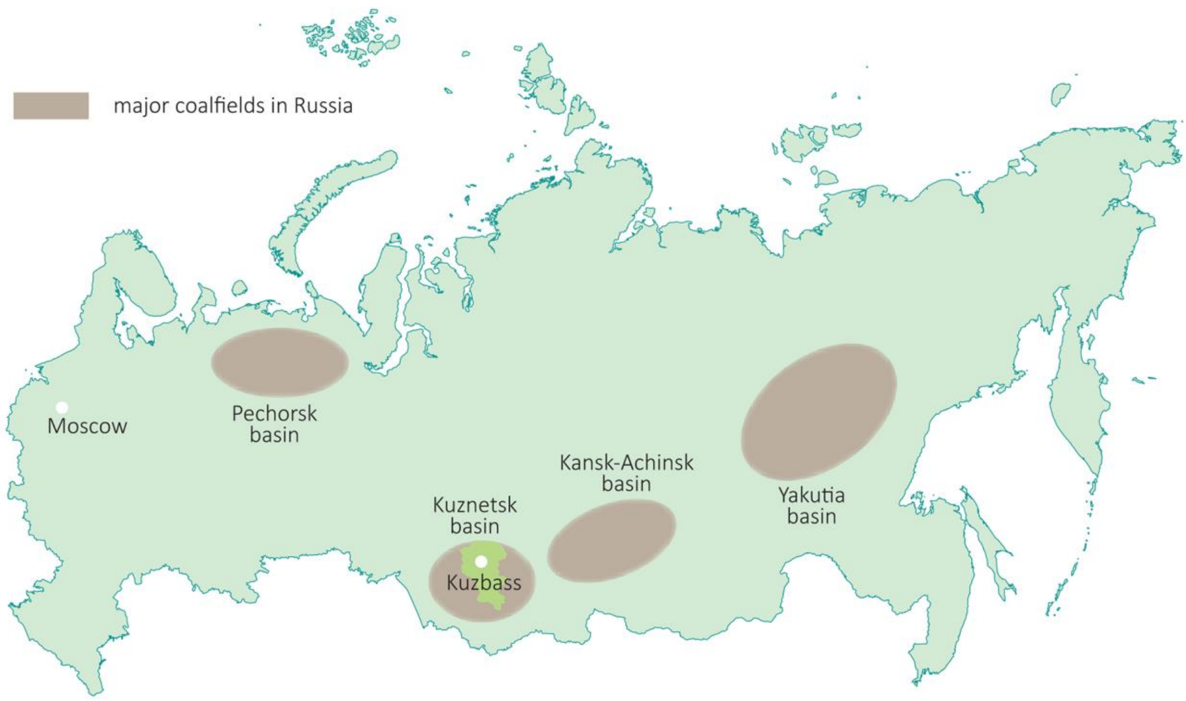

Figure 6 Major Russian coalfields

The bulk of coal deposits are in Siberia (64%) and the Far East region (30%). The remainder is located in the European part of Russia and the Urals. Coal mining is carried out in >120 opencast and ~85 underground mines – total annual production capacity is ~383 Mt. Around two thirds of coal is produced from opencast operations. Most production comes from seven basins, three of which lie to the west of the Ural Mountains (in the European part) and four which lie to the east in the Siberian region of Asia. However, ~90% of all Russian coal is produced in just four major basins (56% in the Kuzbass hard coal basin, 12% in the Kansk-Achinsk lignite basin, 12% in East Siberia, and 10% in the Far East) (Mills, 2011). Thus, all types of coal are produced, including low quality subbituminous coals and lignite. For example, there are significant deposits of both in the Kansk-Achinsk Basin – these have low-medium ash content and are generally low in sulphur. This basin is the largest individual producer of lignite in southern Siberia. Because of favourable geological conditions, thin overburden, and thick lignite seams, mining operations within the basin have increased significantly. What is claimed to be the world's largest mine/power project (the Katek Complex) is located within the basin. This includes large opencast mines with productive capacities of up to 60 Mt/y. In recent years, annual output has been around 38 Mt. The basin has lignite reserves of ~80 Gt.

Recent years have seen the restructuring and privatisation of much of the Russian coal industry, including the parts that produce **lignite**. Nearly 80% of the sector is now controlled by eleven major mining companies and five steel smelters (EMIS, 2013). In 2012, the Russian government introduced a long-term programme (three stages) for the development of the coal industry in the period up to 2030. It is anticipated that, as a result of improvements introduced, this will increase coal production to ~430 Mt/y. Furthermore, there is a goal that 80% of mined coal will pass through some sort of processing (currently, ~40% is washed).

Recent annual Russian coal output has been ~354 Mt, of which 78 Mt was lignite. Since 2010, annual lignite production has been between 76 and 77 Mt, although it dipped slightly in 2014. A significant amount of bituminous coal is exported (127 Mt in 2012). However, as elsewhere, lignite is used close to the mine primarily. Not all mining districts contain lignite deposits. In 2012, the main areas producing lignite were the Siberian District, Far Eastern District, and the Urals District. Smaller amounts also came from the Central and Volga Districts. Depending on the source, lignite properties can vary widely. Moisture content can range between 8% and 58%, ash content between 3% and >50%, and sulphur between 0.17% and 7.7%. Russian long flame coal D (equates elsewhere with some subbituminous coals) can have a moisture content between 4.6% and 13.3%, an ash range between 6% and 40%, and a sulphur content of between 0.2% and 4.5%. Lignite supplied to power plants can have a moisture content between 13% and 35%, ash content between 4% and 48%, and sulphur content between 0.2% and 2.7%. CV generally falls between 8 and 16 MJ/kg (LHV) (Mills, 2011).

OJSC Siberian Coal Energy Company (OJSC SUEK) is the largest Russian coal mining company, followed by Ural Mining and Metallurgical Company, Evraz Plc, and Mechel OAO. In 2012, SUEK produced around 97.5 Mt of coal (62% hard coal and 38% lignite). As elsewhere, the bulk of lignite production continues to be used for power generation. The country has ~440 thermal power plants – although there are no official statistics about the number firing lignite, it is estimated that there are around 25. The main companies operating lignite-fired power plants are shown in Figure 7. Although most lignite is used for power generation, around 10–12 Mt/y is also used for heating applications.

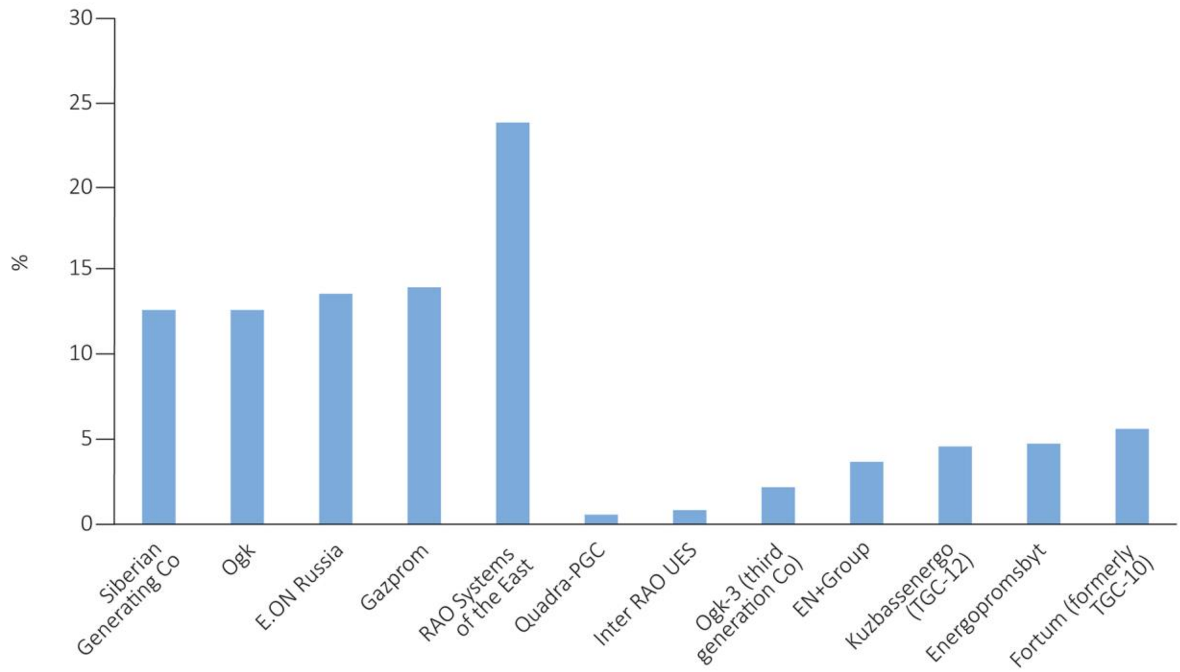

Figure 7 Russian electricity production from lignite by company (%, May 2012)

About 14% of Russia's electricity comes from coal-fired plants. However, this masks large geographical variations as the energy mix varies across the regions. Thus, Siberia (90% lignite-fired) and the Far East (~78% lignite-fired) rely heavily on coal-fired plants (about half of total electricity), while gas dominates in the European part and the Urals. Against a background of ongoing government support, coal-fired power generation in selected areas is expected to increase. This will free up increasing amounts of natural gas for export markets. In the period up to 2030, as part of a wider investment programme, it is forecast that the country will spend >US$8 billion on the further development of the coal sector. As part of this, in order to meet growing domestic and global demand, coal output will be boosted to 430 Mt. The investment programme is focusing on developing traditional coal mining centres (Kuzbass, Eastern Donbass, and Vorkuta) as well as exploring new fields in Tuva and Yakutia (EMIS, 2013).

As noted, there are around 25 major thermal power plants that rely on lignite, located mainly at pitheads or close to the appropriate mines. Some consume between 1 and 2 Mt/y. One of the largest individual lignite consumers is the LuTEK, JSC's Primorskaya (Primorsky) power plant in the Far Eastern region. The plant has nine units comprising 4 x 110 MW, 4 x 210 MW, plus a 215 MW cogeneration unit. It consumes >2 Mt/y of Luchegorsk lignite (39% moisture, 25% ash, 0.2% sulphur, CV of 8.09 MJ/kg).

Russia's **subbituminous coal** reserves are the world's second largest, after those of the USA. Combined, Russian and American subbituminous reserves account for >70% of the global total. Several basins contain coal in the European part of Russia (Moscow, Donetz and Pechora Basins), in western Siberia (Kuznetsk and Kansk-Achinsk basins) and in eastern Siberia (Lena and Tunguska basins). The Kuznetsk basin holds most of the proved reserves and represents more than half of Russian production. The country has reserves of 49 Gt of bituminous coal, 10.5 Gt of lignite, and 97.3 Gt of subbituminous (US EIA, 2013). Around three quarters of the latter are potentially extractable via opencast mining.

As elsewhere, the Russian power generation sector is a major consumer of low quality coals. Around a third of total coal output is used for generation and cogeneration purposes. Overall, only 17% of the country's electricity is currently produced from coal, compared to the global average of ~39%. However, this figure masks huge regional variations in the level of dependence, and coal dominates in the Far East (78%) and Siberia (90%). Essentially, natural gas dominates power generation in western Russia and coal is dominant east of the Urals.

6.1.3 China

Chinese coal deposits are located in most of the country's regions, although around three-quarters of proved recoverable reserves are in the north and northwest, particularly in the provinces of Shanxi, Shaanxi and Inner Mongolia. Total proved recoverable reserves amount to 114.5 Gt – this comprises 62.2 Gt of bituminous coal + anthracite, 18.6 Gt of lignite, and 33.7 Gt of subbituminous coal. Thus, low rank coals (lignite and subbituminous coals) account for >50% of China's total reserves and production. Estimated proven coal reserves and production are shown in Table 16.

Table 16 Chinese proven coal reserves (Mt) and production (Mt/y) (WEC, 2013)

	Anthracite + bituminous	Subbituminous	Lignite
Reserves	62,200	33,700	18,600
Production	3236.8	–	146.9

In recent years, these have become an important component part of energy supply. Such coals often have high moisture content, low CV and/or low reactivity. However, because of their strategic importance and the quantities available, government policies have been put in place to encourage their upgrading and utilisation for power generation and chemicals production. For example, under the terms of the NDRC's *Demonstration Projects – Planning of Coal Deep Processing*, upgrading is included as one of seven major areas of demonstration. As part of this, there is a target for upgrading projects totaling 1 Mt/y, plus other large-scale technologies to be in place by 2016. However, although China is comparatively rich in lignite, the development and utilisation level is lower than some other countries (Chunhui and others, 2011).

Although coal consumption and production growth has recently slowed, China still dominates world energy – the country is the world's largest energy consumer, producer and net importer. However, in the past year (2015), coal use, particularly for power generation, has fallen. This has resulted largely from a combination of clean-fuel policies plus a general slowdown in the economy. Furthermore, some power companies have been using a wider energy mix of hydro, nuclear and other renewable options. In 2014, overall coal use for power generation dipped – energy production grew by just 0.2%, well below the 10-year average of 5.9%. The main factor was that coal production fell by 2.6%, the first fall in China since 1998. Conversely, production from all other fossil fuels and nuclear increased, as did input from renewables (especially hydro). During the course of the year, renewables grew by >15% (BP, 2015).

In 2014, coal use amounted to 1.34 Gt, down slightly from 1.36 Gt in 2013. Although it still makes up nearly two-thirds of China's energy mix, utilisation rates at coal-fired power plants have fallen from 57.3% in 2013, to 53.7% in 2014, and ~52% in early 2015 (Gronholt-Pedersen and Stanway, 2015). During the first half of 2015, power plants were estimated to have burned 3.63 Mt/d of coal, down from an average of 3.66 Mt/d in 2014, and 3.71 Mt/d in 2013. Furthermore, as China later introduced further measures to restrict the import of some types of low grade coals, imports fell. The main aims were to improve air quality and aid the domestic coal industry – efforts were focused on more stringent coal quality requirements, plus limitations on transport distances. In the future, these moves could reduce the production of low CV and high-ash coals. New restrictions prohibit the production of lignite with ash and sulphur content >30% and 1.5% respectively. Curbs have also been placed on levels of arsenic and mercury (Vitelli, 2015). However, there are indications that the level of imports is again picking up. Mid 2016, it was reported that coal imports had increased by 9% over the corresponding period in 2015; between April and June, some 44 Mt were imported. More than half comprised subbituminous coals from Indonesia.

Lignite is found mostly in the eastern areas of Inner Mongolia and in the northeast provinces. China currently produces ~370 Mt/y of lignite, mostly in Eastern Mongolia (~340 Mt) plus some in Yunnan – lignite from the former has an average CV of 14.6 MJ/kg and under the new guidelines, is not permitted to be transported more than 600 km. In some cases, washing would increase the CV, allowing it to be transported beyond the current limit. However, not all supplies are amenable to upgrading in this way. In addition, transport of the >30 Mt/y of lignite produced in Yunnan with an ash content >35% may become an issue in the future (Cornot, 2014). In recent years, annual lignite production has increased steadily. It is used for a range of applications that include power generation, gasification, pyrolysis, coking, and liquefaction. For example, lignite is being gasified by Datang International Chemical Technology (lignite-to-SNG and olefins production).

Roughly half of China's low quality/rank coal production is used for power generation, around 30% in various types of boilers and kilns, with the balance used for chemical conversion. Thus, subbituminous coals are used extensively in the power sector, sourced both from domestic reserves as well as imported. However, recent moves by the Chinese government to restrict the import of certain types of lower quality coal (and protect its domestic industry) are having an impact on the amount used. The restrictions are aimed at reducing power plant emissions and boosting the Chinese coal mining sector. During the past year, coal imports dropped considerably. Amongst the importers, Indonesia has been hit the hardest, with a number of major thermal coal producers (such as Adaro Energy, Bumi Resources and PT Harum) reducing coal production. The current oversupply of subbituminous coal has meant that prices have been depressed and are not expected to recover during 2016.

China also produces a significant amount of **high-ash bituminous coal**. Depending on geographical location and other factors, properties can vary, although such coals typically have an average ash content of ~23% and a sulphur content of <1%. However, in some regions, ash content is higher (Cornot, 2014).

For a number of years, as the Chinese economy boomed, the import of bituminous coals increased significantly. Between 60% and 70% of coal supplied to southern coastal power plants was imported. Large tonnages are still being brought in although levels have reduced as a consequence of recent quality restrictions on the import of certain types of coal. New restrictions for low CV coal and high ash and sulphur content coals were published by the NDRC in 2014 and became effective in 2015. They apply to both domestic and imported coal, and prohibit the production of bituminous coal with ash and sulphur content >40% and 3% respectively. Additional restrictions apply in certain designated areas where the sale of high ash (>16%) and high sulphur coals (>1%) is now prohibited. As well as environmental considerations, an additional motive behind these moves has been to increase support for domestic coal producers. Thus, although over the longer term China will continue to rely heavily on coal, the country is making efforts to minimise the environmental footprint of coal utilisation (primarily emissions of particulates, SO_2, NOx, and CO_2). This is being pursued through the reduced utilisation of high ash/sulphur coals, coupled with the greater use of high efficiency, low emissions (HELE) coal technologies in the power sector. Furthermore, a recent government announcement stated that many smaller power plants that fail to meet environmental standards would face closure.

The widespread use of low quality domestic coal in Chinese power plants impacts negatively in a number of ways that include increased emissions and plant operating costs, and decreased operational lifetime. Under the terms of the 9th Five-Year Plan (1996-2000), greater quantities of domestic coals were to be washed to reduce ash levels. However, much of this new washing capacity has not yet been built although in recent years, the level of coal washing in China has increased. Historically, the washing rate of thermal coals has been much lower than in other more developed economies, due mainly to a lack of effective regulatory mandates and relevant supportive measures. The current level of ~55% is still lower than in some other countries. However, nearly all coking coal is washed, as is that used for chemicals production and PCI purposes. The government is encouraging the more extensive washing of coal and suggests that by 2020, around 70% of all raw coal will be washed (Yinbiao, 2013; Wang, 2013).

In the period up to 2035, Chinese coal consumption was forecast to double. However, in March 2016, it was announced that in a bid to reduce environmental impacts and over-capacity, the National Energy Administration had suspended the construction of new coal-fired plants in 15 provinces. Planned power projects have been suspended in provinces such as Shanxi, Guangdong, and Inner Mongolia. The aim is to reduce coal consumption by ~500 Mt over the next five years.

China's coal-based generating fleet (with a median age of less than 20 years) is by far the youngest currently in operation. A significant number of the newer plants employ SC or USC steam conditions (Barnes, 2014). In 2014, China's total generating capacity amounted to 1247 GW – coal-fired capacity was >768 GW. China is the world's largest producer of power from coal and for some years, the capacity of the power sector has increased steadily.

The bulk of China's current power fleet is made up of variants of PCC technology although alongside this, there are a growing number of plants based on CFBC technology. These have the advantage of greater fuel flexibility and the capability of burning a wide range of fuels or combinations of fuels. Chinese CFBC-based power plants burn various low quality coals, but also wastes such as those from washing plants. These make up ~10–20% of total coal production and are characterised by high levels of ash, moisture, and sulphur. CFB technology plays an important role in that it permits the utilisation of such low quality coals and wastes with economical emission control (Guangxi and others, 2015).

A further source of low grade coal utilised is **coal waste** from washing plants (which includes gangue, slurry, and middlings). This makes up between 10 and 20% of total coal production and is characterised by high ash and sulphur contents, and high moisture (for the coal washing slurry). This is difficult to burn in conventional pulverised coal boilers but is usually satisfactory for use in CFBC-based facilities (Guangxi and others, 2015) of which, China has a growing number. Middlings are also used in some gasification systems. For example, Synthesis Energy Systems (SES) operates a commercial-scale coal-to-syngas facility in Zhao Zhuang City (the ZZ Plant), Shandong Province. Based on a modified design of U-gas gasification technology licensed from the Gas Technology Institute, the plant produces syngas that is supplied to a methanol facility. The ZZ plant has been operating successfully since early 2008 on a design coal of high ash middlings (washery wastes) from run-of-mine (ROM) bituminous coal (up to 40% ash).

6.1.4 Australia

The fourth largest coal reserves in the world are held by Australia. Estimated proved reserves amount to ~76.9 Gt (US EIA, 2013). Black coal reserves are concentrated mostly in New South Wales and Queensland, which together account for more than 95% of Australia's black coal output. **Lignite** makes up nearly half of Australian reserves. Most (~96%) are in the state of Victoria, where individual seams are often thick (up to 100 metres) and near the surface – all production is via low-cost opencast mining. Estimates suggest that the state holds ~430 Gt of lignite, with more than 80% of resources located in the Gippsland Basin (South East Victoria). The Latrobe Valley is an inland geographical district of the Gippsland region. Here, seams contain an estimated 65 Gt, around half of which has been identified as 'potentially economic'. Of this total, some 13 Gt are yet to be allocated by the Victorian Government to prospective developers. Production is currently dominated by three major Latrobe Valley mines: Hazelwood, Loy Yang and Yallourn. In 2013-14, output from Victorian mines was 57.8 Mt. Latrobe lignite has a moisture content of 48–70%, and an average CV of 8.6 MJ/kg (wet) and 26.6 MJ/kg (dry). Typically, Victorian lignites are low in ash, sulphur, heavy metals and nitrogen. However, most have high moisture content (Table 17). Elsewhere, there are also lignite deposits in the Otway Basin and across the Murray Basin.

Table 17 Characteristics of 'typical' Victorian lignites (Government of Victoria, 2015)

Property	Value
Calorific value (MJ/kg)	5.8–11.5 (net, wet)
	25–29 (gross, dry)
Moisture content (%)	48–70
Ash content (%)	<4
Carbon content (%)	65–70
Oxygen content (%)	25–30
Hydrogen content (%)	4–5.5
Nitrogen content (%)	<1
Sulphur content (%)	<1

Six major lignite-fired stations with a combined capacity of 6.76 GW generate ~90% of Victoria's electricity. The biggest individual stations are Hazelwood, Loy Yang A and B, and Yallourn.

As part of its efforts to promote the greater utilisation of the state's lignite, in 2012, the Victorian Government, in partnership with the Commonwealth Government, launched the *Advanced Lignite Demonstration Program* (ALDP). This aims to accelerate the development of pre-commercial lignite upgrading technologies via large-scale demonstration projects. These focus on producing high-value energy products that include oil, fertilisers and upgraded coal for local and export markets. Major projects include those of Coal Energy Australia (fertiliser, oil and high-value coal for steelmaking), Ignite Energy Resources (upgraded coal products for local/export markets and synthetic oil), and Shanghai Electric Australia Power & Energy Development Pty Limited (development and production of lignite briquettes for export to the Chinese power sector). It is considered that the success of such projects will play an important role in maintaining a secure future for lignite, both for power generation and non-power applications (Minerals Council of Australia – Victorian Division, 2015).

6.1.5 India

India is the world's third largest coal producer, with significant deposits of **bituminous coal** located in the eastern parts of the country (Figure 8). Total proven reserves amount to 87 Gt, roughly equivalent to 140 years of current output. Total coal resources (inferred and indicated) are estimated at 213 Gt (IEA India Energy Outlook, 2015). Most of India's hard coal is in the east, with two-thirds of reserves located in the states of Jharkand, Odisha and Chhattisgarh. Bituminous coals make up 95% of the country's reserves (the balance is lignite). Most reserves are not particularly deep, lying mainly at depths of less than 300 metres. Indian hard coals tend to have relatively low moisture content, but contain high levels of ash. Three quarters of current coal production has an ash content of 30% or greater – some contains 55% or more.

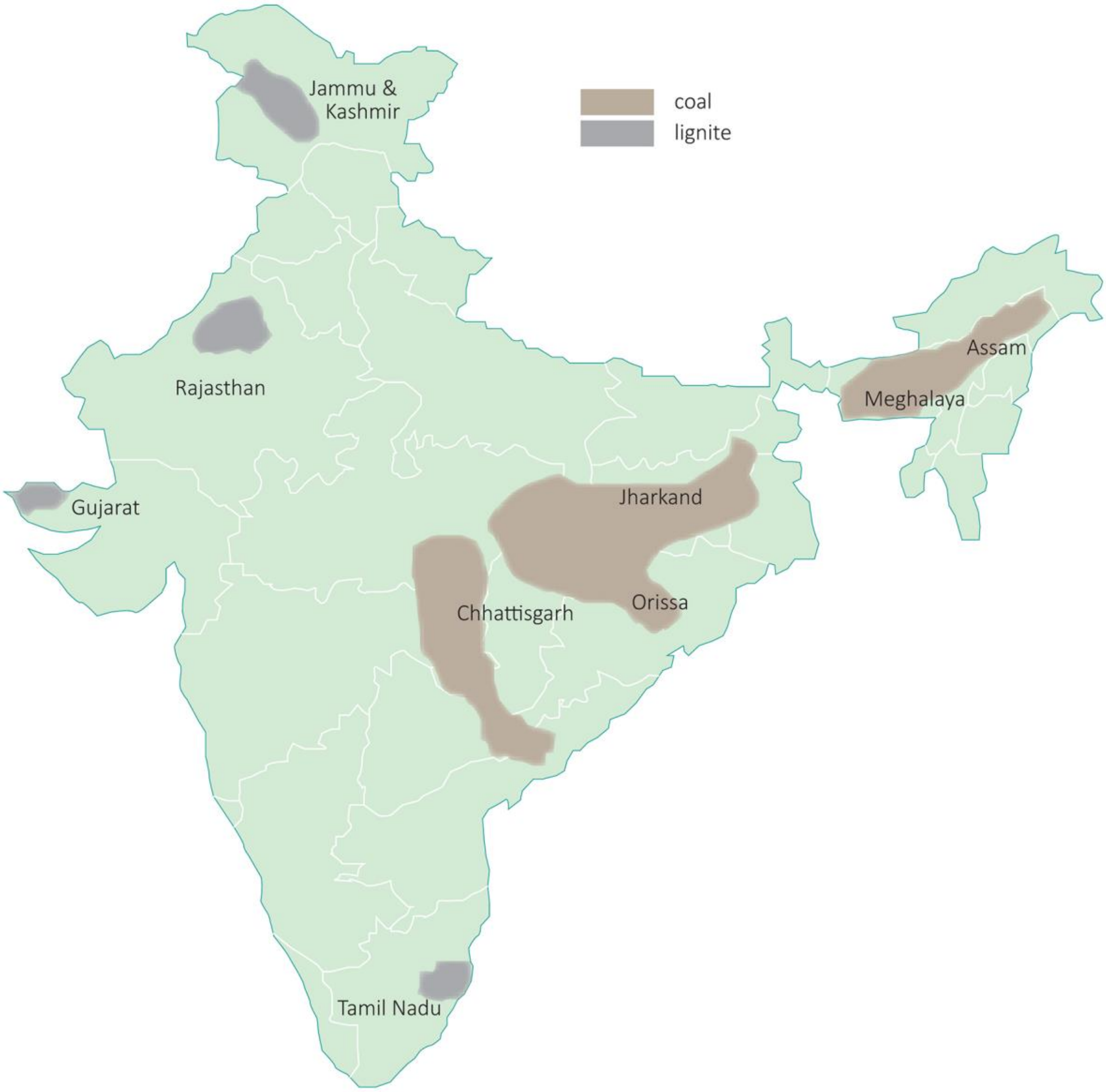

Figure 8 Location of main coal reserves in India

The country's economy is expanding rapidly, with much of its electricity generated by coal-fired power plants. Although in recent years, a growing amount of coal has been imported, much of the country is supplied from indigenous high ash resources. India is one of the biggest global economies to rely heavily on low quality bituminous coal. As a consequence of their drift origin, most Indian coals contain high levels of inorganic impurities – this is often bound within the coal matrix, making it difficult to remove beyond a certain level. Ash separation processes are often hindered by the presence of large amounts of near-gravity materials. Furthermore, depending on origin and location, the properties of coal supplied to Indian power plants can vary considerably:

- ash content between 25% and >55%. Impurities may include shale and stones;
- moisture content between 4% and 7%. In rainy seasons, it can increase substantially;
- sulphur content between 0.2% and 7%;
- volatile matter content between 1% and 36% (generally between 18% and 25%); and
- CV between 13 and ~21 MJ/kg.

Indian coals generally fall into three defined categories: Low-energy, Mid-energy, and High-energy. High-energy refers to coals with a CV of more than 23.4 MJ/kg (gross air-dried, GAD); mid-energy have values between 17.6 and 23.4 MJ/kg; and low-energy coal contains less than 17.6 MJ/kg (IEA India Energy Outlook, 2015). Most of the coal currently produced falls between 14.6 and 20.9 MJ/kg.

India is currently the world's third largest energy consumer, and its energy use is projected to continue increasing for the foreseeable future. Electricity demand is being fuelled by a combination of rapid economic development, urbanisation, and rural electrification. Coal-fired power plants currently generate >70% of the country's electricity, although the government has set ambitious targets for increasing the use of renewable technologies. However, significant increases in the coal-fired power sector are also planned.

Between 2008 and 2014, installed generating capacity almost doubled. Since 2010, almost 75 GW of coal-fired capacity has come on-line, bringing the total capacity to almost 165 GW in 2015. A further 512 GW of capacity has been proposed (but to date, only 75 GW is currently permitted and 69 GW under construction). Many proposed power plants fail to proceed – a major problem is often the lack of a suitable coal supply. Historically, much of the power sector was based on subcritical pulverised coal combustion technology, with plants designed to use domestically-sourced coal. However, from 2017, all new coal-fired projects will be required to adopt supercritical technology, a trend that is already well underway. A growing proportion of India's installed generating capacity is relatively new and has many years of operational life remaining.

Given the scale of investment underway in the sector, coal is set to remain a major component of the country's electricity supply for a considerable time. However, domestic coal production has been insufficient to meet power sector demand. Thus, some demand has been met by imports (much from Indonesia). However, the government aims to greatly increase domestic coal production by 2020.

The combination of characteristics of Indian coals has implications for their use in power plants. Thus, depending on the source, the major challenges are low heating value, high level of abrasive ash (high quartz content), a propensity for slagging and fouling, and high electrical resistivity of ash (resulting from low sulphur content). When designing power station boilers, these properties have to be taken into account and suitable features incorporated (Muthukrishnan, 2016). Design issues include:

- because of low CV, the need for larger coal storage areas, bunkers, conveying system and pulverisers;
- the high ash content necessitates bigger ESPs and ash disposal systems;
- some coal ashes can cause slagging and/or fouling;
- ash quality influences furnace heat transfer (by shielding the radiation) hence furnaces need to be bigger – higher ash loadings require larger furnace size;
- a greater number of soot blowers is required (plus more frequent soot blowing);
- downstream pressure parts (such as superheater, reheater, and economiser) need to be arranged and spaced in such a way that gas velocity is kept low in order to minimise ash-induced erosion (due to

high ash silica content of up to 60%). Thicker tubes are required and sacrificial shields/baffles are also sometimes used on leading tubes/bends; and

- the sizing and selection of various auxiliary systems can also differ (compared to other coal types).

Within India, BHEL has unique experience in the design and installation of boilers of up to 800 MW firing low CV/high ash/erosive Indian coals. The company also manufactures boilers that are fuel-flexible and capable of firing a range of coal types. This can be particularly useful where the properties of the coal feed vary significantly.

Even though India is making efforts to diversify its sources of energy, under the 12th Five-Year Plan (2012-17) coal will continue to dominate the power sector (Table 18). During this period, the Plan anticipates capacity additions amounting to ~88.5 GW. Of this, more than 72 GW (82%) will be provided by thermal plants. The National Thermal Power Corporation (NTPC) is India's biggest power producer and is planning to add 22.2 GW of new generating capacity – 93% will be in the form of coal-fired plants. These will require an additional 90–100 Mt/y of coal (Sharma, 2015). It is accepted widely that for the foreseeable future, coal will remain a major source of power for the Indian economy, and that concerted efforts will be made to ensure that it is used in an efficient and environmentally acceptable way. The current Five-Year Plan specifies a target of 50–60% of coal plants based on supercritical technology, whilst the next (2017-2022) seems likely to stipulate that all new plants must be supercritical or better and that no new subcritical plants will be allowed. The specific challenges posed by Indian coals has led to a conservative approach to improved technologies, with supercritical plant being first choice until a body of experience has been accumulated that will permit progress to ultrasupercritical units (Barnes, 2016).

Table 18 Planned generating capacity addition under 12th Five-Year Plan (Sharma, 2015)

Type	12th Plan target (MW)	Achieved by December 2014	Achieved by December 2014 (%)
Thermal	72,340	47,163	65
Hydro	10,897	1895	17.39
Nuclear	5300	0	0
TOTAL	88,537	49,058	55.4

The average efficiency of India's coal-fired fleet is lower than that of other large electricity consumers such as China and the USA. A contributing factor is the high ash content of Indian coals. However, for several decades, the energy content of the country's coal has been declining steadily (Sharma, 2015) as better reserves have been depleted. Although Indian coals have always had high ash contents, quality has fallen as the increased adoption of opencast mining (up from 20% in 1970 to the current level of ~87%) has increased levels of inert materials present in the coal produced. During the 1960s, the average coal energy content was 24.7 MJ/kg. By the 1970s, this had fallen to ~22 MJ/kg, falling further to 17.6 MJ/kg in the 1980s, 16.7 MJ/kg in the 1990s, and 14.7 MJ/kg in the 2000s (Penney and Cronshaw, 2015). It is currently ~14.6 MJ/kg.

The decline in domestic coal quality has been a major factor in reducing overall efficiency and creating operational difficulties in coal-fired power plants, many of which were designed for coals of a particular quality. A combination of higher ash levels and more variable properties has resulted in a range of problems. For example, electricity generation in Uttar Pradesh is regularly compromised and reduced, partially as a result of coal quality issues affecting power plant operations. Such problems are replicated elsewhere in the country.

Despite efforts to reduce ash levels, some power plants continue to receive coal supplies containing excessive amounts. In 2014, the National Green Tribunal (NGT) asked Coal India Limited (CIL), its subsidiary Western Coalfields Limited (WCL), and Maharashtra State Power Generation Company (Mahagenco) to follow the clean coal norms mandated by the Ministry of Environment and Forests (MoEF). In January of that year, MoEF banned coal and power utilities from supplying or using coal with more than 34% ash content. However, this is still not being fully complied with; for example, coal supplied to the Koradi and Khaparkheda stations. In August 2015, the average ash content of coal received at Koradi was 38.3% – by November, it had increased to 41.5%. Coal companies were also continuing to supply coal with >40% ash to the Khaparkheda plant (Roy, 2016). It is unclear how widespread the problem is.

To reduce ash levels, India plans a significant increase in coal washing. Historically, much of the focus was on washing coals for the steel industry – a combination of legal and pricing obstacles limited its uptake in the power sector. The situation changed when MoEF guidelines mandated that coal transported >1000 km must be washed to below 34% ash content. To date, CIL has been washing ~15% of its coal production. Recently, the company has been bidding out washeries to private contractors, with mixed results (Chandra, 2015). However, a significant increase in washing capacity is planned for the coming years and the government is pursuing a policy whereby all coal would be washed prior to use. Integrated mine-washery projects are being actively encouraged. During the past few years, CIL has been developing at least 20 new washery projects (with a total capacity of ~110 Mt/y) at existing mines. Six will be for treating coking coal (19 Mt/y) and the rest for thermal coals (91 Mt/y). A further 25 sites are under consideration for additional washeries (Sachdev, 2012; Wu, 2016).

An example of a large-scale project currently under development is that of South Eastern Coalfields Limited (SECL), a CIL subsidiary. This involves the construction of the country's largest coal washing plant (the Kusmunda washery in the Korba district of Chhattisgarh) with a capacity of 25 Mt/y. This will be an integral part of the Kusmunda opencast mine and will feed different thermal power plants across the country. Currently, India's largest washery (with a capacity of 12 Mt/y) is also located in the Korba district.

There have been a number of recent announcements indicating that in the future, India will place greater emphasis on the deployment of renewable technologies, particularly solar power. There is an optimistic target for a total of 100 GW of solar power to be operating by 2022. Reportedly, there will also be a scaling back of thermal power plant capacity additions (reduction from original proposal for 289 GW in

2022, to 239 GW). A number of coal-fired projects have been cancelled. These include four proposed Ultra Mega Power Projects (UMPPs) totalling 4 GW of capacity. However, even with a large increase in the use of renewable technologies, the general opinion is that the Indian economy will remain heavily dependent on coal for at least several decades. Although the country is making investments to transition to other sources, coal is expected to remain the dominant source of energy. Mid-2015, the Indian Coal and Power Ministry announced that more than 60 new mines would be opened in the near future. These formed part of the overall plan to double CIL production in five years – the aim was to reach the country's optimistic production target of ~1 Gt/y by 2020. However, it seems that the Indian government may not pursue this option as lower than expected electricity demand has meant that excess coal stocks have built up. Electricity demand has been increasing at 4–5 %/y, not 7–8 % as expected. In January 2016, it was announced that for the first time ever, CIL was likely to scale-back coal production as a result of growing unsold stocks (estimated at 40 Mt) – between April and December 2015, CIL output was 373 Mt, an increase of 9.1% (Kanungo, 2016). The situation arose through a combination of increased output and lower than expected offtake. It is assumed that this is a temporary situation. Coal India has a production target of 550 Mt for 2016.

In September 2016, the government announced that more than 400 coal mines had been identified for possible closure. Most are likely to be smaller, less productive mines as various plans are still underway focused on new mining projects. For example, Western Coalfields is currently acquiring 4000 hectares of land for new projects in Maharashtra and Madhya Pradesh. The intention is to open 36 new mines in these locations. Other new projects are proposed or in development elsewhere in India.

Although produced in lower quantities, **lignite** is also of significance, particularly in states that lack significant hard coal deposits. It helps meet the growing demand for electricity in a secure and economically sustainable manner. The bulk of lignite resources are located in Tamil Nadu followed by Rajasthan, Gujarat, Pondicherry, Jammu & Kashmir, Kerala, and West Bengal. State-wise resources are shown in Table 19. Production started at Neyveli (in Tamil Nadu) during 1961-62, in Gujarat in 1979-80, and in Rajasthan in 1997-98. During recent years, intense exploration has increased reserves by 4.46 Gt. Proved reserves increased from 4.177 Gt in 2007, to 6.18 Gt in 2013.

Table 19 India – State-wise lignite resources, 2013 (Mt) (Joshi, 2014)

State	Proved	Indicated	Interred	Total	%
Tamil Nadu	3735.23	22900.05	7712.43	34347.71	79.48
Rajasthan	1167.02	2671.93	1850.57	5689.52	13.16
Gujarat	1278.65	283.70	1159.70	2722.05	6.30
Pondicherry	0	405.61	11.00	416.61	0.96
J&K	0	20.25	7.30	27.55	0.06
Kerala	0	0	9.65	9.65	0.02
West Bengal	0	1.13	1.64	2.77	0.01
TOTAL	6180.90	26282.67	10752.29	43215.86	100.0

In some regions, lignite is an important fuel for power generation. However, there are various factors that constrain its greater use. These include excessive seam depth, high stripping ratios, thin seams, spontaneous combustion, the economics of long distance transport, low CV, and high moisture content. Mining is limited to opencast methods, with most output being directed to pithead power plants.

The country's total estimated lignite reserve is ~43.2 Gt. However, proven reserves are ~8.77 Gt. Only ~20% of the total reserves lie at a depth of less than 150 metres (Joshi, 2014), with about 13.4 Gt (31%) at 150–300 metres. However, the latter cannot be mined economically using current technology. Nearly half lies at depths greater than 300 metres. About 60% of total lignite reserves in Tamil Nadu lie below 300 metres. Thus, although Tamil Nadu holds >34.8 Gt (nearly 80% of the country's resource) the mineable amount is limited to 3.735 Gt (~9%). Currently, the remainder is too deep to mine economically, limiting significantly future increases in production. However, in some other areas, there is greater potential. For example, in 2015, it was announced that during the current fiscal year, Rajasthan was to auction 10 lignite blocks (identified by Neyveli Lignite Corporation) to boost power generation and increase revenue. At present, the state has 13 lignite-fired units in operation (DMC, 2015) although there are plans to increase this.

Under a succession of Five-Year Plans, Indian lignite production has increased steadily (Table 20). In 1973-74, it was 3.3 Mt, rising to 43 Mt in 2012. It is forecast to reach >68 Mt/y by 2016-17, the end of the current 12th Plan (Joshi, 2013). During this five-year period, total lignite production is expected to amount to ~290 Mt. Of this total, 125 Mt will come from Tamil Nadu, 94 Mt from Gujarat, and 71 Mt from Rajasthan.

Table 20 Indian lignite production under successive Five-Year Plans (Joshi, 2014)

Plan period	Terminal year	Production (Mt)	Incremental production increase over preceding plan (Mt)
IV	1973-74	3.32	0.76
V	1978-79	3.30	(-) 0.02
VI	1984-85	7.84	4.54
VII	1989-90	12.36	4.52
VIII	1996-97	22.64	10.28
IX	2001-2002	24.81	2.17
X	2006-2007	31.13	6.32
XI	2011-2012	43.10	11.97
XII	2016-2017	68.60*	25.50

* projected

The biggest individual lignite producer is the Neyveli Lignite Corporation (NLC), set up in 1956 by the Government of India to develop and exploit the country's lignite. NLC is now a major source of lignite and electricity for India's southern states. The company operates three highly mechanised opencast mines (producing >28 Mt/y) at Neyveli and one (2.1 Mt/y) at Barsingsar, Rajasthan. At these locations, it operates five lignite-fired pithead power plants (total capacity 3.24 GW) (Velan, 2013). These comprise Thermal Power Stations I (600 MW), II (1470 MW), I Expansion, II Expansion, Barsingsar (250 MW), and Tuticorin (1 GW). Most use conventional pulverised coal combustion technology although the TPS II Expansion plant is based on CFBC technology (2 x 250 MW). These units came on line in 2015, the first time that CFBC technology was deployed at this scale in India.

In 2015, two new 500 MW units at Tuticorin in Tamil Nadu also came on line. These are operated by NLC Tamil Nadu Power Limited (NTPL), a joint venture between NLC and TANGEDCO. Over the years, NLC's mines (Mine I, II, and IA) have been expanded and their respective outputs increased. The overall scale of mining is influenced by factors that include the presence of groundwater aquifers below the lignite beds, high overburden ratios, and hard (sandstone) overburden strata.

NLC has a number of projects planned or under development that encompass both mining and power generation (NLC, 2015). These include:

- Neyveli New Thermal Power Project (2 x 500 MW) – to replace 600 MW of outdated capacity. Due for commissioning October 2017 and April 2018;
- Bithnok Thermal Power Station (250 MW) with linked lignite mine (2.25 Mt/y) in Rajasthan. Commissioning expected in 2019;
- Barsingsar Thermal Power Station Extension (250 MW) with linked Hadla lignite mine (1.9 Mt/y) in Rajasthan. Commissioning expected in 2019;
- Neyveli Uttar Pradesh Power Limited (3 x 660 MW) – a joint venture between NLC and Uttar Pradesh Rajya Vidyut Utpadan Nigam Limited;
- Thermal Power Station II – Second Expansion – 1000 MW with new linked Mine-III (9 Mt/y) at Neyveli;
- Expansion of lignite Mines I and IA – increasing combined output by 1.5 Mt/y; and
- Mine-II Augmentation – increasing output from 15 Mt/y to 18.75 Mt/y.

Some Indian lignite is washed to reduce levels of clay and sandy materials. Under some circumstances, washing is necessary to increase CV to an adequate level and minimise plant SO_2 emissions. Raw lignite is crushed and screened prior to treatment. This may be followed by electromagnetic separation of marcasite granules (Ramasamy and others, 2013). In some cases, washing has been found to effectively double CV from, for example, 7.3 MJ/kg to 14.7 MJ/kg.

As the country's biggest lignite producer, NLC continues to make efforts to minimise the environmental impact of its mining operations, especially as these have increased significantly in recent years. Wherever possible, there is a strong focus on applying sustainable practices and avoiding environmental damage from the outset, rather than applying remedial actions retrospectively. For example, stockpiled lignite is sprayed continuously with water to keep down dust levels, and specialised spraying systems have been installed on lignite conveyors and transport roads. In addition, automatic dust suppression systems have been installed in all NLC power plants to minimise dust emanating from lignite bunkers and mills. However, large-scale opencast mining can have considerable localised impact (Velan, 2013). Issues can include soil erosion and wash-off from overburden spoil heaps, and impacts on drainage and water bodies; groundwater pumping can affect the water level in wells and underground aquifers.

A number of issues need to be taken into account when firing lignite in conventional Indian PCC-based power plants. As a consequence of the often high moisture content, mill capacity is reduced and outlet temperature lower. This increases the flue gas density and velocity, reducing boiler efficiency. This issue is usually addressed by designing boilers with flue gas recycle, capable of handling the higher moisture content (Muthukrishnan, 2016).

6.1.6 Germany

For many years, Germany has been the world's largest **lignite** producer. Lignite is mined in Eastern-German Lusatia (Lausitz) and Saxony-Anhalt. More than half of the country's reserves are located in the Rhineland coalfield, with much of the remainder in the Lausitz and Central German coalfields (Figure 9). More than 90% of total output is used for power generation (German Federal Statistical Office, 2015).

Figure 9 Location of German lignite deposits

Over the past 15–20 years, the majority of investment in coal-fired power plants was directed towards units in eastern Germany, where most were overdue for refurbishment. As a result, many of these plants are newer and have long operational lifetimes remaining. During this period, a total of 9.3 GW of lignite and hard coal-fired units came on line, and nearly 25 GW were retired (15.8 GW lignite + 8.3 GW hard coal). As of 2016, no new lignite-powered stations were under construction, although 4.3 GW of hard coal-fired capacity was being built; around 4 GW was expected to be retired by 2018.

Unlike hard coal, Germany's opencast lignite mining operations have remained profitable, with most production used in pithead power stations or close to the mines. There are four main coal-mining districts where RWE, Vattenfall, E.On and MIBRAG operate mines and/or power plants (although Vattenfall is in the process of selling its German lignite assets (2016)). Current estimates suggest that ~5.6 Gt of lignite are accessible via existing or planned opencast mining; total reserves of minable lignite amount to 34.8 Gt (Appunn, 2015). In recent years, production increased although it dipped slightly to ~178 Mt in 2014. However, because of major changes taking place within the German energy market, in the coming years, levels of production are expected to decline further.

Around 93% of Germany's electricity is currently generated from domestic resources. At 23%, lignite makes the biggest contribution. Hard coal supplies 17%, renewables 19%, nuclear 16%, gas 13%, and other sources 5%. A further 5% is imported (German Federal Statistical Office, 2015). Alongside the country's large push towards renewables for electricity generation, the make-up of the coal/lignite-fired sector is changing – for example, Vattenfall's withdrawal.

While Germany continues to expand solar and wind power, the decision to phase out nuclear energy means it has had to rely heavily on lignite for its electricity. This has been used in large quantities as it has enjoyed a cost advantage. The price of lignite-produced electricity has been kept low by several factors. For example, as European economies weakened as a result of the global financial crisis, companies reduced their production and thus had to buy fewer EU certificates for emitting CO_2. As a result, the price utility companies have paid for emitting a tonne of CO_2 fell from nearly 30 €/t in 2008 to just over 3 €/t in 2013. This made burning lignite very attractive (Schwägerl, 2015). Studies undertaken by the Berlin-based Öko-Institut found lignite to be more competitive for power generation than hard coal or natural gas at ETS (EU Emissions Trading Scheme) prices below €40 per tonne.

2014 saw the country's lowest consumption of electricity since re-unification. However, in that year, although the share of hard coal in power production fell to its second-lowest level since 1990, power from lignite remained at a high level, still making up 25.6%. In the German power sector, lignite-fired power plants currently compete in the merit order with hard coal and gas plants. They provide low cost electricity although CO_2 emissions per unit of electricity are higher. The cost of electricity from lignite plants is relatively unaffected by changes in the price of other fuels. However, a steep increase in the cost of carbon emissions would affect overall costs and impact on the level of lignite production. High CO_2 emissions make lignite power sensitive to changes in carbon prices (Little, 2015).

On the German wholesale market, power prices remain low partly as a result of the input from renewables. As a result, electricity generation using lignite is the only fossil fuel-based system that remains profitable. This has been a major factor in the increased electricity exports to neighbouring countries (Appunn, 2015). In 2013, Germany exported a record amount (~5%) of its total electricity production. The surplus came not only from the growing number of German wind farms and solar installations, but also from increased lignite use.

In June 2014, the government of Brandenburg (Germany's second largest lignite mining region) ruled that Vattenfall (or its successor) could continue mining in Welzow-Süd beyond 2026. However, in October 2014, in a move to reduce the company's CO_2 footprint, Vattenfall announced its intention of selling its German lignite operations. This includes power plants such as Boxberg, Jänschwalde, and Schwarze Pumpe (combined capacity >8 GW) and corresponding mines. The sale process is expected to continue into 2017 (Magnusson and Andresen, 2015). Mid 2016 it was announced that Vattenfall had received and accepted an offer from Czech energy group EPH, together with private equity group PPF Investments. In the near term, the sale of Vattenfall's assets is not expected to lead to any significant reduction in the level of lignite used (Michel, 2015a). In North Rhine-Westphalia, another important mining area, in March

2014, the state government decided to cut future lignite production by 1.3 Gt, whilst acknowledging that mining here would continue until at least 2030.

The four biggest electricity generators that use lignite are RWE, E.On, EnBW and Vattenfall – between them, they own ~85% of power plant capacity. The age and capacity structure of the respective lignite fleets varies significantly. Based on average unit age, RWE and Vattenfall operate the newest. RWE has the greatest number of old plants (+40 years old) but also two units that came on line within the past two years. The average age of Vattenfall units is 21 years, although >3 GW of capacity came on line in recent years (Little, 2015). Potentially, Germany's lignite reserves could sustain one quarter of national electricity generation for another two centuries. However, their future will depend largely on political decisions taken.

In the coming years, the German power sector will continue its transformation. In particular, electricity from renewables is expected to carry on displacing that from some other sources. However, as elsewhere, because of their intermittency, other forms of generation will be required when output falls or is unavailable. This 'reserve capacity' may take a number of forms although a significant proportion is likely to comprise lignite-fired stations. Potentially, these could make up to 50% of reserve capacity (Williams, 2015). Lignite plants can apply to be included in the capacity reserve from 2017. They will be paid to supply electricity during times of power shortages although will not be allowed to sell on the market. However, they will not be required to buy extra EU emission permits from that year, as originally planned for coal-power plants that are >20 years old.

In October 2015, in a move aimed at reducing CO_2 emissions by 12.5 Mt/y by 2020, it was announced that Germany's three biggest utilities had agreed to begin placing some of their lignite-fired plants into the country's power reserve. Thus, RWE, Vattenfall (or successor) and MIBRAG will be paid ~US$1.76 billion to keep ~2.7 GW of lignite plants offline except when power demand exceeds supply. Units will be taken off grid over the period 2016-19 and used only as 'facilities of last resort'. This strategy is intended to help Germany meet pledges on CO_2 emissions, but keeps the plants available if required. RWE intends to shift capacity from two units at Frimmersdorf, in North Rhine-Westphalia in October 2017, followed by two more at Niederaussem in 2018 and one at Neurath in 2019. After four years, they could all be shut permanently. Vattenfall's successor will move capacity from two 500 MW units at Jänschwalde to the reserve in 2018 and 2019. The German Energy Agency (dena) noted that that attaining the government's proposed 80% renewable electricity target by 2050 would only provide 24% of dependable grid supplies. In addition to 9% power storage and 25% reduced demand, 60% fossil fuel back-up capacity would still be required to accommodate fluctuating solar and wind availability (Michel, 2015a).

German lignite plants currently comply fully with existing regulations for emissions such as SO_2 and particulates. The main issue surrounding the continued use of lignite for power generation in Germany centres on CO_2 emissions (1 MWh of lignite-generated electricity produces ~1 tonne of CO_2). Since the enactment of nuclear phase-out legislation in 2011, German lignite mining output has increased by 8%. CO_2 emissions had fallen steadily from 1051 Mt in 1990 to 813 Mt in 2011, but, partially because of the country's nuclear phase-out, increased again to 842 Mt in 2012 and 2013. This was largely attributable to the increased use of lignite for electricity production. However, based on present fossil fuel usage trajectories, some studies suggest that Germany's 40% CO_2 reduction target for 2020 may be unattainable. It has been suggested that by decommissioning the least efficient half of the lignite-fired fleet, up to 88 Mt/y of CO_2 emissions could be avoided (Michel, 2015a).

Because of its often high moisture content and low CV, there can be obvious drawbacks in transporting raw lignite over long distances. As more than 50% of its composition can comprise water and ash, it can be prohibitively expensive for bulk transport to distant power stations or other end-users. Under some conditions, there can also be other problems such as spontaneous combustion. Consequently, in many locations, lignite is used in power plants located close to the particular mine or mines. Often, transport from mine to power plant is limited solely to a dedicated conveyer system. However, such systems can sometimes be lengthy – for example, at Schleenhain in Germany, MIBRAG operates a 10 km-long overland conveyor system; a 43 km conveyor system is in use at the Megalopolis Lignite Centre in Greece; and a 19.3 km-long single flight conveyor is operating in Texas, USA. There are many other examples around the world.

Clearly, transporting lignite in bulk by road or rail increases overall costs; transport costs can easily be more than those of the lignite itself. However, although rail costs vary enormously between different countries, in some, the total cost of the transported lignite remains sufficiently low for the process to be economically viable (Michel, 2015a). Modelling suggests that under some circumstances, the additional energy required for transport can constitute <1% of the delivered lignite energy content. Thus, it is cost effective to transport some lignite to distant end-users – much of this takes place in and around Germany.

Lignite's main continuing advantage is its low cost. In Germany, minemouth prices for lignite have increased from ~4 €/MWth in 2000, to ~6 €/MWth in 2015 (adjusted for CV and sulphur content). However, production costs are largely unaffected by changes in the global energy market. The effective fuel price at the most efficient plants is ~1.5 €cents/kWh generated electrical power (Michel, 2015a). At a typical plant efficiency of 40%, lignite's power generation costs amount to about €15 per MWh (Michel, 2015b). Both raw and processed lignite are cheaper than natural gas (in 2015, trading in Europe at >20 €/MWth). For example, fuel costs for a new 19.5 MW plant (firing pulverised lignite) operated by Allessa Chemie at Fechenheim near Frankfurt in Germany are 40% less than if using natural gas. Other plants have reported similar savings. Clearly, the situation may differ in other locations and/or countries.

It is often perceived that lignite is rarely transported far from its source. However, this is something of a misconception as relatively large tonnages are regularly dried and shipped for considerable distances. This trend has become increasingly apparent in Germany where moves are underway to reduce the amount of lignite burned in the country's large centralised power plants. German energy policies are aiming towards the gradual replacement of large lignite-fired plants mainly by renewables. However, comparable transitions are not occurring with municipal heating and industrial boilers. Some of the lignite that was originally supplied to large stations is being redirected to smaller, more diverse and more distant decentralised applications. Some from Middle Germany is now exported to the Czech Republic. Even with transport costs factored in, lignite has proven to be more economical than competing sources of energy such as gas. Examples of 'remote' lignite markets are given in Table 21.

Table 21 Examples of European lignite markets remote from mine site (Michel, 2015a)

Sector	Supplier	Examples of customers	Lignite supply
Asphalt mixing	Rheinbraun Brennstoff	~1000 installations across Europe	3 Mt/y dry pulverised lignite
Cement	Rheinbraun Brennstoff	Plants between the Ruhr industrial region and the Alps. For example, Swiss Siggenthal cement factory	Two trainloads (3000 t/w) from Rhineland (600 km away) to Siggenthal
Cogeneration	Vattenfall Europe Mining	Ten municipal cogeneration plants	Various grades of pulverised lignite
Cogeneration/ chemicals production	MIBRAG Mining Corporation	Schkopau CHP plant (2 × 450 MWe) – chemical production and railway electrical power generation	Lignite from Profen mine – 40 km distance
Power plants	MIBRAG Mining Corporation	Six power plants (for example, Dessau and Chemnitz)	Lignite railed between 40 and 402 km from Profen
Industrial sites	MIBRAG Mining Corporation	Three sugar factories (for example, Südzucker mill, Zeitz) plus a biofuels production facility	Lignite transported up to 120 km
Industrial power plants	MIBRAG, RWE, Vattenfall	*Allessa Chemie, Fechenheim, Germany (19.5 MW)	Pulverised lignite
		*WeylChem chemical company, Griesheim (start-up 2017) (19.5 MW)	Finely pulverised grade. 3 trucks per day (200 km from Rhineland)
		Buschhaus power plant, Lower Saxony	
		*Proposed 19.5 MW plant at Darmstadt (2015)	
Heating plants	MIBRAG Mining Corporation	Various plants in the Czech Republic	Lignite briquettes. Imports of ~140 kt/y
	Vattenfall Europe Mining	Various plants in Germany, Poland, Czech Republic, and other European countries	Lignite briquettes
Fluidised bed combustion plants	RWE, Vattenfall, MIBRAG	Various plants in Germany	Sifted grades (19% moisture, CV ~19 MJ/kg
Travelling grate plants, commercial and domestic heating	RWE, Vattenfall, MIBRAG	Various plants in Germany and adjacent countries	Various grades and configurations produced

*plants of less than 19.5 MW avoid the need to purchase EU Emission Trading Allowances

In Germany, some sources of lignite are not pre-dried prior to shipment although they tend to lose water during transit and this can increase their energy content significantly. Alternatively, where dried, pulverised lignite typically has a moisture content of ~10% and a higher CV (~21–22 MJ/g) – this is often moved by rail container cars. Between 4 and 5 Mt/y of dry, pulverised lignite is directed to various plants utilising fluidised bed combustion technology. It is used widely within Germany as well as exported to a number of other European countries. In some situations, pulverised lignite has found niche markets. For example, around a thousand asphalt mixing plants throughout Europe have been converted to fire pulverised lignite. These plants are particularly sensitive to energy costs – pulverised lignite forms a low-cost option that has been taken up by a large part of the sector. In Germany, ~80% of all such plants now use this fuel. A major supplier is Rheinbraun Brennstoff GmbH (RBB), a subsidiary of RWE Power AG. Transport is normally via truck or rail.

Annually, German producers also manufacture between 1.5 and 2 Mt of lignite briquettes of various types. These are used widely for industrial, commercial and domestic heating purposes within Germany and are also exported to various European countries such as the Czech Republic and Poland.

In some cases, markets for lignite have developed for specific reasons. For example, in 1991, the Czech parliament adopted measures to limit lignite mining in North Bohemia. As a result, the country now imports large amounts of lignite by rail from Germany. Major recipients include 1.3 Mt/y of raw lignite from MIBRAG, supplied to a cogeneration plant (363 MWe + 698 MWth) at Opatovice. Transport distance from the mine at Profen to the Czech plant is nearly 200 km. The plant receives two trainloads per day. Smaller amounts are also railed 120 km to the Komořany cogeneration plant (239 MWe) near Most.

Since 2014, MIBRAG's Czech owner EP Energy has also contracted lignite from its Polish subsidiary KWK Silesia in Czechowice-Dziedzice. Up to three trainloads are delivered daily (distance 334 km). EPH has been negotiating the purchase of Vattenfall's lignite operations in Germany. Their bid appears to have been successful – Lusatian lignite could now find export markets for power plants in Northern Bohemia, where a number of mining licenses will expire in 2022 (Michel, 2015c).

6.1.7 Ukraine

Ukraine has 16.6 Gt of proven **subbituminous coal** reserves (WEC, 2013). The main ones (>45%) are concentrated in the Donetsk coal basin. A further 34% is located in the Luhansk region, 15% in the Dnipropetrovsk region, with the remaining 5% located in the regions of Lviv, Volyn and Kirovograd. As in other countries, much subbituminous coal output is directed to the power sector. Most Ukrainian mines are deep, although there are also three opencast sites that produce subbituminous coal (plus some lignite).

Largely as a result of the ongoing conflict with pro-Russian separatists in the Donetsk and Luhansk regions, Ukrainian coal production has fallen by ~24 Mt/y. In order to provide adequate supplies, the country has started importing coal. For example, in August 2015, a shipment of 160 kt of bituminous coal was ordered from South Africa. The order was placed by CenterEnergo, one of Ukraine's four major fossil fuel-burning power companies. However, boosting coal imports from the USA, South Africa and other countries has proved problematic as Ukrainian ports are of limited capacity and sea depths are insufficient for large sea-going vessels.

Other coal shipments continue to come from Russia (for example, 200 kt in September 2015). In 2015, Ukraine needed to stockpile ~3.2 Mt of coal (including 1.4 Mt of bituminous coal) in order to meet the high winter demand. To help avoid an energy crisis, the country has since renewed the import of Russian coal to supply thermal power plants across the country. By the first quarter of 2015, this made up about 40% of Ukrainian thermal coal supply. As they are transported by rail, Russian supplies do not suffer the same restrictions as seaborne imports.

Prior to the start of Ukraine's political instability and the outbreak of hostilities, in 2011, the government instigated a programme to convert gas-fired generating capacity to use domestic coal. The aim was to reduce dependence on imported Russian gas by 30–32 billion m^3/y by 2018–19; demand for domestic coal was forecast to increase by 18 Mt/y. In 2012, the Ministry of Energy and Coal Industry signed an agreement with the China Development Bank for a US$3.6 billion loan for the financing of gas-to-coal conversions and the construction of coal gasification plants.

Given the present situation in the country, it remains unclear whether the necessary increase in coal output from domestic mines can be achieved in the foreseeable future. Boosting thermal coal output at mines controlled by the government or private investors requires time and investment, but both are lacking (Ignatov, 2015). For political reasons, the Ukrainian government is reluctant to increase further the import of Russian coal; the country is already heavily dependent on Russia for gas and oil.

6.1.8 Kazakhstan

Kazakhstan has significant reserves of bituminous and **subbituminous coals** and **lignite**. Around two thirds of these are bituminous/subbituminous coals. The country contains central Asia's largest recoverable coal reserves, 3.69 % of the world total. After Russia, it is the former Soviet Union's second largest producer. It has >400 coal deposits of which a third are classified as lignite. The 16 largest deposits are located in three main basins. These comprise 24.7 Gt of bituminous coal and 37.5 Gt of lignite – estimated recoverable amounts are ~22 Gt and 12 Gt respectively.

Coal reserves are found mainly in the Karaganda, Ekibastuz and Turgayskiy basins. The two major hard coal-producing areas comprise the Ekibastuz and Karaganda basins. The latter has long been the country's main coal supplier, producing up to 50 Mt/y. The Ekibastuz coalfields, which are among the largest in Kazakhstan, lie to the northeast, 200 km from Karaganda.

Following the country's independence, coal production declined. However, in the following years, in order to meet growing domestic demand and for export markets, production recovered, although there have been recent dips in output. In 2014, total coal production amounted to 116 Mt, of which, >95 Mt was used within the country, with ~22 Mt exported. Around a quarter of the country's coal production is exported to countries such as Russia, Finland, Kyrgyzstan and Ukraine; combined, these account for 97.8% of Kazakhstan's total coal export. The majority of coal demand in Kazakhstan is from the power sector. Typically, between 75% and 80% of the country's electricity is generated by coal-fired power plants, located mainly in northern coal-producing regions. There have been several initiatives aimed at improving the country's power sector. This included the 1320 MW (2 x 660 MW) Balkhash Thermal Power Plant that was to be developed on the south-western bank of Lake Balkhash. This was being developed by Samsung of Korea and the national energy corporation of Kazakhstan. The project was being developed as part of an intergovernmental agreement signed by the governments of Kazakhstan and South Korea signed in 2011. However, Samsung cancelled the US$2.5 billion project in September 2016. Had it proceeded, it would have provided ~9% of Kazakhstan's total power output.

Much of the country's power infrastructure needs modernising. Some thermal power plants are fairly old and operate at relatively low efficiencies. A contributing factor is the heavy reliance on low quality indigenous coal, although this helps free up coals of better quality for export. Most Kazakh power plants burn high-ash coal (over 40%). The ash is highly abrasive and can cause plant operational problems (Yesserkepova, 2012). However, the country produces some of the cheapest coal available worldwide.

Hard coal- and lignite-fired power plants generate >75% of the country's electricity as well as provide much of its domestic heat. By 2030, the share of electricity from such plants is expected to remain at ~75%. In recent years, in order to satisfy growing domestic demand, Kazakhstan steadily increased the level of coal production. Historically, annual production has been at least 120 Mt, although levels have since decreased – in 2014, it was 116 Mt. Reportedly, in 2015, it was 107 Mt. However, in the future, coal consumption is expected to again increase. Forecasts suggest that by 2020, it will reach 121 Mt/y, increasing further to 158 Mt/y by 2030. Of the 121 Mt produced in 2013, 97 Mt was consumed internally, with the balance exported. There are 33 companies currently mining coal in Kazakhstan. Combined, they produce >90% of total coal output. All of the larger mining companies have indicated that they plan further investment and business development in the coming years.

Some 37% of Kazakhstan's confirmed coal reserves are lignite, located mainly in the Turgay, Nizhne-Iliyskiy and Maikuben basins. Recent annual lignite production has varied between 2.5 and nearly 6 Mt/y. In 2015, it was 5.5 Mt, 20% less than in the previous year (Daily Monitor, 2016). Most is used for power generation in plants close to the mine.

Indigenous lignite is currently the focus of efforts to produce other products. Since 2013, the Kazakh Institute of Chemistry, Coal and Technologies has been undertaking a project aimed at producing petrol and diesel from indigenous lignite. In April 2015, an experimental complex with a capacity of 0.8 t/d of lignite was set up in the Saryadyr field in Akmoly region (Bayramov, 2015).

6.1.9 South Africa

South Africa's most abundant source of energy is **bituminous coal**, and the country is a major producer, consumer and exporter (Mills, 2010a). Around 77% of South Africa's energy needs are met by coal and as economically-viable alternatives are lacking, this situation is unlikely to change significantly during the next two decades. At current rates of extraction, proven coal reserves will last for well over a century.

Coal production is split roughly evenly between underground and opencast operations, with the bulk of output produced by a handful of major mining companies. Eleven mines are responsible for ~70% of total production. By international standards, many South African coal deposits are relatively shallow with thick seams, making them easier and cheaper to mine. Coals directed to local electricity production are some of the cheapest in the world, although these usually have higher ash content and lower CV than export grades. For some applications, coals are used unwashed. Transport costs account for a significant proportion of the delivered product cost – as a result, purely for economic reasons, power plants remote from mines are often supplied with washed coal with a higher CV (SANEDI, 2011). Some coal supplied to South African power plants and Sasol's CTL operations are produced from the middlings fraction of export coal washing plants.

There has been a gradual decline in the quality of many coal reserves, plus a general deterioration of geological conditions in mining operations across the country. This has resulted in changes to the thermal coal export mix. Understandably, there has been a tendency for reserves of higher quality to be mined first – their depletion means that focus has now shifted to the mining of deposits of lower quality. These are usually of adequate quality for domestic power plant use, or possibly directed to export markets requiring a lower CV.

The country relies heavily on coal-fired power plants for electricity, using mainly coals of poorer quality than those exported. For example, the Majuba station uses a combination of colliery discards and coals from a number of opencast and deep mined sites. The coal as delivered has an average ash content of ~35% (range 19–40%), a moisture content of 3.1% (range 1.7–4.4%), and sulphur content of 0.8% (range 0.7–7%). Nominal CV is 21.5 MJ/kg. Although the coal feed does not usually contain high moisture levels, there can be issues with the level of fines present. This can result in handling problems such as blocked chutes and bunker bridging.

Coal quality has been an issue at several Eskom power plants and the company has repeatedly blamed mechanical breakdowns and underperformance on the poor quality of delivered supplies. Declining quality has been cited as a major factor in the reduced plant availability – during the past five years, this fell from 86% to 75%. Various plant problems have been cited; for example, increased boiler residues at the Duvha station (in 2014) that reportedly, contributed to a plant explosion. Also, the Department of Public Enterprises blamed fine poor quality coal for damaging conveyor belts at Kendal power station in March of the same year – this resulted in three units shutting down, the loss of 3 GW of power, and rolling blackouts (Jurgens, 2015).

Alongside domestic use, a significant percentage (generally between 25% and 30% of saleable coal) of South Africa's production is exported through the Richards Bay Coal Terminal. This is located on the country's Indian Ocean coast (Figure 10). It has a capacity of 91 Mt/y and ships coal for several large operators that include Glencore and Anglo American. In 2015, exports from the terminal increased by 5.7% to 75.4 Mt, helped by demand in Africa and India. A similar level is expected for 2016 (Reuters, 2016).

Figure 10 The Richards Bay coal export terminal (photograph courtesy of Richards Bay Coal Terminal Proprietary Ltd)

Export coals are normally washed to reduce their ash content, usually using variants of Dense Medium Separation. This results in the production of between 60 and 65 Mt/y of discards (Republic of South Africa, nd). To date, well over 1 Gt of discards have been accumulated. In the past, washed coking and export grade steam coals required a CV of between 26 and 27.5 MJ/kg, although in some cases, average values have declined to <25 MJ/kg. Coals with CVs as low as 23 MJ/kg have been acceptable for some export markets. The main export quality grades have traditionally fallen within the RB1 and RB2 grade categories – these range from 24.5 to 25.1 MJ/kg (net, as-received) calorific value. A more recent addition was the RB3 category, essentially a new class of lower grade thermal export coal. This covers products with a CV of less than 23 MJ/kg.

The possibility of washing greater quantities of lower quality coals for export has been considered. The growth in demand for lower grades (particularly for Asian markets) offered the possibility of opening up new markets. With minor upgrading, some coals traditionally only of value for domestic power plants, showed the potential of becoming an export fuel. Clearly, relatively high prices for exported steam coal would be a prerequisite. However, more recently, prices have fallen, presumably reducing the economic feasibility and commercial attractiveness of this option. A number of possible advantages were cited for South Africa to pursue this option – these included increased yields and coal recoveries, higher saleable tonnages of coal available, less waste and reduced environmental impact, longer life of mines and reserves, plus some mining blocks/reserves (currently uneconomical) could become cost-effective (Bergh and others, 2013). The viability/sustainability of producing specific low grade export coals depends heavily on the coal price and international supply and demand. Clearly, the potential income from increased exports would need to be balanced against the risks of reduced supplies to the South African power sector.

Historically, as many low cost coal deposits have been exploited, a large mining sector has developed. Despite its high ash content, coal is used extensively for power generation – Eskom generates 95% of the country's electricity; 90% of Eskom's output is produced by its coal-fired stations – an example is shown in Figure 11. The company uses around 90 Mt/y of coal. Eskom is the seventh largest electricity generator in the world, and Sasol, the largest coal-to-chemicals producer.

Figure 11 Eskom's 3.6 GW base load coal-fired Matla power plant, South Africa (photograph courtesy of Eskom)

For some years, South Africa has experienced a shortage of electricity. This is being partly addressed through Eskom's construction of two new supercritical coal-fired power plants, Mendupi and Kusile. Both multi-unit plants will be gradually brought on line. Medupi is located in Limpopo Province, and is the fourth dry-cooled, baseload station built by Eskom in 20 years (after Kendal, Majuba and Matimba). The plant will be the fourth largest coal plant in the southern hemisphere and the biggest dry-cooled power station in the world. Once fully-operational, Medupi will comprise six units of 794 MW (total capacity of 4.764 GW). Synchronisation of the first unit (Unit 6) took place in March 2015. The Kusile project is located near the existing Kendal power station, in Mpumalanga. This will comprise six 800 MW units (total installed capacity of 4.8 GW). The plant is the first in South Africa to install flue gas desulphurisation. Synchronisation of Unit 1 is scheduled for the first half of 2017.

Some existing coal production capacity is reaching the end of its economic life and it seems likely that development costs for new reserves will be higher than those of older deposits. Coal quality is also likely to be lower. South Africa still has large, although not unlimited, amounts of coal. However, the Witbank and Highveld coalfields are approaching exhaustion, and new deposits will need to be exploited. Currently, emphasis is being placed mainly on exploring and developing the Waterberg coalfield as well as others in Limpopo province. However, coal quality and/or mining conditions of some alternatives (such as the Waterberg, Free State and Springbok Flats coalfields) could be significant barriers.

In 2015, it was reported that after 2016, Eskom would have insufficient coal for its power plants and faced a 17 Mt shortfall (Jamasmie, 2015). This was expected to become an issue particularly for the Matla, Tutuka, Hendrina, Kriel and Arnot power plants. Eskom is building additional generating capacity but projects have been delayed and some older plants have experienced failures. In addition, several major mining companies (such as Glencore and Anglo American) intend to cut back on production as a result of low coal prices.

6.1.10 Indonesia

Indonesia remains one of the biggest global producers of **subbituminous coals**, with a sizeable percentage of national output exported. The country has ~28 Gt of proven reserves of subbituminous coal (WEC, 2013). Although the quantities exported have recently declined (largely because of Chinese cutbacks) Indonesia remains a major exporter of this type of coal. In 2014, exports amounted to 410.9 Mt (IEA, 2015). Despite recent cutbacks, alternative markets may develop for some Indonesian coals. For example, Pakistan is currently exploring the possibility of forming joint ventures with Indonesian coal producers. The attraction of Indonesian coals is the low sulphur level, but mainly the cost at which electricity can be generated. Government sources suggest that Pakistani electricity produced using such coals would cost <1.5 Rupees/unit (1 US cent) whereas that from fuel oil would be ~13 Rupees, and from gas, 5.5 Rupees (Ahmen, 2016).

Against a background of falling exports, Indonesia's internal energy demand has continued to increase. As well as coal, consumption of oil and gas has risen. In 2014, domestic coal consumption increased by 5% (BP, 2015). In that year, coal production rose by 8.9 Mt, reaching 458 Mt, its highest ever. Although this was the smallest increase since 2000, it was still the fifth largest increase in the world. Indonesia has plans to ramp up its domestic coal-fired power generation and forecasts suggest that if coal exports decline further, some excess capacity could be taken up by increased electricity demand within the country. This move would effectively remove millions of tonnes of coal from the (currently oversupplied) seaborne market.

The Indonesian government has ambitious plans to increase power generation by 35 GW in the period up to 2020 – at least 20 GW would be coal-fired. A further additional 35 GW is planned for the following five years, which would add a total of 70 GW to the country's existing capacity of 47 GW. Each phase would require up to an additional 70 Mt/y of coal (Russell, 2015). However, recent comments by government officials suggest that this total might now be reduced. However, a number of new power projects are underway. For example, the 1 GW Cirebon coal-fired expansion power plant will be built in West Java. This will employ ultrasupercritical steam conditions. Indonesia's state-owned electricity utility has signed an agreement with Marubeni and its partners to purchase power produced. This will be supplied to state-owned utility PT PLN (Persero) under a long-term purchase agreement. The US$2 billion plant is expected to be commissioned in 2020. Japanese technology vendors are supplying much of the equipment. A second project (2 x 660 MW) is also being developed in Cirebon. In December 2015, it was announced that YTL Power had won a US$2.7 billion contract to develop the 1320 MW Tanjung Jati A power plant. Again, electricity generated will be supplied to Persero.

6.1.11 Turkey

The country has deposits of hard coal and lignite and both are produced commercially. Reserves of **lignite** are significantly greater – it is Turkey's most important indigenous energy resource, with deposits spread across much of the country (Figure 12). Whereas hard coal is limited to one area, lignite is available in all geographical regions and in more than 40 provinces. In Turkey, the term 'lignite' is used to describe any low rank coal. Thus, it also covers a number of indigenous coals that, according to some international classifications, actually rank as subbituminous.

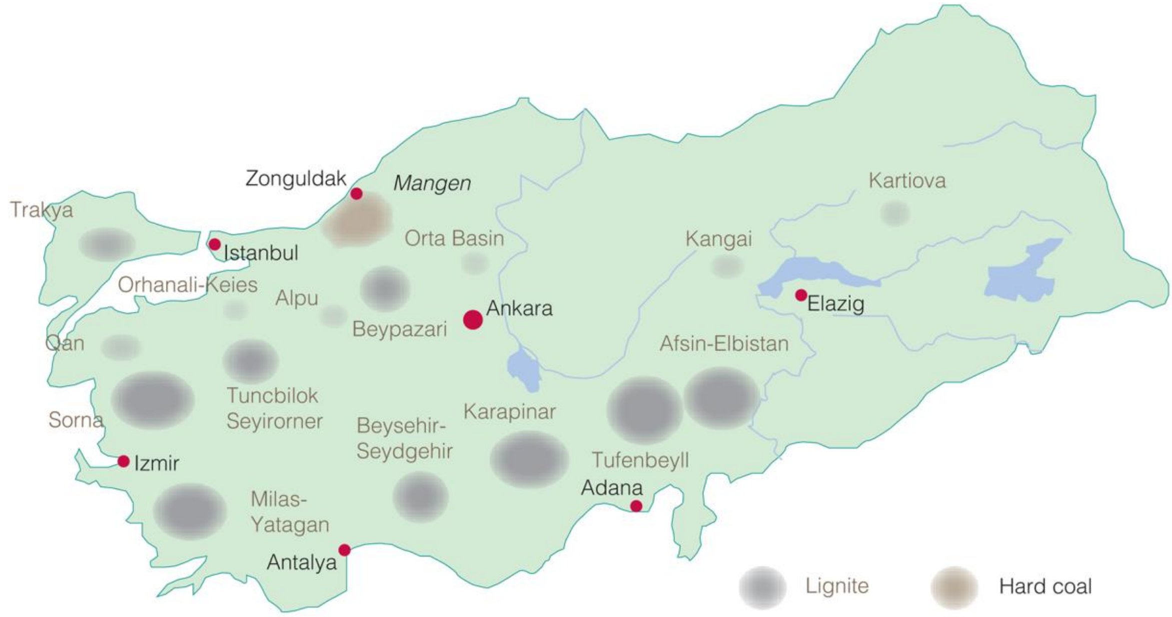

Figure 12 Location of main Turkish lignite deposits

Hard coal resources are estimated to be ~1.3 Gt (534 Mt proven) – at nearly 12 Gt, those of lignite are much greater (proven reserves of ~10 Gt). However, despite considerable progress over the past decade, large areas of the country have yet to be explored fully. In others, evaluation has only been carried out at relatively shallow depths. Potentially, lignite (and hard coal) reserves could be much greater than current estimates suggest. An estimated 40% of Turkey's quoted economically exploitable lignite reserves are located in the Afşin-Elbistan basin. There are also important deposits in Soma, Cayhiran, Tunçbilek, Seyitömer, Bursa, Çan, Muğla, Beypazari, Sivas and Konya Karapinar. The greatest concentration of lignite mines is in the northwest region around the towns of Soma, Seyitömer and Çan. Most lignite (~90%) is produced from opencast mines, although there is some underground mining, mainly in the Soma, Tunçbilek and Beypazari basins. Much of Turkey's lignite production is supplied directly to power plants (by tonnage, 82% in 2012) (Figure 13) with most of the balance going to industrial users.

Figure 13 The 1.44 GW lignite-fired Afsin-Elbistan B power plant in Turkey (photograph courtesy TKI)

In 2005, an ongoing national project (the *Lignite Exploration Mobilization Project* –LAP) was initiated to further develop existing reserves and locate new deposits. This has since focused mainly on six regions and explored 10,000 km^2. As a result, in some locations, reserves have increased or new ones been discovered. Increases have been particularly substantial in the Afşin-Elbistan basin. Within the past few years, new discoveries have included 1.8 Gt of lignite in the Central Anatolian province of Konya, capable of powering 5 GW of generating capacity for 30 to 40 years. In 2013 it was announced that a further 950 Mt of lignite reserves had been discovered in the western province of Afyon, capable of supporting 3.5 GW of power generation projects. More discoveries are anticipated. In order to further incentivise Turkish lignite/coal, in 2012, the government announced that it will be given free of charge to 'serious' investors for a period of 30 years, provided that it is used for power generation.

Nearly 90% of Turkey's lignite reserves are operated by public sector organisations. TKI holds 23%, EÜAŞ 48%, MTA 18%, and the private sector 11%. In a 'typical' year, TKI produces ~33 Mt of saleable lignite, EÜAŞ ~36 Mt, and the private sector, ~7 Mt/y. Over the past few decades, there have been some fluctuations in annual Turkish hard coal and lignite production (reflecting prevailing economic and other factors), although in the case of lignite, the overall trend has been upwards.

Thermal and hydroelectric generation currently provides most of Turkey's electricity. In 2012, gas-fired plants generated 43%, followed by hydro (24%). Domestic lignite and hard coal provide ~16%, with imported hard coal providing a further 12%. Small amounts are also provided by oil, asphaltite, wind, and geothermal. Much of Turkey's lignite production (>82%) is used for power generation, with around 9% used by industry, and a further 9% for heating applications.

The Turkish government is promoting the country's lignite resources to both domestic and foreign energy investors. New incentives are encouraging development of coal-fired generating capacity and liberalising Turkish coalfields and other assets. The Ministry of Energy and Natural Resources considers that the increased utilisation of indigenous lignite is crucial asphaltite – it views this as the energy source of greatest importance for future power generation. Thus, the country's current balance deficit would be improved through the greater use of lower cost indigenous lignite, plus the further opening up of reserves to the private sector. In September2016, the Turkish government announced the imposition of import duty of 15 US$/t on imported coal, used to power a number of major power plants. The main aim is to increase utilisation of indigenous coal resources and thus, minimize the cost of imported energy supplies.

There is an on-going process of privatising much of the power sector and some coalfields, plus encouraging private investment in both. A number of new projects are combining power generation with lignite production. Some new generating capacity will be sited within existing lignite-producing areas although much of the potential for new capacity lies in lignite fields that are not yet being fully exploited. In April 2016, at the opening of Enerjisa's new 450 MW lignite-fired Tufanbeyli power plant in Adan, Turkey's president stated that he wanted to minimise the amount of coal imports in favour of the greater use of indigenous lignite. The main reason cited was to reduce the country's dependence on imported forms of energy. The new US$1.1 billion facility is the largest lignite-fired plant built by the private sector. It will use 5.5 Mt/y of local lignite (Energy Central, 2016).

Many Turkish lignites are of poor quality. Most have a low CV and many contain high levels of ash, volatile matter, moisture and sulphur. Depending on the source, CV can vary significantly, even within the same area – around 70% of reserves are less than 8.4 MJ/kg, with some below 6.3 MJ/kg. Around 17% are between 10.5 and 12.6 MJ/kg. Only 6–8% exceed 12.6 MJ/kg. However, around 50% of total lignite output is currently washed, allowing some sources to compete with imported coals.

Under the terms of an *Energy Supply Security Strategy Paper* approved by the Turkish High Planning Council, by 2023, the country's electricity will be produced as shown in Figure 14.

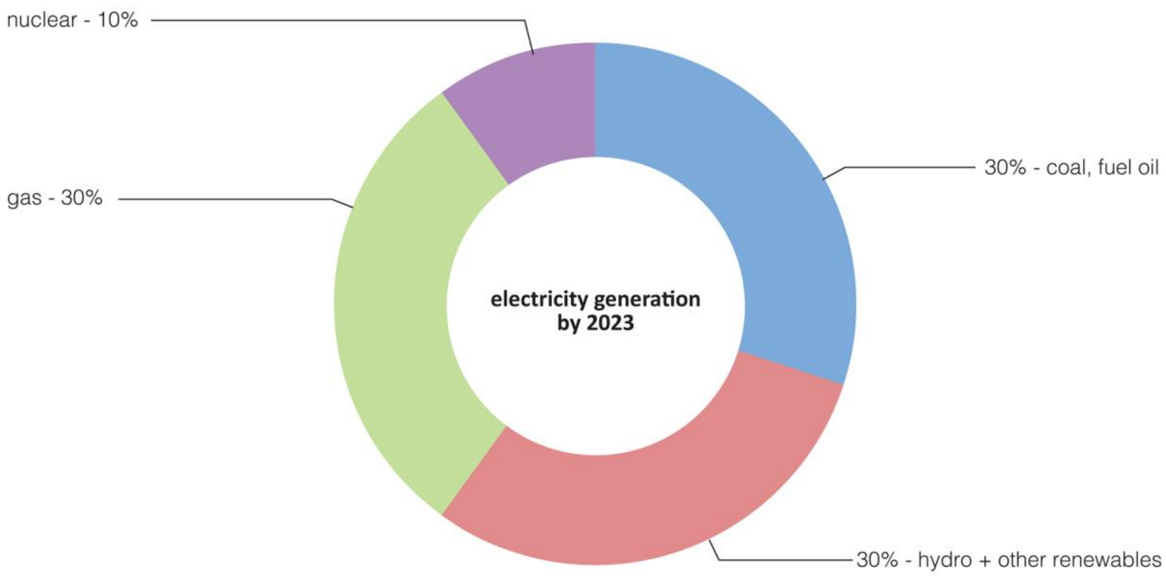

Figure 14 Planned Turkish electricity generation by 2023

6.1.12 Canada

Recent estimates suggest that the country has a total of 6.6 Gt of recoverable coal reserves. These encompass bituminous and **subbituminous coals** and **lignite**. More than 90% of coal deposits are located in western provinces – this provides a strategic advantage because of the close proximity of west coast ports (for coal exports). Coking coal is an important export commodity.

Canada has 24 major coal mines although subbituminous coal production is limited to Alberta, where nine mines are located. Canadian production capacity is ~76 Mt, split roughly evenly between coking and thermal coals. Subbituminous coal accounts for about 38% of Canada's coal production. As in other countries, its main use is for power generation – in 2013, 25.5 Mt was used in power plants (IEA, 2015a). Canada currently has 15 coal-fired plants comprising around 35 units. However, the country's coal consumption is falling as a result of environmental policies aimed at reducing greenhouse gas emissions. Furthermore, in some provinces, the present low price of natural gas is contributing towards a shift away from coal. Ontario was the largest consumer of coal in Canada but by April 2014, had stopped using coal for power generation. The availability and low cost continues to make coal the main fuel for electricity generation in Alberta, Saskatchewan, and Nova Scotia.

Subbituminous coal is used in a number of power plants – for example, Genesee 3 (Figure 15). Opened in 2005, this 450 MW plant was Canada's first coal-fired supercritical unit. It fires Albertan ROM subbituminous coal with a sulphur content of 0.2–0.3%, sourced from an adjacent opencast mine. The coal feed is of variable size and usually has a moisture content of ~20%. It is ground in vertical spindle roller mills. The plant's coal handling system was designed to accommodate coal particles of 0–38 mm in size, with moisture content up to 26 wt%.

Figure 15 The 450 MW Genesee 3 power plant in Canada, fired on Albertan subbituminous coal (photograph courtesy Capital Power)

6.1.13 Poland

Hard coal is Poland's most important mineral resource. Most is located in Upper Silesia and the Lublin coal basins – the former accounts for 93% of the total exploitable reserves. Poland is the ninth largest global hard coal producer and the largest in the EU, with estimated exploitable reserves of ~191 Gt. Indigenous coal is considered strategically important, particularly from an energy security perspective. The Polish government is supportive of the coal industry and envisages that it will remain a key source of energy for some considerable time. Currently, domestic coal is used to produce up to 90% of the country's electricity and heat.

The country also has significant deposits of **lignite**, located mainly in the basins surrounding the cities of Turoszow, Konin, and Bełchatów (Mills, 2010b). Total proved recoverable reserves are estimated to be 1287 Mt (WEC, 2013; BP, 2015). Government figures suggest a total of 1635 Mt of 'commercial reserves', most of which are considered exploitable. The largest lignite deposits are in Bełchatów and provide almost 60% of domestic lignite output. The Bełchatów basin incorporates two lignite fields, and the Bełchatów mine is expected to remain in operation until 2038. This supplies the 4.4 GW power plant of the same name that generates ~20% of Poland's electricity. Lignite is expected to play an important role in Poland's energy supply until at least 2030, with Polish mining maintaining a production output of at least 60 Mt/y (Euracoal, Poland country report, 2013). Lignite is also produced from the Turów deposit near Bogatynia, and from deposits in the Konin region (Pątnów, Lubstów and Adamów). Virtually all lignite is produced from large opencast mines. Further reserves exist in the areas around Legnica, Poznań, Łódź and Zielona Góra. These are not currently being exploited – the most likely future candidate is the latter area.

As elsewhere, the bulk of lignite production is used for power generation and/or cogeneration. Lignite is used in major power plants that include Adamów, Bełchatów, Konin, Pątnów and Turów. In 2013, total production was nearly 66 Mt, 99.7% of which was used in minemouth power plants. In that year, lignite-fired plants generated >32% of Poland's electricity (WEC Poland, 2014). The partially state-owned PGE Gornictwo i Energetyka Konwencjonalna Spolka Akcyjna (PGE) operates two lignite mines (Bełchatów and Turów) with an annual capacity of ~66–67 Mt, as well as a number of major power plants. The company has coal reserves of ~1 Gt.

Lignite is expected to continue making an important contribution to electricity generation in Poland. Hopes that the country would be able to produce significant amounts of shale gas have proved unfounded, and the focus has since shifted towards lignite. Poland needs some new generating capacity, and the Polish government and utilities, encouraged by firm popular support, are looking to domestic lignite reserves as a cheap way to fuel that new capacity and thus, reduce imports of Russian gas. The Economy Minister (noting that Poland has only limited reserves of gas and oil) stated that "lignite was the stabilising factor for Poland's energy safety" and that reserves would last for 200 to 300 years. Its role in the country's energy mix will be defined by new energy policy covering the period up to 2050, and will depend on the future of renewables and nuclear energy, as well as the development of new mines (Barteczko and Gloystein, 2013). However, government and industry sources expect lignite to remain important in Polish energy production for some considerable time.

Whereas output from hard coal-fired power plants has fallen in recent years, that from lignite-fired units has increased year-on-year. PGE, Poland's biggest utility, plans several new lignite projects including a power plant in Turów, with the lignite fields in Legnica as a potential fuel source. The low cost of lignite is a major factor – mid 2016 it cost ~6.5 zlotys (US$2.05) per GJ, whereas hard coal was 10–11 zlotys.

At a time when many European power companies are exploring possible options to reduce their investment in coal-fired generation, some of their Polish counterparts are moving in the opposite direction, with plans for significant investment to modernise existing lignite/hard coal-fired plants, or to build new, more efficient ones (Kureth, 2015). At least four new coal-fired power plants are expected to come on line by 2019. For example, a new €800 million 450 MW lignite-fired ultrasupercritical plant is currently under construction at the Turów site. Mitsubishi Hitachi Power Systems Europe (MHPSE) is building this (in cooperation with Polish company Budimex, and Técnicas Reunidas of Spain) for PGE. MHPSE is supplying the steam generator, flue gas cleaning equipment, piping, turbine/generator, instrumentation and control, and will also bring the plant into service. The new unit is due to be operational in 2019. It is expected that it will make a significant contribution to a dependable supply of power for the Polish economy (Ross, 2015).

6.1.14 Greece

Greek coal reserves comprise almost entirely **lignite**. This is abundant in several regions, with proved reserves of between 3.9 and 5 Gt (Mills, 2015). It is of strategic importance and used almost exclusively for power generation/cogeneration. The quality of most deposits is poor. However, productivity levels are high and extraction costs low – as a result, electricity is generated relatively inexpensively. Recent production has varied between 54 and 60 Mt/y. Greek lignite production ranks third within the EU after Germany and Poland, and sixth in the world. The use of indigenous lignite helps reduce significantly energy import requirements.

The state-owned Public Power Corporation (PPC) is Greece's largest power generator, electricity supplier and lignite producer. PPC's current power portfolio consists of conventional thermal, hydroelectric and other renewables-based power plants – combined, these make up approximately two thirds of Greek installed capacity. Seven major PPC lignite-fired power plants represent 24% of the country's total capacity and generate almost half of its electricity. Most lignite production comes from PPC's mines, the third largest producer in the EU. The company has significant operations in Western Macedonia and the Peloponnese region. There are also a small number of privately operated mines that produce a few million tonnes a year, some of which is supplied to PPC. In 2012, total Greek production was 61.9 Mt.

Greek lignites are characterised as low rank coals. Many have low CV and high ash and moisture levels. Depending on the source, characteristics can vary widely, both within and between different geographical regions. Even within individual seams, properties can differ significantly. As a result, the quality of mined lignite can vary considerably in all timescales. Moisture content can fall between 30% and 66%, ash content between 3.5% and 40%, sulphur content between 0.3% and 6.4%, and CV between <4 and 9.6 MJ/kg (LHV). As a general rule, lignites mined in the northern part of the country have higher calorific values and lower sulphur contents than those from the south.

In 2013, Greece was the 10th largest energy importer in the EU 28. Alongside oil and gas, lignite is also a major source of energy – it accounts for around a quarter of gross inland consumption. As a result, Greece is one of the EU member states most heavily dependent on solid fuels. The reliance on indigenous lignite helps counter some of the country's dependence on imported oil and gas. Its use reduces the level of imported energy and crucially, helps the national trade balance. For an annual lignite production of 50 Mt, Greece avoids the import of ~36 million barrels of oil. Based on a nominal price of 53 US$/bbl, the estimated saving is US$1.9 billion per year.

Although lignite production has been partly opened to private sector companies, PPC remains the largest producer (Figure 16). The company has a license corresponding to 63% of total exploitable lignite reserves. To date, ~5% of these have been leased to the private sector via long-term contracts. A further 23% have yet to be leased or conveyed.

Figure 16 Lignite mining at PPC's West Macedonia Southern Field (photograph courtesy of PPC)

Greek lignite is characterised by high productivity levels and can be mined cheaply. Estimates of production costs suggest figures of between 11 and 19 €/t. A study of 2014 undertaken for PPC determined that the average excavation cost of Greek lignite was the second lowest of the eight European lignite-producing countries considered. Of these, Greek lignite had the lowest CV but despite this, the cost of power generation using indigenous lignite was found to be the most competitive of the fossil fuels.

There are four main production centres. PPC has significant operations in Western Macedonia (Main Field, South Field, Kardia Field, Amynteon Field, and Florina), as well as in the Peloponnese region (the Megalopolis Field). In 2012, combined Greek production exceeded 62 Mt. However, in 2013, there was a fall in consumption to 53.8 Mt. This resulted from the decommissioning of old lignite-fired generating capacity, coupled with unexpectedly high input from renewable energy sources – these enjoyed favourable weather conditions during the period.

At the beginning of 2014, the Greek interconnected electricity system had a combined capacity of ~18 GW. This included ~5 GW of lignite-fired plants, 5 GW fired on natural gas, and 700 MW based on oil. Some 3 GW was based on large hydropower and 4.3 GW on other renewables. On the non-interconnected islands, the installed capacity comprised 1.78 GW of oil-fired generators plus 448 MW of renewables. Thus, the total national installed capacity was ~20.2 GW (61% thermal power plants, 15% large hydropower plants, and 24% other renewables).

Since 2010, the contribution of lignite-fired power plants has decreased from 52.1% to 48.1%. The input from gas-fired stations has fluctuated more widely. In 2014, PPC's lignite-fired plants generated 22.7 TWh of electricity; a further 2.8 TWh was imported – combined, this covered around two thirds of total demand. In 2014, gas-fired stations generated 48% of Greek electricity (total Greek generation of 53.5 TWh).

The Greek government had previously announced that in order to decrease energy imports, it would increase the country's use of lignite, particularly for power generation. However, the situation is now less clear. Recent announcements suggest that the focus may now shift more towards renewables. The possible privatisation of PPC and other parts of the energy sector will also impact on future developments. At the moment, only one new major lignite-fired power project (Ptolemais V) is under construction.

Summary

All three categories of low quality coal discussed are of major significance in a number of economies. In most cases, they provide a cost-effective source of energy, used mainly for power generation and/or cogeneration purposes. Each type brings its own combination of advantages and disadvantages. However, in a number of countries, such coals form the only indigenous bulk source of energy available. As such, they are important in providing a secure source of energy at an affordable price. They also reduce dependence on often expensive energy imports.

Lignite's main advantages are its low cost and high security of supply. Although production peaked in 1990 and global output has since fallen, this masks the fact that some countries rely heavily on their reserves of lignite, where they form a strategic asset used extensively for electricity generation. Despite environmental concerns, there are clear attractions and some (such as Turkey) plan to increase lignite output in the future. Because of its often high moisture content and low CV, there can be obvious drawbacks in transporting raw lignite over long distances. Hence, most is used close to its source. However, in Germany, for example, some is transported to distant end-users both within the country and in neighbouring states.

Around a third of the world's proven coal reserves comprise variants of **subbituminous coals**. They are used widely, mainly in power and/or cogeneration and heat plants. Around the world, as the quality of many higher grade sources of coal has declined progressively, there has been growing market acceptance for some types of subbituminous coals. Despite their lower CV, these are now traded internationally, finding ready markets particularly in parts of Asia. Possible new outlets continue to be explored.

Several major global economies rely heavily on **high-ash bituminous coal** for power generation and other industrial uses. Thus, in recent years, such bituminous coals have become of particular importance in the economies of India, China and South Africa. In India and China, most production is used within the country, whereas a significant proportion of South African output is washed and exported. Within these economies, the importance of this type of coal is not expected to diminish significantly in the foreseeable future although in some cases, greater volumes are likely to be cleaned in various ways prior to shipment or use.

7 Comparing the economic value of different coals

Historically, the main reason for switching power plant coal supplies has been based largely on economics – put simply, a lower quality coal generally costs less than one of higher quality. In a desire to quickly acquire alternative or multiple sources of coal, there has often been a tendency to focus almost exclusively on price, and the impact of switching to a lower quality coal on plant operations and the environmental consequences was frequently largely ignored. However, increasingly, other factors are being brought into the equation. For example, will the low quality coal have deleterious impacts on plant operation and maintenance, will there be a significant fall-off in plant efficiency, or will emissions to air increase significantly? Such issues can impact on power plants in a number of ways, both technical and economic. To be a viable option, the advantages accrued must outweigh the disadvantages.

Where the main motive remains cost saving, the full range of possible impacts needs consideration and the associated cost implications should be factored in. For example, a switch to a lower grade coal may result in SO_2 emissions increasing beyond permitted limits, triggering the need for installation and operation of an FGD unit. In addition, a coal with higher ash content will produce greater quantities of fly ash and bottom ash, both of which will require disposal or utilisation. All will entail additional costs – to make economic sense, these should not exceed the saving made from a lower coal buying-in price.

A common approach to coal buying has long been to identify a source that is technically acceptable, but at the lowest price (normally including delivery costs). The lowest priced coal as delivered to the power plant has often been the option selected. However, this is not necessarily the optimum solution – the preferred objective is not to select a coal simply because it is the cheapest, but to choose one that will generate electricity at the lowest cost. In an increasingly competitive marketplace, the full chain of converting coal energy into electricity needs consideration. There are several possible ways that this can be accomplished.

7.1 Value-in-use analysis (VIU)

Coal buyers are moving away from the sometimes overly-simplistic concept of basing plant economics solely on the energy content of a particular coal, opting increasingly to base their calculations on the cost per unit of electricity generated – this is sometimes referred to as 'value-in-use' or VIU analysis. VIU can be determined by modelling, simulating the performance of the coal in (for example) a modern supercritical power plant. The process measures the impact of coal properties on the utilisation performance of the particular coal and the subsequent effect on costs within the plant. These can be compared with those incurred by simulating the use of other coals in order to estimate their values relative to each other. Analysis suggests that the cost of electricity generated when using a low quality coal (compared with a low ash one of higher rank), the value-in-use price difference is greater than the *pro rata* difference based solely on energy content (Juniper, 2013).

When using VIU, costs (positive or negative) are assigned to each step that has the potential to impact on plant performance. By these means, it is possible to determine and optimise the overall cost of generation.

In many cases, most impacts related to coal quality can be assigned a cost - in some cases, absolute costs can be calculated, although estimates may be adopted for some aspects. Thus, by incorporating a range of factors other than simply the calorific value of the coal, VIU has the potential to allow reasonably accurate assessments to be made, such that the best value coal is selected (not necessarily the cheapest). Once environmental costs are fully factored in, the optimum strategy may be to pay more for a coal of better quality, whilst still keeping the cost of electricity at an acceptable level.

As already noted, coal quality impacts on boiler efficiency – for example, moisture content causes energy losses through the latent heat of evaporation required to dry the coal prior to combustion. In addition, poor combustion efficiency increases unburnt carbon-in-ash; if high enough, this may preclude utilisation of the ash. Furthermore, the use of a higher quality coal can help minimise environmental issues (such as emissions of particulates, SO_2, and CO_2). Thus, a plant operator must determine if a cheaper coal is actually the best from an environmental as well as economic perspective. For instance, VIU simulations determined that a modern SC power plant burning a low ash (10%) Australian coal would produce up to 75% (depending on the actual ash content) less particulate emissions than a low quality Chinese coal (containing ~25% ash and 30% moisture). Furthermore, boiler efficiency would be higher (~89% as opposed to ~84%).

The use of VIU on coal-fired technologies is not limited to power generation. It can also be applied to coal-based processes such as steel making. For example, switching from a 'standard' coal to a high volatile one with higher sulphur content can impact negatively for several reasons. Thus, if the new coal is introduced at the coking plant, it will decrease coke production. As a result, more external coke will be needed at the blast furnace. This will have a cost. Furthermore, the higher sulphur content in the coke will increase the level in the hot metal produced. As a result, a greater amount of flux will be required for desulphurisation – again, a cost is involved. These various additions will effectively increase the overall cost of the coal (N-SIDE, 2015). As with power generation, a lower quality coal, albeit with a lower buying-in price, may not necessarily lead to significant overall savings when all such steps are taken fully into account.

Value-in-use analysis is now offered commercially by a number of companies. It can involve the use of interactive databases that examine specific coals, and profile and model costs at major coal mines. Modelling is sometimes combined with coal testing and analysis, in order to fully assess a coal's physical handling, blending propensity, and other performance and behaviour characteristics – combined, these can provide a fuller picture of value-in-use. Many industry observers opine that for effective value-in-use analysis, a combination of both physical laboratory testing and simulation software is necessary.

7.2 Energy Return on Investment (EROI)

Another area that can influence decisions on coal choice is the *Energy Return on Investment* of a fuel. This is defined as the energy that has to be expended in order to produce a certain amount of energy. Put simply, it is the ratio of energy returned, to energy invested in that source, along its entire life cycle. Essentially, it is a matter of dividing the energy output by the energy input – a high EROI means a lot of energy is obtainable for minimal energy expenditure. Thus, a large number signifies that energy from that source is easy and cheap to obtain. When the number is small, the energy is more difficult and expensive to acquire.

EROI is a key determinant of the price of energy – sources that can be tapped relatively cheaply will allow the price to remain low. The ratio decreases when energy becomes scarcer and more difficult to extract or produce. EROI can be applied to all forms of energy production and can enable meaningful comparisons to be made between very different fuels – it has been particularly applied to fossil fuels.

There are a number of variants of EROI analysis. As is often the case when comparing energy sources, the outcome can be influenced by which factors are included in the calculations. These may not necessarily include the environmental costs of different energy sources, such as greenhouse gas emissions. For example, application of a carbon tax would make coal more expensive to burn by requiring the installation of carbon capture technology, making it less attractive from an economic perspective.

As noted earlier in this report, the overall quality of many sources of coal (such as in the USA, China and India) has been deteriorating for a number of years. Reserves of easily mined coals of better quality have become increasingly depleted, with production moving to those less accessible or of lower quality – extraction and processing is becoming more energy-intensive (for example, the increased necessity for washing). Thus, the EROI for many sources of coal has fallen. However, it can still compare well against some other forms of energy (Carbon Brief, 2013). For example, if power grids are unable to cope adequately with intermittent supplies from renewables, it makes such sources more expensive, potentially reducing their EROI (if thermal power plants are needed for back-up generation). Most renewable energy technologies have substantially lower EROI values than traditional conventional fossil fuels (Hall and others, 2014).

Although EROI is not the only factor that needs to be considered when selecting the most appropriate fuel, it highlights the fact that in general, increasing amounts of energy are required in order to meet demand as well as keep emissions down to manageable levels. In this respect, coal is similar to other fossil fuels in that many cheaper, better quality reserves have been exhausted. For instance, the EROI for Chinese and US coals is declining (Hall and others, 2014). Studies have shown that a decline in EROI of major fuels such as coal, oil and gas can have significant impacts on the performance of national economies.

8 Conclusions

Low quality/value coals are of huge importance, particularly to global electricity markets. Around half of the world's estimated recoverable reserves are made up of such coals, comprising mainly lignite, subbituminous and high ash bituminous coals. Although all have their respective drawbacks, they are of great significance in a number of economies and are used widely for electricity generation and heat production. In some cases, they comprise the country's only economically-viable bulk source of energy. As such, they are of strategic importance in that they provide a secure source of energy. Put simply, there may be few (if any) cost-effective alternatives at this time.

Low quality coals can be cleaned and upgraded in various ways so as to increase their energy content and improve other properties, enabling some to compete directly with coals of higher quality. Clearly, the benefits accrued by upgrading must not be outweighed by the increased processing costs. Such coals can be used successfully in many coal-based processes, including all main forms of clean coal technologies. In some cases, they can be used directly, whereas in others, a degree of pre-treatment is required. Some coals of these types are already used widely in a number of processes; others hold potential for the future.

In many parts of the world, there is an ongoing push towards the greater use of renewables such as wind and solar power. Although in day-to-day operation their environmental impact is minimal, invariably, output is intermittent and reliant on prevailing weather conditions. Consequently, back-up systems are required to take over when demand exceeds availability. This often takes the form of either nuclear and/or conventional thermal power. In some countries, coal power is being increasingly displaced by renewables. However, thermal power plants can still maintain an important role alongside renewables. In many cases, coal-fired generation remains the cheapest and most reliable option. Despite this, in countries such as Germany, a large segment of the coal/lignite-fired fleet (that has traditionally operated on base load) is slated for retirement or relegation to back-up duties. As elsewhere, a major driver is the quest to reduce the level of CO_2 emissions emanating from the sector. However, other governments are taking a different view and intend to increase reliance on indigenous coal. For example, Turkey already relies heavily on its lignite reserves for much of the electricity needed to power its thriving economy. Here, the main drivers are to reduce energy imports and attract private sector investment from both within and outside the country.

Within the EU as a whole, coal use in general is set to decline further. However, this masks the importance that it retains in some individual member states such as Bulgaria, Romania, Slovenia, Poland, the Czech Republic and Greece. Similarly, in the coming years, coal use in the USA seems likely to reduce further, although it will continue to make an important contribution for some time. This is particularly true for subbituminous coals from the Power River Basin. These may well fare better than some other US sources. PRB coals are crucially important for power generation – their low sulphur content and production cost gives them an edge over coals from elsewhere.

In contrast, for the foreseeable future, coal will continue to dominate the electricity sectors in the economies of India, China and South Africa. In India, recent years have witnessed a large increase in the amount of coal consumed. As the economy has burgeoned, consumption has increased year-on-year. However, although coal use is now higher than it has ever been, moves are underway to curtail its use and rein in associated environmental impacts. To contribute towards these goals, many of the new larger power plants are based on supercritical technology and are both cleaner and of greater efficiency than their predecessors. Furthermore, coal washing (to decrease the inherently high ash content of Indian coals) is also being actively promoted, and some smaller less efficient mines are likely to close. Such moves will help minimise impacts resulting from India's large increase in coal-fired generating capacity. Significant further capacity additions have been planned for the future and although a number have recently been cancelled, others are proceeding. Thus, it will be important for this momentum for coal washing to be maintained.

China has also seen a huge increase in the tonnage of coal burned each year. Like India, for some years, coal demand has increased dramatically. This peaked in 2014 although annual consumption is high and likely to remain so. Similar to India, a major push towards renewables is underway and efforts to minimise the environmental impact of coal-fired power generation are in hand. As part of this, legislation has been introduced to reduce the production and importation of some lower grades of coal (although, following a dip, imports have recently started to increase again). Alongside this, a growing proportion of the country's coal-fired power fleet comprises efficient modern plants that use supercritical or ultrasupercritical steam conditions. Increasingly, older coal-based generating capacity is being phased out in favour of newer technologies, increasing amounts of coal are being washed to reduce ash content, and a number of CCT and carbon capture projects are underway. These measures will help minimise the environmental impact of coal burning within the country. Despite the increased deployment of renewables and other technologies, coal will remain of vital importance for some considerable time.

High ash bituminous coal has also become of particular importance in the economies of India, China and South Africa. In India and China, most production is used within the country, whereas in South Africa, a significant proportion is washed and exported. Indigenous coal remains vital to the country's economy, generating most of its electricity and producing much-needed income from its export. The importance of this type of coal is not expected to diminish significantly in the foreseeable future although in some cases, greater volumes may be cleaned in various ways prior to shipment or use.

Although some major economies are currently pursuing policies designed to eliminate or at least reduce coal consumption, in many others, it will continue to be used as a provider of electricity. Despite environmental concerns, the growing demand for electricity (particularly from a number of developing economies) means that the three types of low quality coal/lignite examined in this report are expected to continue to be used in significant quantities for some considerable time. In some of the long-developed countries, coal use is in decline, whereas in a number of others, perhaps earlier in their respective development, there is a strong focus on the use of clean coal technologies (such as SC/USC technology coupled with state-of-the-art emission control systems). In some situations, economic considerations are likely to prevail - electricity produced by coal-fired plants is often the cheapest option. For various reasons, many such economies will need to rely on coals of lower quality. For example, major developments are proposed for exploiting large lignite deposits in the Thar coalfield in Pakistan, estimated to hold at least 175 Gt of resources. Power generation projects are now being developed aimed at capitalising on this. These would provide much-needed low cost electricity, boost economic activity in general and reduce energy import requirements. Potentially, considerable coal demand could develop from such new markets, effectively supplanting lost consumption elsewhere.

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