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BLENDED FIRING OF COAL AND LIGNITE

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SUSTAINABLE CARBON

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PREFACE

This report has been produced by the International Centre for Sustainable Carbon (ICSC) 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 organisations.

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The overall objective of the International Centre for Sustainable Carbon is to continue to provide our members, the International Energy Agency (IEA) Working Party on Fossil Energy and other interested parties with definitive and policy relevant independent information on how various carbon-based energy sources can continue to be part of a sustainable energy mix worldwide. The energy sources include, but are not limited to coal, biomass and organic waste materials. Our work is aligned with the UN Sustainable Development Goals (SDGs), which includes the need to address the climate targets as set out by the United Nations Framework Convention on Climate Change. We consider all aspects of solid carbon production, transport, processing and utilisation, within the rationale for balancing security of supply, affordability and environmental issues. These include efficiency improvements, lowering greenhouse and non-greenhouse gas emissions, reducing water stress, financial resourcing, market issues, technology development and deployment, ensuring poverty alleviation through universal access to electricity, sustainability, and social licence to operate. Our operating framework is designed to identify and publicise the best practice in every aspect of the carbon production and utilisation chain, so helping to significantly reduce any unwanted impacts on health, the environment and climate, to ensure the wellbeing of societies worldwide.

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ABSTRACT

Many emerging economies depend on coal for secure, affordable and reliable electricity generation and supply. Therefore, it is vital to ensure that coal is used efficiently with minimum environmental impacts. Firing indigenous lignite with high quality coals in countries like India, Pakistan and Bulgaria can help to cut the cost of energy generation and keep generating electricity at high efficiency and low emissions to provide energy at an affordable price. In general, coal quality is declining as reserves become depleted, so more lignite, subbituminous and high ash bituminous coals are being fired in power plants, which can create complications, such as slagging and fouling. The disadvantages of firing lignite may be reduced by blending it with higher quality coals. Conversely, adding some lignite to higher quality coals may be used to reduce fuel costs. This report summarises commonly used coal blending methods and where blending can be carried out at coal-fired power plants. Coal blending methods include stockpile, bin, belt and furnace blending and can happen onsite or offsite at a power plant. Some coal properties, such as proximate and ultimate analysis data and the heating value, remain additive after blending. The effect of some physical properties on blending, such as grindability, ash fusion temperature, swelling, and combustion characteristics, is harder to predict. The main issues related to firing lignite blends at power plants are blending ratio, boiler and mill performance, combustion characteristics, and ash deposition. Firing low ratio lignite blends (less than 15%) can be carried out without plant modification at coal-fired power plants. Case studies of firing lignite blends include examples from Bulgaria, China, India, Pakistan, and the USA. Firing lignite with coal can play a role in the achievement of some of the United Nations Sustainable Development Goals, particularly, Goal 7 affordable and clean energy, Goal 8 decent work and economic growth, Goal 9 industry innovation and infrastructure, Goal 12 sustainable consumption and production patterns, and Goal 13 climate action.

ACRONYMS AND ABBREVIATIONS

AB	Australian bituminous coal
AFT	ash fusion temperature
BGR	Federal Institute for Geosciences and Natural Resources, Germany
CEA	Central Electricity Authority, India
CFD	computational fluid dynamics
CPS	coal preparation systems (Maritsa East 2)
DTA	differential thermal analysis
DTF	drop tube furnace
DTG	derivative thermogravimetric
ESP	electrostatic precipitators
FC	fixed carbon
FGD	flue gas desulphurisation
GCV	gross calorific value
HGI	Hardgrove Grindability Index
HHV	higher heating value
ICSC	International Centre for Sustainable Carbon (formerly IEA Clean Coal Centre, IEACCC)
IEA	International Energy Agency
IL	Indonesian lignite
ITPCL	IL&FS Tamil Nadu Power Company Limited, India
LHV	lower heating value
NLC	Neyveli Lignite Corporation
PM	particulate matter
PRB	Powder River Basin
SCR	selective catalytic reduction
SDGs	Sustainable Development Goals, United Nations
SOFA	separate overfire air
TGA	thermogravimetric analysis
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
VM	volatile matter
WEO	World Energy Outlook
ZL	Zhundong lignite, China

UNITS

Bt	billion tonnes
Gt	gigatonne
IDR	Indonesian rupiah
kJ	kilojoule
kW	kilowatt
kWh	kilowatt-hour
kWth	kilowatt-thermal
MJ	megajoules
MJ/y	megajoules per year
MPa	megapascal
Mt	million tonnes
Mt/y	million tonnes per year
wt%	weight per cent

CHEMICALS

As	arsenic
Ca	calcium
CO	carbon monoxide
Fe	iron
HCN	hydrogen cyanide
H ₂ S	hydrogen sulphide
Mg	magnesium
Na	sodium
NH ₃	ammonia
NO	nitric oxide
NO _x	nitrogen oxides
S	sulphur
Se	selenium
Si	Silicon
SO ₂	sulphur dioxides
SO _x	sulphur oxides
SO ₃	sulphur trioxide

Note: all monetary values are in United States dollars (\$) unless otherwise stated.

CONTENTS

PREFACE	4
ABSTRACT	5
ACRONYMS AND ABBREVIATIONS	6
CONTENTS	8
LIST OF FIGURES	10
LIST OF TABLES	11
EXECUTIVE SUMMARY	12
1 INTRODUCTION	15
2 THE CHARACTERISTICS AND RESERVES OF DIFFERENT COAL RANKS	17
2.1 Coal ranks and their characteristics	17
2.2 Coal reserves and production	19
2.3 Comments	21
3 COAL BLENDING	22
3.1 Blending characteristics	22
3.2 Sampling and analysis	23
3.3 Blending methods	24
3.3.1 Stockpile blending	24
3.3.2 Bin blending	25
3.3.3 Belt blending	26
3.3.4 Boiler/furnace blending	26
3.4 Where blending can occur	27
3.4.1 Offsite blending	28
3.4.2 Onsite blending	28
3.5 Practice at power plants	31
3.6 Comments	31
4 FIRING LIGNITE BLENDS	33
4.1 Boiler and mill performance	33
4.2 Combustion characteristics	34
4.3 Lignite ratio	36
4.4 Ash deposition – slagging and fouling	37
4.5 Emission control impacts	41
4.5.1 Nitrogen oxides	41
4.5.2 Sulphur dioxide	43
4.5.3 Trace elements	44
4.5.4 Particulate matter	44
4.6 Plant modification	44
4.7 Comments	45
5 CASE STUDIES	46
5.1 Bulgaria	46
5.1.1 Maritsa East 2 power plant	46

5.2	China	49
5.2.1	Firing lignite at a 600 MW bituminous coal-fired plant	50
5.3	India	51
5.3.1	Cuddalore power plant	52
5.4	Pakistan	55
5.4.1	Coal-fired units at Jamshoro thermal power plant	56
5.5	USA	57
5.5.1	The Big Brown power plant	58
5.6	Turkey	60
5.7	Comments	60
6	SUSTAINABLE DEVELOPMENT GOALS	61
7	CONCLUSIONS	63
8	REFERENCES	65

LIST OF FIGURES

Figure 1	Top lignite-producing countries, 1980-2020	15
Figure 2	Coal classification	18
Figure 3	Impacts of coal characteristics in a pulverised coal power plant	18
Figure 4	Top ten countries by coal power generating capacity, January 2020	20
Figure 5	Tier blending	30
Figure 6	Computational fluid dynamics simulation of tier blending test	30
Figure 7	Effect of blending Australian bituminous (AB) and Zhundong lignite (ZL) coals at blend ash sintering temperature	39
Figure 8	Diagram of Bulgaria's Maritsa East 2 coal preparation system	48
Figure 9	Fuel-handling equipment upgrade at Big Brown power plant, USA – IntelliFlo® system (Image courtesy of: Power)	59
Figure 10	Fuel-handling equipment upgrade at Big Brown power plant, USA, to eliminate fuel build-up (Image courtesy of: Power)	59

LIST OF TABLES

Table 1	Selected US coal characteristics	19
Table 2	Top 10 lignite-producing countries, 2019	20
Table 3	Blending methods	27
Table 4	Tier blending test results	30
Table 5	Combustion characteristics of a lignite and bituminous coal blend	35
Table 6	Ash content of some lignites	37
Table 7	Ash fusion temperatures of blended coals in an oxidising atmosphere	40
Table 8	Characteristics of Maritsa East lignite and Pernik coal	47
Table 9	Test results of firing lignite blends at Maritsa East 2 power plant	49
Table 10	Coal characteristics for a 600 MW power plant	50
Table 11	Characteristics of coals fired at Cuddalore power plant, India	52
Table 12	Parameters of imported and blended coal at Cuddalore power plant, India	54
Table 13	Current emissions standards for coal-fired power plants in India	55
Table 14	Design coal characteristics for Jamshoro power plant, Pakistan	57
Table 15	Blended coal properties for Jamshoro power plant, Pakistan	57
Table 16	Lignite and PRB coal used at Big Brown power plant, USA	58

EXECUTIVE SUMMARY

Globally, coal supplies nearly 30% of energy consumption. Many emerging economies depend on coal for secure, affordable and reliable electricity generation and supply. Therefore, it is vital to ensure that coal is used efficiently with minimum environmental impact. Centuries of active coal extraction have resulted in depletion of reserves of higher grade coals. The result has been the firing of more lower quality coals and lignites in power plants, which can create complications. The disadvantages of firing lignite may be reduced by blending it with higher quality coals. Conversely, adding some lignite to higher quality coals may reduce fuel costs. Blending coals is one way to use the poorer fuel while maintaining output from coal-fired power plants. Firing indigenous lignite with high quality coals in countries such as India, Pakistan and Bulgaria can help to cut the cost of energy generation and keep generating electricity at high efficiency and low emissions to provide energy at an affordable price.

COAL PROPERTIES

There are four main ranks of coal, in order of quality: anthracite, bituminous, subbituminous, and lignite. The characteristics of low quality coal, especially lignite, may include: low calorific value; high moisture content; high ash content; low ash fusibility; high alkali/alkaline content; low volatile matter content; high sulphur content; high mercury and nitrogen content; and low Hardgrove Grindability Index (HGI).

The top three producers of lignite in 2019 were Germany (131 Mt/y), Turkey (7.3 Mt/y), and the Russian Federation (82.2 Mt/y). As it is not economic to transport over long distances, most lignite is used close to the source.

COAL BLENDING

Many power plants have blended coals to adjust the composition of the fuel and to provide a consistent feedstock for power generation. Other reasons to blend coal include: a shortage of high quality coal; the cost of the fuel; to alleviate coal transportation problems; to reduce fouling and slagging; and to lower emissions of pollutants.

Coal blending is a physical process designed largely to impact fuel chemistry. Blending can be achieved at any point in the supply chain from coal mine to boiler, onsite or offsite to a power plant. Blending offsite at the coal mine, preparation plant, or transshipment point, can save capital investment for the power plant and the blend is handled as a single coal at the power plant. Blending onsite at the power plant yard or in the boiler provides flexibility to adjust the blend according to the characteristics of the coal. This approach can be cost-intensive and requires large amounts of space at the power plant. Blending methods include stockpile, bin, belt and furnace blending.

Some coal properties, such as proximate and ultimate analysis data and the heating value, remain additive after blending. The effects of some physical properties on blending, such as grindability, ash fusion temperature, swelling, and combustion characteristics, are harder to predict. The main issues related to firing lignite blends at power plants are the blending ratio, boiler and mill performance, combustion characteristics, and ash deposition.

Coal characterisation data can be coupled with pilot plant studies to formulate optimum blend ratios and design boilers' efficiency for blended coal firing. In theory, blending is a straightforward process. In practice, the process can be more challenging due to the vast amount of coal that has to be handled physically and the complexity of coal characteristics. The coal blend received at the power plant may not be the same as expected. Power plant operators' experience plays a large part in successful coal blending.

The blending ratio is important for ensuring the safe operation of a power plant and to improve emissions control. Firing low ratio lignite blends (less than 15%) can be carried out without plant modification at coal-fired power plants. When the blending ratio is greater than 15% or the volatile matter difference of the coals is greater than 15%, laboratory tests and field trials must be carried out first. To fire a high ratio coal blend, modifications to the boiler or burners may be needed. Many plants need to modify their coal handling system to accommodate onsite out-furnace blending processes.

COMBUSTION

Reactions taking place in the combustion zone become more complex when coals of different ranks are blended or cofired. Although blending lignite with higher rank coal can improve combustion behaviour, decrease gaseous pollutant emissions, and mitigate some operational problems, it does not always reduce issues with grinding, flame stability, heat absorption balance, ash deposition, and so on. A blended product that closely resembles the design coal specifications may not burn in the same way as single coals. Interactions can occur between the component coals, which may or may not be beneficial. Thus, the compatibility of the coals concerning their combustion performances should be evaluated. Generally, low rank coal influences the ignition temperature of a coal blend, whereas high rank coal influences the burnout temperature. The blending ratio plays a vital role in firing lignite blends. Blending less than 10% lignite into bituminous coal has almost no impact on the boiler and combustion efficiency, and vice versa. The effects of blending on emissions control are hard to predict due to the complex chemical contents of coals. Apart from sulphur and nitrogen contents, some coals have higher oxygen contents, which may contribute to the formation of oxides. Local combustion conditions and furnace operating conditions have impacts on the emission of NO_x, SO_x, trace elements, and particulate matter.

Lignite-fired plants may choose to blend in higher quality coals to improve combustion efficiency and to reduce slagging and fouling and other difficulties. Conversely, at bituminous coal-fired power plants lignite may be blended to reduce fuel costs and reduce emissions of SO₂ and NO_x.

For developing countries, such as Pakistan and India where lignite resources are abundant and energy demand is growing rapidly, utilising indigenous lignite can also help create jobs and contribute to the local economy. In poorer countries with large lignite resources, a growing energy demand and a need to improve air quality cheaply and easily, the blending of lignite and coal is one way to provide cleaner energy to support rapid economic development and a growing population.

1 INTRODUCTION

Coal remains vital as it supplies nearly 30% of global energy consumption and plays a crucial role in industries such as iron and steel. Its demand is on course to rise 4.5% in 2021 pushing global coal demand above 2019 levels, when total production was 7921 million tonnes (Mt). The majority was steam (thermal) coal at 6175 Mt and 739 Mt of lignite was produced (IEA, 2019, 2020a,b). More than 80% of the growth is concentrated in Asia. As the largest user of coal, China alone is projected to account for over 50% of global growth (IEA, 2021a).

Centuries of active coal extraction have resulted in depletion of the reserves of higher grade coals so that many coal-producing countries have witnessed a steady decline in the quality of their coal. Particularly in those with a long history of coal mining, reserves of better quality coals have diminished. Coal quality is also declining in some developing countries. The result has been a shift towards the greater use of coals with lower heating values or other undesirable properties, such as high ash contents. Lignites with high ash and moisture contents and attendant low calorific values, as well as their high propensity for spontaneous combustion, are an important example. Due to their ease of extraction and low cost, the use of lignites for power generation is increasing despite the disadvantages of a tendency to cause slagging and fouling and reduce power generation efficiency. The major lignite producers in order of scale of production (2019) are Germany, Turkey, Russia, Poland, the USA, Australia, India, and Greece (*see Figure 1*). The importance of low quality coals has been addressed at the International Centre for Sustainable Carbon (ICSC) by Mills (2011, 2016). Lignite upgrading and utilisation have also been reviewed extensively by the ICSC (Dong, 2011, 2014; Reid, 2016; Zhu, 2012).

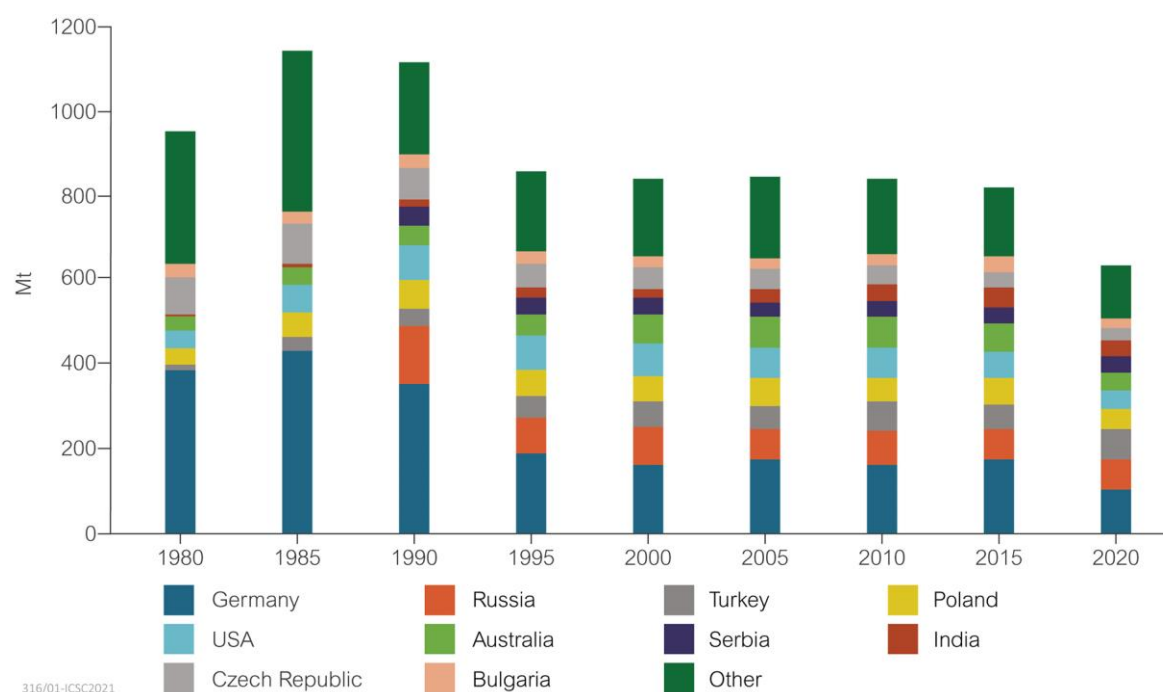


Figure 1 Top lignite-producing countries, 1980-2020 (author's estimates based on IEA, 2021b)

One way to utilise low quality coals such as lignite for power generation is to blend them with higher quality coals. Coal blending mixes the most available coals and/or the cheapest coals with higher quality coals to form a new fuel mix that can be fired without causing damage to the power plant. Most power utilities have defined coal specifications that are dependent on the design of their boilers and flue gas clean-up systems, operating and maintenance philosophy and the environmental requirements in their local area. Power station operators focus on minimising the cost of sent out power from their facilities while meeting all applicable regulations. This requires them to adjust the blend taking into account the purchase cost of the coal and the coal's properties that impact generation operating costs and waste disposal costs. As a result, power station operators rarely burn a single coal. More typically two to three coals are blended prior to combustion. The motivation is to reduce costs whilst still achieving boiler output (Morris, 2021).

Most coals can be blended but not all. Coal blending techniques have been covered in ICSC reports by Carpenter (1995, 1998) and Sloss (2012). Blending is designed to meet certain overall objectives, such as economic, environmental, and technical requirements for a power plant. It is becoming more common for plants to have to consider accepting coals that do not match the characteristics for which they were originally designed to enhance fuel flexibility and control the mineral content of the coal. Since coal characteristics affect almost every area of plant performance and operation, it is necessary to predict, as closely as possible, the physical and economic challenges that will arise when switching coals.

This report reviews the incorporation of higher quality coals with lignites to improve their ease of utilisation and also the blending of lignites with higher quality coals to reduce fuel costs. Following this introduction, Chapter 2 gives a brief description of the different coal ranks and their characteristics. The global reserves, production, and consumption of coal, especially lignite, are also reviewed. Chapter 3 summarises coal blending methods that are commonly used at coal-fired power plants and where the blending can occur. It covers those characteristics which can contribute to coal blending. Issues related to firing lignite and coal blends at power plants are studied in Chapter 4, including combustion, ash deposition, and emissions control. Coal gasification and coking can also benefit from lignite and coal blending but are outside the scope of this report. Case studies from selected countries around the world are presented in Chapter 5. Chapter 6 discusses how firing lignite and coal blends can contribute to achieving some of the United Nations Sustainable Development Goals (SDGs).

2 THE CHARACTERISTICS AND RESERVES OF DIFFERENT COAL RANKS

This chapter provides the basic concepts of different coals and their characteristics with a focus on lignite. Coal reserves and production data are analysed. This information is to help understand why power plants choose to fire lignite blends and how best to fire these blends.

2.1 COAL RANKS AND THEIR CHARACTERISTICS

Coal classification and categorisation systems vary in detail around the world but are comparable in where they place the different qualities (see Figure 2) and are discussed in an ICSC report by Chapman (2021, in draft). Detailed descriptions of these systems can also be found in earlier ICSC reports (Carpenter, 1988; Mills, 2011, 2016). Based on the degree of coalification (metamorphism), coal is usually divided into four main ranks: anthracite, bituminous, subbituminous, and lignite. Lignite and subbituminous coals are often referred to as low in rank (in the early stages of coalification), while bituminous coals and anthracites are classified as high rank coals. With the increase of rank, carbon content increases and the moisture content and volatile matter (VM) decrease. The quality of coal depends on its rank and the geographical location where the coal has formed. The term ‘low quality’ or ‘low grade’ refers to a coal that possesses one or more of the following troublesome properties which means that its use in coal boilers, gasifiers or other equipment may cause low efficiency or operational difficulties:

- low calorific value;
- high moisture content, which also translates into low calorific value;
- high ash content, related to ash problems and low calorific value;
- low ash fusibility, having high fouling potential;
- high alkali/alkaline content, having high potential for fouling and/or slagging;
- low VM content, related to ignition difficulty and flame stability;
- high sulphur content, implying high emissions of sulphur oxides (SO_x) and pollutant control costs;
- high mercury and nitrogen content, with consequent emissions;
- low Hardgrove Grindability Index (HGI), implying high power consumption for milling and increased mill wear and hence maintenance costs (Mills, 2016).

Many of these properties apply to lignites.

Coal types and peat			Total water content, %	Energy content af*, kJ/kg	Volatiles daf**, %	Vitrinite reflection in oil, %
UNECE	USA (ASTM)	Germany (DIN)				
Peat	Peat	Torf				
Ortho-lignite	Lignite	Weichbraunkohle	75	6,700		
Meta-lignite		Mattbraunkohle	35	16,500		0.3
Subbituminous coal	Subbituminous coal	Glanzbraunkohle	25	19,000		0.45
Bituminous Coal	High volatile bituminous coal	Flammkohle	10	25,000	45	0.65
		Gasflammkohle			40	0.75
		Gaskohle				
	Medium volatile bituminous coal	Fettkohle			35	1.0
	Low volatile bituminous coal	Eßkohle			28	1.2
					19	1.6
Anthracite	Semi-anthracite	Magerkohle			14	1.9
	Anthracite	Anthrazit	3	36,000	10	2.2

* af = ash free UNECE: Ortho-lignite up to 15,000 kJ/kg USA: Lignite up to 19,300 kJ/kg
 ** daf = dry, ash-free Meta-lignite up to 20,000 kJ/kg
 Subbituminous coal up to 24,000 kJ/kg
 Bituminous coal up to 2% average vitrinite reflection

Figure 2 Coal classification (BGR, 2011)

The rank and geographical location of coal have an important bearing on the fuel's physical and chemical properties. Even for the same coal rank from the same region, coal properties vary between different mines and seams. As listed above, in a power plant, coal characteristics can affect coal pulverisation, ignition and combustion of coal particles, ash behaviour, erosion of the refractory lining, formation of pollutants and their emissions, and the overall boiler availability and efficiency (see Figure 3). Of the many coal characteristics, moisture, volatile matter, fixed carbon (FC), ash and heating values, including higher heating value (HHV) and lower heating value (LHV), are the most important to plant operation.

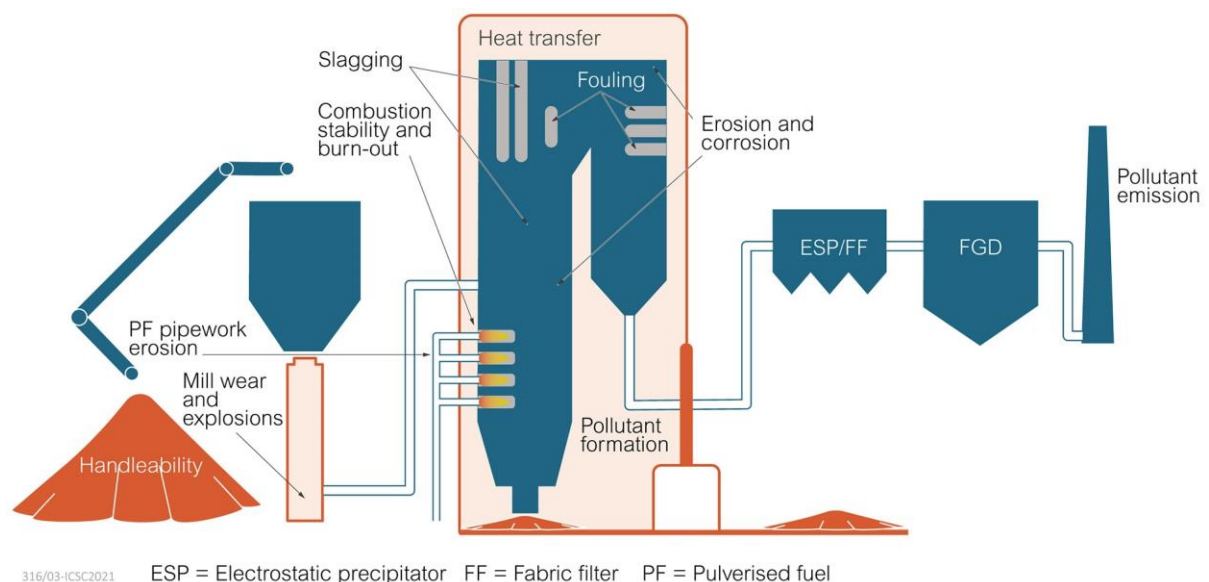


Figure 3 Impacts of coal characteristics in a pulverised coal power plant (Raaj and others, 2016)

Based on selected American coals, Table 1 gives a basic idea of the different characteristics across the four ranks. In general, compared to other coal, lignite has a high moisture and ash content, and a low calorific value and fixed carbon content. Some lignite can have a moisture content of up to 70% and an ash content of 20%. Lignite is also susceptible to spontaneous combustion. The undesirable characteristics of lignite have strong implications for its use in coal-fired power plants.

TABLE 1 SELECTED US COAL CHARACTERISTICS (MILLER, 2017)				
Weight per cent (wt%), as-received	Anthracite	Bituminous	Subbituminous	Lignite
Fixed carbon	65–84	41–70	35–45	12–23
Ash content	6–25	4–18	5–7	6–15
Volatile matter	3.9–12	16–42	32–38	37–44
Moisture content	0.8–3	1–11	11–26	28–33
HHV, MJ/kg	25–33	28–35	20–30	23–26

In Europe, brown coal includes subbituminous coals and lignite (Australian Government, 2014).

2.2 COAL RESERVES AND PRODUCTION

The importance of low quality coals has emerged in recent years as around half of the world's estimated recoverable coal reserves are of low quality or value. These comprise predominantly subbituminous and high ash bituminous coals, and various grades of lignite (Mills, 2016). According to the Federal Institute for Geosciences and Natural Resources (BGR) of Germany, confirmed coal reserves worldwide at the end of 2018 totalled 1070 gigatonnes (Gt), split between 749 Gt hard coal (with an energy content of ≥ 16.5 MJ/kg, including anthracite, bituminous, and subbituminous) and 320 Gt lignite (with an energy content of < 16.5 MJ/kg). Coal resources are coals with a reasonable prospect of eventual economic extraction while coal reserves are the economically mineable part of a measured or indicated resource. Thus, coal resources worldwide are many times higher than coal reserves (Chapman, 2021, in draft). Global total resources of hard coal were 16,190 Gt, whilst the global resources of lignite were 3672 Gt (BRG, 2020). For a discussion of the value of these figures, see Chapman (2021, in draft). The IEA (2020a) calculated world total coal production in 2019 as 7921 Mt, comprising 97 Mt anthracite, 5213 Mt bituminous coal, 865 Mt subbituminous coal, and 739 Mt lignite. The remaining 1007 Mt was coking coal. These figures show that lignite accounts for 30% of total coal reserves but less than 10% of total coal production in 2019.

The top ten lignite producing countries in 2019 are listed in Table 2 and the top ten countries by installed capacity of coal power plants (as of January 2020) are shown in

Figure 4. Of these, Germany, Russia, Poland, the USA, and India are in both groups. India and Poland still heavily rely on coal to generate electricity and will continue to do so for the foreseeable future.

As the largest consumer of coal, China does not produce a vast amount of lignite, but imports it from Indonesia for power generation due to its low cost. In 2005, Zhundong coalfield in Xinjiang province, with reserves of 39 Gt lignite was explored. Although a low rank, Zhundong lignite (ZL) is regarded as a high quality coal for power generation as it has a high volatile matter content but is low in ash and sulphur. International trading of lignite was non-existent in the early 2010s. However, in 2019, imports reached 6 Mt and 17 Mt were exported globally (Mills, 2011; IEA, 2020a). Lignite is being burnt widely, but is better used locally or within a short distance of the mine as its high moisture content and propensity to combust spontaneously make transport difficult.

TABLE 2 TOP 10 LIGNITE PRODUCING COUNTRIES, 2019 (BARUYA, 2021)

Country	Production, Mt
Germany	131.3
Turkey	87.3
Russian Federation	82.2
Poland	50.3
USA	48.1
India	44.1
Australia	43.3
Serbia	39.1
Czechia (Czech Republic)	37.5
Bulgaria	28.0

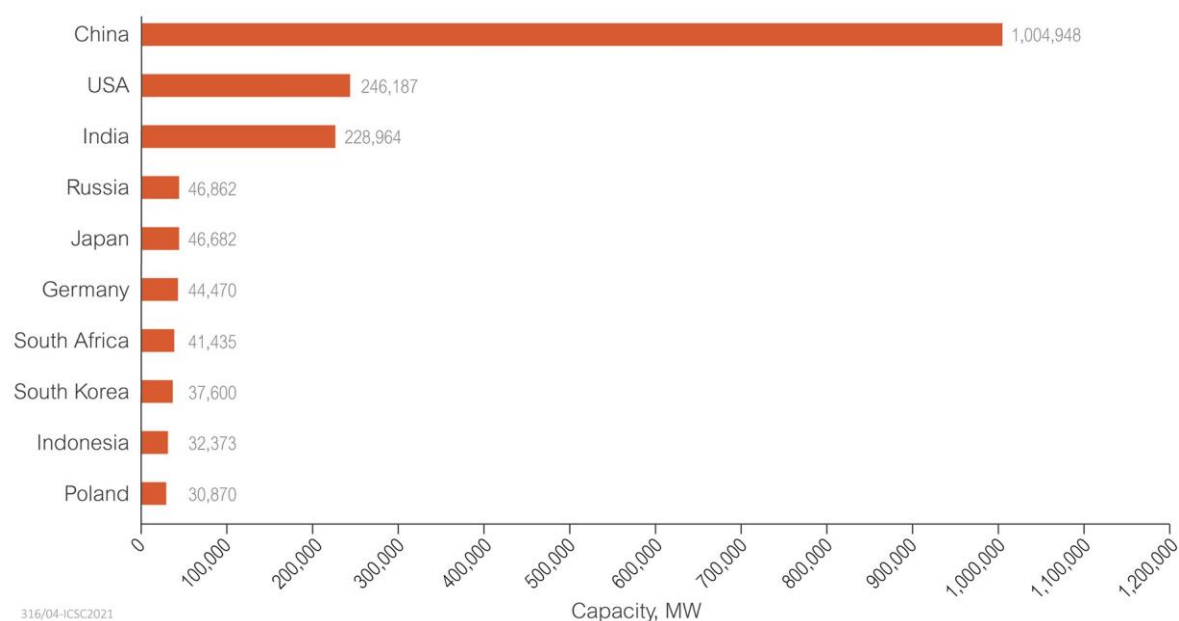


Figure 4 Top ten countries by coal power generating capacity, January 2020 (Statista, 2020)

2.3 COMMENTS

Generally, subbituminous and lignite are categorised as low rank and low quality/grade coals while anthracite and most bituminous coals are high rank and good quality. Lignite is the lowest rank coal. Its low energy density and high moisture content make it less favourable for power generation. Lignite is low cost but is not economical to transport far so is usually used close to the source.

3 COAL BLENDING

The boiler in a coal-fired power plant is designed for a particular coal specification, with defined variability limits to combust a certain type of coal. Over time, the source of coals within the necessary quality range may become less readily available or more expensive, forcing the plant operators to consider switching to firing coals of qualities outside the design range. Consequently, it is likely that, globally, at least 20% of power plants, and probably significantly more, cannot achieve their design output due to difficulties in sourcing coals that consistently meet the requirements of the boiler (Omar and others, 2017). The power plant has to either modify the boiler to accommodate the new fuel or to adjust the fuel composition to meet the boiler specifications or minimise the boiler modification or both. Many power plants have blended coals to adjust the composition of the fuel and to provide a consistent feedstock for power generation or for other requirements. Other reasons to blend coal include: a shortage of high quality coal; the cost of the fuel; to alleviate coal transportation problems; to reduce fouling and slagging; and to lower emissions of pollutants. However, the behaviour of blended coal is not additive to that of the parent coals. Additive properties are those which can be mathematically predicted from the properties of the component coals. Hence, a thorough understanding of the blended coal must be obtained before using it in power plants. Blending coal to meet power plant requirements has been reviewed comprehensively by Sloss (2014) for the ICSC. This chapter outlines the main procedures for coal blending to provide a foundation for understanding firing lignite blends.

3.1 BLENDING CHARACTERISTICS

Coal blending is a physical process designed largely to impact fuel chemistry. Some properties associated with coal blending are additive, such as the proportionally weighted average value of the coals within the blend, the chemical properties, moisture content, ash content, volatile matter, fixed carbon, and calorific value (Saravanan, 2014; Sloss, 2014).

In practice, predicting the properties of a coal blend is more complicated than simple mathematical calculations. If the sizes of the different coals are significantly different, blending leads to ‘stockpile drainage’, which reduces the moisture content of the blend from the predicted value. The finest fraction contains lower volatiles than the coarse fraction in the mixture of hard and soft coals. The ash content of coal blends determined by the standard test methods can be higher than the ash values calculated from the individual coals, particularly for blends between coals of widely differing ranks, for example, when blending lignite or subbituminous coals with bituminous coals. The higher than predicted ash values are due to the increase of sulphate in the ash from sulphur oxides trapped by the alkaline minerals in the lower rank coals. Carbon, hydrogen, nitrogen, sulphur, and oxygen contents are generally additive. The calorific value mostly depends on the carbon content present in the coal

and alters with the contents of moisture and ash. The calorific value is generally found to be additive as it is a quantitative parameter (Saravanan, 2014).

While blending is performed principally to modify the fuel chemistry, the physical properties of the blend cannot be ignored in designing an ideal coal mix. These properties cannot be predicted from the properties of the component coals and are non-additive so they do not provide a sufficient basis for predicting blend performance. Physical properties include grindability, evaluated by the Hardgrove Grindability Index (HGI), ash fusion temperature (AFT), combustion reactivity, and swelling characteristics. When introducing two coals to a mill, the pulveriser will grind the softer (higher HGI) coal more completely than the harder coal, resulting in disproportionate particle sizes. Coal particle size and drying level are also taken into consideration when blending coal. The fluxing action of iron and smaller molecules such as sodium (Na), calcium (Ca), and magnesium (Mg) from one coal may influence the other coal to decrease the fusion temperature. Studies on blending subbituminous coals with bituminous coals indicate greater fouling characteristics than those of the component coals (Saravanan, 2014; Sloss, 2014).

The complication of non-additive characteristics for coal blending can be shown further using HGI as an example. As grindability is non-additive, there is no general method for predicting the HGI of a coal blend, hence, it must be determined experimentally on a case-by-case basis. This makes it difficult to set the grindability specification of the coals to be blended and leads to the problem of selective grinding of coals and impacts the mill output. High moisture content in coal facilitates grinding and yields higher HGI values. The HGI of the coals to be blended must be in a narrow range to overcome this issue of preferential grinding. For equal tonnage of coal processed, coals with lower HGI values require higher power and mill capacity than coals with a higher HGI and also produce fewer fine particles during pulverisation. Interestingly, a study on blending Pakistani indigenous lignite and coal in various proportions shows that HGI values of the blends appear to be the proportionally averaged HGI values of the parent coals from which the blends were made. But the coals studied all had a relatively low moisture content, including Lakhra lignite with a moisture content of 23%. At power plants, the operator often tries to understand what the HGI test reveals rather than the actual test results (Hatt, 2020; Saravanan, 2014; Shahzad and others, 2014).

3.2 SAMPLING AND ANALYSIS

Both additive and non-additive features need to be analysed to address combustion efficiency, carbon loss, fouling and slagging, and emissions of nitrogen oxides (NO_x), SO_x and particulate matter. Adequate sampling and analysis are needed to ensure that the characteristics of the blended coal meet the requirements of the power plant. Although coal is highly heterogeneous in nature, several advanced analytical techniques are available for its characterisation. Coal sampling and analysis were the subject of a previous ICSC report (Zhu, 2014). The report describes standard procedures for coal sampling, preparation and routine tests of coal specified in the international standards.

The International Standards Organisation (ISO) provides guidelines on coal sampling and analysis. ISO standard sets, *ISO 13909-1-8:2016 Hard coal and coke - Mechanical sampling*, describe sampling coal from moving streams and stationary lots, and sample preparation and testing, but the set does not include the sampling of brown coal and lignite (ISO, 2016). *ISO 18283:2006 Hard coal and coke - Manual sampling* specifies procedures and requirements for establishing a manual sampling scheme, the methods, sampling equipment, sample preparation, handling and storage and a sampling report. Again, it does not include the sampling of brown coal and lignite (ISO, 2006). This standard is currently under review (2021). The draft was out in November 2020 for public comment. The updated standard covers the sampling of brown coals and lignites. Guidelines for manual sampling in stationary situations are given in Annex B (BSI, 2020).

Thermogravimetric and scanning calorimetry is used for coal analysis. Online sampling and analysis tools, such as Thermo Scientific™ CQM FLEX Analyzer and AllScan® on a belt elemental gauge, are available to provide real-time and instant measurements of the quality of a coal blend (Real Time Instruments, 2020; ThermoFisher, 2020).

3.3 BLENDING METHODS

Blending coal is more complicated than just mixing two or more coals together. Coal mixing is often defined as randomly putting different coals into a pile, so individual components can still be located within a small quantity in the 'mixed' pile. Coal blending is defined as integrating several coals with different physical or chemical properties to create a required specification or blend in which the elements are evenly distributed and no large pockets of one type can be identified (Hatt, 2020a, b). It requires the selection of a blending process and then monitoring it. A coal blending operation can create some homogenisation. Coal homogenisation refers to the process of mixing coal to reduce the variance of a single coal or a coal blend to ensure constancy of the fuel characteristics with even quality and/or size distribution. The coal homogenisation process is performed during the coal stockpiling operation by layering coal onto feeding conveyors and setting up a series of homogenised stockpiles. This process has a low production rate and is expensive at a large scale, hence it is not always included as part of coal blending at many coal-fired power plants (Begić and others, 2003; Saravanan, 2014; Sloss, 2014). Earlier reports from the ICSC (Carpenter, 1995, 1999; Sloss, 2014) describe these techniques in detail. The following section reviews some blending methods which are commonly used in coal-fired power plants (Carpenter, 1995, 1999; Rajdeva, 2014; Saravanan, 2014; Sloss, 2014).

3.3.1 Stockpile blending

Stockpile blending which involves placing different coals into one single pile is the simplest and cheapest method of coal blending. Layers of the coals are stacked in a pile in the proportions required to give the desired composition of the blend when the pile is reclaimed. Sometimes, different coals are stacked in separate stockpiles, and then predetermined amounts for the blend are withdrawn from

each pile using a loader. Common stockpile blending methods include strata, skewed chevron, chevron, windrow and chevron-windrow. Some degree of particle segregation occurs in all stockpiles. Windrow and chevron-windrow methods have less segregation and are considered more efficient than the other methods.

ABB has a stockyard management system which claims to enable the fully automated operation and control of coal-fired power plant stockyards (ABB, 2021). This could be beneficial for lignite stock management and blending. The ABB Ability™ Stockyard Management System provides real time information of handled material, enables real live adjustment of the data and provides support for operators to improve overall performance. It is a configurable system that can be used to digitalise the complete material handling chain, acting as its digital twin. The material flow can be modelled across all belt conveyors and transportation equipment with material properties and quality information via automated data interfaces. The data can be used for operational optimisation, such as efficient space utilisation in a yard, better planning and scheduling, or more accurate mixing and blending processes. The system has been used at the Schleenhain lignite mine in Germany which supplies the Lippendorf (2 x 993 MWe) power plant. The stockyard system comprises of a stacker (4200 t/h) with tripper car, two portal scrapers (2 x 2400 t/h) and the conveyor system, which includes the conveyors from the mine and to the power plant. The piles have a capacity of 400,000 t. The stockyard system as well as the belt conveyor systems are fully automatic and have been in operation since 1999 but have recently been upgraded to the latest technology (2021). ABB conclude that their experience shows that an integrated fully automated stockyard system can contribute to a safe and efficient coal supply for modern power plants. ABB identified the challenges of inputs of various coal qualities combined with the hard quality requirements from the customers for their coal-fired power plant and the need to manage a high process capacity. ABB provided: a control station with complete connection to the Schleenhain mine; a material tracking feature for quality management; manless operation for stacker and reclaimers; different stacking methods and various other features.

3.3.2 Bin blending

A blend can be created using silos or bunkers; both are often referred to as bins. Bins can be used to hold pre-blended coals or as part of the blending process, called bin blending. In the bins, the coals to be blended are added in the required ratio. Batches of different coals are added sequentially to the bin. A series of bins are loaded with different coals and fed to a conveyor running under the bins. The central part of coal falls out first, then coal in the ‘dead’ zone falls, which means that bins do not always follow the first-in-first-out concept. Flow models are used to identify active and dead zones and track the flow of coals.

There are various online blending systems available. The Accutrack system, from the Engineering Consultants Group, has been installed in several coal-fired power plants in the USA that have used a blend of PRB coal with eastern bituminous coals, and could be used for blending lignite. The Accutrack

online coal analysers measure the coal quality variables which are tracked through the bunker coal flow model. This allows precision blending of fuels and information as to the exact location of the fuel with respect to the boiler (AccuTrack, 2021).

3.3.3 Belt blending

Blending can also be achieved on a moving belt, referred to as belt blending. One type of belt blending involves putting different coals in different stockpiles and reclaiming them separately, then combining them on moving belt conveyors. The other type is that one coal is reclaimed from the yard and the other coal is fed directly from the transporting track hopper/wagon tipper. Both coals are dropped onto the belt. The coals are from separate bins and blended by discharging them to the variable speed feeders. The desired blending ratio is controlled by controlling the speeds of separate feeders that pass the coal onto a conveyor, and then to the raw coal bunkers. Conveyors should have an accurate weighing facility and speed control system which will give a precise mass flow rate. Multi-weighing scales are often used to get more reliable data.

3.3.4 Boiler/furnace blending

Coals can be pulverised separately and mixed in the boiler during combustion, often known as boiler/furnace blending (*see* Section 3.4.2). In this blending method, each coal is injected into the boiler from a separate burner with no prior mixing. This method is not popular in power plants because of the difficulties of transporting and distributing two coals separately to the coal bunkers.

Blending methods often used in coal-fired power plants are summarised in Table 3 with their advantages and disadvantages.

TABLE 3 BLENDING METHODS (RAJDEVA, 2014; SLOSS, 2014; THAKUR, 2014)

Method	Description	Location	Advantages	Disadvantages
Beds/stockpiles	Stacking of two or more coals in layers in yard	Blending during reclaiming on the conveyor belt Homogenisation at transfer point	Only one system required for bunkering coal Relatively inexpensive	Entire quantity of coal must be stacked before blending Increases coal handling and duration. May lead to spontaneous combustion and ignition of coal Not possible to change the blending ratio Not suitable for low blending ratio
Silos	Coal in one silo is dropped onto a conveyor below carrying a second coal	On the conveyor belt below silo Homogenisation at transfer point	Accurate blending ratio Ratio can be varied	High capital cost Central part of coal out first then 'dead' zone falls down
Ground hopper or emergency reclaim hopper	First coal is bulldozed into the hopper. Second coal is added via wagon tippler or track hopper	At common transfer point Homogenisation at transfer point	Ground hopper is an additional source for reclaiming. Ratio is controlled through belt feeder speed	Feeding rate is not accurate
Blending on moving belt 1	Two types of coal are stacked in two yards and gathered by separate stacker/reclaimer	At common transfer point Homogenisation at transfer point	Blending ratio can be changed at any time	All coal must be stacked first in stockyard More running hours
Blending on moving belt 2	One coal is reclaimed from the coal yard and the other coal is fed directly from the track hopper/wagon tippler	At common transfer point Homogenisation at transfer point and bunkers	Blending ratio can be changed at any time Only one coal (often imported) needs to be stacked, other can come in as delivered	Lower blending accuracy than silo blending
Furnace/boiler	Different coals are loaded into separate silos, run through separate pulverisers, fired in a separate burner and fed into the boiler at a pre-determined ratio	In furnace or boiler	Blending ratio can be changed at any time Avoid coal pre-mixing	
Mills	One or two mills for one coal and the rest of mills for another	Coal mills	Easy to control blending ratio	

3.4 WHERE BLENDING CAN OCCUR

Blending can occur at any point in the supply chain from the coal mine to the boiler, onsite or offsite a power plant. For the power plant, meeting the design requirement, cost and practicability are the most important attributes. Where the coal is blended depends on the site conditions, the level of blending required, the quantity to be stored and blended, the accuracy required, and the end-use of the blended coal. The decision is often made on a case-by-case basis.

3.4.1 Offsite blending

Blending offsite at the coal mine, preparation plant, or transshipment point, can save capital investment for the power plant and means the blend is handled like a single coal at the power plant. Offsite blending is suitable for coals with similar HGIs to avoid uneven grinding. However, the blend cannot be changed at the power plant to respond to the boiler needs. If the blend is not suitable, the power plant may incur operation and maintenance (O&M) costs (Chen and others, 2014; Hatt, 2020a,b; Sloss, 2014; Tillman and others, 2012).

Blending at coal mines

As mining operations continue at a single mine site, the quality of the coal can change. Coal blending may be required to meet customers' specifications. At the mine, coals are from the same rank but different seams. Blending is usually carried out to optimise the ash and sulphur contents, as well as other elements such as chloride and sodium.

Blending at coal handling and preparation plant

Coal is often handled to wash off soil and rocks, crush into graded sizes, and stockpile grades preparing for transport. Blending can be carried out at the preparation plant by stockpiling two coals together.

Blending during transportation/at a centralised stockpile

A centralised stockpile is often created at the preparation plants or ports. Two or more coals can be blended according to customers' specifications on the same moving belt when loading or unloading the coals to or from trucks, rail cars, barges, and ships.

3.4.2 Onsite blending

Blending onsite at the power plant yard or in the boiler provides the flexibility to adjust the blend according to the coal characteristics to minimise slagging, fouling, and control emissions. But this approach can be cost intensive and requires large amounts of space at the power plant.

Blending at the power plant stockpile

The most desirable and common blending location is in the coal yard of a power plant as it can provide the maximum flexibility for the power plant to alter the coal blend quickly. But this incurs extra cost and space requirements. Stockpile blending can be applied when unloading the coals. Blended coal should be compacted to avoid sliding. The coal stockyard should be covered with polythene sheets during the rainy season. For example, Pontes Power Plant in Spain burned 50% local lignite and 50% imported subbituminous coal from 1993 until the closure of the local lignite open cast mine in 2008. The coal blending took place in the coal storage area, where the blend was homogenised. Local lignite and imported subbituminous coal were stacked separately in stockyards and mixed subsequently at a common transfer point (Dios and others, 2013).

For smaller plants with little storage space and only one hopper or bin, coal can be bulldozed into the hopper in the required proportional quantities to create the blend. Larger power plants are likely to have more storage space and a greater number of silos/piles and more hoppers to allow more coordinated blending. For example, imported coal can be stored in a silo, then blended with domestic coal from a track hopper, wagon tippler or stockyard reclaimer.

Some plants have underground hoppers which can be used for blending. One coal, often imported, can be stacked in the yard and dozed through underground reclaim hoppers, which get mixed with another coal (indigenous) received from track hopper or wagon tippler while passing through the transfer points. By adjusting the unloading rate and reclaiming rate, the desired blending ratio can be achieved. For example, in India, imported coal is usually stored in the yard where it waits to be blended with domestic coal when it is delivered (Hatt, 2020a; Rajdeva, 2014; Sloss, 2014).

Blending in the boiler or furnace

For blending within the furnace, different coals are loaded into separate silos, run through separate mills and pulverisers, fired in a separate burner and fed into the boiler at a pre-determined ratio. Some refer to this method as cofiring two coals in a boiler. This method is especially suitable for coals with a broader range of HGIs. The coal blending ratio is easy to control and adjust with this method, but attention needs to be paid to control the air to fuel balance as the different calorific value of coals demands different air flows to burn optimally. This method can be used to control burnout rates and promote the complete combustion of fuel through fuel staging. It should be noted that this blending approach is more suited to tangentially-fired PC boilers than wall-fired boilers. Tangentially-fired PC boilers have a single fireball, whereas wall-fired boilers have distinct flames at each burner. There is less mixing of the fuel and flame in such installations. A disadvantage of this method is that some of the chemical benefits of blending are not achieved within furnace blending (Chen and others, 2014; Tillman and others, 2012).

Tier blending is a method of boiler blending developed in India (Saravanan, 2014). Coals are put in different bunkers and pulverised separately, and then mixed in the boiler during combustion (*see* Figure 5). This method was tested in a boiler where coals were blended at a ratio of 85% Indian coal and 15% imported coal. Boiler blending methods were compared with pre-blended coal at the same ratio. Pre-blended coal was injected into A, B, C, D and E, all five burners (case 1). For tier blending, imported coal was injected into the boiler at two different elevations of the burner, A (case 2) or C (case 3) burners. Indian coal was injected into the remaining four burners (*see* Figure 6). Test results are listed in Table 4. For the pre-blended coal case, carbon was fully converted for both the Indian and the imported coal. For the tier blending method, carbon conversion of Indian coal achieved 100% for both cases but the imported coal had a different carbon conversion rate for cases 2 and 3. The average furnace exit gas temperature was different for the three case studies, with

pre-blended coal having the lowest temperature and case 3 the highest. The results show that the coal injection position affects the blending result, consequently affecting combustion of the coal blend.

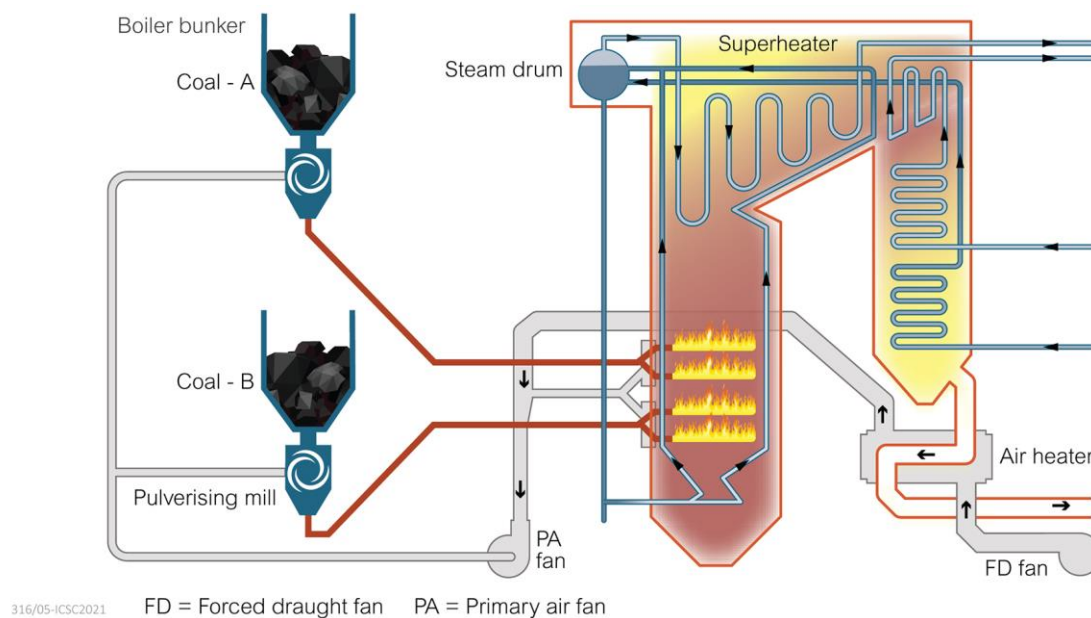


Figure 5 Tier blending (Saravanan, 2014)

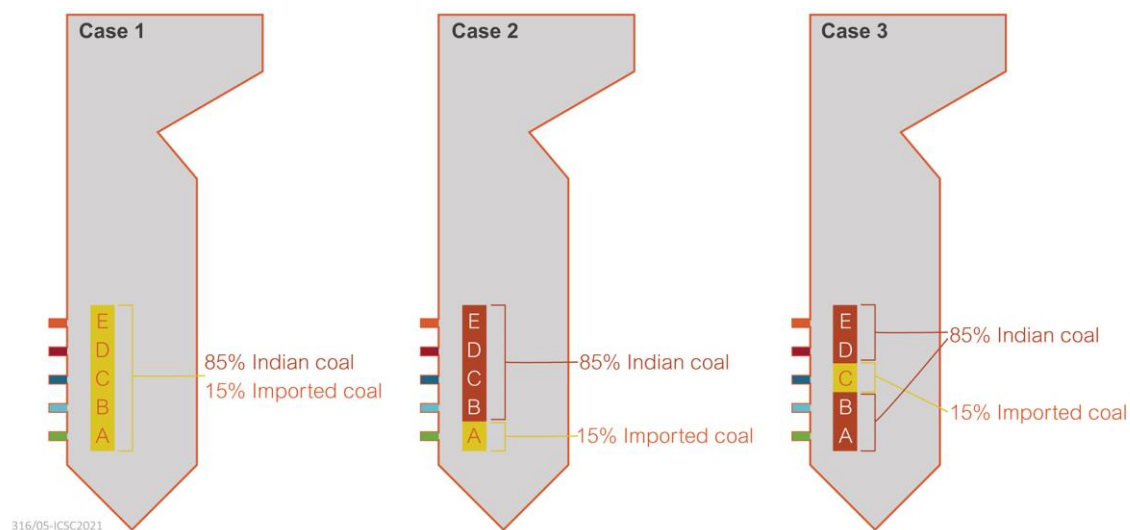


Figure 6 Computational fluid dynamics simulation of tier blending test (Saravanan, 2014)

TABLE 4 TIER BLENDING TEST RESULTS (SARAVANAN, 2014)			
Case	Carbon conversion, %		Average furnace exit gas temperature, °C
	Indian coal	Imported coal	
1	100	100	826
2	100	99.5	910
3	100	96.5	1037

3.5 PRACTICE AT POWER PLANTS

It takes practice to achieve a successful coal blend at a coal-fired power plant. The properties of the coals and the blend should be known prior to their utilisation to avoid fuel-related issues. For example, power plants need to analyse proximate parameters for ash content and composition to prevent slagging, and the FC/VM ratio to understand the combustion reactivity. It is important to know the characteristics of the coals proposed for blending in advance, including the organic and inorganic properties, to ascertain their compatibility.

As previously described, merely averaging the coal quality parameter is not adequate as the blended coal does not simply demonstrate the added characteristic of all the coals in the blend as interactions can occur between the components within the blend. A blended product that closely resembles the coal design specifications may not burn in the same way as pure coals. Thorough laboratory analysis and field trials are needed, but small-scale combustion tests cannot compare with full-scale plant performance. Power plants have to determine the most appropriate blend through a combination of operational experience and tests of the blend onsite. Operators' expertise also plays an important role. Much of the coal blending carried out at power plants is performed by plant operators who have considerable experience of coal blending, who understand the additive and non-additive characteristics of coal, and know from experience what may work in practice. The laboratory analysis may only look at one or two aspects of coal use, rather than the seam to stack approach used by plant operators (Hatt, 2020; Sloss, 2014, Thakur, 2014). The coal blending trial usually starts with a low mixture ratio, with 95% design/regularly used coal and 5% added coal. For roughly one week of operation with a new blend, plant operators must pay close attention to parameters such as steam temperature and pressure, exit gas temperature, unburnt carbon, and loading of bottom ash (Ekbote, nd; Moon and others, 2015).

Coal blending decisions are often made in the same way that complex scheduling decisions are handled within manufacturing and other industries, namely through satisficing and heuristics. Optimisation software has been considered to assist in identifying the best blending scheme. However, the designed optimisation algorithms often simplify assumptions to eliminate problem complexities and can generate solutions that are sometimes not practically feasible and of lower quality than those generated by a skilled engineer. In practice, each coal has unique characteristics in its blending situation that are understood by engineers but cannot be accounted for by reconfiguring the blending optimisation algorithms (Whitacre and others, 2014).

3.6 COMMENTS

Some coal properties, such as proximate and ultimate analysis data and the heating value, remain additive after blending. In contrast, physical properties, such as grindability, ash fusion temperature,

swelling, and combustion characteristics, such as ignition, flame stability, slagging, and fouling, are non-additive, so the effect of blending is harder to predict.

Coal characterisation data can be coupled with pilot plant studies to formulate optimum blend ratios and design boilers' efficiency for blended coal firing. In theory, blending is a straightforward process. In practice, the process can sometimes be more challenging due to the vast amount of coal that has to be handled physically and the complexity of coal characteristics. The coal blend received at the power plant may not be the same as expected. Power plant operators' experience plays a large part in successful coal blending.

In an existing plant, there may be space limitations to creating infrastructure for coal blending. In a new plant, it is possible to make the best provisions for the use of blended coal.

4 FIRING LIGNITE BLENDS

Blending can influence the chemical composition and calorific value of coal, and consequently have an impact on the flame temperature, NO_x formation and ash reactivity. However, practical experience has shown that the coal blend often does not comply with the expected weighted average value of parameters from the pure coals comprising the blend and the overall boiler performance cannot be predicted from the performance data of the component coals. Further, the flow characteristics of the blended coal will differ from those of the component coals, changing the overall flow pattern in the bunker. Even if the composition of the blended coal closely resembles the design coal for the boiler, the desired combustion performance may sometimes not be obtained from coal blends. This has posed challenges for both power plant designers and operators. It is important to investigate the combustion characteristics and emission and burnout characteristics of coal blends, especially when low rank coals are blended with those of a higher rank. Information on combustion of coal blends is scarce. This chapter studies the theories of combustion behaviour of coal blends based on the limited published literature, focusing on blends of lignite with bituminous coal. Field tests and practice trials of burning lignite and coal blends are presented as case studies in Chapter 5.

4.1 BOILER AND MILL PERFORMANCE

Reactions taking place in the combustion zone become more complex when coals of different ranks are blended or cofired. The compatibility of coals for blending needs to be examined to avoid problems with operational variables and emissions or grinding requirements. The main characteristics of coal that affect boiler performance and combustion efficiency include:

- additive characteristics: moisture content, ash content, volatile matter, fixed carbon, sulphur and heating value; and
- non-additive characteristics such as Hardgrove Grindability Index, coal reactivity and ash fusion temperatures.

The ash content of coal influences the sizing of the furnace as well as its performance. A high ash content means more mills are required and it also influences the sizing of primary air fans, air preheaters, electrostatic precipitators (ESP) as well as coal and ash handling systems. When blending a higher proportion of low ash coal and firing it in boilers designed for high ash coal, such as lignite, the heat transfer profile between the radiative and convective sections of the boiler is affected and may lead to difficulty in achieving the design main steam and reheated steam temperatures (Raaj and others, 2016).

A high moisture content coal reduces the mill capacity. It requires a higher heat input for coal drying in the mill, thus necessitating a higher air temperature at the mill inlet and further impacting the economiser and size of the air preheater. If a low-moisture bituminous coal is blended with lignite, less

heat is required to dry the coal blend and the amount of air passing through the air heater is reduced, resulting in a higher flue gas exit temperature.

FC and VM provide an insight into the reactivity of coal. The lower the fuel's FC:VM ratio, the better is the combustion efficiency and ignition stability. Lignite with a high VM content requires careful handling under high ambient temperatures as it is prone to spontaneous combustion. When firing a lignite blend, the mill inlet temperature must be carefully maintained to ensure coal drying and avoid mill fires (Raaj and others, 2016).

When high calorific value coal is blended with low calorific value lignite, the heat extraction should be increased to avoid slagging inside the furnace. The calorific value determines the rate at which the blend has to be pulverised to meet the design firing rate of the boiler.

Considerable variation in HGI of the lignite blends poses a problem of selective grinding of one coal over another and difficulty in achieving the desired coal fineness for proper combustion, as well as affecting the mill output (Raaj and others, 2016).

4.2 COMBUSTION CHARACTERISTICS

Combustion of coal blends has been studied in terms of the ignition temperature, peak temperature, burnout temperature, mean flame temperature, and characteristics of the combustion region. Methods often used to analyse combustion performance include thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), differential thermal analysis (DTA), and drop tube furnace testing (DTF).

Generally, the volatile matter content of the low rank coal in a blend influences the ignition temperature of the blended coal in the low temperature region, whereas the char residue of the high rank coal in a blend influences the burnout temperature in the high temperature region. In the first stage, before the onset of combustion, the reactivity of a coal blend is similar to that for the low rank coal because, in this region, low rank coal is preferentially decomposed. In the second stage, from the onset of combustion to burnout, the reactivity of a blend is intermediate between those of the low rank and high rank coal at the lowest temperatures, whereas at the highest temperatures, the reactivity of a blend is close to that of the high rank coal since the reaction of high rank coal is predominant over that of low rank coal (Mittal and others, 2020; Moon and others 2013; Raaj and others, 2016; Sarkar and others, 2013).

In research by Moon and others (2013), the pulverised coal flame was divided into three combustion regions: Zone I - particle heating, Zone II - volatile reaction, and Zone III - char reaction. In Zone I, the heating region, the blending ratio influenced the lengths and mean flame temperatures of the coal blend, and the values were closer to those for the coal with a higher fuel ratio. In Zone II, the volatile matter reaction region, the fuel ratio of the individual coals affected mainly the length of the reaction region for a coal blend, but the mean flame temperature was closer to that for the low rank coal at the

end of the reaction region. The position of the maximum combustion reactivity of a coal blend in the pulverised coal flame shifted slightly to a lower position, which showed that blending coal could contribute to flame stability. The length of the heating region of the pulverised coal flame changed linearly with the ignition temperature of each coal sample, whereas the volatile reaction region was inversely proportional to the burnout temperature. The thermal evolution profiles and kinetics analysis showed that the behaviour of the coal blends was independent of their parent coal components. However, the combustion characteristics of blended coal can change with the blending ratio which is discussed in Section 4.3.

Similar patterns were observed in a lignite and bituminous coal blend by Liu and others (2019) through TGA-DTG. In coal blend combustion, lignite plays a leading role in the ignition stage, while bituminous coal influences the burnout stage. As the proportion of lignite in the coal blend decreased, the ignition temperature of the blend increased from 330°C to 439°C (see Table 5) due to the change of volatile content of the coals. However, there was no apparent change in the burnout temperature of the coal blends at about 880°C, indicating that the lignite blending ratio had almost no impact on burnout temperature. With the increase of bituminous coal, the activation energy also increased.

Lignite ratio, %	Temperature of max weight loss, °C	Ignition temperature, °C	Burnout temperature, °C	Activation energy, kJ/mol
100	430	330	810	12.58
70	448	341	884	23.42
50	493	363	879	30.83
30	583	391	897	35.07
0	583	439	884	38.40

Oxyfuel combustion is a promising technology for reducing emissions of CO₂, as the fuel is burnt in a high concentration of oxygen resulting in a more concentrated CO₂ flue gas which needs less treatment post-capture. In recent years, some research has been conducted on firing coal blends under oxyfuel conditions (Ma and others, 2020a,b; Sahu and others, 2014; Wang and others, 2021). Sahu and others (2014) blended three high rank coals with one low rank coal in different proportions and studied the combustion behaviour of the individual coals and their blends with TGA and DTF in enriched oxygen. TGA results showed that low rank coal influenced the ignition temperatures of blends whereas high rank coals influenced their burnout behaviour. Both TGA and DTF studies showed that blends containing up to 10% of high rank coal had the best combustion performance, even better than other greater percentages of high rank coal. The higher concentration of oxygen increased burning efficiency but the increase was more prominent for high rank coal than for low rank coal.

Ma and others (2021a,b) observed strong combustion interactions between the parent coals in a blend from their TGA-DTF tests under oxyfuel conditions. The ignition of the low volatile coal was promoted by the rapid combustion of the volatiles from the high volatile coal, which was referred to as ignition promotion. However, the char burnout of the low volatile coal was compromised due to the rapid consumption of oxygen by a large amount of volatiles, known as burnout inhibition. The interactions under oxyfuel conditions were sensitive to the excess oxygen, oxidiser inlet temperature and coal particle size. Increasing excess oxygen reduced the combustion interactions, in which the effects of both ignition promotion and burnout inhibition on low volatile coal become less apparent. Increasing the oxidiser inlet temperature promoted the ignition of the low volatile coal but weakened its inhibition of burnout. The effects of reducing particle size were similar to those of increasing oxidiser inlet temperature. Adding water vapour into the oxyfuel atmosphere notably delayed combustion ignition, resulting in faster burnout and better comprehensive combustion characteristics. In addition, the presence of water vapour strengthened ignition promotion, burnout inhibition and comprehensive interactions.

4.3 LIGNITE RATIO

The blending ratio is of great interest when firing coal blends, not only because of the economic benefit from using cheaper low rank coals, but also for ensuring the safe operation of a power plant. For a blending ratio of 10% lignite, despite the low heating value and high moisture it contributed, the combustion temperature distribution of the blend was found to be similar to that for bituminous coal, based on the results from combustion studies of bituminous, lignite and their blends in a 15 kWth pulverised coal-fired furnace (Moon and others, 2015). The reactivity of combustible gas species released from the lignite volatile matter influenced the initial combustion of the coal blend. With lignite blending ratios in excess of 10%, the peak temperature and overall temperature distribution decreased with the increase of lignite blending ratio. This is because the initial combustion was hindered and the peak temperature was delayed due to the high moisture content of lignite and the increased flow rate of the oxidiser.

Mathematical models and neural networks are good tools for optimising the coal blend ratio. For example, Jin and others (2019) used a fuzzy matrix mathematical model to find the best coal blend to replace the designed coal for a 350 MW supercritical lignite-fired power plant. Xing'an lignite, Shaltala lignite, Ura lignite, and Inner Mongolia bituminous coal were chosen for the blend. Volatile matter, low calorific value, comprehensive slagging index of coal blend, and coal price were selected as the evaluation factors. Results showed that the best blending ratios were 4:1 Ura lignite:Mongolia bituminous coal, 2:3 Shaltara lignite:Mongolia bituminous coal, and 3:2 Xing'an lignite:Mongolia bituminous coal.

Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) uses a collection of mathematical models to validate different mix schemes. Liu and others (2018) used TOPSIS to find an

optimal blend of Zhaotong lignite, Xiaolongtan lignite, and Fuyuan bituminous coal based on the blends' combustion performance, such as flammability index, burnout temperature, and economic costs. The coal blend had the best performance when the Xiaolongtan lignite, Zhaotong lignite, and Fuyuan bituminous coal were mixed in a ratio of 2:1:2.

Santoso and others (2016) used a neural network to find the optimised blend of low rank coal and high rank coal for PT PJB Paiton Power station in Indonesia, with a focus on reducing production costs while achieving the best heating value. The results showed that an optimum blending ratio of 80:20 of low rank coal and high rank coal could reduce production costs from Indonesian rupiah (IDR) 395/kWh (0.028 \$/kWh) to 342 IDR/kWh (0.024 \$/kWh), resulting in fuel cost savings of approximately IDR 132 billion (\$9.23 million) per year or IDR 11 billion (\$0.78 million) per month.

Extensive operational tests on firing blended coal were carried out in India in the 2010s (see Section 5.3 on Indian case studies). The experience showed that it was safe to fire coal blends of 15% imported coal in the existing boiler. For a blending ratio of more than this, laboratory studies and field trials are needed (India CEA, 2012). Operational experience in China also suggests that when the VM difference of the coals is greater than 15%, a laboratory test should be considered. When the blending ratio is greater than 15%, a combustion test in the laboratory and field trial must be carried out before plant operation (Mao, 2021).

4.4 ASH DEPOSITION – SLAGGING AND FOULING

Slagging and fouling are mainly determined by the inorganic constituents and their interactions during the combustion process. Table 6 lists the ash analyses of some lignite coals.

TABLE 6 ASH CONTENT OF SOME LIGNITES (HUANG AND OTHERS, 2018; LI AND OTHERS, 2017A; TILLMAN, 2012)					
Region	USA			China	Indonesia
	Sandow	San Miguel	Indianhead	Zhundong	
Silicon dioxide, SiO ₂	44.0	53.0	22.0	5.31	35.0
Aluminium oxide, Al ₂ O ₃	25.0	15.0	9.5	5.25	32.0
Iron(III) oxide, Fe ₂ O ₃	32.1	2.7	11.0	2.30	3.7
Calcium oxide, CaO	7.1	7.3	18.0	36.00	12.7
Magnesium oxide, MgO	3.5	0.41	5.0	6.90	5.77
Potassium oxide, K ₂ O	0.37	1.5	0.07	0.34	0.18
Sodium oxide, Na ₂ O	0.2	4.8	3.4	5.76	0.94
Sulphur trioxide, SO ₃	13.0	11.0	25.0	34.75	4.24

Compared to high rank bituminous coals, ashes from lignite coals are generally rich in alkali and alkali earth compounds and therefore have a high propensity for slagging and fouling. Blending lignite with bituminous coals in general increases this characteristic. However, other inorganic constituents such as compounds of iron (Fe), calcium (Ca), silicon (Si) and aluminium (Al) and their interactions in the combustion process also have an important influence on ash fusion temperatures. Therefore, blending of bituminous coal and lignite creates a complex mechanism of slagging and fouling. However, coal blending can provide an opportunity to manipulate the chemical composition of the blended fuel to avoid or minimise adverse effects and to reduce slagging and fouling.

Blending of high rank bituminous coals with Powder River Basin (PRB) coals is common in the USA. Though PRB coals are subbituminous, being slightly higher than lignite in coal rank, the principles and industry experience are useful for the management of blending bituminous and lignite coals. Tillman (2012) summarised studies on ash deposition and industry experience in the USA of coal blending. The combustion and gasification behaviour of inorganic constituents in coal blends is non-additive or non-linear. The main reason for this behaviour is the interactions between the constituents arising from different coals in the blend. For example, blending of bituminous coal containing a high level of Fe_2O_3 with a high CaO level PRB coal results in lower ash fusion temperatures because of the eutectic formation between Fe_2O_3 and CaO. Such behaviour can be demonstrated in phase diagrams of relevant chemical constituents.

In recent years, there has been substantial interest in ZL due to its large reserves in China (Huang and others, 2018; Li and others, 2016; Li and others, 2017a; Zhang and others, 2020; Zhu and others, 2019). Zhundong coal has a chemical profile rich in alkalis (Na and K) and alkaline earth metals (Ca) but it is low in silicon and aluminium. Severe slagging and fouling are observed in pilot and industrial boilers so blending ZL is necessary.

The specific chemical characteristics of ZL, blending it with coals with a high content of refractory minerals SiO and Al_2O_3 and low alkali/alkali earth minerals would reduce ash fusion temperatures. Li and others (2016) studied the ash deposition characteristics of ZL blends with an Australian bituminous coal (AB) using a drop tube furnace. As the ratio of AB/ZL increased to 20 wt% and above, the refractory ash particles from AB diluted the sodium-bearing mineral phases and the contact between fine ash particles, leading to the absence of nepheline and, correspondingly, an increase in the ash sintering temperature indicating that the severe ash deposition of ZL could be effectively controlled through coal blending (Figure 7).

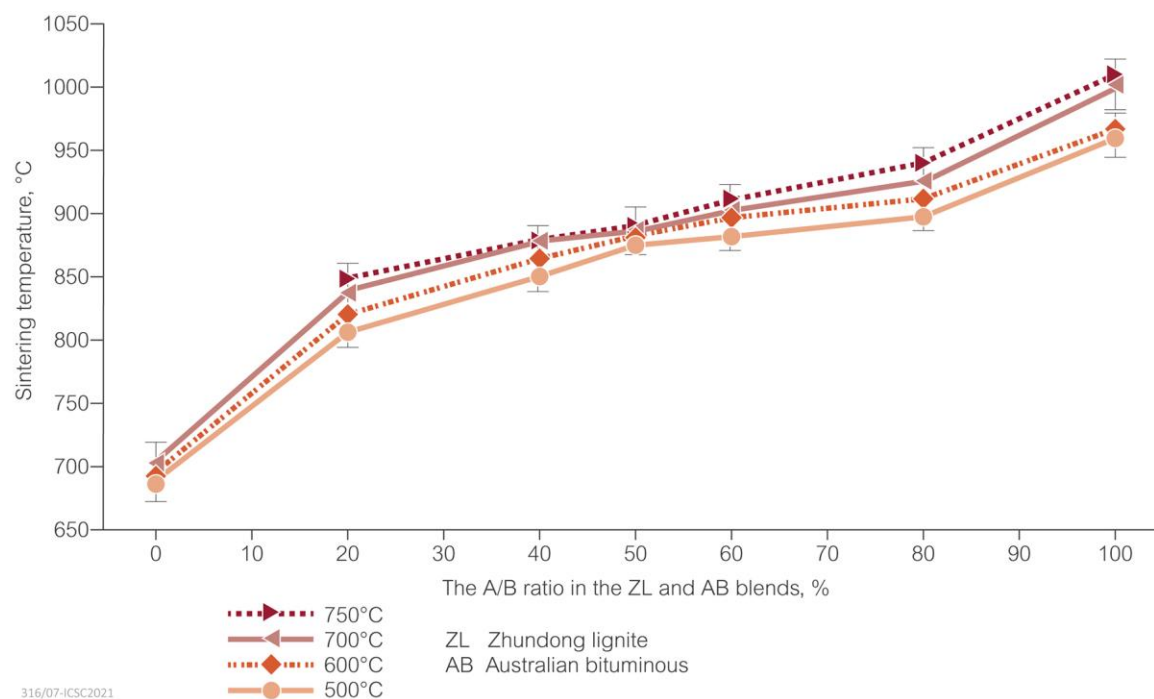


Figure 7 Effect of blending Australian bituminous (AB) and Zhundong lignite (ZL) coals at blend ash sintering temperature (Li and others, 2016)

Li and others (2017a) also studied the effect of adding an Indonesian lignite (IL) to the blend using a muffle furnace. The sintering temperature of the ash increased as the AB or IL ratio in the coal blends increased, suggesting that the addition of AB or IL decreased the sintering tendency of the ash. However, the ash fusion temperatures of the blends did not always vary in proportion to the changes in the blending ratios (Table 7). The ash fusion temperatures of the ZL/AB blends decreased first when the AB ratio increased from 0% to 40% and then increased as the AB ratio further increased. For the ZL/IL blends, the flow temperature decreased first, reaching the lowest values at the 20% IL ratio, and then increased. Sintering of the ZL ash was attributed to sodium- and chlorine-bearing minerals. In contrast, fusion of the ZL ash was attributed to the eutectics formed between calcium (Ca), aluminium (Al), iron (Fe), and sulphur (S). The addition of 20% AB into ZL inhibited ash sintering because of the introduction of refractory minerals at 850°C. Still, they promoted ash fusion due to the formation of hauyne, gehlenite and nepheline at 1250°C. In addition, the addition of 80% AB into ZL inhibited both ash sintering and fusion owing to the abundant refractory minerals including mullite and quartz in the ash. This non-linear behaviour was also reported by Zhu and others (2019) with ZL blended with a different lignite with a high Si/Al level.

TABLE 7 ASH FUSION TEMPERATURES OF BLENDED COALS IN AN OXIDISING ATMOSPHERE (LI AND OTHERS, 2017a)				
Coal sample with blending ratio	Deformation temperature, °C	Softening temperature, °C	Hemisphere temperature, °C	Flow temperature, °C
Pure coal, %				
100 AB	1350	>1500	>1500	>1500
100 IL	1253	>1500	>1500	>1500
100 ZL	1070	1273	1358	1447
Zhundong lignite and Australian bituminous coal blends, %				
80 ZL – 20 AB	1208	1245	1253	1283
60 ZL – 40 AB	1216	1219	1229	1253
50 ZL – 50 AB	1250	1299	1360	1388
40 ZL – 60 AB	1284	1344	1386	1441
20 ZL – 80 AB	1299	1406	1441	1478
Zhundong lignite and Indonesian lignite blends, %				
80 ZL – 20 IL	1263	1337	1349	1383
60 ZL – 40 IL	1269	1343	1361	1386
50 ZL – 50 IL	1290	1359	1391	1406
40 ZL – 60 IL	1327	1378	1438	1490
20 ZL – 80 IL	1364	>1500	>1500	>1500

Although ash fusion temperatures are often used to assess the propensity for ash deposition, the effects of non-chemical factors such as inertial impaction and stickiness are also important. ZL is known to have a heavy ash deposition problem in boilers while Jincheng anthracite has a high ash fusion temperature. Zhang and others (2020) studied the influence of blending ZL with Jincheng anthracite coal on ash chemical composition, fusion behaviour and particle size. The impaction efficiency is dependent on the particle size, density, sticking ability, and aerodynamics of the gas. Large particles with high density have a much greater velocity of arrival than small, low density particles. Furthermore, not all the arriving particles that reach a deposition surface will stick to the surface. The stickiness of the ash particles plays a critical role in the formation of ash deposits. The study shows that when the ZL is blended with the Jincheng anthracite, ash fusion temperatures of all the density fractions in the coal blends are increased by 60–70°C, which will greatly decrease the sticking ability of the ash particles. Therefore, the propensity of the blended coal ash to deposit is improved not only because of an apparent increase in ash fusion temperature but also because of the decrease in the total volume of possible ash particles arriving on the deposition surface.

4.5 EMISSION CONTROL IMPACTS

Another key driver for blending coal at a power plant is to improve emissions control. Many studies on the emissions and ash behaviour of blended coals have been conducted in the laboratory and at pilot-scale furnaces and full-scale utility boilers.

4.5.1 Nitrogen oxides

Emissions of nitrogen oxides (NO_x) from the combustion of blends can be between those of the parent coals or lower or higher, depending on coal characteristics such as volatile matter, moisture content, nitrogen content and release, and combustion parameters such as temperature, primary air ratio and total excess air. Generally, NO_x emissions from lignite combustion are lower than those from bituminous coal combustion due to a larger amount of volatile matter in the lignite. Research shows that blend firing of lignite with bituminous coal can reduce NO_x emissions from coal-fired power plants and the combustion efficiency will not be compromised if the lignite blending ratio is below a certain level. However, NO_x emissions from the combustion of a blend of lignite and bituminous coal are often lower than linearly extrapolated values. This may be due to the higher volatile matter content of lignite than of bituminous coal. The release of a larger mass of VM can generate fuel-rich conditions locally in the vicinity of burning particles. This may impede transport of bulk oxygen to the particles and, consequently, impede the formation of nitric oxide (NO) (Moon and others, 2015; Rokni and others, 2016a).

The influence of operating conditions, such as the excess air ratio and separate overfire air (SOFA) system, on NO_x emissions from a 600 MWe tangentially-fired utility boiler burning bituminous coal (with a mass fraction of 80%) and lignite coal (with a 20% mass fraction) were investigated using computational fluid dynamics (CFD) (Li and others, 2017b). The results showed that the fuel type exhibited an effect on the NO_x emissions due to different mass fractions of volatile matter and nitrogen, which was the source of the NO_x. The NO_x concentrations when burning the coal blend were higher than from bituminous coal, probably because there was a larger mass fraction of nitrogen in the coal blend than in the bituminous coal. A higher excess air ratio could cause a fuel-lean atmosphere and promote NO_x emissions. The SOFA arrangement also had a significant effect on NO_x emissions. Without the SOFA system, the temperature and the oxidant concentration would both reach the highest peak in the vicinity of the burner zone, which would have an adverse effect on the NO_x emissions control.

The influence of staged air injection, primary zone air ratio, coal types, and blending ratios of bituminous coal and lignite on NO_x emissions and particle burnout were evaluated in a 15 kW_{th} pulverised coal-fired furnace (Moon and others, 2015). At a given value of primary zone air ratio and staged air injector level, NO_x emissions were lower for coals with a low nitrogen content, as expected. NO_x emissions decreased slightly with a decreasing primary zone air ratio and increasing staged air

injector level for the bituminous coal. For lignite, the NO_x concentration was the highest, higher than that from the blended material, due to an increased air flow rate in this region to maintain the same thermal output. For multistage combustion, increasing the distance between the staged air injectors had a positive effect on NO_x emissions but a negative effect on particle burnout. The blends with 10% lignite showed a minimum value for NO_x concentration and similar temperature distribution as the bituminous coal case when firing a blend of bituminous coal and lignite. For other lignite blending ratios, however, NO_x emissions increased as the blending ratio of lignite increased. This was because the operating conditions required a constant thermal output in a pulverised coal-fired furnace. As the blending ratio of lignite increased, the flow rate and velocity of the oxidiser at the burner exit gradually increased. The effect of flow characteristics was more dominant on NO_x emissions than the coal properties and the devolatilisation process of lignite in the primary combustion zone. This suggested that there is a critical blending ratio of lignite (around 10%) for positive NO_x reduction without a loss of combustion efficiency.

Cai and others (2020) conducted experiments with Zhundong bituminous coal and commercial GE lean coal and their blends with different mixing ratios in a drop tube furnace at 1200–1400°C with an excess air ratio of 0.6:1.2. This research investigated the formation of NO_x and hydrogen sulphide (H₂S) in the reductive zone of blended coals during staged combustion. Nitric oxide (NO) and H₂S from blended coal combustion were almost directly dependent on the concentration of carbon monoxide (CO), and the CO concentration of the blended coal combustion depended on the single char gasification conversion. For reactive Zhundong bituminous char, the concentrations of CO, hydrogen, and H₂S were higher, whereas the concentration of NO was lower than that for low-reactivity GE lean coal. When the blending ratio of Zhundong bituminous coal was increased, CO, hydrogen, and H₂S concentrations decreased, whereas the concentration of NO increased. At a lower excessive air ratio, oxidation was inhibited and gasification was promoted; the reductive atmosphere was stronger, more char was gasified, and more CO and hydrogen were produced. More NO was reduced in the stronger reductive atmosphere.

The reduction of NO_x emissions from combustion of bituminous coal and lignite (50:50 wt% ratio) blend under oxyfuel conditions was studied in a laboratory-scale drop tube furnace (Rokni and others, 2016b). The results confirmed that the NO_x emissions from lignite oxyfuel combustion were lower than those from bituminous coal. NO_x emissions from the oxyfuel combustion of the coal blend were slightly lower. This slight reduction might be due to the larger amount of volatiles in the lignite coal, as compared to the bituminous coal, which impeded NO_x formation by promoting locally fuel-rich environments when the two coals were cofired.

The complexity of coal blending practices means that simulation, laboratory tests, and field tests do not always produce consistent results. Baek and others (2014) investigated the effects of the in-furnace and out-furnace blending methods on NO_x emissions from a 500 MW coal-fired boiler with CFD

simulation and power plant tests. The simulation predicted no difference in NO_x emissions from the blending methods. Further validation tests at the actual coal-fired plant demonstrated that the in-furnace blending method produced a substantial reduction in NO_x emissions compared with the out-furnace method. Baek and others (2014) reported that NO produced from the bituminous coal in the lower burners reacted with radicals of hydrogen cyanide (HCN) and ammonia (NH₃) formed from the subbituminous coal in the upper burner. They suggested that although different coals were used in simulation and field tests, it was the uncertainties in the plant's operational conditions and the practical difficulties in transporting and distributing the two coals which impacted the blending result and reduction in NO_x emissions.

4.5.2 Sulphur dioxide

Sulphur dioxide (SO₂) emissions from high sulphur bituminous coal are higher than those from low sulphur lignite. Burning a lignite and bituminous coal blend at power plants can be part of a strategy to meet SO₂ emission limits, provided the blended coal is compatible with the power plant design. The blend ratio plays a large role in controlling SO₂ emissions because the sulphur content is not the only contributor to the generation of SO₂; minerals such as sodium and potassium can promote self-ignition, while calcium and magnesium can increase the chemical inertness of coal at low temperature and desulphurisation, thus decreasing emissions of SO₂. Calcium- or magnesium-rich fragments of the lignite can be effective in capturing gas-phase sulphur. The moisture content can influence the formation of H₂SO₄ from FeS₂ as the higher the moisture content of the fuel, the more H₂SO₄ is released, which in turn influences the generation of SO₂ (Chen and others, 2016; Rokni and others, 2016a).

Rokni and others (2016a,b) at Boston University, USA, carried out a series of studies on SO₂ emissions from burning lignite and a bituminous coal blend. They selected two high and medium sulphur bituminous coals, two low sulphur lignite coals, and one subbituminous coal and blended bituminous coal with lignite or subbituminous coal at 50:50 wt%. The pulverised coal combustion experiments operated at a furnace temperature of 1125°C under fuel-lean conditions. Results showed that bituminous coals burning under substoichiometric conditions released most of the sulphur in the form of SO₂, whereas low-ranked coals only partly released their sulphur. Furthermore, the SO₂ emissions from coal blends were lower than those predicted by linear interpolation, suggesting significant beneficial synergisms. Rokni and others (2016b) also carried out their studies in a DTF under both air and oxyfuel combustion conditions. Results showed that cofiring bituminous coal with lignite reduced the SO₂ emissions by 60% in all combustion environments. Of this value, an estimated 45% may be attributed to the blend, based on linear interpolation of the respective SO₂ emissions of the two coals, and the remaining 15% may be because the alkali-rich lignite ashes acted as sulphur sorbents for the substantial emissions of SO₂ from the bituminous coal.

4.5.3 Trace elements

Bituminous coals typically produce a higher fraction of oxidised mercury in the flue gas than subbituminous coals. Since oxidised mercury is water-soluble, it is readily captured in wet flue gas desulphurisation (FGD) systems. Blending coals may increase the amount of oxidised mercury in the flue gas; hence, it has been used to improve mercury removal in downstream air pollution control equipment (Tillman, 2012).

The distribution of arsenic (As) and selenium (Se) in the combustion of bituminous and lignite blends have been investigated in a temperature range of 500–1500°C (Han and others, 2020). The results suggested that the temperature and blending ratio are important factors affecting the retention of arsenic and selenium in the lignite blends. The retention ratio of arsenic and selenium in ash was decreased with the increase of temperature in the temperature range of 500–900°C and bituminous coal had more effects on the retention capacity of arsenic and selenium than lignite. Generally, more arsenic is retained at 25% lignite than 75% lignite. The retention ratio of selenium in the coal blend ash combusted at different temperatures was lower than 7%. Nearly all the selenium species were volatilised at 800–900°C.

4.5.4 Particulate matter

Particulate emissions, especially those with a diameter of 10 microns or less (PM₁₀), can also be addressed by coal blending. Lignite has a high ash content; thus, more fly ash is produced and more PM emitted. However, many lignites have a high sulphur content resulting in the formation of more sulphur trioxide (SO₃) during combustion. Ash resistivity decreases due to the increased adsorption of conductive gases on the fly ash and enhances the collection efficiency of ESP. A higher lignite ratio increases the production of larger size PM and produces a lower mass of small diameter particles. Thus, blending lignite into bituminous coal can help to reduce emissions of fine PM. The ash content of lignite and bituminous coal blends, determined by the standard test methods, can be higher than the ash values calculated from the individual coals. This is because of the increase of sulphate in the ash from sulphur oxides trapped by the alkaline minerals in lignite (Avagianos and others, 2020).

4.6 PLANT MODIFICATION

Some power plants have carried out minor modifications to burn blended coal. Most of the modifications are to the coal handling system to accommodate on-site, out-furnace blending processes. Some plants may install or retrofit a separate overfire air system, low-NO_x burners, and an intelligent soot blowing system to optimise the sequencing of operating wall blowers and long retracts. Examples of plant modifications are included in the Case studies in Chapter 5.

4.7 COMMENTS

Although blending lignite with higher rank coal can improve combustion behaviour, decrease gaseous pollutant emissions, and mitigate some operational problems, it does not always reduce issues with grinding, flame stability, heat absorption balance, ash deposition, and so on. A blended product that closely resembles the design coal specifications may not burn in the same way as single coals. Interactions can occur between the component coals, which may or may not be beneficial. Thus, the compatibility of the coals concerning their combustion performances has to be adequately evaluated. Generally, lower rank coal influences the ignition temperature of a coal blend, whereas higher rank coal influences the burnout temperature. The blending ratio plays a vital role in firing lignite blends. Blending less than 10% lignite into bituminous coal has almost no impact on the boiler and combustion efficiency, and vice versa. The effects of blending on emissions control are hard to predict due to the complex chemical contents of coals. Apart from sulphur and nitrogen contents, some coals have higher oxygen contents, which may participate in the formation of oxides. Local combustion conditions and furnace operating conditions have impacts on the emission of NO_x, SO_x, trace elements, and PM.

5 CASE STUDIES

Dynamic coal blending is considered a clean coal technology in some countries to facilitate the use of all types of coals, improve their combustion behaviour, reduce costs, and meet emission limits. The first wave of studies on coal blending was in the 1990s, led by the USA and followed by Europe. In the USA, the studies focused on blend firing of Powder River Basin coal. As more coal-fired power plants in the USA are shut down, the need for coal blending technology will also disappear. India supported the blending of imported high quality coal with indigenous lignite during the 2010s. For example, the Indian Central Electricity Authority (CEA) Guideline of April 2011 recommended that all new coal-based projects be designed for a blend of domestic coal with up to 30% imported coal (Rajdeva, 2014). However, 10 years later in 2020, the Indian Ministry of Coal announced that imported thermal coal would stop being blended with domestic coal from 2023 (Mining Technology, 2020). China started coal blending in the early 2000s and continues to do so. Coal power remains an important energy source in parts of eastern Europe. Some Asian countries, especially those that have gained support from China's Belt and Road Initiative to build new coal-fired power plants, will have coal in their energy mix for the foreseeable future. These countries are adopting coal blending to enhance fuel flexibility. Coal blending activities in selected countries are discussed in this chapter.

5.1 BULGARIA

Lignite power dominates the Bulgarian energy mix and represented 30% of the nation's generation capacity in 2019. Coal or lignite-fired generation increased by 8% in Bulgaria in the first half of 2019 (Lazarova and Vanov, 2020). Based on the country's slow democratisation and diffusion of renewables, coal will continue to play an important role in the Bulgarian energy mix for the foreseeable future.

5.1.1 Maritsa East 2 power plant

The Maritsa East lignite basin in Bulgaria has significant deposits, amounting to 1933 Mt lignite as of 1 January 2018. Production in 2019 was 26,372 t. It is the largest energy complex in Bulgaria, comprising three opencast mines and four thermal power plants. The largest plant is the state-owned 1588 MW TPP Maritsa East 2 consisting of 4 x 165 MW units (commissioned between 1966-68 and refurbished in 2005-09) and 4 x 232 MW units (commissioned between 1979-95 and refurbished from 2009-11). The Maritsa East 2 power plant alone contributes about 41% of Bulgaria's coal-fired power generation and received over 10,000 t of the local lignite in 2019. It has eight Russian-made P-62 T-shaped boilers, two of which are equipped with FGD equipment (Lazarova and Vanov, 2020; TPP Maritsa East 2, 2021; Spatari, 2016).

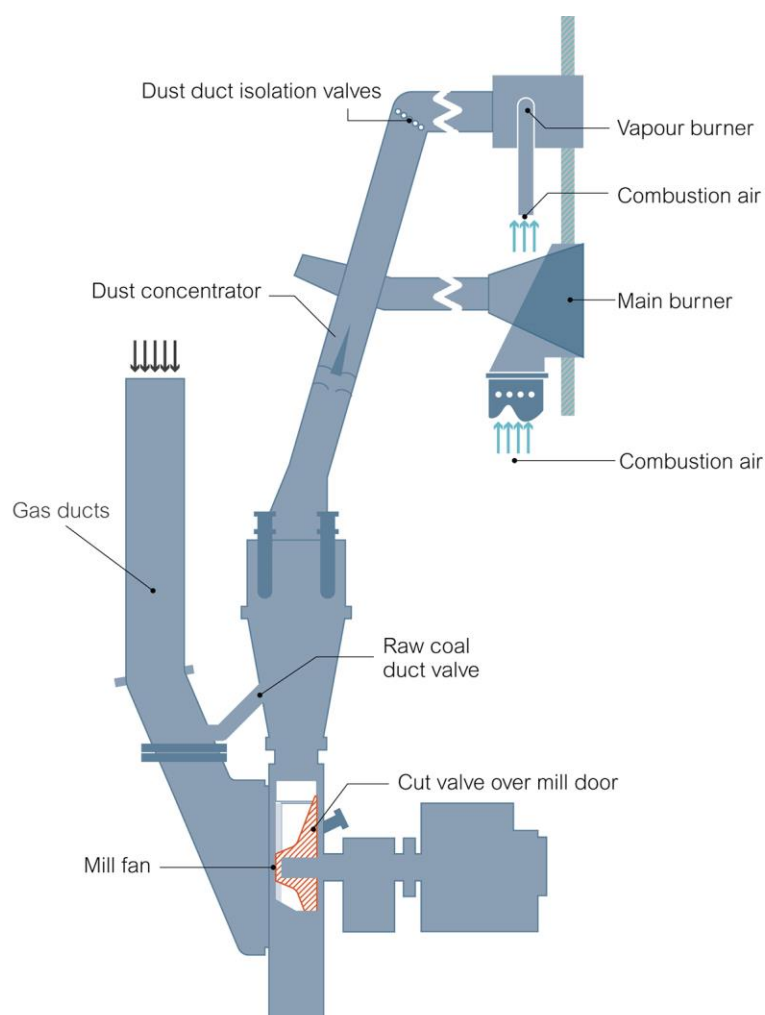
The Maritsa lignite has a low calorific value and high sulphur and moisture contents. To increase the efficiency of the plant and the FGD system, a pilot-scale test to burn a blend of lignite and brown coal was carried out at unit 12 with the corresponding FGD unit. The brown coal was from the Bela Voda

coal mine, near Pernik in western Bulgaria. The characteristics of the Maritsa East lignite and Pernik coal are listed in Table 8. The lignite was tested singly and in blends of four different ratios:

- 10% Pernik coal + 90% Maritsa East lignite;
- 15% Pernik coal + 85% Maritsa East lignite;
- 20% Pernik coal + 80% Maritsa East lignite; and
- 25% Pernik coal + 75% Maritsa East lignite.

The tests included assessing the operation of two coal preparation systems (CPS), boiler performance, concentrations of pollutants namely SO₂, NO_x and CO, and FGD performance. The CPS here is designed for dosing, transporting, drying, milling and feeding the pulverised coal to the boiler. The P-62 boiler is equipped with a CPS with direct injection and a dust concentrator. The components of the CPS are illustrated in Figure 8.

TABLE 8 CHARACTERISTICS OF MARITSA EAST LIGNITE AND PERNIK COAL (TOTEV AND KANEV, 2014)		
Characteristics	Maritsa East lignite	Pernik coal
Proximate analysis		
Ash content, %	33	47.5
Moisture content, %	53.9	21.3
Volatile matter, %	55-60	52.2
Ultimate analysis		
Carbon, %	20.19	26.35
Hydrogen, %	1.7	1.9
Sulphur, %	2.09	0.98
Nitrogen, %	0.35	0.82
Oxygen, %	6.12	4.86
Net calorific value, kJ/kg	6600	9760
Ash melting temperature – deformation, °C	1050	1141
Ash melting temperature – hemisphere, °C	1200	1275
Ash melting temperature – fluidity, °C	1250	1308



316/08-ICSC2021

Figure 8 Diagram of Bulgaria's Maritsa East 2 coal preparation system (Totev and Kanev, 2014)

The results showed that firing lignite blends increased the circulating flue gas temperatures while the ventilation efficiency of the mills remained the same as when firing just lignite. The amount of coal handled by the CPS increased by around 15% when firing blended coal due to the lower moisture content and increased temperature of the drying agent. Boiler efficiency was also increased by 0.34% compared with firing lignite. There was no significant change in the temperature in the combustion chamber between firing lignite and the blends. Firing lignite blends reduced SO₂ emissions but increased NO_x emissions due to the lower sulphur and higher nitrogen contents in Pernik coal compared with Maritsa East lignite. The impacts on SO₂ and NO_x emissions are demonstrated by the concentration at the FGD inlet, listed in Table 9. Firing lignite blends decreased the limestone slurry flow of the FGD by around 25%. The power consumption for milling and total power consumption both decreased when firing the lignite blends (see Table 9). The tests concluded that a blending ratio with more than 10–15% Pernik coal was not recommended due to the significant increase in NO_x emissions and the requirement for CPS with a larger capacity (Totev and Kanev, 2014).

TABLE 9 TEST RESULTS OF FIRING LIGNITE BLENDS AT MARITSA EAST 2 POWER PLANT (TOTEV AND KANEV, 2014)		
Characteristics	Lignite*	Lignite blends†
SO ₂ concentration at the FGD inlet, mg/m ³	16,520	13,884
NO _x concentration at the FGD inlet, mg/m ³	380	489
Milling power consumption, MW	2.72	2.28
Total power consumption, MW	17.78	16.73
* average value of two Maritsa East lignite † average value of blends of four different ratios		

5.2 CHINA

Although the share of coal-fired power in the overall generation mix has been declining, coal power generation still dominates China's power sector, accounting for 60.8% of national power generation output in 2020 (Tu and others, 2021). By the end of 2020, operational coal-fired power capacity in China stood at 1095 GW. While strongly encouraging renewable energy development, China's 14th Five-Year Plan (2021–2025) is ambiguous about the future of coal, especially coal-fired power plants. As a result, Zhang (2021) forecasts that coal consumption will continue to increase for a period before starting to decrease.

The fast-growing power sector has used a vast amount of China's good quality coal resources, so their reserves are decreasing rapidly and coal prices are rising. For example, they were 60 \$/t in October 2020 and reached 120 \$/t in June 2021 (Murtaugh, 2021). One way to deal with this situation is to blend fire low-quality coals at power plants, which China started to do in the early 2000s. As the majority of China's lignite reserves are located in Inner Mongolia and northeast China, it has become common practice to fire these lignite blends at bituminous coal-fired power plants in north China to limit transport of the lignite. More recently, there has been significant interest in firing a Zhundong lignite blend due to its substantial reserves in China and its high volatile matter content and low levels of ash and sulphur. China has also imported lignite from Indonesia for blending, especially at the power plants along the southeast coast of China.

Many power plants originally designed for bituminous or subbituminous coals have now fired lignite blends. Most of them adopted the boiler blending method, referred to as cofiring lignite with bituminous coal. The combustion characteristics for this cofiring method have been thoroughly studied by Chinese academics and engineers (Bai, 2021; Dong, 2021; Han and others, 2021; Lin, 2018; Su and others, 2018; Xu and others, 2019).

5.2.1 Firing lignite at a 600 MW bituminous coal-fired plant

A case study is presented here of a 600 MW once-through supercritical coal-fired boiler. The boiler has an opposed wall-firing arrangement. The boiler was originally fitted with 30 low NO_x swirl burners, arranged in six-burner rows with three rows on the front wall and the other three rows on the rear wall. The 10 burners in the bottom two rows are plasma-ignition burners. Above the six-burner rows, there were 12 overfire air (OFA) burners arranged in two rows on the front and rear walls, respectively. The boiler is equipped with six coal mills; each mill feeds coal to one row of coal burners.

The boiler was originally designed to burn bituminous coal but has since started to fire Indonesian lignite on the top two rows of burners and Shenhun bituminous coal on the lower four rows of burners to reduce fuel costs. The characteristics of the design coal, Shenhun bituminous coal, and Indonesian lignite are shown in Table 10.

TABLE 10 COAL CHARACTERISTICS FOR A 600 MW POWER PLANT (HAN AND OTHERS, 2021)			
Characteristics	Design coal	Shenhun bituminous coal	Indonesian lignite
Proximate analysis			
Ash content, %	16.17	10.45	5.6
Moisture content, %	12.5	16.86	45.2
Volatile matter, %	39.56	36.26	51.83
Fixed carbon, %	43.11	46.33	23.17
Ultimate analysis			
Carbon, %	56.12	60.1	34.85
Hydrogen, %	3.77	3.81	2.43
Sulphur, %	0.92	0.27	0.29
Nitrogen, %	0.95	0.99	0.52
Oxygen, %	9.57	7.53	11.12
Lower heating value, kJ/kg	22,080	23,188	12,370

Cofiring lignite with bituminous coal resulted in several operational problems with the boiler, including reduced furnace heat absorption, overheating of the platen superheater at low loads, increased spray-water attenuation flow rates to the reheater, as well as increased NO_x emissions. Cofiring also significantly increased the reducing atmosphere in the furnace side water walls, which may cause corrosion of the water walls and impair the safe operation of the boiler.

The following modifications were made to resolve these issues:

- replacement of the existing 20 coal burners in the middle and top rows with ultra-clean combustion swirl burners;
- replacement of the existing 12 OFA burners with 10 new OFA burners;
- modification to the top row lignite burners by increasing the exit flow area of the primary air pipes and reduction in the exit flow areas of the secondary air pipes;
- adjustment to the secondary air windbox damper openings to reduce the secondary air flow rates of the lignite burner rows and increase the secondary air flow rates of the bituminous coal burner rows;
- partial closure of the OFA burner nozzle outlet to increase the OFA velocity to suppress the furnace flame centre; and
- increased the OFA resistance redirecting the secondary air flow from OFA burners to coal burners thus restoring the coal burner secondary air velocities to the design values.

CFD modelling was performed to simulate the combustion process and investigate the profiles of the velocity, temperature, oxygen concentration and nitrogen oxide concentration for a single burner as well as the whole furnace.

Plant operational data and CFD modelling have shown that the modifications and optimisations improved the overall combustion performance, reduced the furnace exit gas temperature, lowered the furnace flame centre, and reduced the spray-water flow rate for the reheater. At 600 MW full load with the top two rows firing Indonesian lignite and the lower four rows firing Shenhun bituminous coal, the spray-water flow rate to the reheater was reduced to zero. NO_x emissions at full load are now between 260–300 mg/m³. At lower loads below 550 MW, NO_x emissions are below 250 mg/m³.

5.3 INDIA

Coal-fired power generation is the primary energy source in India, providing 70% of electricity. In addition to 230 GW existing coal-fired power plants, the country currently has 40 coal-fired power projects under construction, accounting for 61 GW of capacity. There are also 73 coal-fired power plants currently in the planning stage, adding up to 124 GW of capacity (Mint, 2021). The Indian coal power sector has been comprehensively reviewed in another ICSC report by Adams and others (2021).

India has massive coal reserves. According to the BP Statistical Review of World Energy for 2019, India has 106 billion tonnes (Bt) of proved reserves or 9% of the world total. Some 101 Bt comprise hard bituminous coal and anthracite and 5 Bt is lignite and subbituminous in rank (BP, 2020). India ranks sixth for lignite production in the world. Indian coals tend to have a lower calorific value, higher ash and, lower sulphur content than internationally traded coal. The calorific value of the Indian coals (16.74 MJ/kg) is approximately 60% of the imported coals from Australia and the USA (29.29 MJ/kg).

There are issues with ash disposal, fouling and slagging, and emissions of PM (Mittal and others, 2020). Firing imported coal blended with indigenous coal was adopted by many coal-fired power plants in India to save on fuel costs and reduce SO₂ emissions by taking advantage of India's low sulphur content coal. The blending began with a ratio below 15% by weight as this proportion does not require plant modification (Thakur, 2014). The CEA April 2011 Guideline has recommended that all new coal-based projects be designed to blend domestic and imported coal up to a blending ratio of 30%. From 2012, Indian coal imports increased year-on-year. However, the Indian government has announced that it will cease blending imported coal by March 2023 (Mining Technology, 2020).

5.3.1 Cuddalore power plant

IL&FS Tamil Nadu Power Company Limited (ITPCL) is developing a 3180 MW thermal power plant in Chidambaram Taluk, Cuddalore, Tamil Nadu. Phase I of the project comprises 2 x 600 MW subcritical units, which were commissioned in September 2015 and April 2016. Phase II comprises 3 x 660 MW supercritical units which are under construction (2021). All the units are designed to fire imported Indonesian coal. However, due to the change of policy by the government to promote the use of indigenous coal, ITPCL proposed to use local lignite with imported coal in the two operational 600 MW units. The aim is to also reduce the operational cost and environmental impacts of the plant.

The Indonesian coal imported by ITPCL is transported by ship to Karaikal Port, and then 128 km by rail to the power plant. ITPCL proposed to source indigenous coal from NLC India Limited (formerly Neyveli Lignite Corporation Limited). NLC India has four mines with a total lignite production of 30.6 million tonnes per year (Mt/y) located about 25 km from Cuddalore power plant. Coal is blended in the ratio of 25:75 lignite/coal. The beds/stockpile blending method and blending on moving belts method are proposed as the facilities necessary such as a suitable stacking area, conveyors, and track hopper system are already available at the power plant. The characteristics of the imported coal, the Indian lignite, and the blend of the two are summarised in Table 11.

TABLE 11 CHARACTERISTICS OF COALS FIRED AT CUDDALORE POWER PLANT, INDIA (L&T INFRA ENGINEERING, 2018)			
Characteristics	NLC India lignite	Imported coal	Blended coal
Moisture, %	51	26–35	35.265
Ash, %	7.5	0.25–6	6
Volatile matter, %	23.5	32–41	–
Fixed carbon, %	19.75	27–32.75	–
Sulphur, %	0.85	0.13–0.4	0.8
Calorific value, MJ/kg	11.36	16.74–20.92	17.57

ITPCL assessed the environmental and social impacts and mitigation measures resulting from using a blend of lignite and coal. Some parameters for using imported and blended coal are compared in Table 12. The results suggest that no changes are needed in the plant configuration or boiler because the plant is designed to fire imported coal with a gross calorific value (GCV) in the range of 17.57–19.25 MJ/kg and the GCV of the blended coal is in the low end of the range at 17.57 MJ/kg. For the same reason, the quantity of blended coal required is estimated to be the same as the imported coal. The existing stockyard can be used for lignite storage so there is no need for additional land. The ash content of the coal blend is the same as that of the imported coal, so no additional generation of ash is anticipated, and no extra ash ponds are needed. The power plant has installed ESP, wet limestone FGD, and low NO_x burners as emissions control measures. Dust suppression measures include wind barriers, covered conveyors, covered transfer points, water sprinklers, and fitting the silos and track hopper with appropriate controls. With these measures in place, the emissions of pollutants from the power plant are below the national standards (*see* Table 13). The sulphur content in the coal should not exceed 0.8% to keep SO₂ emissions below the 200 mg/m³ standard; this is achievable with the blended coal. As the same amount of coal is used, the requirement for desalinated water and seawater (for cooling) is not changed. The amount of discharge water remains the same.

TABLE 12 PARAMETERS OF IMPORTED AND BLENDED COAL AT CUDDALORE POWER PLANT, INDIA (L&T INFRA ENGINEERING, 2018)

Parameter	Imported coal	Blended coal	Remarks
Coal requirement, t/h per unit	336	335.8	No change
Allowed sulphur content, %	0.8 with FGD	0.8 with FGD	No change
Ash, %	6	6	No change
Gross calorific value, kcal/kg	17.57–19.25	Average 17.57	Meets imported coal low
Station heat rate, MJ/kWh	9.83	9.83	No change
Ash generation, Mt/y	29,996.7	29,996.7	No change
Fly ash, kt/y	239.9	239.9	No change
Bottom ash, kt/y	59.9	59.9	No change
Ash pond area for 3180 MW, ha	107	107	No change
Coal requirements, days	30	30	No change
Lime requirement for FGD, t/d per unit	15	15	No change
Gypsum generation from FGD, t/d per unit	20	20	No change
Circulating water requirements (Intake), m ³ /h	11,535 for 2 x 600 MW units	11,535 for 2 x 600 MW units	No change
Discharges/outfall, m ³ /h	8,539 for 2 units	8,539 for 2 units	No change
Freshwater requirement, million L/d	10 for 2 units	10 for 2 units	No change
Furnace/boiler specifications/modifications if any	Tangential fired water tube furnace	No modification	No change
Pollution control measures provided/considered	ESP, FGD, Low NOx burners	ESP, FGD, Low NOx burners	No change
Emissions, mg/m ³ PM SO ₂ NO ₂	<50 <200 <300	<50 <200 <300	No change
Traffic rate	5 trains per day	6–7 truck/h and 4 trains/d	
Total plant area, ha	478	478	No change

TABLE 13 CURRENT EMISSIONS STANDARDS FOR COAL-FIRED POWER PLANTS IN INDIA (ADAMS AND OTHERS, 2021)

	PM, mg/m ³	SO ₂ , mg/m ³	NO _x , mg/m ³	Mercury, mg/m ³
Old standard	350	None	None	None
2015 norms				
Units installed before 31 December 2003	100	600 (<500 MW) 200 (≥500 MW)	600	0.03
Units installed between 2004-16	50	600 (<500 MW) 200 (≥500 MW)	300 450*	0.03
Units installed from 1 January 2017	30	100	100	0.03
* relaxed in 2020				

5.4 PAKISTAN

In Pakistan, most of the primary energy supply comes from oil and natural gas, although coal is also a significant contributor. Hydropower is the main source of renewable energy but the share of wind and solar power is slowly growing. As of 2017, gas accounted for 40% of generation, oil for 26%, and hydropower for 27% (National Transmission and Dispatch Company, 2019). Natural gas was the main fuel used for Pakistan's baseload power plants, but the country's dwindling gas reserves have resulted in the increasing use of expensive imported fuel oil, which has raised its cost. In order to lower the costs and diversify the energy mix, the Pakistan government plans to increase coal-fired power generation. In 2020, there were 5025 MW of coal-fired power plants in operation with an additional 3930 MW under construction (Baruya, 2021, based on S&P Global 2021). By 2040, indigenous coal will make up 25% of the energy mix and imported coal 5%, while hydropower will supply 35%, other renewables 9%, nuclear 7%, natural gas 2%, and re-gasified liquefied natural gas 1% (National Transmission and Dispatch Company, 2019; Majid and Rehman, 2019). At the Climate Ambition Summit in December 2020, the Prime Minister of Pakistan, Imran Khan, announced that growth in coal imports could be limited, with most of the country's incremental coal-fired capacity prioritising domestic production. The presence of the Thar coalfield has supported this ambition. The Thar coalfield is one of the world's largest lignite deposits and has 175.5 Bt of coal (Ford, 2020). Pakistan operates four major coal-fired plants, with around 4.4 GW running on imported coal and 660 MW using Thar lignite. Most of the coal mining and power generation projects in development are in this region. From 2021-23, 2.6 GW of new capacity fuelled by Thar lignite is expected to come online (Argus Media, 2021). Thar lignite has low sulphur and ash contents but a high moisture content, so there is interest in firing it blended with high quality coal.

5.4.1 Coal-fired units at Jamshoro thermal power plant

At the site of the existing oil-fired Jamshoro thermal power station, 2 x 660 MW supercritical pulverised coal-fired units are under construction (2021). This will be the first supercritical coal-fired power plant in Pakistan once operational in 2023. The boiler is designed to fire a blend of 80% imported subbituminous coal and 20% Thar lignite. The main steam pressure of the turbine is 24.1 megapascal (MPa) at 593°C and the single reheat steam pressure is 4.5 MPa at 593°C. The flow rate of the mainstream is 2100 t/h and the feedwater temperature is 300°C. The designed gross efficiency (LHV) is 43.4% for subbituminous coal and 42.8% for the coal blend. The power plant will have ESP, FGD and selective catalytic reduction (SCR) installed for emissions control. The boiler will be served by six coal silos, sized to allow full output with five in operation, with one spare (Hagler Bailly Pakistan, 2013; Jamshoro Power Company Ltd, 2021; NS Energy, 2021).

Subbituminous coal will serve as the main fuel, with 10–20% of lignite blended. Subbituminous coal will be imported from Indonesia and unloaded initially at Karachi Port. The lignite will be from the Thar coalfield. Coal will be delivered to the power plant primarily by rail; however, provisions will be made to receive, unload, and store coal transported by trucks as well.

For the first stage, a maximum of four trainloads each carrying 2500 t of coal will be delivered daily to the storage yard of the power plant. For the second stage, the number will increase to six to seven trainloads when the second coal unit comes online. For the 1320 MW generation capacity, a total of 540,000 t of coal is to be stored at the plant at any given time to provide the plant with 40 days of operation. The coal will be stockpiled in two storage areas, of which the active pile will be 40,000 t, based on three-days of full-load coal consumption, and dead storage (long term) will be 500,000 t. The active coal pile will have a cover to protect it from rainwater and will be used continuously. The dead storage coal will be stacked in three piles, each 10 m high and occupying an area of about 5.67 hectares. The piles will allow separation by coal source and type. Coal blending will occur when reclaiming coal from the dead piles to the active pile according to the blending ratio. The design specification of the fuel is shown in Table 14.

TABLE 14 DESIGN COAL CHARACTERISTICS FOR JAMSHORO POWER PLANT, PAKISTAN (HAGLER BAILLY PAKISTAN, 2013)

Characteristics	Indonesian subbituminous coal		Thar lignite	
	Range	Selected value	Range	Selected value
Moisture content, %	<26	26	44.9–50.4	50.4
Ash content, %	<9	9	4–15.1	15.1
HHV, MJ/kg	>20	20	9.3–13.6	9.3
Carbon, %	50–65	50	28–37.4	28
Hydrogen, %	1–3	1	1.6–3.1	1.6
Oxygen, %	30–50	30	6.6–10.5	6.6
Sulphur, %	<1	1	0.2–2.7	2.7
Nitrogen, %	<2	2	0.2–0.4	0.4

Three different blending proportions of lignite have been considered for the design, namely 10%, 15%, and 20%. The fuel properties under these blending scenarios are shown in Table 15. The actual blending ratio will be decided when the plant is operational (Hagler Bailly Pakistan, 2013).

TABLE 15 BLENDED COAL PROPERTIES FOR JAMSHORO POWER PLANT, PAKISTAN (HAGLER BAILLY PAKISTAN, 2013)

Characteristics	10% Lignite blends	15% Lignite blends	20% Lignite blends
Moisture content, %	24.19	25.38	26.58
Ash content, %	8.17	8.48	8.80
HHV, MJ/kg	18.93	18.40	17.86
Carbon, %	40.65	39.96	39.26
Hydrogen, %	0.90	0.96	0.93
Oxygen, %	23.52	22.67	21.80
Sulphur, %	1.00	1.07	1.15
Nitrogen, %	1.56	1.51	1.45

5.5 USA

Coal still plays an essential part in the US energy mix. The US Energy Information Administration (EIA) forecast in May 2021 that the share of generation from coal would rise from 20% in 2020 to 24% in 2021 and 23% in 2022 due to higher natural gas prices. Coal blending began in the USA in the 1990s. One reason was to reduce emissions of SO₂ by blending high sulphur eastern American coal with low sulphur PRB coal or another low sulphur coal at the maximum reasonable percentage. Another reason

is to utilise lignite and other cheaper or more readily available coals, such as PRB. For example, NRG Energy's Limestone Electric Generating Station in Texas fired a blend of Texas lignite and PRB coal before switching to fire 100% PRB coal in 2017 (Cassell, 2016). Luminant's Martin Lake coal-fired power plant in Tatum, Texas has three 750 MW supercritical pulverised coal boilers that fire Texas lignite along with PRB coal at a rate of less than 10 wt%. The power plant dedicates certain bowl mills to low-cost lignite for firing the blended coal (Hassell and Brown, 2020). The US coal fleet is relatively old and a number of power plants are closed down each year. Luminant Power Generation Company's Big Brown power plant began operation in 1971 and closed in February 2018 due to economic factors such as low natural gas prices and the growth in low-cost renewable energy. However, it is an excellent example of modifications made to a power plant and coal handling system when firing lignite blends as described below.

5.5.1 The Big Brown power plant

The Big Brown power plant, 145 km south of Dallas, TX, had 2 x 595 MW supercritical units. It first fired 100% local lignite, then a blend of lignite and PRB coal (42% PRB coal, 58% lignite for many years, which gradually moved to 60% PRB coal with 40% lignite). Finally, it fired 100% PRB coal. The characteristics of lignite and PRB coal are listed in Table 16.

TABLE 16 LIGNITE AND PRB COAL USED AT BIG BROWN POWER PLANT, USA (PELTIER, 2008)					
As-received	Calorific value, MJ/kg	Moisture, %	Ash, %	Volatile matter, %	Sulphur, %
Lignite	16.05–16.51	28–31	14–18	24	0.65
PRB	18.84–19.30	24–30	4.5–5.5	34	0.35

PRB coal has the potential to increase boiler slagging and fouling. However, the blend of PRB coal and lignite at Big Brown power plant actually reduced the concentration of fuel ash, resulting in a higher volatile matter content, lower sulphur content, and higher calorific value when compared to firing 100% lignite. With the installation of Alstom Power's (GE) separated overfire air, low-NO_x burners and an intelligent soot blowing system optimising the operation of wall blowers, slagging decreased significantly.

Big Brown was designed to receive Texas lignite from draglines and bottom-dump hauliers moving the coal directly from the mine to a truck hopper, through secondary crushers, and then to a transfer tower above a surge bin. The plant added a rail spur and unloading facilities at a remote site to receive PRB coal. Hauliers moved the PRB coal to the plant and then loaded it into a truck hopper which forwarded it to the same surge bin via a stacker, stackout tube, and reclaimers. This approach allowed for blending of the coals by alternating deliveries of lignite and PRB coal which meant the fuels could be mixed at stackout piles and surge bins before being loaded into the storage silos.

Fuel leaks at the transfer points of conveyors were a potential hazard. One of the worst locations was the transfer point where cross-conveyors from the common transfer tower fed onto the conveyor for the tripper cars, which filled the boiler silos. A high efficiency loading system called InteliFlo® designed by Benetech was installed at the north and south tripper houses on unit 1 (red arrow in Figure 9) to eliminate the problem. Before (left photo in Figure 9) and after (right photo in Figure 9) shows the modification at the headbox where conveyor 7 fed the InteliFlo® chute that directed fuel onto conveyor 8. After the new transfer chute was installed, pluggage problems were experienced when attempting to run with the wet fuel (red arrow in Figure 10). The solution was to add larger access doors and install compressed air injection nozzles to eliminate fuel build-up (right photo in Figure 10).



Figure 9 Fuel-handling equipment upgrade at Big Brown power plant, USA – InteliFlo® system (Image courtesy of: Power)



Figure 10 Fuel-handling equipment upgrade at Big Brown power plant, USA, to eliminate fuel build-up (Image courtesy of: Power)

Big Brown added a telescopic chute in the fuel yard to minimise dust dispersal when stacking coal. An enclosed lowering tube was added to the fuel yard's stackout system to reduce airborne dust. A sensor on the end of the chute adjusted the chute length based on the height of the coal pile to reduce fugitive dust emissions. An improved dust collection system, which mixed the dust with water and drained it to the lignite discharge pond, was installed in the south tripper house on unit 1. A foam dust suppression system was employed at multiple locations in the fuel-handling system to limit fugitive dust problems at feeders, crushers, and transfer points. A series of compressed air nozzles designed to provide short bursts of air to break up fuel and dust in these transfer points were also added to reduce fuel build-up at critical transfer points in the system. Another dust suppression method used by Big Brown was the injection of dust suppression chemicals such as Benetech BT-105 at the primary crushers, where all stackout fuel was processed before being sent to the plant.

Big Brown also improved coal containment in its fuel-handling systems. New access doors were installed at all transfer points and feeder locations, which reduced spillage problems. In addition, numerous impact roller beds and skirting systems were replaced. New skirting that rolled under the belt was added at transfer points. The key objective was to update the systems to ensure that fuel and dust were contained within the fuel transfer and handling enclosures rather than covering the floor or equipment, where it was a safety hazard (Peltier, 2008; Tillman and others, 2012).

5.6 TURKEY

As the second largest producer of lignite, with 87.3 Mt produced in 2019, Turkey plans to continue to use its domestic coal for power generation. Thus, Turkey has implemented a series of policies to incentivise power plants that run on imported coal to use indigenous coal. At the end of 2020, 10 power plants with 8900 MW capacity, burning imported coal were operational in Turkey. Some of them applied for the incentives to support the use of domestic coal in 2020, for example, Diler Atlas, Eren Energy, İçdaş Biga, İzdemir Energy, and Çolakoğlu-2. Tamzok (2021) estimated that these power plants used 3–15% domestic lignite from local mines in their total coal consumption in 2020. However, there is insufficient information in the public domain to summarise the situation of firing lignite blends in Turkey.

5.7 COMMENTS

The Big Brown power plant in the USA used the bin blending method. Its fuel handling system was upgraded to ensure dust and containment control. Although now closed, its experience in plant modification is useful for countries where coal blending continues. Coal-fired units at Jamshoro power plant are still under construction but designed to fire lignite blends. The case studies from Bulgaria, China, and India are for existing plants. To fire lignite blends in existing power plants, some need modification, and some do not, depending on the blending method and ratio, and each plant's circumstances. The Chinese 600 MW supercritical power plant uses the furnace blending method. Burner modifications and adjustments to the secondary air flow rate were carried out to facilitate firing lignite blends.

6 SUSTAINABLE DEVELOPMENT GOALS

The 2030 Agenda for Sustainable Development announced in September 2015 is a plan of action for people, the planet, and prosperity. At its heart are the 17 Sustainable Development Goals (SDGs). According to the United Nations, the 17 SDGs recognise that ending poverty and other deprivations must include strategies that improve health and education, reduce inequality, spur economic growth, and tackle climate change while working to ensure acceptable environments for air, water, and land. The implementation pathway calls for a partnership between developed and developing countries to work together in a combined global effort to achieve the declared aims by 2030 (United Nations, 2015).

Cofiring lignite with coal can play a role in the achievement of the SDGs, particularly those for:

- affordable and clean energy;
- decent work and economic growth;
- industry innovation and infrastructure;
- sustainable consumption and production patterns; and
- climate action.

Goal 7 Affordable and clean energy: Access to electricity in the poorest countries has begun to accelerate, energy efficiency continues to improve, and renewable energy is making gains in the power generation sector. Coal remains a cheap and abundant energy resource. Many emerging economies depend on coal for secure, affordable and reliable electricity generation and supply. Therefore, it is vital to ensure that coal is used efficiently with minimum environmental impacts. Firing indigenous lignite with higher quality coals in countries like India, Pakistan and Bulgaria can help to cut the cost of energy generation and keep generating electricity at high efficiency and low emissions to provide energy at an affordable price.

Goal 9 Industry, innovation and infrastructure: The aim is to upgrade certain aspects of industry by 2030 to make it more sustainable, with increased resource-use efficiency, whilst adopting clean and environmentally sound technologies. Some innovative materials have been applied to the boilers at coal-fired power plants to overcome ash deposition and corrosion issues from burning lignite. Modifications to coal mills and boilers are also needed when a high percentage coal blend is fired. Many power plants update other parts of the plant while these retrofits are carried out, resulting in an overall improvement of the efficiency of the power plants, reduced emissions, and an extended life of the plant.

Goal 12 Ensure sustainable consumption and production patterns: to achieve the sustainable management and efficient use of natural resources. Blending locally available lignite with good quality coal to generate electricity has improved the fuel flexibility of power plants, kept the plants in operation and maintained their performance. Using local resources is especially beneficial for

developing countries, such as India and Pakistan, to create more jobs and help with national economic development. This is also in line with **Goal 8: Decent work and economic growth**.

Goal 13 Climate action: Climate change is disrupting national economies and affecting lives. Most countries adopted the Paris Agreement at the 2015 COP21 to strengthen the global response to the threat of climate change. Global CO₂ emissions declined by 5.8% in 2020. Despite the decline, global energy-related CO₂ emissions remained at 31.5 Gt. In 2021 global energy-related CO₂ emissions are projected to recover and grow by 4.8% as demand for coal, oil and gas rebounds with the economy (IEA, 2021a). Coal continues to be the largest single source of electricity generation in fuelling some of the world's largest economies; hence, coal-fired power generation remains the single largest emitter. Efforts are needed to reduce CO₂ emissions from coal-fired power plants. Lower efficiency of lignite power plant means more CO₂ is released for each kilowatt-hour of electricity generated. Adding good quality bituminous coal to lignite-fired power plant can improve efficiency and help with cutting emissions of SO₂ and NO_x. Using local lignite can reduce CO₂ emissions from long-distance coal transportation.

The 2030 Agenda for Sustainable Development poses a critical challenge to the energy sector: how to provide clean energy to support rapid economic development and a growing population while simultaneously decarbonising the global energy supply? The power sector tries to generate as much energy as is required at an affordable price, while minimising the emission of pollutants. Firing blends of lignite and coal can contribute to this goal in some regions.

7 CONCLUSIONS

Many coal-using countries have witnessed a steady decline in coal supply and deterioration in the quality of the coal produced. The importance of using low quality coals has therefore become more apparent. However, burning low quality coal, such as lignite, can reduce power generation efficiency, increase CO₂ emissions and increase the propensity of slagging and fouling in a power plant. Blending is one way to enable the use of low quality coals while maintaining the output of a plant. Coal blending is defined as integrating several coals with different physical or chemical properties to create a required specification or blend in which the elements are evenly distributed and no large pockets of one type can be identified.

Coal blending is not new. Some power plants in the USA started to burn blends produced from different indigenous coals in the 1990s. Most of China's lignite reserves are located in Inner Mongolia and Northeast China. Firing these lignite blends with bituminous and subbituminous coal has been common practice in power plants in north China since the early 2000s. China has also imported lignite from Indonesia and Australia for blending. The Indian government aims for coal blending to play a transitional role in switching from burning imported coal to indigenous coal in India. Blending domestic lignite was introduced in early 2010 to reduce fuel costs and to achieve compliance with environmental standards. However, the Indian government has decided to reduce thermal coal imports so blending will decline. Blending local lignite is of interest in some eastern European countries. Some Asian countries, which will have coal in their energy mix for the foreseeable future, are adopting coal blending in power plant design for greater fuel flexibility.

Blending can be achieved at any point in the supply chain from coal mine to boiler, onsite or offsite to a power plant. Blending offsite at the coal mine, preparation plant, or trans-shipment point, can save capital investment for the power plant and the blend is handled as a single coal at the power plant. Blending onsite at the power plant yard or in the boiler provides flexibility to adjust the blend according to the characteristics of the coal. This approach can be cost-intensive and requires large amounts of space at the power plant. Coal blending methods include stockpile, bin, belt, and boiler/furnace blending.

Lignite-fired plants may choose to blend in higher quality coals to improve combustion efficiency and to reduce slagging and fouling and other difficulties. Conversely, at bituminous coal-fired power plants lignite may be blended to reduce fuel costs and reduce emissions of SO₂ and NO_x. In the latter, generally speaking, a blending ratio of less than 10% has almost no impact on the boiler. When the blending ratio is greater than 15% or the volatile matter difference of the coals is greater than 15%, a combustion test in the laboratory and field trials must be carried out before operating in a plant. To fire a high ratio coal blend, modifications to the boiler or burners may be needed. Many plants need to modify their coal handling system to accommodate onsite out-furnace blending processes.

In theory, blending is a straightforward process. In practice, the process can sometimes be more challenging due to the vast amount of coal that has to be handled physically and the complexity of the coal characteristics. Additive coal compositions, such as proximate and ultimate analysis data and the heating value, remain additive after blending. Combustion characteristics such as milling, ignition, flame stability, char burnout, slagging and fouling are non-additive. The overall boiler performance cannot be predicted from the performance data of component coals. Also, the flow characteristics of blended coal will be different from those of the component coals, changing the overall flow pattern in the bunker. Even if the blended coal composition closely resembles the design coal for the boiler, the desired combustion performance may sometimes not be obtained using coal blends.

Modelling and laboratory studies, pilot-scale evaluations, and field trials can provide useful information for predicting the combustion behaviour of blended coal. However, the coal blend received at the power plant may not be the same as expected. It takes considerable practice to achieve a successful coal blend at power plants. Much of the coal blending carried out at plants is performed by plant operators who gain personal experience in coal blending through trial and error, understand the additive and non-additive characteristics of coal, and know from experience what may work in practice. The operators often try to understand what the test reveals rather than the actual test results. Such personal experience and understanding are often not published due to commercial sensitivities. Thus, these details were not available for this report.

Despite the lack of standard procedure and quality control, firing lignite blends is a common practice at coal-fired power plants in some countries. It permits a broader fuel supply and helps to cut the price of fuel for power plants. Lignite blending is also implemented to limit slagging and fouling and control emissions. For developing countries, such as Pakistan and India where lignite resources are abundant and energy demand is growing rapidly, utilising indigenous lignite can also help create jobs and contribute to the local economy. In poorer countries with large lignite resources, a growing energy demand and a need to improve air quality cheaply and easily, the blending of lignite and coal is one way to provide cleaner energy to support rapid economic development and a growing population.

8 REFERENCES

- ABB (2021)** ABB Ability™ Stockyard Management System. Available at: <https://new.abb.com/mining/mineoptimize/digital-applications/operations/abb-ability-stockyard-management-system> (Oct 2021)
- Accutrack (2021)** AccuTrack real-time fuel tracking system. Available at: <https://www.ecg-inc.com/products/accutrack> (Oct 2021)
- Adams D, Lockwood, Baruya P, Wiatros-Motyka M, Zhu Q (2021)** *A pathway to reducing emissions from coal power in India*. IEACCC-CIAB. London, UK, International Centre for Sustainable Carbon, 157 pp (Jan 2021)
- Argus Media (2021)** Pakistan power-sector coal demand growth set to slow. Available from: <https://www.argusmedia.com/en/news/2173778-pakistan-powersector-coal-demand-growth-setto-slow> (4 Jan 2021)
- Australian Government (2014)** Department of Industry, Geoscience Australia and Bureau of Resources and Energy Economics, *Australian Energy Resource Assessment*, 2nd Edition, p 130 (2014)
- Avagianos I, Vounatsos P, Papandreou I, Maier J, Grammelis P, Kakaras E (2020)** Nanoparticle Emission and Characterization from Pre-Dried Lignite and Bituminous Coal Co-Combustion. *Energies*, 13(9), 2373, 19 pp (Jan 2020)
- Baek S H, Park H Y, Ko S H (2014)** The effect of the coal blending method in a coal fired boiler on carbon in ash and NO_x emission. *Fuel*, 128, 62-70 (Jul 2014)
- Bai F (2021)** Research on the safety and economics of blend firing lignite in bituminous coal boiler. In *Workshop on coal blending technology and fuel intelligence for coal-fired power plants*, Zhibo, Shangdong, China, 27-29 Apr 2021. 21 pp (Apr 2021 in Chinese)
- Baruya P (2021)** London, UK, International Centre for Sustainable Carbon (ICSC), *personal communication* (Jul 2021)
- Begić F, Kazagić A, Tanović F, Avdić H, Tuzla T P P (2003)** Improvement of sustainability indicators of coal fired power plants by coal homogenisation. In *2nd Conference on sustainable development of energy, water and environmental systems*, Dubrovnik, Croatia, 2003.
- BSI (2020)** BS ISO 18283. *Coal and coke. Manual sampling*. Draft for public comment. Available at: <https://shop.bsigroup.com/ProductDetail?pid=000000000030387290>, 72 pp (16 Nov 2020)
- BP (2020)** *Statistical Review of World Energy 2020*, 69th edition. Available at: <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>, 68 pp (Jun 2020)
- Cai J, Li D, Chen D, Li Z (2021)** NO_x and H₂S formation in the reductive zone of air-staged combustion of pulverized blended coals. *Frontiers in Energy*, 15(1), 4-13 (Mar 2021)
- Carpenter A M (1995)** *Coal blending for power stations*. IEACR/81, London, UK, International Centre for Sustainable Carbon, 65 pp (Jul 1995)
- Carpenter A M (1999)** *Management of coal stockpiles*. CCC/23, London, UK, International Centre for Sustainable Carbon, 83 pp (Oct 1999)
- Cassell B (2016)** *NRG to switch lignite-fired Limestone plant in Texas to 100% PRB coal*. Available at: <https://www.transmissionhub.com/articles/2016/08/nrg-to-switch-lignite-fired-limestone-plant-in-texas-to-100-prb-coal.html>, (30 Aug 2016)

- Chapman G (2021)** *Long-term coal supply availability*. London, UK, International Centre for Sustainable Carbon, (in draft 2021)
- Das A (2020)** India aims to stop coal imports blending by thermal power producers. *Coal Age*, Available at: <https://www.coalage.com/world-news/india-aims-to-stop-coal-imports-blending-by-thermal-power-producers/> (30 Jun 2020)
- Dios M, Souto J A, Casares J J (2013)** Experimental development of CO₂, SO₂ and NO_x emission factors for mixed lignite and subbituminous coal-fired power plant. *Energy*, 53, 40-51 (May 2013)
- Dong N S (2011)** *Utilisation of low rank coals*. CCC/182, London, UK, International Centre for Sustainable Carbon, 92 pp (Apr 2011)
- Dong N S (2014)** *Techno-economics of modern pre-drying technologies for lignite-fired power plants*. CCC/241, London, UK, International Centre for Sustainable Carbon, 46 pp (Sep 2011)
- Dong X (2021)** Optimization of operational controllable factor for firing lignite blend at bituminous coal-fired boiler. In *Workshop on coal blending technology and fuel intelligence for coal-fired power plants*, Zhibo, Shangdong, China, 27-29 Apr 2021. 30 pp (Apr 2021 in Chinese)
- Ford A (2020)** Oracle Power's Thar project will benefit significantly as an important component of the China-Pakistan Economic Corridor. Available from: <https://www.proactiveinvestors.co.uk/companies/news/919819/oracle-powers-thar-project-will-benefit-significantly-as-an-important-component-of-the-china-pakistan-economic-corridor-919819.html> (18 May 2020)
- Hagler Bailly Pakistan (2013)** *Environmental impact assessment for Jamshoro power generation project*. Available at: <https://www.adb.org/sites/default/files/linked-documents/47094-001-eiaab.pdf>, 313 pp (Jun 2013)
- Han J, Xiong Z, Zhao B, Liang Y, Wang Y, Qin L (2020)** A prediction of arsenic and selenium emission during the process of bituminous and lignite coal co-combustion. *Chemical Papers*, 1-11 (Jan 2020)
- Han J, Guo X, Wang J, Yu J, Yin Y, Xu J (2021)** Analysis on problems from blend firing lignite in 600 MW bituminous coal boiler and boiler modification. *Power system engineering*, 37(2) 43-45 (2021 in Chinese)
- Hassell E, Brown W (2020)** *Unit Flexibility Improvements*. Available at: <https://www.coalusersgroup.org/>, 7 pp (2020)
- Hatt R (2020a)** Versailles, KY, USA, Coal Combustion, Inc, *personal communication* (Sep 2020)
- Hatt R (2020b)** *Practicalities of coal blending*. Coal Users' Group webinar. Available at: <https://coalusersgroup.org/page/Webinars>, (22 Jul 2020)
- Huang Q, Zhang Y, Yao Q, Li, S (2018)** Mineral manipulation of Zhundong lignite towards fouling mitigation in a down-fired combustor. *Fuel*, 232, 519-529 (Nov 2018)
- IEA (2019)** *Statistics, Coal information, Overview*. Available at: <https://webstore.iea.org/coal-information-2019-overview>, 11 pp (2019)
- IEA (2020a)** *Statistics report, Coal information, Overview*. Available at: <https://www.iea.org/reports/coal-information-overview>, 28 pp (Jul 2020)
- IEA (2020b)** *Statistics report, Electricity information, Overview*. Available at: <https://webstore.iea.org/electricity-information-overview-2020-edition>, 23 pp (Jul 2020)
- IEA (2021a)** *Global Energy Review 2021*. Available at: <https://www.iea.org/reports/global-energy-review-2021>, 36 pp (Apr 2021)

- IEA (2021b) Coal Information 2021.** Available from: <https://www.iea.org/data-and-statistics/data-product/coal-information-2>
- India CEA (2012) Report of the group for studying range of blending of imported coal with domestic coal.** Available at: https://cea.nic.in/wp-content/uploads/2020/04/blending_coal.pdf, 50 pp (Apr 2012)
- ISO (2006) ISO 18283:2006 Hard coal and coke - Manual sampling.** Available at: <https://www.iso.org/standard/31776.html>, 71 pp (Sep 2006)
- ISO (2016) ISO 13909-1-8:2016 Hard coal and coke — Mechanical sampling.** Available at: <https://www.iso.org/standard/63907.html>, (Jul 2016)
- Jamshoro Power Company Ltd (2021) Coal project.** Available at: <http://jpcl.com.pk/coal-project/> (Retrieved 1 Jun 2021)
- Jin Y A, Cheng J W, Bai Q, Li W B (2017) Study on the coal mixing ratio optimisation for a power plant.** In *IOP Conference Series: Materials Science and Engineering*, IOP Publishing. Vol 283, No 1, p 012019 (Dec 2017)
- Lazarova I, Vanov M (2020) Newcomers in the initiative: Stara Zagora, Bulgaria.** In *Current outlook of the Coal Regions in Transition Initiative, EU coal regions in transition virtual week*, 16 Nov 2020. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/16_november_-_current_outlook_of_the_coal_regions_in_transition_initiative.pdf, 75 pp (Nov 2020)
- Li J, Zhu M, Zhang Z, Zhang K, Shen G, Zhang D (2016) The mineralogy, morphology and sintering characteristics of ash deposits on a probe at different temperatures during combustion of blends of Zhundong lignite and a bituminous coal in a drop tube furnace.** *Fuel Processing Technology*, 149, 176-186 (Aug 2016)
- Li J, Zhu M, Zhang Z, Zhang K, Shen G, Zhang D (2017a) Effect of coal blending and ashing temperature on ash sintering and fusion characteristics during combustion of Zhundong lignite.** *Fuel*, 195, 131-142 (May 2017)
- Li D, Lv Q, Feng Y, Wang C A, Liu X, Chen K, Che D (2017b) Effects of coal blending and operating conditions on combustion and NOx emission characteristics in a tangentially-fired utility boiler.** *Energy Procedia*, 105, 4015-4020 (May 2017)
- Lin S (2018) Problems of blending Indonesia coal.** *Power equipment*, 13, 3 pp (Sep 2018)
- Liu Y, Zhang H, Zhang X, Qing S, Zhang A, Yang S (2018) Optimisation of Combustion Characteristics of Blended Coals Based on TOPSIS Method.** *Complexity*, article ID 4057983, 9 pp (Jan 2018)
- Liu L, Wang Z, Qin Y (2019) The combustion characteristics of coal blends under low oxygen atmosphere using the thermogravimetric analyser.** In *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, Vol. 472, No. 1, p. 012066 (Feb 2019)
- Ma L, Yu S, Chen X, Fang Q, Yin C, Zhang C, Chen G (2021a) Combustion interactions in oxy-fuel firing of coal blends: An experimental and numerical study.** *Journal of the Energy Institute*, 94, 11-21 (Feb 2021)
- Ma L, Chen X, Yu S, Fang Q, Zhang C, Chen G (2021b) Effect of H₂O on the combustion characteristics and interactions of blended coals in O₂/H₂O/CO₂ atmosphere.** *Journal of the Energy Institute*, 94, 222-232 (Feb 2021)
- Majid A, Rehman K M (2019) Can Pakistan make its energy sector greener, cheaper and more reliable? The government thinks so.** In *World Economic Forum*, Available at: <https://europeansting.com/2019/09/17/can-pakistan-make-its-energy-sector-greener-cheaper-and-more-reliable-the-government-thinks-so/> (17 Sep 2019)

- Mao X (2021)** Coal blending tests at large power plants. In *Workshop on coal blending technology and fuel intelligence for coal-fired power plants*, Zhibo, Shangdong, China, 27-29 Apr 2021. 47 pp (Apr 2021 in Chinese)
- Miller B (2017)** Chapter 1 The Chemical and Physical Characteristics of Coal. In *Clean Coal Engineering Technology*, 2nd edition, Elsevier. 3-60 pp (2017)
- Mills S J (2011)** *Global perspective on the use of low quality coals*. CCC/180, London, UK, International Centre for Sustainable Carbon, 80 pp (Sep 2011)
- Mills S J (2016)** *Low quality coals – key commercial, environmental and plant considerations*. CCC/270, London, UK, International Centre for Sustainable Carbon, 111 pp (Sep 2016)
- Mining Technology (2020)** *India to stop thermal coal imports from FY24*. Available at: <https://www.mining-technology.com/news/india-stop-thermal-coal-imports/#:~:text=India%20to%20stop%20thermal%20coal%20imports%20from%20FY24&text=India%20Coal%20Ministry%20has%20announced,the%20substitutable%20import%20of%20coal> (19 Feb 2020)
- Mint (2021)** *Coal-fired power plant development to remain growth driver in India: FITCH*. Available at: <https://www.livemint.com/industry/energy/coal-fired-power-plant-development-to-remain-growth-driver-in-india-fitch-11618312799083.html> (13 Apr 2021)
- Mittal S, Pathak S, Dhawan H, Upadhyayula S (2021)** A machine learning approach to improve ignition properties of high-ash Indian coals by solvent extraction and coal blending. *Chemical Engineering Journal*, 413, 127385, 12 pp (Jun 2021)
- Moon C, Sung Y, Ahn S, Kim T, Choi G, Kim D (2013)** Thermochemical and combustion behaviors of coals of different ranks and their blends for pulverised-coal combustion. *Applied Thermal Engineering*, 54(1), 111-119 (May 2013)
- Moon C, Sung Y, Eom S, Choi G (2015)** NO_x emissions and burnout characteristics of bituminous coal, lignite, and their blends in a pulverised coal-fired furnace. *Experimental Thermal and Fluid Science*, 62, 99-108 (Apr 2015)
- Morris P (2021)** MCA, Australia, *personal communication* (Sep 2021)
- Murtaugh D (2021)** *China Tightens Grip on Coal Market as Prices Continue to Rise*. Available at: <https://www.bloomberg.com/news/articles/2021-06-21/china-tightens-grip-on-coal-market-as-prices-continue-to-rise> (21 Jun 2021)
- National Transmission and Dispatch Company (2019)** *Indicative generation capacity expansion plan 2018-40*. Available at: [https://nepra.org.pk/Admission%20Notices/2019/09-September/IGCEP%20Plan%20\(2018-40\).pdf](https://nepra.org.pk/Admission%20Notices/2019/09-September/IGCEP%20Plan%20(2018-40).pdf), 164 pp (Feb 2019)
- NS Energy (2021)** *Jamshoro Coal-Fired Power Plant*. Available at: <https://www.nsenergybusiness.com/projects/jamshoro-coal-fired-power-plant/> (Retrieved at 1 Jun 2021)
- Omar Q M, Umar S, Ahmad M, Fatima S, Javeed A (2017)** Proximate analysis of low and high quality pure coal and their blends from Pakistan. *Austin Chemical Engineering*, 4(1), 1048, 3pp (Apr 2017)
- Peltier R (2008)** Luminant's Big Brown Plant wins for continuous improvement and safety programs. *Power*, 152(7) (15 Jul 2008)
- Raaj S S, Arumugam S, Muthukrishnan M, Krishnamoorthy S, Anantharaman N (2016)** Characterisation of coal blends for effective utilisation in thermal power plants. *Applied Thermal Engineering*, 102, 9-16 (Jun 2016)

- Rajdeva I K (2014)** Blending of imported/high grade and domestic coals. In *Workshop on Environment friendly Technologies for Indian Power Sector-CFBC Boiler/Coal Blending*, New Delhi, 14 Nov 2014. 44 pp (Nov 2014)
- Real Time Instruments (2020)** *AllScan Onbelt Coal Analyser Use in Blending*. Available at: <https://www.realtimegrp.com/real-time-instrument/coal-power/coal-blending/> (Retrieved Sep 2020)
- Reid I (2016)** *Retrofitting lignite plants to improve efficiency and performance*. CCC/264, London, UK, International Centre for Sustainable Carbon, 97 pp (Apr 2016)
- Rokni E, Panahi A, Ren X, Levendis Y A (2016a)** Reduction of sulfur dioxide emissions by burning coal blends. *Journal of Energy Resources Technology*, 138(3), 032204, 9 pp (May 2016)
- Rokni E, Panahi A, Ren X, Levendis Y A (2016b)** Curtailing the generation of sulfur dioxide and nitrogen oxide emissions by blending and oxy-combustion of coals. *Fuel*, 181, 772-784 (Oct 2016)
- Santoso H, Hasan A, Harsono D, Susilawati E, Kurniawan W, Arifin W, Setiawan H, Biyanto T R (2016)** Optimisation of coal blending to reduce production cost and increase energy efficiency in PT. PJB UP PAITON power plant. *International Journal of Engineering Science Invention*, ISSN 2319-6726, 5(8), 25 -30 (Aug 2016)
- Saravanan V (2014)** Impact of blended coal firing on the power plant performance. In *Workshop on Environment friendly Technologies for Indian Power Sector-CFBC Boiler/Coal Blending*, New Delhi, 14 Nov 2014. 44 pp (Nov 2014)
- Sarkar P, Mukherjee A, Sahu S G, Choudhury A, Adak A K, Kumar M, Biswas S (2013)** Evaluation of combustion characteristics in thermogravimetric analyser and drop tube furnace for Indian coal blends. *Applied thermal engineering*, 60(1-2), 145-151 (Oct 2013)
- Sloss L (2014)** *Blending of coals to meet power station requirements*. CCC/238, London, UK, International Centre for Sustainable Carbon, 68 pp (Jul 2014)
- Spatari M (2016)** *Industrial regions and climate change policies. Reference document for the region of Stara Zagora (Bulgaria)*. Available at: https://www.etuc.org/sites/default/files/document/files/stara_zagora_report_-_final_en.pdf, 27 pp (Apr 2016)
- Statista (2020)** *Installed capacity of coal power plants worldwide as of January 2020, by select country*. Available at: <https://www.statista.com/statistics/530569/installed-capacity-of-coal-power-plants-in-selected-countries>, (2020)
- Su P, Zhang J, Cao R, Han J (2018)** Study of an Indonesia—originated lignite mixed and diluted combustion test in a 600 MW utility boiler and its numerical simulation. *Journal of engineering for thermal energy and power*, Vol 33, No 2, 79-86 (Feb 2018 in Chinese)
- Tamzok N (2021)** Ankara, Türkiye, Turkish Coal Enterprises, *personal communication* (Jan 2021)
- Thakur S K (2014)** Use of blended coal in thermal power plants. In *Workshop on Environment friendly Technologies for Indian Power Sector-CFBC Boiler/Coal Blending*, New Delhi, India, 14 Nov 2014. 14 pp (Nov 2014)
- ThermoFisher (2020)** *CQM Flex Coal Analyzer*. Available at: <https://www.thermofisher.com/order/catalog/product/CQMFLEX#/CQMFLEX> (Retrieved Sep 2020)
- Tillman D, Duong D, Harding N S (2012)** *Solid fuel blending: principles, practices, and problems*. Elsevier. 352 pp (Apr 2012)

- Totev T, Kanev D (2014)** Comparative analysis of firing different coal blends for boiler 12 at TPP “Maritsa East 2”. *International Journal of Science: Basic and Applied Research (IJSBAR)*, ISSN, 2307-4531, 14 pp (2014)
- TPP Maritsa East 2 (2021)** *TPP Maritsa East 2 EAD About the plant*. Available at: <https://www.tpp2.com/page/about-us.html> (Retrieved Jul 2021)
- Whitacre J, Iorio A, Schellenberg S (2014)** *Coal blending: business value, analysis, and optimisation*. arXiv preprint arXiv:1405.0276. Available at: <https://arxiv.org/abs/1405.0276>, 7 pp (May 2014)
- Xu Y, Guo X, Yu Q, Huang Y, Wang J, Sun H, Jia G, and others (2020)** Experimental and numerical investigation of combustion system improvement on 600MW bituminous coal boiler for burning lignite coal. In *IOP Conference Series: Earth and Environmental Science*, IOP Publishing. Vol 467, No 1, p. 012042 (Mar 2020)
- Zhang H, Wu S, Yang Y, Cheng J, Lun F, Wang Q (2020)** Mineral Distribution in Pulverized Blended Zhundong Coal and Its Influence on Ash Deposition Propensity in a Real Modern Boiler Situation. *ACS omega*, 5(9), 4386-4394 (Feb 2020)
- Zhang X (2021)** *Post-pandemic China energy sector*. Available at: <https://www.sustainable-carbon.org/blogs/post-pandemic-china-energy-sector/> (22 Apr 2021)
- Zhu C, Tu H, Bai Y, Ma D, Zhao Y (2019)** Evaluation of slagging and fouling characteristics during Zhundong coal co-firing with a Si/Al dominated low rank coal. *Fuel*, 254, 115730, 11 pp (Oct 2019)
- Zhu Q (2012)** *Update on lignite firing*. CCC/201, London, UK, International Centre for Sustainable Carbon, 75 pp (Jun 2012)
- Zhu Q (2014)** *Coal sampling and analysis standards*. CCC/235, London, UK, International Centre for Sustainable Carbon, 123 pp (Apr 2014)