Blending of coals to meet power station requirements

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Preface

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

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

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

Abstract

Blending of imported and domestic coal is becoming of increasing importance. Until recently, coal blending in power stations was mainly adopted to reduce the cost of generation and increase the use of indigenous or more readily available coal. Low-grade (high ash) coal can be mixed with higher grade (imported) coal without deterioration in thermal performance of the boiler, thus reducing the cost of generation. With coal markets changing, new reasons for coal blending are becoming apparent. As indigenous coals become less available, of lower quality or more expensive to mine in some regions, blending of imported coals becomes necessary. It can be challenging to ensure that the resulting blend will maintain plant output without damaging the boiler. For example, in regions such as India the increased use of imported coals in boilers which have been designed for very different coal characteristics could lead to significant plant issues.

It some cases coal blending is used as a form of pollution control, such as the combination of inexpensive high sulphur coals with more costly low sulphur coals to ensure compliance with sulphur emission limits. It is even possible to blend different coal types to maximise mercury reduction.

Many methods of coal blending are used. Coals can be blended at the coal mine, at the preparation plant, trans-shipment point, or at the power station. The method selected depends upon 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. Normally in large power stations handling very large quantities of coal, the stacking method with a fully mechanised system is followed.

This report discusses the different reasons and priorities for coal blending. It summarise the methods used in coal blending, from coal characterisation though to mixing and storage methods, including some case studies in challenging situations.

Acronyms and abbreviations

ASTM	American Society for Testing and Materials
Btu	British thermal unit
CCC	Clean Coal Centre
CEN	Comite European de Normalisation (European Standards Committee)
COBOS	Coal optimisation blending system
CQIM	coal quality impact model
CQM	coal quality management
DFTS	digital fuel quality tracking system
DSC	distributed control system
EPRI	Electric Power Research Institute, USA
EFR	entrained flow reactor
ESP	electrostatic precipitator
FBC	fluidised bed combustion
FGD	flue gas desulphurisation
GCV	gross colorific value
IEA	International Energy Agency
ISO	International Standards Organisation
kJ	kilojoule
MAF	moisture and ash free
PGNAA	prompt gamma neutron activation analysis
PLC	programmable logic controller
PM	particulate matter
PRB	Powder River Basin
ROM	run-of-mine
SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
TPC	Taiwan Power Company
US EPA	US Environmental Protection Agency

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1 Introduction

Coal-fired power plants are designed to burn coal with defined characteristics, commonly indigenous coals or coals that are cost-effective to deliver to the plant. However, over time, the accessibility of coals change and coal plants must make do with the coals that are available to them. These new coals may perform differently to the design coals in such a way that blending is required to reduce detrimental effects on the plant.

It is likely that, globally, at least 20% of power plants, probably significantly more, cannot achieve design output due to difficulties in sourcing coals which consistently meet boiler requirements (Petrocom, 2014). This could be resulting in a reduction of 10% or more in potential output from the plants and may be causing a loss of 2% in total output from the power sector as a whole. By optimising blending to provide compliant and consistent fuel stock, plants can increase their power output while reducing negative effects on the plant (such as corrosion and fouling) and potentially reducing emissions of pollutants of concern.

As emission standards tighten globally, the number of coals which can meet these standards drops. This pushes up the demand for compliant coals, and this generally results in a price increase. Blending allows the use of lower quality, non-compliant coals, thus increasing coal reserves and ensuring that all coals can be fully utilised. However, blending coal requires that two major questions be answered:

- How can the characteristics of the final blend be predicted/guaranteed?
- Where and how is the coal to be blended?

This report concentrates on blending of coals alone. It does not consider the blending of coals with other materials such as biomass or waste. These issues are dealt with in complementary reports from the IEA CCC (IEA Clean Coal Centre) (Fernando, 2007, 2012; Sloss, 2010). Blending of coal means different things to different producers and consumers – from simple mixing of coal from different seams at the mine through to refined homogenisation of a quality controlled combination of coals. This report covers all of these but concentrates on the level of blending which is relevant to most coal-fired power station operators.

Chapter 2 concentrates on why coal is blended, discussing the needs of the coal industry and how they are to be met. The chemistry of coal blending, the parameters required and how they may changing during the blending process, is covered in Chapter 3. Chapter 4 then concentrates on the mechanics of coal blending and how quality is maintained in a cost-effective manner in different practical situations, such as at the mine, during transport, or at the coal combustion plant. Where possible, Chapter 4 includes case studies and examples of coal blending sites and practices in various countries around the world.

2 Reasons for coal blending

The physical and chemical characteristics of coal are highly variable. As noted by Anderson and Nowling (2014), coal characteristics affect nearly every operational aspect of a power plant, including forced outage rate, maintenance costs, auxiliary power requirements, net plant heat rate, emissions, and the ability to meet full load. When commissioned, coal-fired power plants are generally designed to combust a certain type of coal. But times change and coals may become less available or less affordable throughout the operational lifetime of the plant. It is becoming more and more common for plants to have to consider accepting coals that do not match the characteristics for which they were originally designed. Since, as noted, coal characteristics affect almost every area of plant performance and operation, it is necessary to predict, as much as possible, the physical and economic challenges that will arise when switching coals.

Coal blending in its simplest form is the mixing of available coals to produce a blend which combusts well to produce heat and/or power. In the past, the focus for plant operators was largely on blending the maximum amount of the cheapest and/or most readily available coals with the minimum amount of higher quality coal to produce a new fuel mix which would produce power without causing plant damage. Whilst cost is still a high priority, as coal markets evolve and the power sector changes, many plants now also have to consider other factors when deciding on an acceptable blend of coals. Power plant operators must decide which parameters are most important in each plant. For example, some plants may consider moisture content a more important parameter than ash content and will blend accordingly. Some older plants may be willing to risk some minor slagging and fouling issues by buying cheaper but less consistent coal supplies.

Blending is very much a case-by-case issue and, in the majority of cases, the decision on the blend will be made by the plant operator based on personal experience and best judgment, rather than by any process that can be summarised for a document such as this. Zhang and others (2012) agree that, '*for most power plants, the operation of coal blend firing seems to be strongly dependent on the experience of the individual power plant operators*'. Many operators either have no reason to share plant-specific blending data or choose not to do so for commercial, legal or other reasons. In some cases, plants may be required by law to report coal data. However, this information is rarely published into the public domain and so the majority of the literature found during this review relates to either experimental academic studies, or to commercial information, such as utility reports, coal production data or material from equipment vendors. However, where possible, examples are included of experiences from full-scale commercial facilities.

The following sections look at the reasons why coal is blended and the ways in which the quality of blends can be predicted. Although fuel blending could be of interest in systems other than pulverised coal fired units, especially in fluidised bed combustion (FBC) boilers and gasification systems, this report focuses on blending for full-scale pulverised coal fired boilers.

2.1 Cost

The fundamental aim of a power plant is to produce power at the lowest possible cost. Once a power plant is constructed, the cost of the coal used to fire the plant is the usually greatest variable affecting the plant economics. It is therefore not surprising that cost is the main driver for coal selection. Blending allows plants to fire less expensive coals. Coals which, on their own, may be of such poor quality that they could cause detrimental plant effects, can be blended with higher quality, more expensive coals. This means that plant managers can take advantage of the changing prices on the international coal market. Blending of relatively local coals may become a necessity when current sources or existing contracts expire as an alternative to buying comparable coals from further afield.

For coal producers, coal blending offers many advantages. Coals can be bought on the spot market for a bargain price and then blended with higher cost coal can produce a saleable coal with profit. In some cases, coals are unsaleable without blending and so an otherwise useless coal can be upgraded to a valuable product through blending. For example, coals that have oxidised or weathered in older stockpiles can be beneficiated through blending. Coal producers are often required to provide coal to a certain specification (*see* later). If the coal available does not meet this, then blending with an appropriate additive coal can ensure that the specification is met and penalties avoided.

2.2 Security of supply

Many coal plants are required to run at high capacity and on a regular basis to ensure the supply of energy to customers. Consistency and security of the coal delivery to the plant is therefore a high priority. However, the quantity of coal in coal mines is finite. In some areas, coal plants are required or encouraged to use locally sourced coals. Some plants are built next to coal mines to keep transport costs down. Coal blending can extend the lifetime of local coal mines by 'diluting' the local coal supply with imported coals.

In some cases, supplies of coal are diversified for security reasons, especially for countries which rely on imported coals which may suddenly no longer be available. For example, the Taiwanese Government requires that the country hold one-third of the total national annual demand of coal as a 'safety reserve' which is only to be used in urgent situations such as energy crisis, war or strikes. The Government also required that the coal supply be diversified with different coals being sourced from different countries (Lyu and others, 1993).

In Korea, most of the coal plants are designed to fire bituminous coal with a moisture content of 2.0–10% as it has a high ignitability, high combustibility and high calorific value. However, due to 'coal import instability', low rank coals from Indonesia with moisture contents of up to 25% have been used. This causes significant operational difficulties in terms of heat loss of moisture vaporisation and high exit gas temperatures, resulting in lower boiler efficiencies. To accommodate these changes, Korean plants are now blending these low rank coals with coals with high volatile contents. The Korean Government has sponsored the development of upgrading plants for dewatering and drying of these higher moisture coals. The Korean Electric Power Corporation's Research Institute has developed the processing of what is known as 'ECO' coal at Indonesian plants with a view to using it as a blending fuel. Upgraded ECO coal alone is not suitable as a single pulverised fuel due to slagging issues in the boiler and spontaneous combustion issues in the pulveriser. However, blending of 30% ECO coal with the usual bituminous coal resulted in a clean burning fuel mix (Kim and Lee, 2011).

Figure 1 shows the flow of traded coal internationally to give a general idea of just how much coal is transported between continents and how far it may travel. As coal demand continues, new mines are developed and new infrastructure is created to make this coal available to the international market. Coal users now have significantly more opportunity to pick and choose coals than ever before. Blending allows plants to take advantage of the different coals available to them. Many modern plants in South East Asia are designed to burn up to 100 different coal types of various quantities and ranks and will blend coals as required prior to use (Isherwood, 2014).

European coal plants all tend to fire imported coals since European coal mining is relatively expensive. In 2018 Germany will stop coal mining as the state sponsorship – 'Kohlepfennig' – will cease. Initially the support for the state sponsorship was high as it kept local jobs and allowed power stations to use local coals. However, the amount of sponsorship has been reducing annually and the two remaining mines will be closed in 2018. Although there is still coal mining in Poland and the Czech Republic, the profit margin is low and production may not remain sustainable in the global market for much longer. This will lead to plants having to source coals from further afield (Gutscher, 2014).

As the demand for coal increases, some countries are expanding their import of coal and, at the same time, building in blending capabilities as they do so. Lieberwirth (2012) reports that an electricity provider in the Philippines plans to build a number of new plants in the region and is investigating the option of a centralised coal blending and homogenising stockyard next to several small coal mines, the combined coal from which will be used to supply three plants – one next to the stockyard and two on separate islands.

As mentioned above, due to '*coal import instability*', Korean power plants must often fire lower rank coals with significantly higher moisture (up to 25%) than they are used to.

In India, many of the indigenous coals are relatively poor quality. Few of the coals are washed and the handling of the coals tends to be relatively basic at some plants. Moisture can cause distinct problems with both coal handling and plant performance, especially during the rainy season. The majority of these plants have been designed to handle dry lumped coal and so changes in coal characteristics can lead to problems. During the rainy season, wet coal can cause disruption to the flow of coal from stockpiles to the plant, in turn leading to capacity dips and decreased performance. Bhatt and others (2010) report that even three days of rain at a 1–3 GW plant can lead to dips in the order of 25–35%. Wet coal leads to problems in tippling, transferring, crushing, conveying and bunkering. Also, coal fines (<1 mm) in coals can also cause issues for handling and conveying systems which have originally been designed for lump coal.

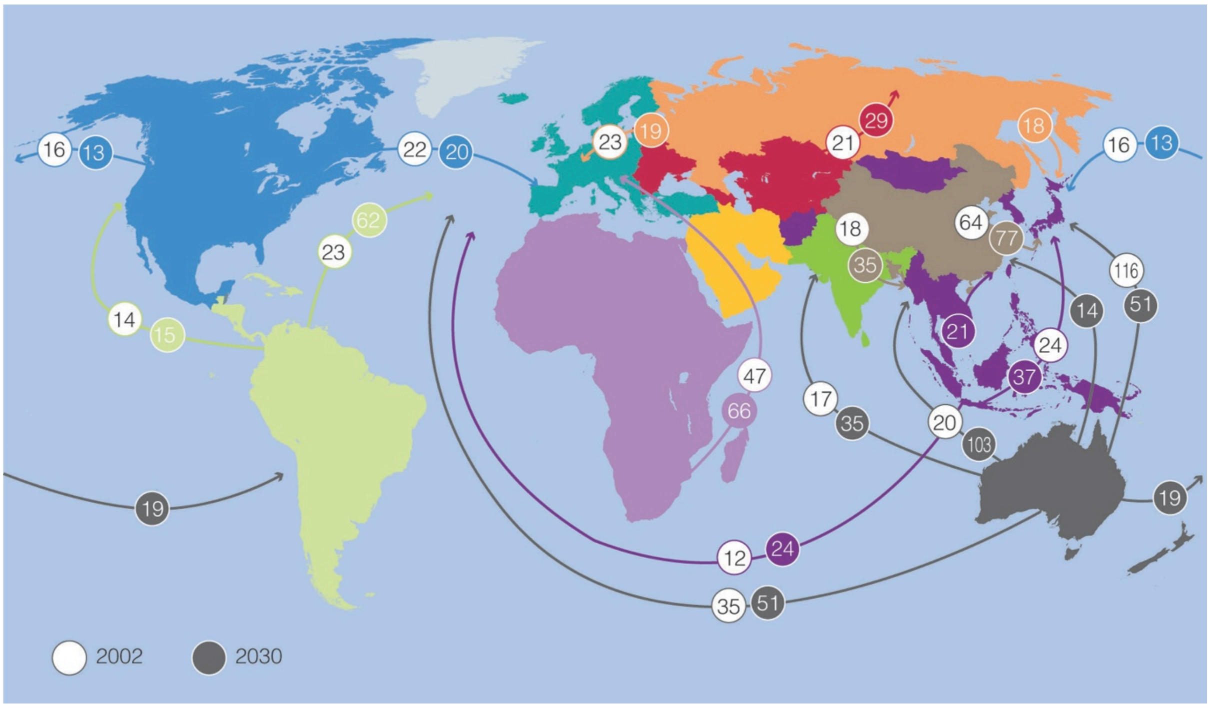


Figure 1 Inter-regional coal trade flows (Mt) (WCI, 2009)

The blending of imported coal with indigenous coal in India is not cost competitive except when the heating value of the indigenous coal is too low to be economically sustainable in the boiler. However, in the monsoon season, the reduction in the availability of dry coal means that fuel oil must be used and the cost of fuel is significantly greater than the cost of imported coal. And so plants could benefit from planning and blending in advance of the rainy season to maximise plant performance whilst avoiding the necessity to resort to fuel oil to meet demand. However, mixing high value coal with low value coal in the stockpile well in advance of when it is needed would be a new concept in India (Bhatt and others, 2010).

2.3 Meeting plant specifications

The first priority of coal plants is to provide electricity/energy on demand. This demand can vary over time and so the operation of the plant will be adjusted accordingly. This often requires changes in fuel – high Btu/kJ blends can be used to reach peak load at any given unit and lower Btu/kJ blends used during lower load periods (Campbell, 2014).

Plant operators know what coals suit their plants and will make coal selections based on meeting minimum specifications. When these specifications cannot all be met, the plant operator must make a decision as to which parameters matter the most. Coal will then be bought, and/or blended accordingly. Coal characteristics and their effect on coal combustion are covered in numerous previous reports from the Clean Coal Centre and the interested reader is recommended to browse our publications list for more details.

As mentioned before, coal-fired power plants are designed to suit the available coal. If the coal is no longer available or the characteristics change for any reason, this can have adverse effects on plant performance, including changes in combustion performance, efficiency, and detrimental effects on equipment. Lower quality coals can cause plant performance issues, such as slagging and fouling. These issues are discussed in more detail in a previous CCC report (Barnes, 2009).

There are a few major coal characteristics which are regarded as important to plant operation. Some of these characteristics are determined by proximate analysis (Carniato and Camponogara, 2001):

- **Moisture**. This applies only to the moisture held within the structure of the coal and not to any moisture from rain and so on. Moisture can have a significant effect on plant efficiency since water is incombustible. Moisture also affects the gas volume and the dew point of flue gases which can lead to condensation which, in turn, causes corrosion, clogging of filters and dust retention on precipitators. Coals which are high in moisture are heavier and therefore cost more to transport. Drying adds an extra stage to coal processing which is undesirable.
- **Volatile matter**. Volatile matter is the more reactive fraction of the coal which is driven off when coal is heated. Coals with high volatile matter tend to ignite easily and are reactive in the combustion zone.
- **Fixed carbon**. This carbon remains after the volatile matter is expelled. A high fixed carbon content indicates that the coal will take a long time to combust. Fixed carbon is the principal element influencing combustion.
- **Ash**. This is the incombustible fraction remaining after combustion. At high temperatures, coal ash becomes sticky and eventually forms molten slag. Ash handling systems are designed to cope with this. Ash content affects flame and ignition stability, heat transfer patterns, char burnout, and combustible carry over to fly ash.

Coal customers will often also ask for information on some of the following parameters (Wall, 2001, Carpenter, 1995):

- heat capacity – the amount of heat necessary to raise the temperature of a given mass by one degree;
- grindability – sometimes recorded as the Hardgrove Grindability Index, a measure of the resistance to crushing. This is affected by moisture and ash content and will determine the type of coal equipment required by the plant to process the coal for combustion;
- granularity – a measure of the size distribution of the coal particles. The range of granularity should be control to prevent spontaneous ignition during grinding;
- free swelling index – gives an indication of how much a coal will swell within the boiler. Coals with higher free swelling indexes tend to have lower combustion efficiencies;
- ash fusion temperature – gives an indication of the softening and melting characteristics of the coal.

Ultimate analysis is performed to provide information on the elemental composition of the coal. This will provide information on the following: carbon, hydrogen, nitrogen, sulphur and oxygen. Sulphur is important for several reasons (Carpenter, 1999):

- it can play a role in spontaneous combustion;
- sulphur compounds can have detrimental effects on boiler operation, such as slagging and fouling;
- many plants now have to comply with sulphur emissions limits.

Some coal customers will also request information on chlorine content of the coal as this can affect the gas pH which, in turn, may affect flue gas desulphurisation (FGD) units. Also, chlorine can have a beneficial effect on mercury control (*see* Section 2.4).

When predicting the behaviour of coal blends, it is accepted that values for proximate, ultimate and calorific contents are additive – that is, the value of the blend will be the average value of the coals within the blend, proportionally. This is not the case for some of the other coal characteristics. In a review of coal blending, Wall and others (2001) summarised those properties that are not additive – that is, the blend property is not the weighted average of the properties of the individual coals. They advised that non-additive or not fully-understood characteristics provide a poor basis for predicting blend performance. Additive versus non-additive coal characteristics are summarised in Table 1.

Table 1 Additive and non-additive coal characteristics (After Wall and others, 2001)

Additive	Non-additive	Unsure
Calorific value	Free-swelling index	Ash
Fixed carbon	Grindability	Nitrogen (some comes from combustion air)
Hydrogen		Ash fusion temperature
Carbon		Volatile matter
Chlorine		Moisture
Sulphur		
Oxygen		

A literature review such as this can cite numerous papers *(see* reference list) studying the behaviour of coal blends using different analytical techniques and these studies all agree with the distinctions described above – that some characteristics of the individual coals in the blend are additive whilst others are not. And whilst trends can be seen when mixing two or three distinct coals which will improve the understanding of one particular blend, there seems to be no general rule which can help operators full predict how all coals will behave. Hence the need for continued study and more work into modelling tools (*see* Section 3.4).

As mentioned above, much of the coal blending carried out at plants is performed by plant operators who have personal experience in coal blending and who understand the additive and non-additive characteristics of coal but know, from experience what may work in practice. For example, plants in northwestern China mix low and high fusion temperature coals to relieve the problem of slagging and coking. Wang and others (2011) note that these blends are determined based on operational experience and not by any predictive method and suggest that a greater understanding of the coals used and their behaviour once blended would be beneficial.

There are excellent examples in the literature of how the behaviour and combustion of coal blends can be maximised by taking advantage of some of the changes that occur when two coals are blended. For example, Zhang and others (2011) studied the grindability of blends, based on the Hardgrove Grindability Index. It was noted that the grindability the coals was mainly bulk crushing with supplementary surface crushing. However, if a blend contains more coal that is hard to grind, the surface crushing effect increases during the crushing process – the coal that is harder to grind will further grind the particles that are already ground. It is therefore feasible to select blends with mixed grindability with the aim of improving the overall grindability of the blend as a result.

The activation energies of blended coals are general noted to be lower than those of the parent coals (Zhang and others, 2012). Increasing the oxygen concentration in the combustion zone results in significant improvement of combustion performance of blended coals. Also, addition of high reactivity coals can improve combustion reactivity and shorten the burning time of blended coals with the ignition performance of the blend being closer to that of the higher reactivity coal and the burnout performance being closer to that of the lower reactivity coal. Cofiring coals with different reactivity leads to multiple peaks in the differential thermogravimetric curve, which is a method of relating temperature to the burn rate of the coal. And so it can be argued that, although coals may be blended to homogeneity in practice before they are fed into the boiler, the actual burn characteristics of a blend will always be that of two or more individual coal types. However, increasing the oxygen concentration in the combustion zone, if possible, can enhance the combustion stability of blended coals greatly.

For some plants, the consistency of the coal quality is as important as the absolute quality (Isherwood, 2014). It is noted that some boilers, particularly those with older types of control systems, will start 'hunting' (fluctuating in pressure) when coals are not homogenous or fully mixed. Some boilers will experience this unless there is less than 1–2% variation in coal characteristics within the coal mix (Stott, 2014). Some plant operators will find a product or blend that suits them and they would prefer to burn this for as long as possible whilst others are happy to experiment and change products or blends on a routine basis, often every few days when a new shipment arrives. This reduces the need to stockpile each shipment. This is referred to as direct bunkering from a ship. The latter approach is becoming more common as power stations seek to diversify supply, seek cheaper sources and, at the same time, reduce operating costs. However, in some companies, the coal may be purchased by a central head office based largely on price and the plant will need to adapt to what is delivered (Isherwood, 2014).

It is also probable that in some regions of Asia, coal plants were bought and installed based on the success of an operational plant burning a certain coal but, upon construction, these newer plants are having to operate with coals which are different to those available at the original plant. Many older plants in China are operating at reduced plant efficiencies. Studies by Petrocem have shown that by switching to coals which are blended to suit the plant, the average efficiency of these older boilers could be increased by at least 4%. Since an increase in efficiency means a reduced coal requirement, this could amount to a reduction of 80 Mt/y coal across China should all of these plants switch to burning blended coal tailored to match their design characteristics. Part of a large grant is currently being used to assist in the build of two coal blending plants in one of Chinas major industrial Provinces and this may lead to the installation of further plants elsewhere. The strategic placement of coal blending plants on the China rail system could also reduce the need for coal wagons and thus reduce transport costs and issues by reducing the unnecessary movement of sub-quality coals (Stott, 2014).

For some plants, coal switching to certain types is simply not possible. Most plants would not be able to switch from burning only high sulphur Eastern US coals to burning PRB coal exclusively without the plant being de-rated due to the lower heating value of the coal. There would also be significant modification costs to cope with the increase slagging and fouling caused by Powder River Basin (PRB) coals having higher friability (McCartney, 2006).

Although outside the scope of this report, coal gasification can also benefit from blending technologies and this is an area of significant study in China (Bai and others 2011; Wu and others, 2011).

2.4 Emission legislation

As legislation on pollution control tightens internationally, many plant operators are finding that they need to reconsider the coals they use in order to comply with emission limits or reduction targets (Sloss, 2009).

As a carbon intensive fuel, coal is well established as a source of **CO_2** emissions to the atmosphere. Some plants cofired other materials such as biomass to reduce the overall CO_2 emissions. This is beyond the scope of this report. However, it is possible that coal and lignite blending could be optimised to reduce CO_2 emissions. Vamvuka and Galetakis (2010) report on the potential reduction of CO_2 from power plants in Greece by variation in the lignite blend. Emissions are known to be higher from those plants fed with lower quality lignite or with lower overall plant efficiency. Greece is heavily dependent on lignite for power production (60% of total energy production) and the majority of this lignite is produced from the Ptolemais and Megalopolis basins. This lignite is low in calorific value and high in ash. The quality of the lignite varies significantly both within and between mines and can fluctuate through seasons due to changes in moisture content. Studies are ongoing in the area to demonstrate that selective mining and appropriate blending/homogenisation could improve plant performance whilst reducing overall CO_2 emissions.

During the 1990s and 2000s, many plants in the USA had to make the decision on how best to comply with the US EPA (US Environmental Protection Agency) national **sulphur** trading requirements. Whilst some plants installed FGD to reduce SO_2 emissions, others opted to switch to lower sulphur coals, including the popular low sulphur PRB coals. Many plants could not make this fuel switch without incurring excessive costs for de-rating plants and modifying systems to cope with this coal which has a lower heating value and higher friability. Therefore many plants chose to blend the low sulphur PRB coal with eastern coal (McCartney, 2006). This significant change in the geography of coals meant that many coal yards and plants had to switch from receiving coal by barge to receiving coal by train. This often also meant a significant change to the plant landscapes and the installation of significant new coal handling systems. However, these adaptations were clearly worth it in terms of avoiding fines or closure requirements through non-compliance with emission limits.

Bhamidipati and others (2004) report on the blending of coals at the B L England Station, New Jersey, USA, to comply with sulphur limits. The limit set for the cyclone boiler was 1.7% on sulphur in fuel on an annual basis and 1.9% on a monthly basis. This required the blending of PRB with Eastern bituminous coal. The blend was maintained at 30% PRB as this could comply with the sulphur limit without adversely impacting the plant performance. On its own, the Eastern coal had a moisture content of 5.15% and this increased to 10.29% in the blend. The ash dropped from 9.8% to 7.46%, the fixed carbon from 49.59% to 46.95% and the volatile matter from 35.79% to 35.29%. The heating value of the blend was also lower at 12,053 Btu/lb (28,035 kJ/kg) as compared with 12,855 Btu/lb (29,900 kJ/kg) in the Eastern bituminous coal alone. The slag viscosity factor decreased only slightly with the blend and so the 30% blend did not require any extensive boiler modification or adaption of the ESP (electrostatic precipitator).

Zhou and others (2012) studied the blending of a mid-sulphur Chinese coal (Pingshuo) with various typical low sulphur coals in different proportions. The study (in Chinese) demonstrated that some of the reduction in sulphur in emissions was due to the reduced sulphur content of the coal blend but also due to the increased retention of sulphur in the ash.

Lignite from the Mae Moh mine in Thailand has higher ash and sulphur contents than most of the lignites from countries such as Germany, the USA and Australia, and this can lead to slagging issues. However, blending lignites from different areas to limit the CaO in ash has proven successful and the blending is also used as a means of reducing the sulphur emissions (Pipatmanomai and others, 2009).

During combustion, **NOx** emissions arise as a result of both nitrogen in the coal and nitrogen in the combustion air. It is therefore often difficult to predict NOx emissions from coals. This has been covered in a previous CCC report (Nalbandian, 2009). NOx emissions from blends are also non-additive, in that the emissions from combustion of a blend of coals cannot easily be predicted from the behaviour of the coals individually.

There are emission limits for NOx in regions such as the EU, North America and several countries in Asia (Sloss, 2009). In most cases these limits are met with flue gas treatment systems such as SCR (selective catalytic reduction) and SNCR (selective non-catalytic reduction). However, coal blending to reduce NOx emissions is an option. In several states in the USA, NOx reduction requirements vary with season, with lower NOx emission required from May to September when solar induced ozone pollution is more of an issue. Many plants will change coals during this season as a means of compliance (Mooney, 2006).

NOx emissions from fluidised bed combustion (FBC) systems, can be more challenging to control than those from pulverised fuel boilers. Boavida and others (2004) studied NOx emissions from an FBC boiler firing individual coals and coal blends. In all cases, the release of NOx increased with temperature up to around 1173°K (900°C) and these started to decrease. However, for some blends, the NOx emissions were higher than from each of the individual coals on their own. The coals studied included Asland, Sasol and Carbocol coals. The production of N_2O was also greater with blends than with individual coals. It was suggested that this was due to the enrichment of precursors responsible for NOx formation, originating from both coals making up the blend. There was also a strong correlation with char oxidation, which could also facilitate the release of volatiles during combustion.

Particulate matter, especially smaller particles (PM_1 – particulate matter <1 micron in diameter) can be extremely harmful to health due to the ability to penetrate deep into the lungs. The CCC has published several reports on this issue (Smith and Sloss, 1998; Sloss, 2004). These smaller particles tend to be richer in toxic heavy metals than larger particles. These particles can also promote fouling and corrosion in the boiler, affecting the safe operation of the boiler and the efficiency of the heat exchanger. Zhou and others (2010) carried out bench-scale studies in a drop-tube furnace of different coal blends to study the effect on PM_1 emissions. It was demonstrated that the lignite studied produced more PM_1 and $PM_{1–10}$ than bituminous coal sample. However, mineral interactions between the two coals in a blend suppressed fine particle generation to a level lower than with either coal individually. Further, the concentrations of Fe and Ca in the fine particles was lower for the blends but the concentrations of these elements, and of Si and Al, were higher in the larger particles (PM_{10+}) during the combustion of blends.

Ji and others (2012) showed that $PM_{2.5}$ emissions are not linearly related to the weight % of the parent coals or coal blends. However, through adjustments of the mineral composition of the blends (Ca, Mg, Al and Si contents), the reduction of PM_1 and $PM_{1-2.5}$ emissions could be achieved. These studies were carried out in a drop-tube furnace and the resulting PM studied by scanning electron microscopy. It was confirmed that fine Si-Al particles are captured by coarse Ca-Mg-Al-Si particles to form larger Ca-Mg-Al-Si particles (>$PM_{2.5}$). Coals higher in Ca and Mg could be used to reduce emissions of fine particulates in coal blends.

Although these two studies, from China, suggest that coal blending can be used to reduce PM emissions and that this could have beneficial effects on both emissions and plant operations, nothing further has been found in the literature to suggest that the results of these studies meet a specific plant concern or that the principals they demonstrate would be used to any great degree in practice in current coal-fired plants.

Emissions of **dust** from the coal handling facility can be of great importance not only to the health of those working or living nearby, but also with respect to potential spontaneous combustion, especially with coals such as PRB. Russell and others (2013) noted that the conversion of the B L England Unit to including 30% PRB in the blend to reduce sulphur emissions resulting in new requirements of dust suppression techniques in the coal yard, crusher house, conveyor and transition points and also in the bunker house.

Jiao and others (2013) report on the effect of blending two unidentified Australian coals (Coal A and Coal B) on the emissions of **trace elements** As and Se. Coal B, containing relatively high amounts of calcium, was more efficient at capturing As and Se in the fly ash fraction. Once in the fly ash, the As and Se have low leaching rates. Coal A, with lower calcium, emitted more As and Se in the gaseous phase. By blending the coals, the calcium in Coal B resulted in overall capture of As and Se in the ash from the blend in a stable form.

Mercury emissions from coal combustion are covered in several previous CCC reports (Sloss, 2008, 2012). The behaviour of mercury in coal combustion systems is complex but it is well demonstrated that oxidised mercury is relatively simple to capture in existing control systems such as bag houses and FGD systems compared to when it is in the elemental form. The chemistry of the coal plays a major role in determining how the mercury will behave. Coals with higher halogen content, such as higher chlorine coals, can produce mercury emissions which are easier to control. Several plants in the US have demonstrated that emissions of mercury from PRB coals is difficult to achieve but that the addition of 5-10% bituminous coal can increase the mercury capture from below 25% to almost 80%. Coal blending may be a useful option for mercury control from coal combustion in developing regions under the new Minamata Convention. More details are available in the CCC report by Sloss (2012).

2.5 Comments

The ultimate aim of coal-fired power plants is to provide the maximum amount of power output at the lowest possible cost. Plant operators must balance the maintenance of plant operation and output with the most inexpensive coals available. Due to changing coal production and markets, many plants will not be able to source coals that meet the exact specifications of their plant and will therefore have to combine the coals available to them to produce a blend that is acceptable.

Cost is an important consideration. However, there are often performance or emission legislation requirements which must be met which will mean that cost is not the overall deciding factor. Security of supply of fuel is a major issue in many regions. Although using indigenous fuels is often the most cost-effective approach, it is often the case that fuels are bought internationally either due to cost, performance specifications, availability or even due to national requirements for stability of stocks and reserves. Operators will have to ensure that the coals bought will be appropriate for the plant as many plants are designed to fire specific types of coal (low ash, low moisture and so on). Tightening emission legislation in some region means that plants may have to source coals which have lower concentrations of pollutants such as sulphur.

3 The chemistry of coal blending

As mentioned in Chapter 2, plant managers will seek blends which will allow them to produce the maximum amount of energy from their plant with minimal detrimental effects on plant performance and equipment and whilst meeting any relevant emission legislation. Determining how to produce the best blend to meet all these requirements can involve a significant amount of work to determine the characteristics of individual coals AND how these coals will behave when they are part of a blend.

In order to ensure that the characteristics of a coal or blend meet requirements, sampling and analysis is required at several steps during the coal delivery chain (Esbensen, 2012):

- to evaluate and confirm the characteristics of the coals before blending;
- to confirm that the blend achieved is as desired;
- in automated blending systems, to confirm or to adjust the blending ratios to ensure the blend remains consistent; and
- in some cases, such as certain plants in the USA, the characteristics of the coal feed, such as sulphur content, are required to be recorded for compliance purposes.

Sampling and analysis of coal is the subject of previous reports from the CCC and the interested reader is referred to these documents for more detail (Nalbandian, 2005, 2011). The sections to follow concentrate on sampling and analysis considerations which are important in any coal blending processes.

3.1 Sampling

The objective of coal sampling is to obtain a small amount of coal for detailed analysis which will be assumed to be representative of all the coal in that batch or shipment. Ideally the sample should reflect the overall variability within a coal batch. For materials such as coal, representative sampling can be a challenge.

In coal mines, samples may be taken after mining and before any sorting or blending. In coal handling and blending facilities, samples are commonly taken from the conveyors, as the coal is taken from the bins or stockpiles to the final transit point before combustion. Samples are grabbed, dropped or scraped from the belt into a container which is then removed for analysis, as shown in Figure 2.

Figure 2 Cross-belt sampler (F L Smith.com, 2014)

According to some, these cross-belt samplers, where the sides of the sampling plough are square on to the belt, should not be used as they are not proportional. It is argued that this approach can throw material off the belt which may end up in the sample (Robinson and others, 2012).

Peabody Energy contracted a project to determine the sample precision being achieved by a standard mechanical coal sampling system. The system studied was a three stage falling-stream mechanical coal sampler which dealt with 9000 t/h of coal being loaded onto rail cars. The falling stream system comprised several rounds of crushing and screening with the aim of producing crushed samples with even distribution of representative coal characteristics. The results from the falling-stream sampler were compared with those from a cross-belt sampler. It was suggested that there was the possibility of material segregation between the stages of sampling. Because the three-stage sampling system included a hammer-mill crusher with a discharge screen to size the coal being fed into the third sampling stage, this could be resulting in segregation of the ash-forming minerals that are typically harder and remain in the crusher for a longer period of time. Overall, the study demonstrated that sampling system bias was reported to be as high as 35.8% in some cases. Many operators do not use cross-belt samplers as they believe them to be biased. The study showed that over 40% of the cross-belt systems were biased as compared to 27.9% of the falling-stream samplers. It is likely that this is due to many sampling systems not being adequately inspected and maintained – cross-belt systems require more maintenance and attention than falling-stream systems (Robinson and others, 2012).

A 'true-belt' cutter system has been proposed that throws material off the conveyor belt by a moving plough (along the length of the conveyor) and then a portion of this thrown material is taken by a fixed cutter. As the material moves along the conveyor belt, samples from a long length of the conveyor are pushed off towards a set of bins at the side, as shown in Figure 3. Selecting bins at random should provide a representative sample. There would be some angling of the bins to ensure that material thrown off the belt would not be affected by the throwing action – particles of different shapes, sizes and weights would be distributed evenly. Trimaran cutters, where flour blades are used but only the centre samples are extracted, are reported to reduce any bias from particles bouncing off sampling blades. Robinson and others (2012) proposes further modelling and practical experiments to assist in the development of less biased materials handling devices. As this report goes to print, it would appear that the first true-belt sampler has been purchased for use in the gold industry.

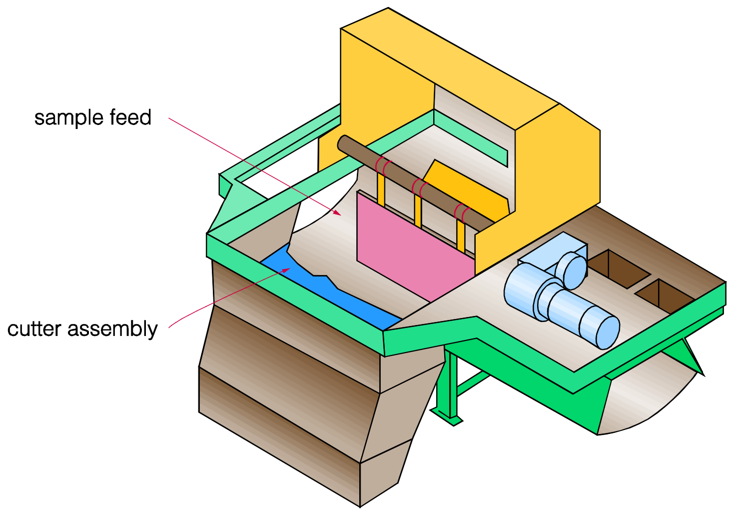


Figure 3 True belt sampling system (IM, 2012)

ISO (International Standards Organisation) standard ISO 13909 (parts1–8) – Hard coal and coke – mechanical sampling – provides guidelines on methods for sampling coal. This method is somewhat dated and so ISO TC27 SC4 Working Group 10 is currently completing an update. Part 8 of the proposed update deals with methods for testing for bias within the sampling method. The proposed new method differs significantly from the original standard method in the statistical methods used and is a simplification of the methodology. Rose (2012b) explains the proposed new multi-variate statistical analyses in detail and the interested reader is referred to this document for further detail.

Rose (2012a) has stated that '*the coal industry would profit from the use of methodology for routinely monitoring the overall measurement precision and the precision of the individual components of measurement – sampling, sample preparation and laboratory testing. This would not only give necessary credence to the measurement results but would also no doubt lead to more efficient sampling systems*'.

3.2 Analysis

Once a sample has been obtained it must then be analysed to establish the physical and chemical characteristics, as required. There are numerous methods for analysing coal and many of these function in a real-time online basis. This was the subject of previous reports by the CCC (Nalbandian, 2005, 2009).

Arch Coal, USA, is the world's single largest user of coal analysers. The analysers are used to provide data to automated coal blending systems and to provide quality assurance data on the final blends. Unlike coal analysis performed in labs, analyses at coal prep plants are done in large quantities to provide better data for large volumes – large volumes of sample will give a better indication of the average qualities of the coal than smaller samples which may reflect minor variations. For example, a sampling system such as the Thermo Gamma-Metrics 1812C handles 4 t/h of coal. These systems can provide real time analysis not only to those sending the coal on to final customers but also back to the mine to confirm whether the coals being sent for blending meet requirements. The analysers are based on prompt gamma neutron activation analysis (PGNAA). The systems include a moisture meter which also allows the estimation of Btu/lb (kJ/kg) (Woodward and others, 2004).

Mooney (2006) describes the development of a digital fuel quality tracking system (DFTS) using data from coal analysers to control coal stockpiling and blending at the Mansfield Plant in the USA. The digital fuel tracking system. Prior to installation of the system, the plant had been suffering from periods of issues with sulphur, despite having FGD installed. The DFTS was able to show that the coal quality and sulphur content was varying far beyond what was expected – the mine supplying the plant had hit a pocket of higher sulphur coal.

The B L England plant in New Jersey, USA, had to start blending 30% PRB coal with Eastern bituminous coal in order to comply with new sulphur limits in coal. A cross-belt thermo gamma-metrics nuclear coal analyser was used to continuously monitor the sulphur content of the blended coal. The results from the analyser were reported directly to the local environmental protection agency to demonstrate compliance. Quarterly manual sampling and analysis of the coal was require to verify the coal analyser accuracy, as per US standard ASTM 6543. Analysers such as the thermo gamma-metrics system are reported to have 0.08% accuracy for a sulphur range of 0.2–1% (as-received) and 0.07% accuracy at a range of 1–3% (Bhamidipati and others, 2004).

Coal analysis systems can be expensive to buy and maintain. Russell and others (2013) considered various options for sampling at the B L England plant in the USA to ensure that the on-site blending system was producing coal with the required sulphur content. They noted that the system used had a significant effect on the cost of the sampling and analysis process. For example, although an online nuclear coal analyser would provide the best data when located with the feeders in the crusher house, equipment and installation costs would be more than nine times the cost of a two-idler belt scale. Sampling would require a cutting system to sample a representative sample of coal and then feed this to the analyser which would need to be calibrated and verified. The sampling system would add a further 35% on to the total cost. It was decided that the cost of an online analyser system at this particular plant was not justified and, instead, a two-idler belt scale was used to control the blend on a weight basis.

3.3 Online blending control systems

Programmable logic controllers (PLCs) can be installed at coal handling facilities to take the data from sampling and analysis and use these to control blending ratios on a real-time basis. For example, a coal mine in West Virginia, USA, uses an online analyser to monitor coal as it passes through the preparation plant. Data from the analyser are used to sort the coal. For example, any coal with ash <16% is sent directly to the stockpiles; coal with ash >16% is sent to the preparation plant. Once the coal is washed, the analyser evaluates the coal and directs it to separate locations, according to quality. All the data on the coals in each pile are stored to be used to determine which coals are shipped and when. Another mine, also located in West Virginia, USA, produces coals from 10–33% ash, 0.5–2.5% sulphur, and 9,200–13,000 Btu/lb. The analyser can provide data to the blending system almost every minute to produce a quality blend to the desired specification (Gordon, 2013).

At the Arch Coal Catenary Coal Samples Mine, the gamma metrics analyser is used in conjunction with the COBOS coal blending system (coal optimisation blending system, *see* Section 3.4 below) to provide coal blends to certain specifications. In addition to the gamma metrics system sampling the coals as they enter the blending system, the Catenary plant also has a gamma metrics CQM (coal quality management) system sampling 5 t/h or the blend as it is produced to confirm blend consistency and feed back to the blending system to adjust feed rates accordingly. The CQM provides data every minute on both sulphur, ash content, and ash constituents, and is reported to be the only system currently available to two variables (such as sulphur and ash content) simultaneously (Woodward and others, 2004).

3.4 Modelling coal blends

As shown in Table 1 in Chapter 2, some characteristics of coal are additive within a blend, others are not. However, the behaviour of coal characteristics also has effects on different aspects of plant performance and some of this is predictable whilst some is not. Those aspects which are not easily predictable may have to be considered using more complex models, based on actual coal studies, in order to make them more predictable in future. Table 2 shows the characteristics of coals within a blend (the blend is assumed to be homogenous) and how predictable the behaviour of each of these characteristics will be in different areas of the plant performance.

Table 2 Predictability of the impact of key coal parameters on power plant performance (Wall and others, 2001)

Property	Handling	Milling and firing	Boiler	Ash management	Particulate removal	SOx control	NOx control
Moisture	No	Yes	Yes				
Ash	Yes		Yes	Yes	yes		
Volatile matter		No	No				No
Specific energy	Yes		Yes	Yes			
Sulphur total	No		No	No	No	Yes	
Sulphur pyritic	No	No	No		No	No	
Chlorine			yes				
Nitrogen							No
Hardgrove Grindability		no					
Ash fusibility temperature			no				
Ash analysis			No	No	No		
Trace elements	No	No	No				
Size distribution			no				

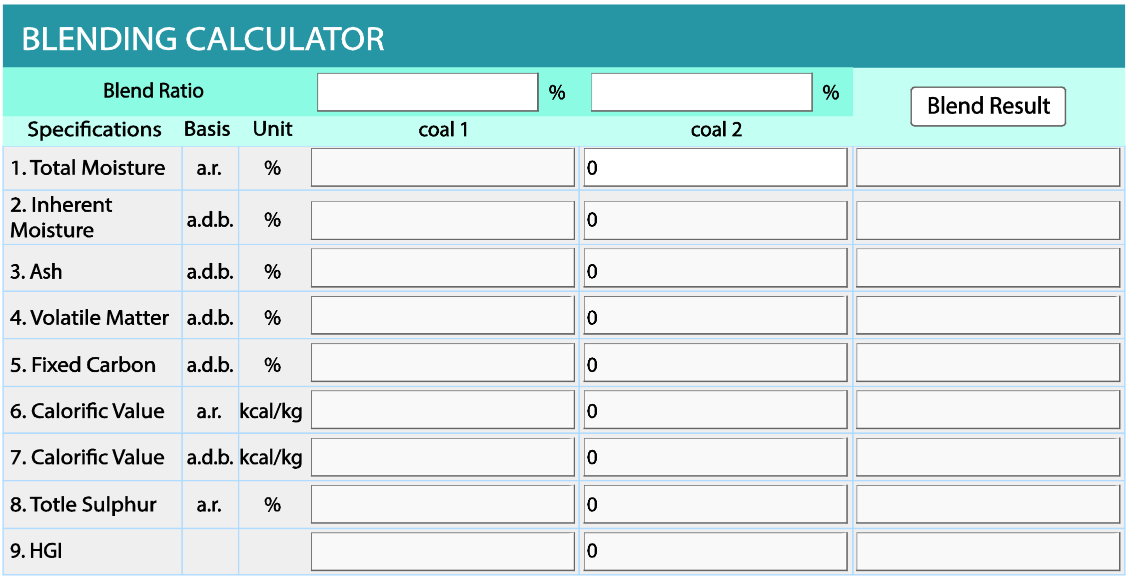
Based on the known additive parameters it is possible to predict blend characteristics based on the characteristics of the individual coals in a blend. Calculation tools are available which will allow coal users to feed data on individual coal characteristics and to receive a 'best guess' on the characteristics of the resulting blend. A simple search on the internet will provide online blend prediction tools such as:

http://www.seabase.in/pop-blending.html

http://www.adaro-envirocoal.com/files/blending.html

http://www.scribd.com/doc/129896718/Coal-Cost-Blend-Calculator

An example of the user interface of such programmes is shown in Figure 4.



BLENDING CALCULATOR

Blend Ratio			%	%	Blend Result
Specifications	Basis	Unit	coal 1	coal 2	
1. Total Moisture	a.r.	%		0	
2. Inherent Moisture	a.d.b.	%		0	
3. Ash	a.d.b.	%		0	
4. Volatile Matter	a.d.b.	%		0	
5. Fixed Carbon	a.d.b.	%		0	
6. Calorific Value	a.r.	kcal/kg		0	
7. Calorific Value	a.d.b.	kcal/kg		0	
8. Totle Sulphur	a.r.	%		0	
9. HGI				0	

Figure 4 Online coal blending calculator (Seabase, 2014)

These calculators are generally simple excel spreadsheets based on empirical data and some gross assumptions on the additive behaviour of certain parameters. Whilst they are useful, most plant operators would use them to ensure consistency when making minor variations in blends but would be unlikely to use such tools when making a major change in the coal mix, such as switching from an indigenous coal to a mix of imported coals. Some plants will use such tools but update them to create their own plant-specific spreadsheets which are tuned to their own plant performance and preferred coals.

Carniato and Camponogara (2011) provide a nice literature review of the development of modelling techniques used to maximise the economics of coal blending. For example 'chance-constrained optimisation models' take random variables (coal characteristics and so on) and convert them into deterministic equivalents which can be used to trade off expected costs against the probability of meeting coal specification requirements such as maximum sulphur or ash content or minimum heat value. These models can be used to help determine whether a plant should invest in equipment to operate with coals other than the base coal rather than placing further investment in coal beneficiation or blending. Carniato and Camponogara (2011) also describe a linear-programming model to take into account the key features of mining operations, such as coal processing and production over time, to produce a model that was agreeable to both mining engineers and mine managers. The model considered the whole of the coal production chain, taking into account variables associated with:

- individual coal types and production rates;
- grinding capacity and speeds;
- processing and washing rates, handling capacities of equipment;
- coal recovery and beneficiation rates;
- blending rates and ratios.

Along with these physical factors, the model could also consider costs of coal production, movement, shipping, cleaning and disposal of associated wastes. Whilst this flexibility can help keep costs down, it causes delays in production as machines have to be adjusted during operation.

Because of unknown variables such as future costs of coal or equipment operation, some blending models must also be expanded to cover uncertainty. Stochastic programming can be performed using 'recourse' as a corrective measure to adjust the calculation based on corrected data. The models can also calculate results based on a number of scenarios to allow the operator to make a judgment call based on the most likely option.

Lyu and others (1993) initiated a 'goal programming' model to determine the optimal quantities of coal from different stockpiles for a consistent feed of blended coal to meet environmental and boiler performance requirements. Of the twenty or so coal-fired plants in Taiwan, the Hsinta plant was selected for a feasibility study for the development of a tunnel, on-belt or coal-silo blending system. The coal yard was divided into two areas each with its own reversible conveyor and stacker reclaimer (*see* Chapter 4). The coal was segregated into several stockpiles. Coal as delivered from around 15 suppliers and falls into 4–6 different grades which then need to be blended to feed four boilers. The software produced was relatively complex to take into account all the relevant parameters and so a simplified user-interface was produced (Figure 5). This system is used to determine the contents of different stockpiles created from incoming coals. The stockpiles are then stored blended and ready to use and the blending model is only required as new stock is delivered. A prediction model was run to simulate one year of use of the model at the Hsinta plant, based on shipment data from the previous year. The simulation predicted the variations in parameters such as volatile matter and sulphur content which would arise in the coal blends as they were fed into the boilers. Although these parameters did vary (for example 0.53–0.94 % sulphur being fed into boiler 1 over the year), the value never exceeded any legislated or prescribed limit.

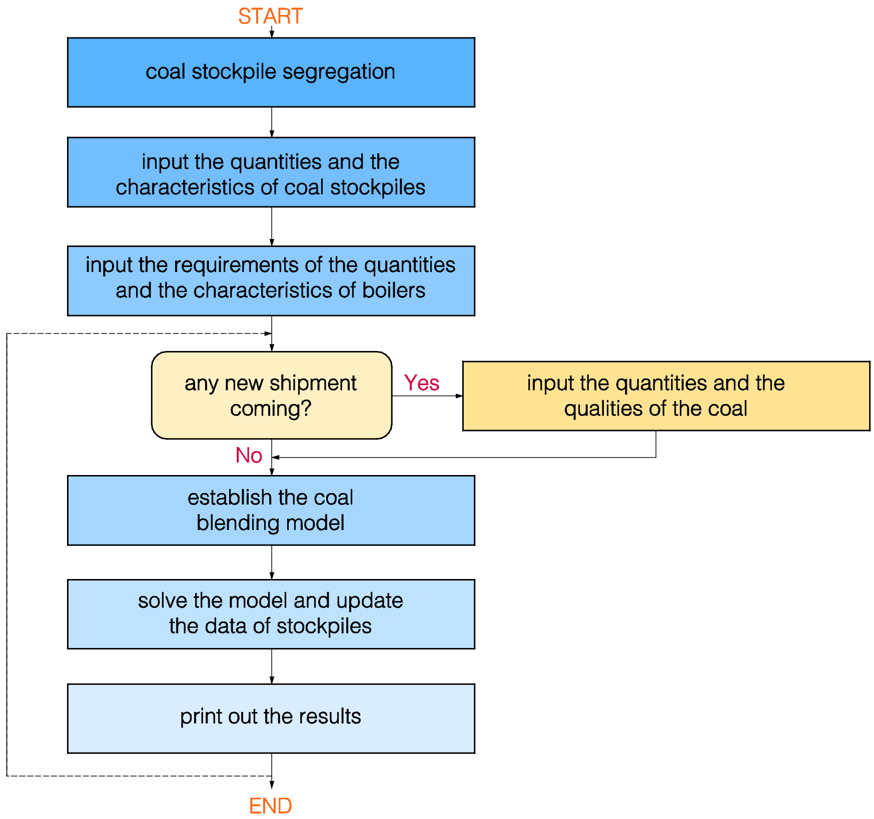


Figure 5 Operational flow chart of a coal blending management system (Lyu and others, 1991)

Zhong and others (2013) are preparing a 'coal selection-blend and generation cost prediction system' based on Microsoft Excel and numerous coal and plant parameters. According to the published paper (in Chinese) the application of the model in a 600 MW thermal power unit indicates that the generation cost prediction is 'reasonable' and could be used to help power plants select coals to optimise both blending and plant economics. There are even advanced coal blending models being developed based on neural networks and fuzzy logic (Xia and others, 2010).

The performance of pulversisers can be optimised to enhance the combustion of blended coals and to minimise the effects of potential burnout and slagging issues. Xia and others (2011a,b) have developed a computer algorithm which can be combined with existing dynamic coal blending systems to ensure that coal blends can perform best in existing plants.

A brief glance at the literature on coal blending models indicates that the vast majority of work being published comes from China. This is probably an indication of the scale of importance coal blending is in such a region, where coal use is increasing and coal quality will become a growing concern.

As mentioned in Chapter 2, changing coals at a plant can affect almost all areas of plant performance. It is therefore difficult to predict the overall cost of switching coals.

COBOS™ is a commercial coal blending optimisation system produced by Thermo Scientific (2014). Up to six coals can be blended to meet specifications taking cost into account. The system can work in conjunction with the analysis equipment also provided by the company. The blend can be based on up to five parameters such as ash, sulphur, moisture, ash oxides or ratios of ash oxides. The system automates the weight averaging of the MAF (moisture and ash free) calorific value, bound moisture and other ash constituents of all the coals being blended. Woodward and others (2004) report on the use of the COBOS system at the Catenary Plant in the USA. Although, as reported, the COBOS system can accommodate up to six different sources on any train or barge, and up to five control parameters, the common approach requires only two or three, usually just sulphur and ash. The Catenary plant loads unit trains from 10-16.5 kt at a load-out rate of 4 kt/h. The plant operators agree that the COBOS system allows them to meet customer requirements whilst allowing more flexibility in their own prep plant operation, since a wider range of coal qualities can be accepted.

The Electric Power Research Institute (EPRI) commission the development of a Coal Quality Impact Model (CQIM), which is a programme designed to predict the performance and cost impacts of burning alternate coals at existing power stations. Since its production in 1989, the CQIM program has become the industry standard for this type of prediction. The current version, known as Vista, provides evaluations such as (Anderson and Nowling, 2014):

- evaluate potential coal supplies and assist in fuel procurement or sales;
- determine the economic advantages of increased unit fuel flexibility;
- support engineering studies to predict impacts of equipment modifications on overall unit performance and economics;
- establish unit-specific coal specifications and property range limits;
- develop or evaluate premiums and penalties for key coal quality parameters for use in coal contracts and negotiations;
- assess changes in maintenance and availability costs;
- quantify the advantages or disadvantages of blending and cleaning coals;
- quantify the advantages or disadvantages of gas cofiring;
- evaluating performance and economic trade-offs from burning high sulphur coals that require flue gas desulphurisation versus burning compliance coals;
- identify the flue gas volume and make-up of potential coals for use in selective catalytic reduction system evaluations;
- screen alternative coals prior to test burns, collect expected impacts to help write test burn procedures, and evaluate results from test burns;
- develop strategies to address emissions limits; and
- document and standardise the fuel procurement decision process.

Although some of the program can be specific to plants in the USA (such as emission limit values and so on), the Vista programme has been applied in countries such as India, although on a theoretical basis (Anderson and Nowling, 2014). The model was run based on typical Indian coal plants and standard Indian coal characteristics. The model demonstrated the effects of increasing the ash content of coals from 26–35% and from 40–50%. As the ash content increases, the calorific value decreases and the coal consumption rate must increase to counteract this. The Vista programme also emphasised potential costs related to a move to higher ash coal. The pulverisers would have to be increased to cope with the increased full capacity, otherwise the plant would be de-rated by up to 12%. The increase in ash which would be produced as a by-product from the plant, which could lead to additional disposal costs. An increase in 5% ash in the coal could lead, theoretically, to an increase of over 20% in ash disposal costs.

The Vista programme was then used to predict potential changes in plant operation as a result of coal cleaning in India. Increased coal cleaning in India has been proposed as a means of removing ash and mineral matter from the coal to increase calorific value whilst reducing sulphur emissions. Coal washing would mean that the coal burn at the plant would decrease – which would reduce costs, but this would be offset by an increase in the cost of producing/buying the cleaned coal. But the cleaned coal would also yield benefits in terms of decreased maintenance costs and increased equipment reliability at the plant. The programme results suggested that if 25% of the coal were washed, the plant would make cost savings. However, at 50% washing, the plant will only break even and, at 75% of coal being washed, the cost reductions due to improved plant performance would not be large enough to offset the additional coal and cleaning costs.

Finally the Vista programme was used to predict the effect of blending Indian coals with higher quality coals available on the international market. For this study, Australian, Indonesian and South African coals were used in the model at 10%, 20% and 30% blends with the indigenous Indian coals. Although the international coals all had different characteristics, they were all lower in ash than the Indian coals. Firing Australian coal with the Indian coal was shown to reduce the fuel burn rate. The lower moisture in the Australian coal increased the boiler efficiency due to lower latent heat loss in the boiler. The unit availability also increased due to fewer steam generator tube failures and reduced pulveriser erosion. However, one negative effect noted was an overall increase in the CO_2 emission rate due to an overall increase in the carbon content per tonne of coal. A 30:70 blend of Australian: Indian coal resulted in CO_2 emissions increasing from 2.664 Mt/y to 2.673 Mt/y, an increase of 0.34%.

Indonesian coals have very low (1.2%) ash which decreased the overall ash content of the blend significantly. However, this meant a higher burn rate and higher flue gas flow rate than the Australian blend. The Indonesian coal also has more abrasive ash than the Australian coal. The Indonesian coal yields a small increase in unburnt carbon level which also reduces the overall efficiency of the unit slightly. When fired alone, the Indian coal had a thermal efficiency of 34.59% and a net boiler efficiency of 93.22%. With 30% Indonesian coal in the blend, the thermal efficiency dropped slightly to 34.34% and the net boiler efficiency to 93.21%.

The South African coal had the highest calorific value of the imported coals studied and the blend yielded the lowest coal burn rate, the lowest tube failures and the best unit availability, due to the lowest erosion potential of the South African coal ash.

This study with Vista shows how a programme can be used to predict the potential for both positive and negative effects arising from the switching of a plant from firing an indigenous coal to a firing a blend of indigenous coals and imported coals. Whilst there is always the risk that these models may not provide results with absolute certainty, it is likely that the cost of running such a model is significantly lower and less risky than running tests with the various coals at the plant.

3.5 Practice

In order to understand how a blend will behave, plant managers must have accurate information on the characteristics of all the coals to be blended. However, as discussed earlier, the combined performance of blended coals is not simply a reflection of the added characteristics of all the coals in the blend. Blending decisions must be made based on the knowledge of the specific behaviour of blends and not on an assumption of linear or additive benefits. It is also not simple to relate small-scale combustion tests to full-scale plant performance, which further complicates the prediction of blend behaviour.

Obviously the best test of any coal blend is to use it in the plant and to measure how well it performs compared to expected performance. Wang and others (2011) note that most coal-fired power plants which burn blended coal are doing so based on operational experience rather than through the use of complex blending models. Xu and others (2010) comment that, 'until now the success of blend combustion seems to be strongly dependent on individual power plant operators' experience'.

Many plants will have determined the most appropriate blend through a combination of operational experience and simply testing combinations of blends on site. For example, Gao and others (2012) carried out an experimental study with increasing contents of Huolinhe lignite added to Shenhua coal at a 1000 MW plant in China (un-named). The study considered the effect on mill output showing that, the more lignite in the blend, the lower the maximum output of the mill. The effect was significant above 40% lignite and it was concluded that 30% lignite was optimal. Testing also determined the optimal bias of oxygen at the outlet of the economiser and the optimal bias of the baffle opening for the overfire air. Coking problems in the boiler were solved by adjusting the combustion conditions whilst still achieving a 0.07% increase in boiler efficiency.

Only experienced plant operators would risk testing new blends on a valuable plant. It is therefore not uncommon for blends to be tested first at a small scale. For example, Sarkar and others (2010) performed bench- and laboratory-scale studies on two blends of un-named coals. One blend combined two coals which were quite similar in characteristics (rank, ash content and so on) while the other combined two coals which were very different. By studying the combustion behaviour of the blends, it was confirmed that some coal characteristics are additive in a blend whilst others are not. Sarkar and others (2010) noted that the lowering of the activation energy can be achieved through blending and that, in some situations, the blend may show an overall lower activation energy than either of the component coals. And so, more benefit may be obtained through blending a low ash coal with a high ash coal in appropriate ratios compared to blending only low ash coals.

At the plant, the coal will be recorded as it arrives, with notes on the characteristics specified by the supplier. These will likely be retested and confirmed at least once during the blending process. For plants performing blending on site, there will be a whole management tool operating to ensure that the personnel and equipment are co-ordinated to move the coal from stockpile to silo, through blending and processing into the plant. There will be a record of every time the coal is moved to ensure traceability of the coal on site. This will ensure that the plant manager always has a record of what coal is available and in what quantities.

Online sampling and analysis systems are useful for ensuring quality control during production of a blend to order. However, for contractual purposes, standard published methods (ISO, ASTM and CEN) are almost exclusively used to certify the quality of the product supplied and hence price paid (Isherwood, 2014).

Although sampling and analysis can be performed anywhere along the coal chain, it is most common for the contractual quality determination to be performed at the loading port using automated sampling systems and quality assured laboratories for the subsequent analysis. Sampling and analysis upon delivery may sometimes be carried out but is often based on manual grab-sampling systems which are less reliable than automated systems (Isherwood, 2014).

3.6 Comments

Sampling and analysis is performed at many places in the coal chain, from the coal mine through to coal washing or processing and through any blending process. The sample taken for analysis must be representative of the whole batch of coal that it has been selected to represent. This poses a challenge as coal is often, by nature, non-homogenous. Sampling is commonly performed as coal is travelling from one place (such as a mine or stockpile) to another (such as a silo or boiler). A random portion of the coal will be withdrawn and analysed. There is concern that many systems, especially cross-bed sampling systems, may not produce representative samples. However, the nature of coal processing makes it hard for this approach to be improved.

Analysis is performed for a number of coal characteristics such as moisture, volatile content, ash content and even elemental content (such as carbon, sulphur, chlorine and nitrogen). Physical characteristics such as grindability may also be measured. In some situations, this analysis can be performed rapidly in real-time allowing the feedback to the coal processing system.

Some coal characteristics within a blend can be calculated or estimated from the coals included in the blend whereas others cannot. Simple online tools are available which will allow coal users to predict basic parameters such as ash and sulphur contents from the data on individual coals in the blend. For more complex characteristics, more complex calculation tools are required. Commercial systems can be bought which can be used to predict how a coal blend will behave, based on the individual coals. However, these are not likely to be used to predict the behaviour of a new blend and a full-scale plant. Rather they will predict possible effects of minor changes. Most plant operators will carry out small-scale tests on new coal blends before risking any significant changes to blends in full-scale plants. Models will benefit from data from actual coal blends and significant work is being carried out in China to create more 'intelligent' models.

4 Blending techniques

This Chapter concentrates on the practicality of coal blending – where and how it can be achieved.

Blending of coal can be done in different ways to achieve different outcomes. Blending is rather more complicated than just the mixing of two or more coals together. However, homogenisation goes even further than blending for those who need a truly optimised combination of coals. Lieberwirth (2012) explains the difference between blending and homogenising:

Blending: – the mixing of two or more different materials to produce a blend with a new average level of certain parameters. This can be done to bring together layers of material brought in from different deliveries. The total of the mix has a predicted average quality, although there will be variation within different regions of the mix.

Homogenising: – the combination of different mixtures to reduce the variation throughout relative to the average. This requires more effort and more dedicated equipment and is therefore more expensive than blending.

One of the simplest ways to physically blend coals is to pile the coals together. Obviously, to achieve an effective mix, there has to be control over how the coal is mixed and combined.

There are two general ways of blending on site:

- blending in advance – creating the blend in a pile as the coal is delivered, by depositing the different coals into the same pile or hopper in a controlled manner;
- blending on demand – storing coals separately but reclaiming them into the mix as they are required for delivery to the boiler.

The following sections describe the different ways in which coal can be handled and/or stored to facilitate blending,

4.1 Stockpile blending

Perhaps the most simple and low cost method of coal blending is to place different coals into one single pile. This is known as 'stockpile blending'. Although the original CCC reports on coal blending and stockpiling (Carpenter, 1995, 1999) are somewhat dated, the diagrams produced to demonstrate the different methods of coal stockpiling to create blends still apply and are therefore included here (Figure 6).

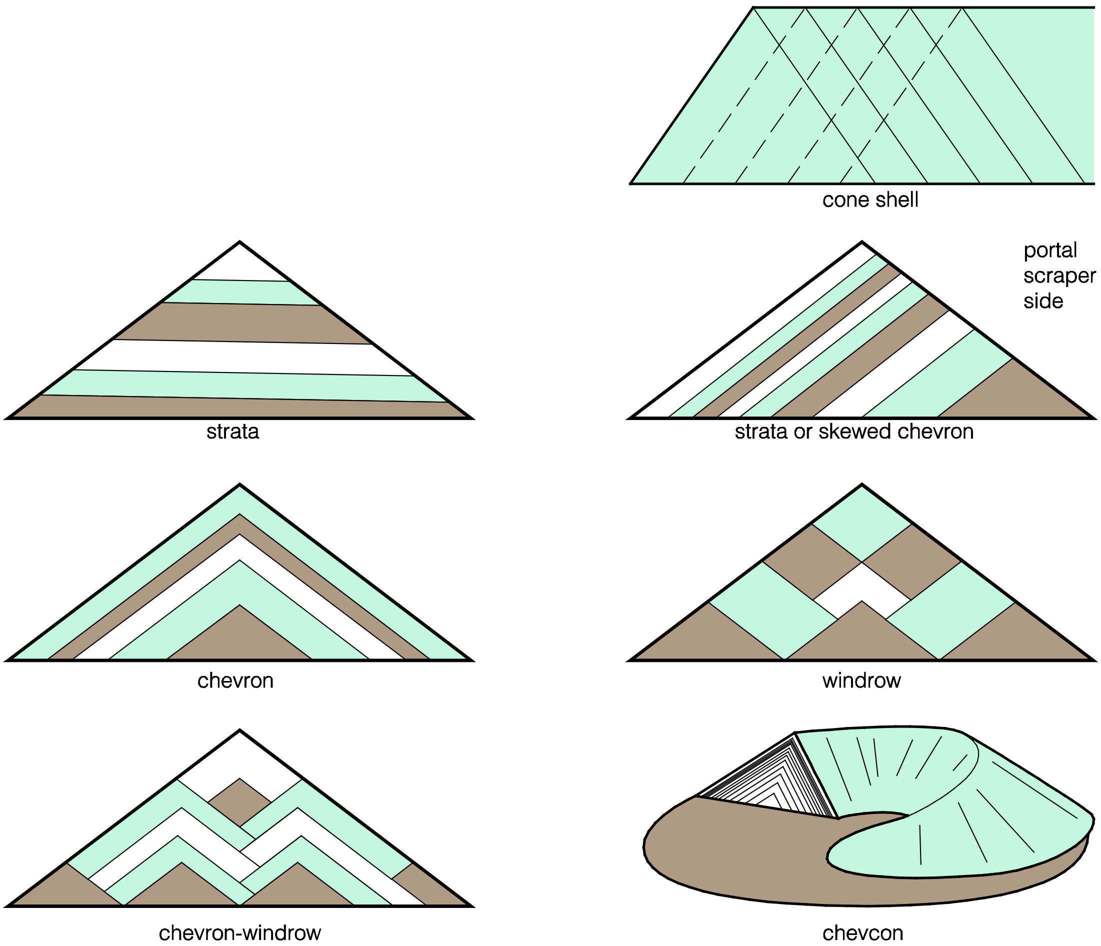


Figure 6 Stacking methods (Carpenter, 1999)

The pile grows as layers of different coals are added in horizontal layers as shown. The different colours indicate the different coals as they are added to the pile. The positioning and thickness of the layers allows the coals to be stored in ways that allow blends to be created as part of the reclamation process. Stacking coal in these formations requires specialist equipment, as shown in Figure 7.

As can be seen form the diagrams, this type of equipment is large and expensive and requires skilled operation. This will add significant cost to the coal handling process. The operation of this equipment varies with design. Fixed boom systems are cheaper but require more space for the whole system to move to facilitate the spread of the coal. Retractable booms allow more flexibility of movement. Luffing booms maintain their level of lift or drop – the jib within the crane ensure than the boom remains at the same height. Slewing booms allow rotation at the gear, meaning the boom can move from side to side on one level.

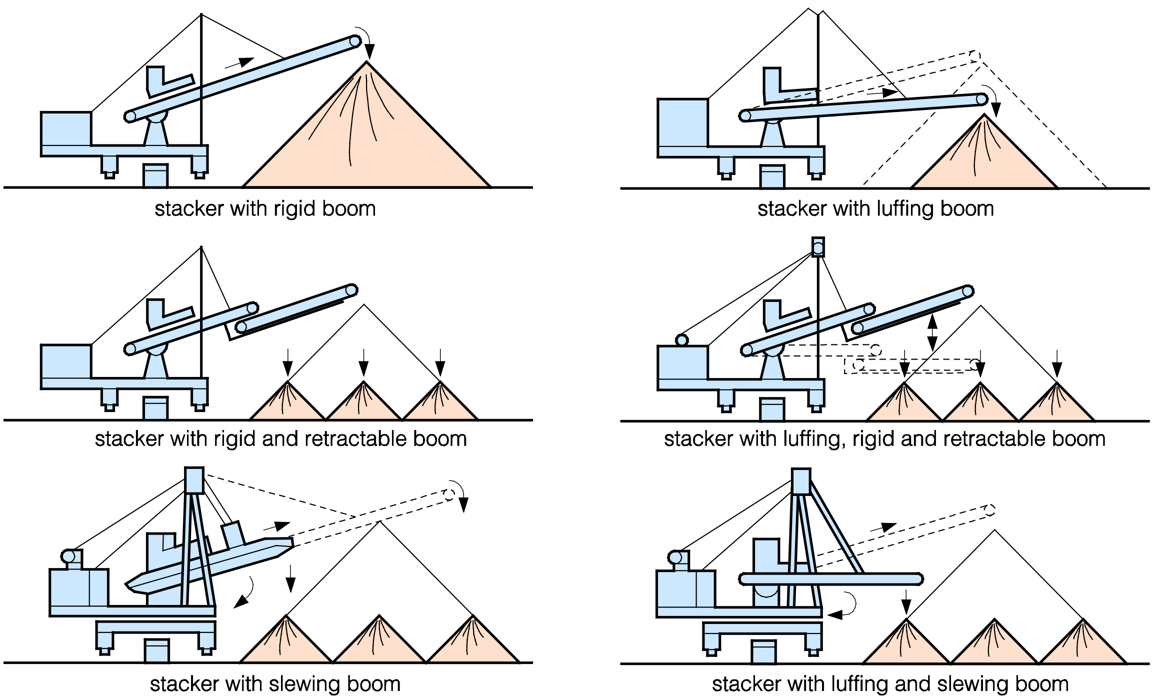


Figure 7 Coal stockpile stacking equipment (Carpenter, 1999)

Depending on the size and layout of the space available, coal piles may be longitudinal, where at least two piles are present and one is being stacked whilst the other is reclaimed. In more restricted areas, circular beds may be more appropriate, as these can allow stacking and reclaiming simultaneously.

According to Oberrisser (2008) circular stockpiles have several disadvantages. These include the fact that the equipment and site requirements are harder to retrofit to existing plants. Also, the design is such that they cannot easily increase capacity and, if this is required, a second stockpile may be needed at further cost. Also, if the coal is sticky and/or has a high clay content, any central chutes may become clogged.

If the coal is stacked in defined layers and the reclaim method is not suitable (for example, reclaimed in similar layers) then is possible that the stockpile could be 'unblended' during loud-out which is not what is desired. Thus it is necessary to consider both the stacking and reclaiming procedures to be used in any such blending (Isherwood, 2014).

The more layers of coal there are in a stockpile, the greater the blending effect. However, the homogeneity of the mix will still be limited by the thickness of the layers and the subsequent movement of the coal between collection from the stockpile and delivery to the boiler. In some cases, simple layering is not enough to create an even blend. The blending of the coal can be improved during the reclamation process. In fact, blending can often be more dependent on the reclamation method than on the method of stacking (Isherwood, 2014).

Some traditional coal blending/reclaiming methods include methods based on extracting the coal from under the stockpile. Figure 8 shows a coal pile with a tunnel running through equipped with a conveyor belt and scraper. The scraper moves through the tunnel, scraping off layers of the different coals in the stockpile, dropping them together onto the conveyor belt, thus creating a mix. Although this method can achieve significant mixing it is a clumsy method, requiring significant construction investment, high maintenance costs and yet does not ensure the homogeneity of the blend produced (Petrocom, 2014).

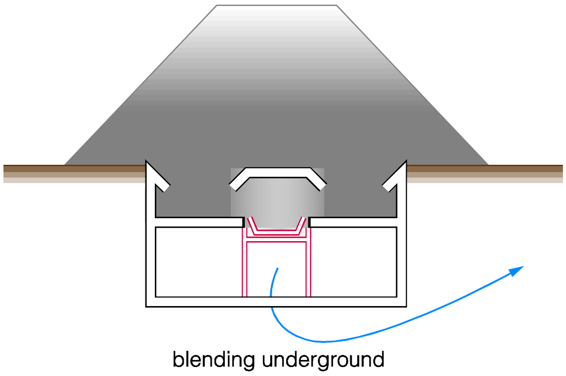


Figure 8 Blending underground (Petrocom, 2014)

Additional moving equipment may be required to shift all the coal towards the central collection area. This approach can provide accuracy down to a 5% difference in the coal mix. The Total Energy Plant in Guayama, Puerto Rico, stockpiles coals from ships into stacking tubes over overlapping piles with a total capacity of 98,000 t. The reclamation from the pile is achieved with 10 vibratory feeders spanning 60 ft (18.3 m) beneath the two piles. Each feeder can take up to 360 t/h, half of the reclaim capacity of the conveyor and so two or more feeders are in service at the same time during reclaim (McCartney, 2006).

For larger sites, it may be more convenient to keep coal piles separate or in longitudinal piles and then create the blend during reclamation of the coal. Whether the blend is obtained from a pre-mixed stockpile or separate piles, the mode of reclamation is determined by the availability or affordability of equipment. Mixing can be achieved by anything from simple bulldozer manipulation through more complex reclaiming systems which use vibration to ensure an even blend. Reclamation systems can be relatively complex pieces of equipment based on long arms and grabbing or sieving units which gather coal from across a coal pile, as shown in Figure 9. These long collection arms can collect linearly along a long coal pile, taking proportional grabs from different piles or even from different distances or depths across a pile which already has coals placed in the required ratio by weight. Alternatively, collection arms can work radially out from the centre of a circular coal pile. In most cases, the size and shape of the coal yard will be the main deciding factor on the blending equipment used.

Most reclaiming systems are rail mounted. The simplest method is probably the bucket-wheel reclaimer which uses buckets in sequence passing through the coal pile to gather the coal from the desired section, usually containing a mix of coals. More advanced systems involve scrapers, which scrape the coal across the face of a pile, giving greater mixing and a more accurate selection. Figure 9 shows the different ways in which these gathering methods – buckets, scrapers or drums – are positioned over or through the coal pile in order to remove the desired coal layer.

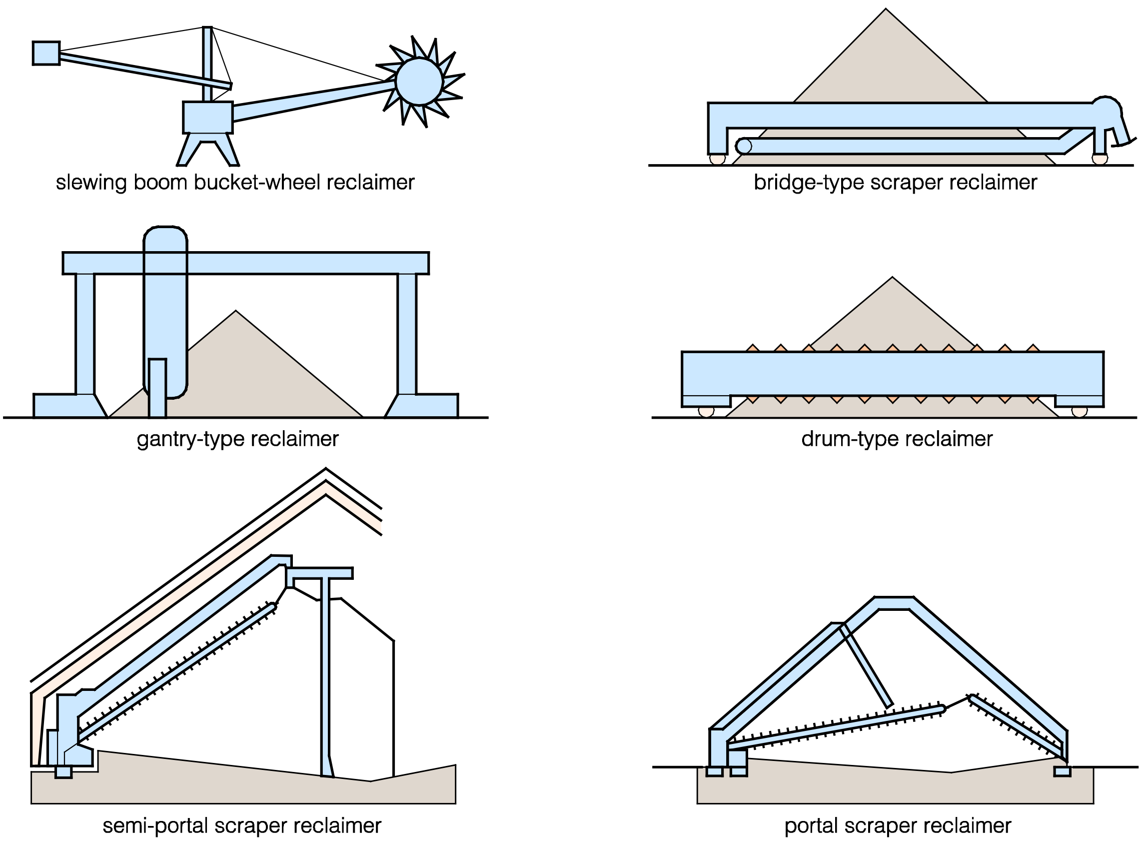


Figure 9 Reclaiming equipment (Carpenter, 1999)

The reclamation of coal with any of this equipment can be achieved by bench reclaiming – where the bucket or scraper passes at a fixed height across the length and or width of a coal stockpile; or by block reclaiming – where the bucket or scraper gathers coal from one or more layers at a fixed level over a pre-determined area of the pile. The method will depend on the layout of the coal stockpile and the blend required and this will be controlled by the coal stockyard manager.

4.2 Bins – silos and bunkers

Blends can be created at sites which have large coal storage units such as coal silos and hoppers. Silos are tall cylindrical storage devices with a single output hole at the bottom whereas bunkers are rectangular systems which may have multiple outlets along the bottom. Both silos and bunkers are often referred to as bins.

Bins generally hold lower quantities of coals than piles and, of course, have a maximum capacity. Bins can be used to hold pre-blended coals or can be used as part of the blending process. A hopper/feeder can be used to create a pile of known weight under the bin. This will be determined by flow rate and/or by weight. This can then be mixed with a known weight of coal from another bin or pile using either digger-type vehicles or using belt feeders or conveyors. These systems are best for blends from 20–100%. These kinds of systems can create a reasonable blend with down to 5% increments of different coals in the mix. Below 5% can be possible but only with appropriate equipment and may become difficult under some weather conditions (McCartney, 2006).

Belt blending is the combination of coal on a moving conveyor. This can be achieved through taking coal from a stockpile, a blending pile or a bin. Coals are dropped onto the belt either from the crane systems shown in Section 3.1.1 or through the hopper systems in Section 3.1.2. The blending is achieved by controlling the rate the coal is added to the conveyor. These systems are designed to include a weighing system, to confirm that the blend is being added as required. The conveyor is also commonly the means of moving the blended coal from the blending area to either a delivery area (if it is to be sent off-site) or to the plant itself. For new plants, future requirements for blending should be considered during the plant design phase.

Figure 10 shows a series of six silos which are controlled by computers to discharge the required quantities of coal onto a conveyor belt. The system is reported to be reliable and consistent to within 1% variability on the specified mix. It's a homogenous process which can take up relatively small areas due to the horizontal storage provided by the silos (Petrocom, 2014).

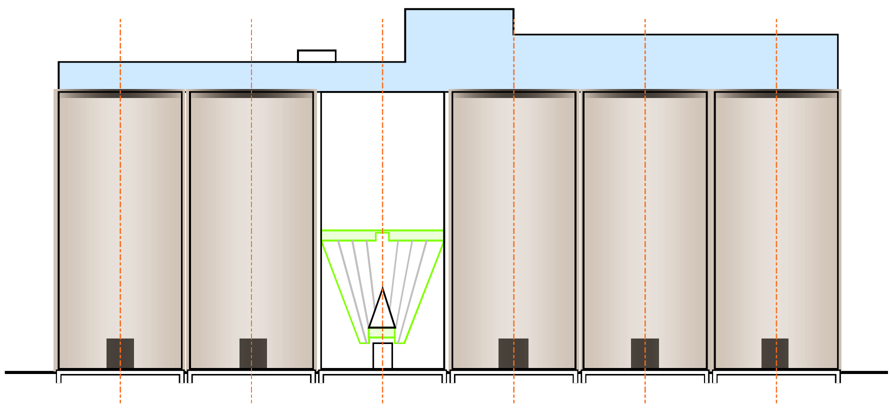


Figure 10 Coal blending from silos (Petrocem, 2014)

A site could have two or more individual hoppers which can drop a required amount of coal down onto a pile or even onto a moving feeder belt. The timing of dropping coals onto the belt will determine the evenness and proportion of the mix of the coals. This approach can provide accuracy down to 5% difference in the coal mix. Belts can simply move laterally to achieve the mix or can vibrate for a more even mix. The Red Hills Generating Facility in Ackerman, Missouri, USA received coal by truck and stores it in two Eurosilos of 20,000 t capacity each. The coal is reclaimed by two 'un-coalers' which feed up to 750 t/h coal via the reclaim to the crusher house. Although the plant does not currently blend coal, the separate silos will facilitate this in future (McCartney, 2006).

Petrocem silos can cope with surprisingly large quantities of coals to be blended. Each plant is designed to blend 10 Mt/y. The standard design consists of six silos each holding 9 kt of coal (totaling 54 kt) and can produce a simultaneous blend of up to six coals at any one time at a rate of around 4–6 kt/h, either to feeder ships or to storage. In newer plants, where online analysis is performed, variations of as little as 1% in a required coal characteristic can initiate a change in the operation of the individual coal feeders. With feed rates between 160 and 1600 t/h possible from each silo feed system, corrections any errors in the blend will occur in less than one minute (Stott, 2014).

Blending can also be achieved within a bin by the addition of known quantities of coal into the bin. However, the dynamics of coal within a bin is not conducive to effective mixing, with areas of dead space either at the sides or in the middle which will not move whilst the coal around it flows past (Carpenter, 1999).

4.3 Homogenisation

Homogenisation is not always included as part of the blending process at many coal plants as most boilers can cope with some variation in coal characteristics within the load. However, it can be required at some plants where coal stocks are delivered from several local suppliers into one single stockyard and also at cement plants. According to Lieberwirth (2012), although homogenisation could be achieved by layering materials onto feeding conveyors and setting up a series of homogenised stockpiles (as shown in Figures 11 and 12), this would have a low production rate and would be prohibitively expensive at large scale.

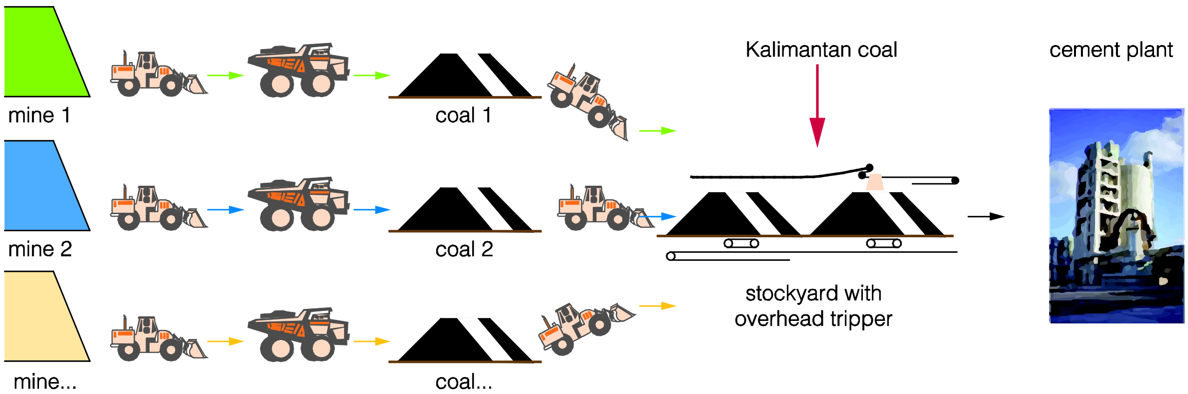


Figure 11 Layering of coal to create a blend (Leiberwirth, 2012)

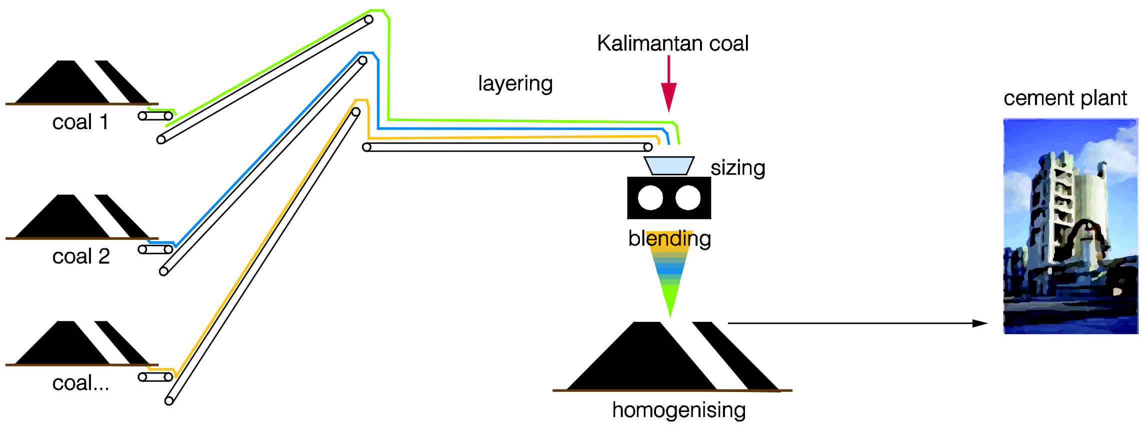


Figure 12 Homogenisation of coal following sizing and blending (Leiberwirth, 2012)

Instead Lieberwirth proposes the dumping of all incoming materials from local mines onto two large ‘incoming coal’ piles, as shown in Figure 13. As one coal pile fills up, the other is reclaimed and fed into the homogenised piles. This system assumes that all coal arriving into the plant is of the desired quality and that even mixing/homogenisation is the goal.

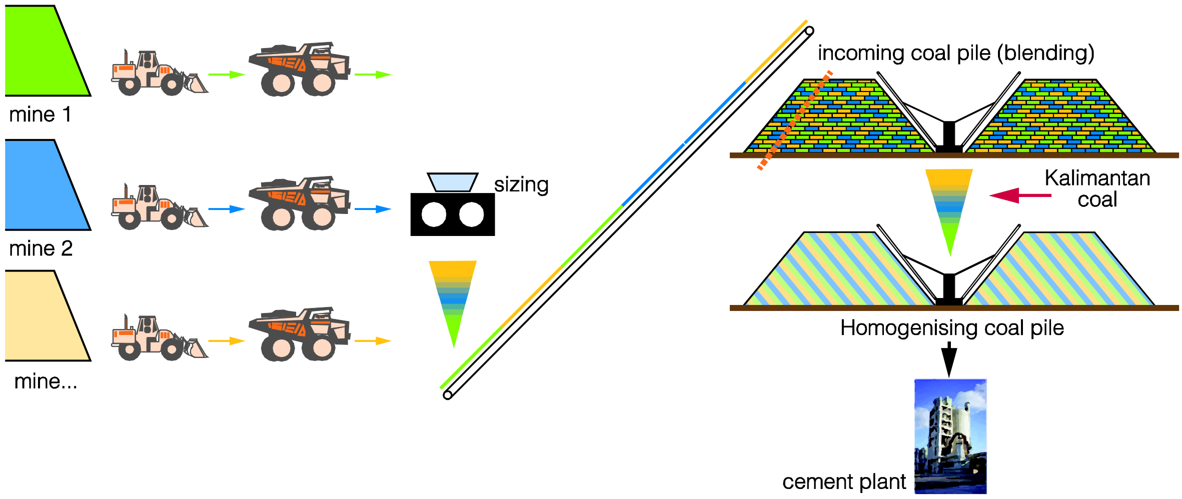


Figure 13 Homogenising coal piles (Leiberwirth, 2012)

This would suit a plant that receives coals from several locations and wishes to ensure a consistent blend to supply to the end user. The coal can be picked up and homogenised using either bridge type scraper reclaimers or drum reclaimers, both of which scrape material from the pile and blend/homogenise it as the machine moves across the site of the pile, as shown in Figure 14. This system is being used at a coal stockyard in Kalimantan, Indonesia.

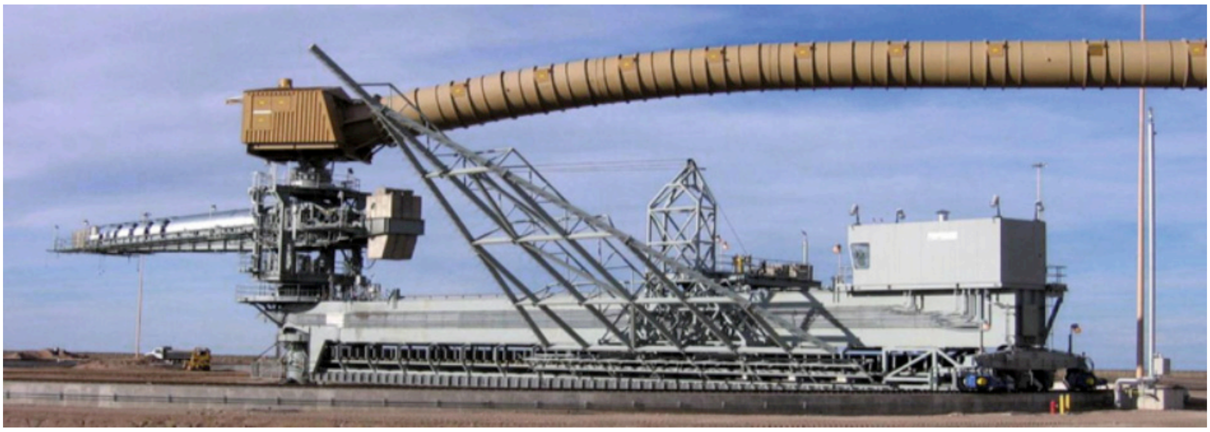


Figure 14 Homogenisation of coal at Kalimantan, Indonesia (Leiberwirth, 2012)

4.4 Comments

Coal blending can be achieved in a number of ways – from simple co-ordinated stockpiling to more advanced, technically challenging methods. The method used will depend on cost, space available and the amount of blending required.

Simple stockpiling in layers combines coal storage with blending. By arranging the coal in layers, the coal can be withdrawn in a manner which produces the blend required. Coal in silos or bunkers can be blended by controlling the drop rate of the coal from the bin onto a conveyor which may already contain coal from a separate bin or stockpile.

The movement of the systems reclaiming coal from piles or bins provides some blending action. Further blending can be achieved by vibration or scraping action during the collection process. If true homogenisation is required, then more advanced mixing technologies can be employed.

5 Blending experience

During this literature review it has become clear that information is readily available on the commercial side of coal blending – the coals, the modelling programmes, the blending equipment and so on – but little is published from the point of view of the plant operator. Nor is there much published on cases of where blending has gone wrong or has faced significant challenges. It would seem that much of the information relative to individual plants and their site-specific blending approaches are regarded as confidential or worth protecting from potential competition. This Chapter therefore focuses on information which is available in the public domain which relates to blending projects at specific sites or plants as much as possible. The following sections include a few examples of countries where coal blending is common or is becoming so and includes case studies of how mines, coal producers or individual coal-fired plants have adjusted to working with blended coals.

Coal blending can be carried out at almost any point in the coal production process. Figure 15 shows the basis coal production flow chart from digging the coal out of the ground to delivering it to the power plant. As will be shown in this chapter, coal blending can be performed at almost any point in this process chain.

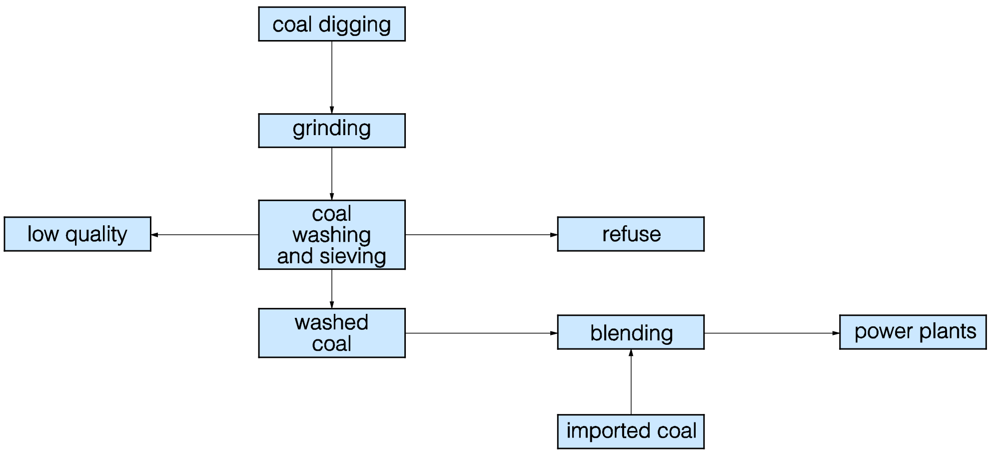


Figure 15 Coal production flow chart (Carniato and Camponogara, 2011)

Where the coal is blended will depend on many different factors, especially cost and practicability. According to Stasiuk and Whitt (2010) coal and coal yard handling costs are often the most significant annual costs that a power plant encounters. Blending coal can take up a significant amount of space. If a plant suddenly requires blending on site, then the coal plant must make space for a significant amount of coal storage and a blending plant. In some cases this is not physically or economically possible. Many plants will therefore prefer to purchase pre-blended coals from mines or from coal producers. However, relying on blended coal from a mine or supplier can limit plant flexibility and add cost. The decision on where and how to blend coal therefore results on a case-by-case basis.

5.1 Blending at coal mines and coal washeries

Blending is required, not only for the combination of different coals to give a combined mix of required specifications, but as a means of ensuring consistency of a single coal type. Coal quality from even a single mine can fluctuate beyond an admissible range. Coal blending can therefore be beneficial if performed at the mine itself or at the coal washing and/or processing plant.

The combination of coal from different seams and areas of a mine is common. For the most part, this is considered mixing rather than blending. The goal is mostly the same – to create an even distribution of characteristics throughout the coal pile – but for mixing the effect is far more basic. True blending requires analysis of the coals prior to combination whereas much of the mixing at the mine is based on evening out the more general physical characteristics of the coal as it is extracted.

Customers purchasing coal from a single mine will expect the coal properties to be largely consistent. The mine will achieve this with mixing and, in some cases, washing of coals are they are produced. Customers who obtain coal mixed from more than one mine may apply greater scrutiny to the quality of the coal. Some customers may choose to accept only coal from one named mine. The mixing of different coals may sometimes be regarded by customers as inferior. On occasions, a customer may request preparation and analysis of individual sub lots of coal (5–10 kt) to review homogeneity (Isherwood, 2014).

As mining operations continue at a single mine site, the quality of the coal can change leaving the operator producing coal which does not meet the original specifications. In situations such as this, coal blending can be performed at the mine so that it can continue to provide coal to the established customer base. This can be done quite simply by mixing two different coal types mechanically based on pre-defined ratios or percentages to give a blend which will meet specifications. For this to be achieved over an extended period of time, the coals supplied must be of consistent quality. If this is not the case then coals must be analysed on a regular basis to ensure that the final blend continues to meet specifications. For this, automated belt sampling systems, as discussed in Section 3.1 are required.

Although only around 6.7% of Brazil's energy matrix was from coal in 2004, this share is predicted to increase. Most domestic coal in Brazil is high ash. However, in order to achieve large-scale production and reach viable levels of investment, it has been proposed that new coal plants in the country will use run-of-mine (ROM) coal. This means that the coals will not be washed at the plants, reducing the risk of pollution around mine sites. However, ROM is far more variable than washed coal and therefore blending will be required. Beretta and others (2010) investigated coal blending in piles from strategically mined coal at a site in Brazil. The mine geography was mapped and the characteristics of different seams were overlaid onto the map. The order in which the areas of coal were extracted and piled was then recorded in order to facilitate co-ordinated mining and blending. An algorithm was developed which takes into account the mass of the piles and the contribution of each seam from each mapped block to the pile. Piles were produced ranging from 30 kt to 130 kt along the life of the mine. The larger piles were shown to have smaller variation between the maximum and minimum characteristics (ash and sulphur content) of random samples. This meant that the larger piles were producing more homogenous blends. This approach aimed to produce saleable coal blends from ROM coals with minimal investment in blending and analysis. By characterising each seam (for ash and sulphur) and monitoring the contribution from each seam to each blending pile, the overall characteristics of the blend could be mathematically predicted.

Beretta and others (2010) studied the movement of coal from the mine in southern Brazil to an (unnamed) power plant nearby. The plant specifications for coal include a set upper limit of 58.5% ash and 2.2% sulphur. Coals exceeding this were rejected by the coal-fired power plant. The stockpile blending method established at the mine proved to be effective in producing coal for the plant to these required specifications. The probability of each pile exceeding the plant-specific limits could be calculated based on the known proportion of different coal seams or blocks placed in each pile. If a pile was likely to include coal which exceeded the acceptable limits then further blending could be applied. The study indicated that the coal from one particular seam was causing some piles to exceed the limits for ash and so the coal from this seam was subsequently regarded as 'waste' and was excluded from further stockpiles. Balancing the contributions from seams with high sulphur and those with high ash was expected to lead to an overall increase in the amount of usable coal from the mine.

An excellent study by Benndorf (2012) summarises the use of mapping and models to optimise coal blending at a large continuous open pit mine in Eastern Europe. This approach, known as 'conditional simulation' has been used for a number of years to optimise operation at coal mines. The method maps in-place variability and uncertainty in the prediction of coal quality parameters and can be used to promote the homogenisation of coal during the mining process. The paper by Benndorf (2012) provides detail on the intricate mathematical modelling required to achieve such a map, in 3-dimensions, across a coalfield and how it can be used to advise on the best mining cuts to provide the required coal blends. The 3D maps produced provide information on the special spread of coal characteristics such as ash content across the field, including depth. Calorific value can be strongly associated with certain layers within coal seams. Excavation techniques can be planned accordingly. Continuous mining systems, based on chain and bucket excavators as discussed in Chapter 3, can be controlled automatically to remove coal from different locations or strata onto conveyors to obtain a product of high consistency. Horizontal slices of around 5 m can be cut, although the depth is limited by the minimum mining thickness of both the seam and the equipment available. This will produce a relatively homogenous blend of coal. It is also possible for the excavation to be operated horizontally, through several seams, to produce a blend of all coals within that area. For deeper cuts, chain excavators are more effective, cutting vertically down through a pre-set depth and providing more consistent blends than the bucket system. This is a means of producing blends whilst avoiding the need for a stockpile or blending area. However, the 'blends' achievable are very dependent on the coals available in each region of the mine and this approach is more appropriate for homogenisation of coals within a region and would not traditionally be considered blending. Alternatively, coals from known areas and/or strata can be stored separately in stockpiles for more specific blending at a later time. This is called 'strata blending'. Coals can be piled in layers of different types and then a blend is produced by cutting through the layers to withdraw the mix for further blending and homogenisation, as discussed in Chapter 3.

The Callide Coal Mine in Queensland, Australia, (originally owned by Shell but bought by Anglo) has a large terminal to store, homogenise and process 'run-of-mine' coal. The site has a longitudinal stockpile and a traveling, luffing and slewing stacker that can form and layer the coal pile at 2100 t/h in a windrow or chevron formation. Reclaiming is achieved at 1800 t/h by a portal scraper which covers the full length of the pile, as shown in Figure 16. This collection of coals across the full length of the stockpile at the same time onto a conveyor ensures homogenisation. The system also enables fast modification of the blending ratio by allowing variation in collection rates across the pile.

Figure 16 Portal scraper at Callide coal mine, Queensland, Australia (Oberrisser, 2008)

Arch Coal, the second largest coal producer in the USA, is the single largest user of elemental coal analysers in the world. Their mines are installed with real-time monitoring systems to sort coal and also to track its quality as it is sorted into stockpiles and silos, as discussed in Chapter 4. These analysers are used in conjunction with the COBOS software (*see* Chapter 3) from Thermo to blend coals from different sources into shipments which meet customer requirements in terms of contract specifications but also provide consistent quality throughout the train. The Catenary Coal Samples mine complex comprises a surface mine, and underground mine, a prep plant and a rail load-out. The site produces coal ranging from 10–33% ash, 0.5–2.5% sulphur and calorific values from 9200 to 13,000 Btu/lb (21,400 to 30,238 kJ/kg). These coals are cleaned and deposited in stockpiles for subsequent blending. The blending is automated and the site kept relatively simple, as shown in Figure 17. The analyser shown in the diagram is used to monitor the quality of the coal being loaded into the silos and also to give feedback to the mine to ensure quality assurance and that customer specifications are met.

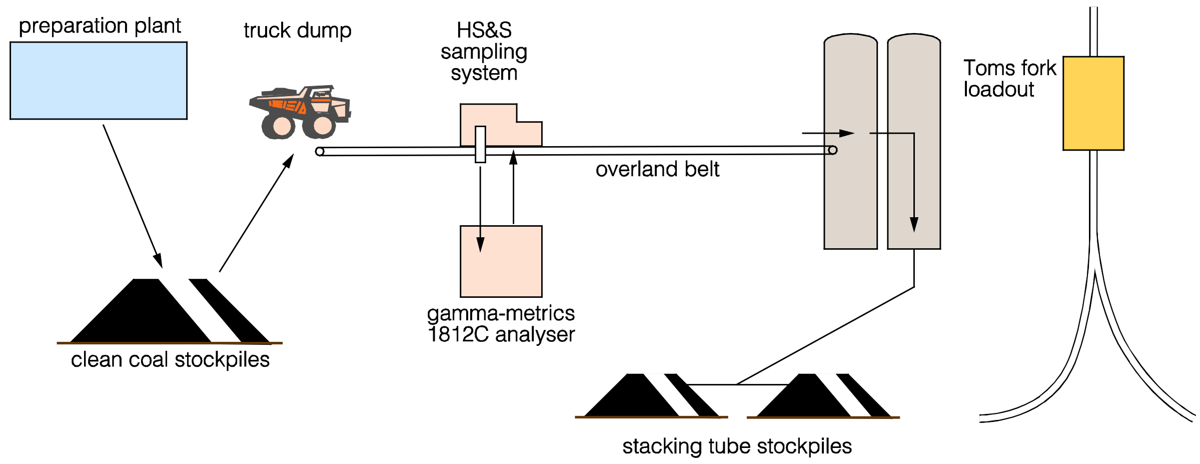


Figure 17 Layout of Catenary Coal Mine blending area (Woodward and others, 2004)

By looking back at blends produced over one sample month, it was shown that the majority of the train loads were produced from coals from three or more sources. However, more than half of the train loads contained one dominant coal (providing >80% of the blend). The source proportions changed 'radically' from train to train confirming that automation was required to keep up with the required production. Figure 18 shows the blending proportions of the coals from the two stacks and two silos going into each of the trains sent out during June 2004. Figures 19 and 20 show the ash and sulphur contents of each of the trains. The ash content was relatively consistent on most trains and only exceeded specifications once and by only 1%. For sulphur, the situation was more challenging with the limit being exceeded on several occasions. It was reported that this was due to insufficient mid-sulphur coal being available (Woodward and others, 2004).

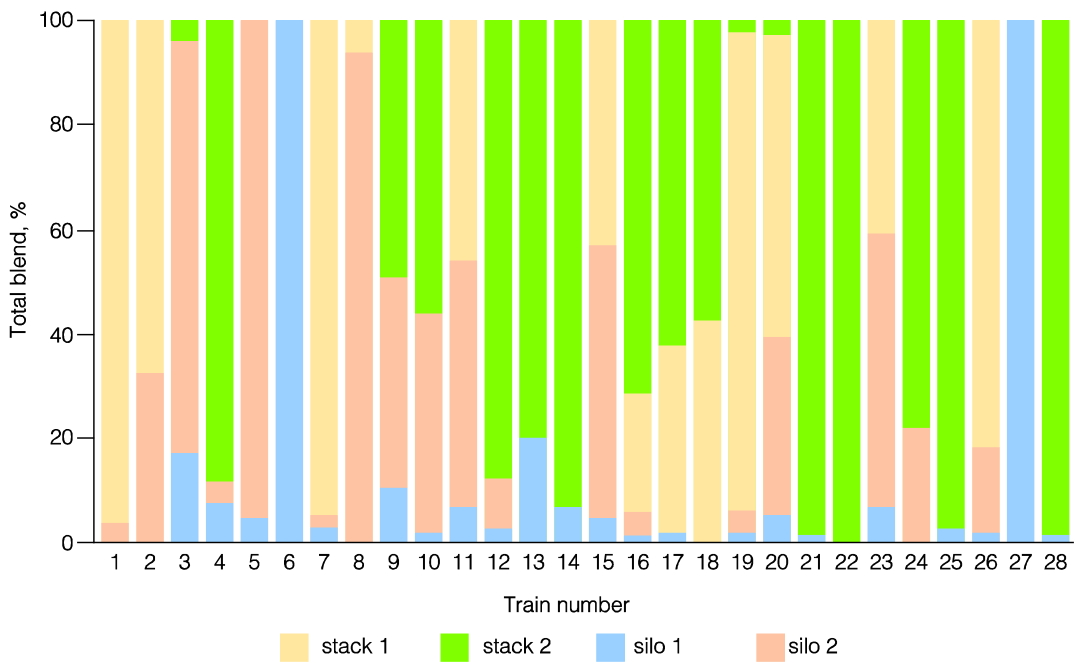


Figure 18 Blending proportions during load-out in June 2004 (Woodward and others, 2004)

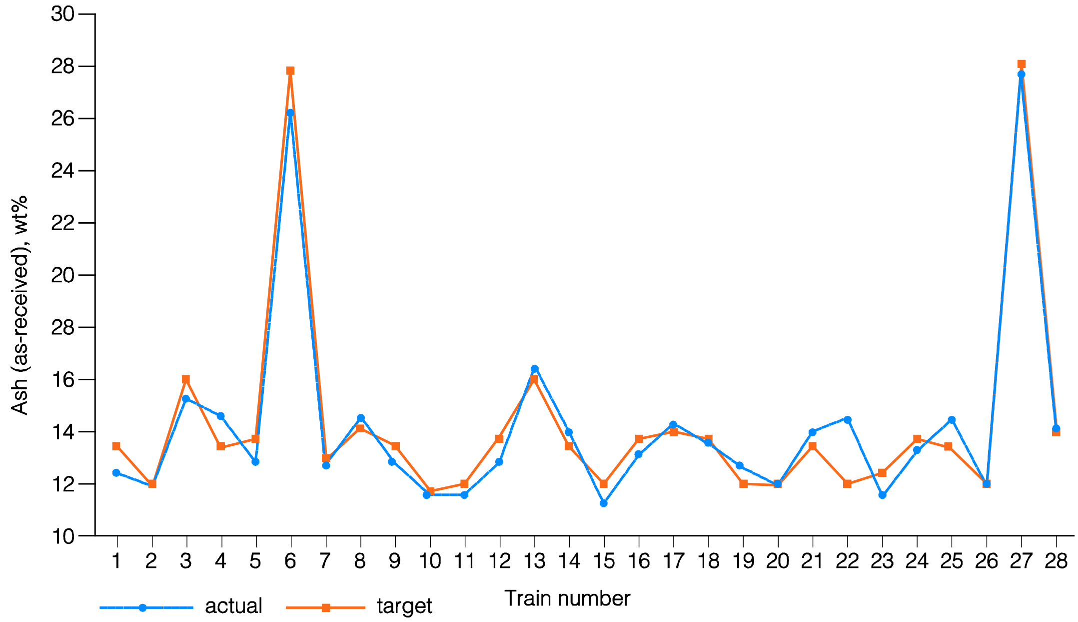


Figure 19 Control system performance on ash (Woodward and others, 2004)

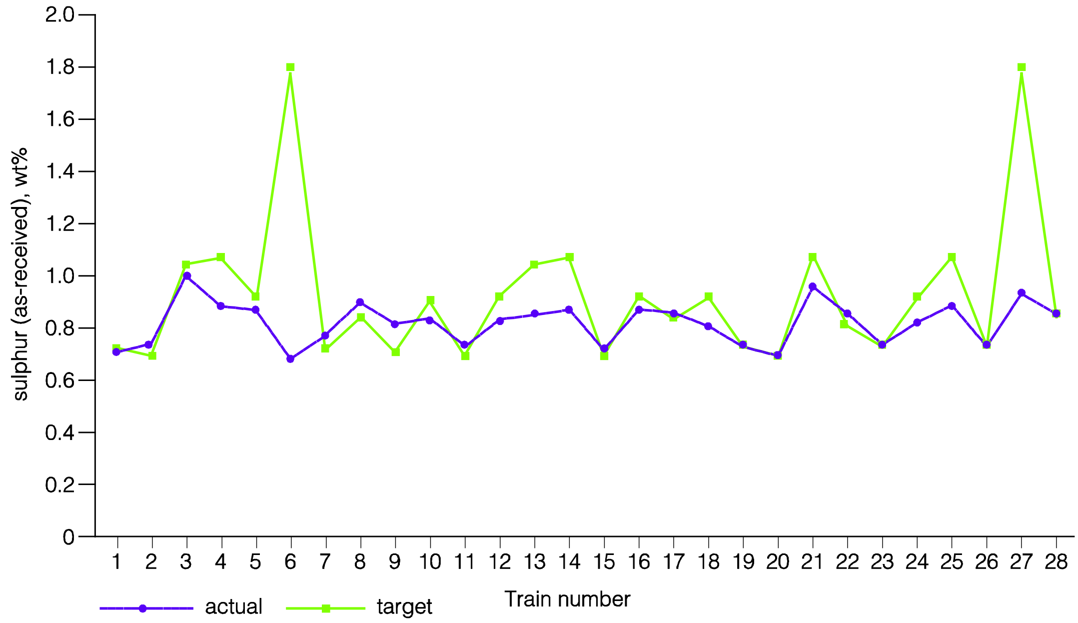
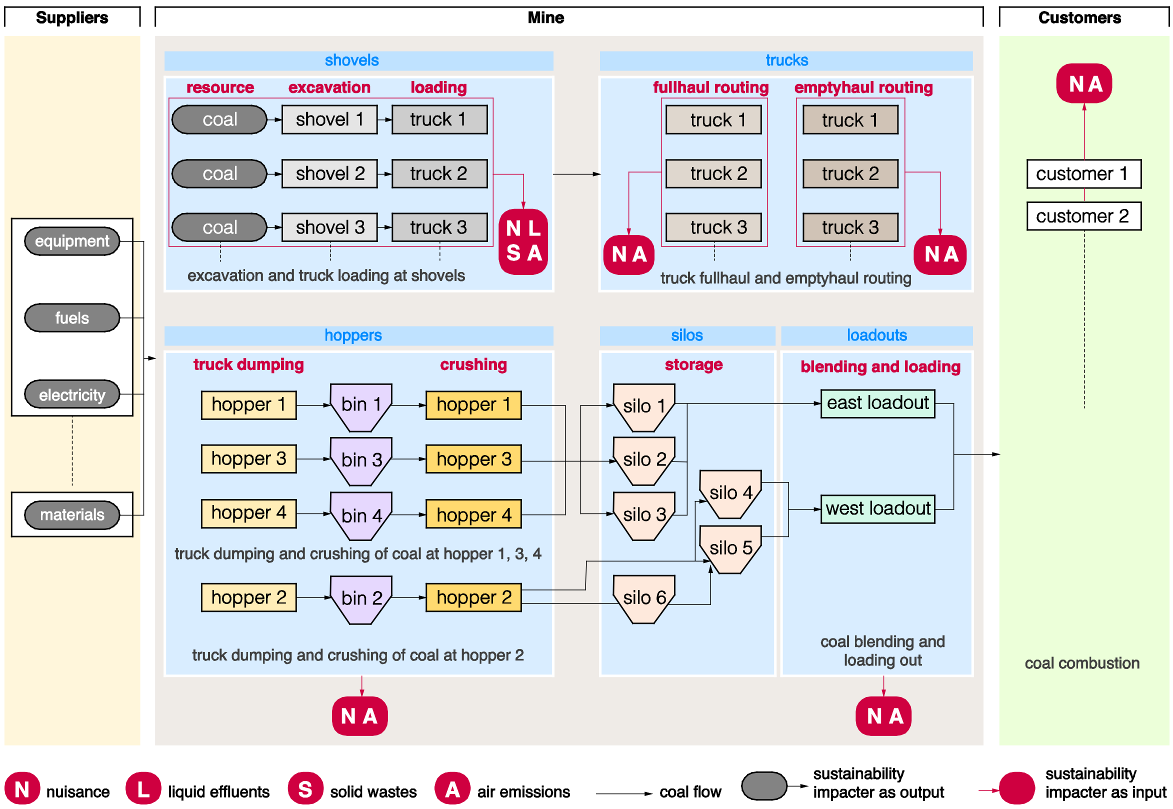


Figure 20 Control system performance on sulphur (Woodward and others, 2004)

Nageshwaraniyer and others (2011) report on the mining operations at an un-named coal mine, identified only as 'one of the largest in the USA'. The mine is clearly a huge operation with fleets of vehicles and significant staff to oversee each section of the mining and supply chain. The scale of the operation requires a computerised system, as summarised in Figure 21a-c). The first layer of control relates to excavation, hauling, crushing and storage, in preparation for blending. In the second layer of control, the fleet manager is in charge of assigning equipment to each area of the mine as well as controlling the hoppers and the blends produced. The third layer shown concentrates on the monitoring data, in real time, relating to coal characteristics, in order to create the blends to the correct specifications and to produce the reports for filing. In this particular plant, data on coal characteristics (ash, sulphur, sodium and so on) and recorded for each shift and for each train.

a)



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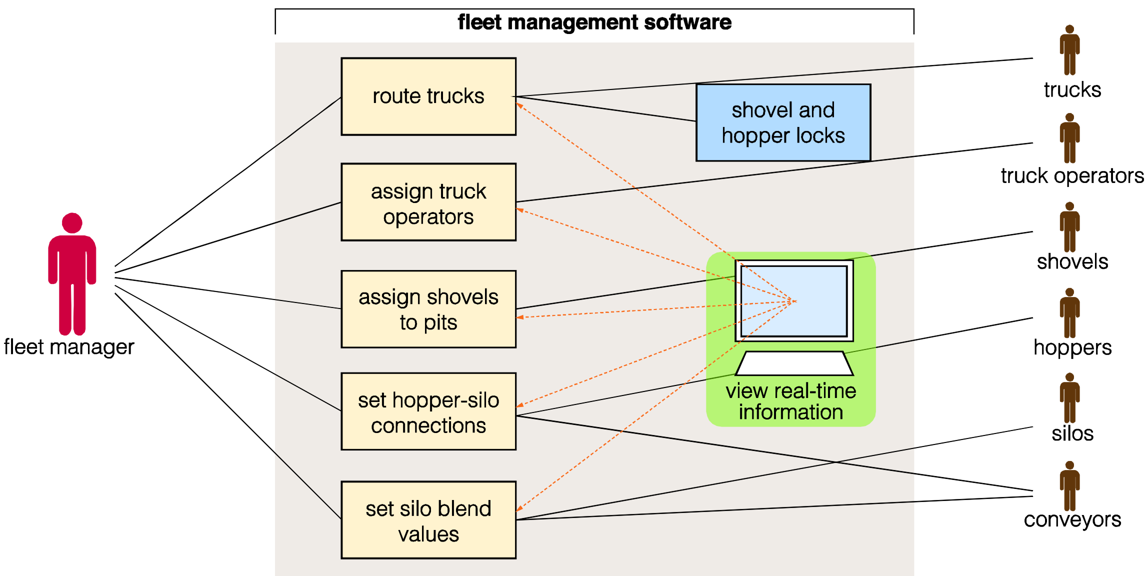

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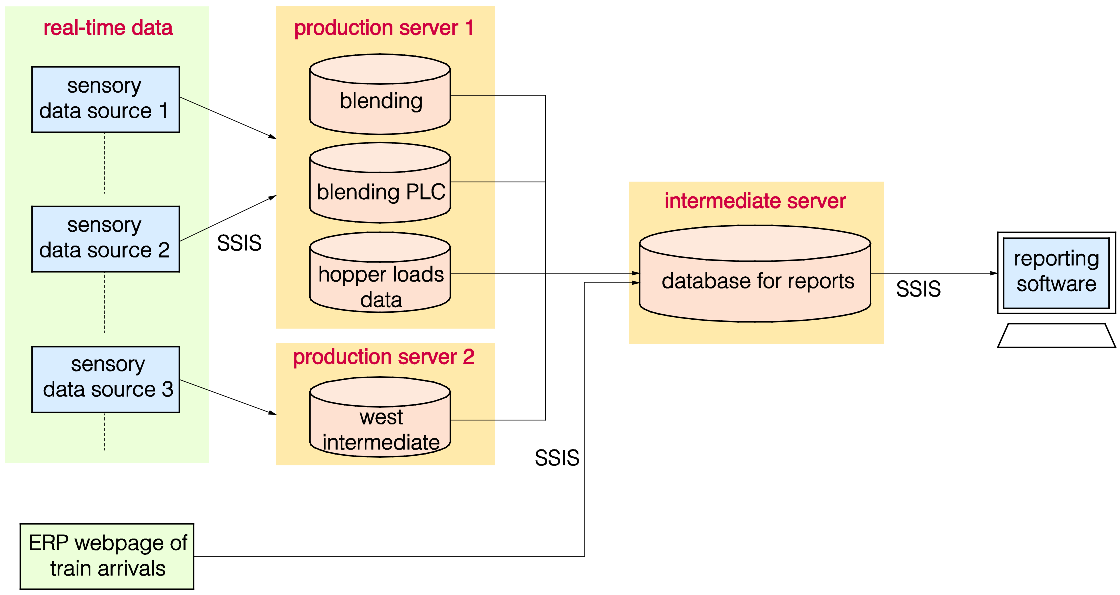

Figure 21 Materials handling programme for coal mine blending (Nageshwaraniyer and others, 2011)

Some coal mines have on-site washeries or centralised washeries nearby to clean the coal. According to Mohanta and others (2010) washeries can have problems when processing raw coals from different seams or collieries which have variations in proportions and characteristics of the individual coals. Washeries commonly blend coals, after preliminary crushing, and then screen them into distinct size fractions which are then washed separately, based on float and sink processes. The behaviour of coals in washeries is complex and difficult to predict as it varies with both the coal characteristics as well as the processes involved. Mohanta and others (2010) produced an interactive spreadsheet which can be updated with the washability characteristics of different coals following their testing at the plant. Interestingly, it was demonstrated that the washing of 'inferior' coals such as Bharatpur, Hingula (seam IX), and Ananta (seam III) simultaneously in the same wash produced a higher amount of clean coal than washing these coals individually. The ash levels of inferior coals can increase during washing but this can be compensated for by the lower ash values of coals which are easier to wash, such as Kalinga, Ananta (seam II) and Hingula (seam VII). The study demonstrated that it is possible to maximise the yield of clean coal by blending a higher cleanability coal with a relatively lower cleanability coal. This effect is not something that can be assumed for all coals. However, Mohanta and others (2010) suggest that maintaining a spreadsheet of coals and washability results will provide information which will be useful in potentially predicting suitable coals for co-washing. Yu Yu and others (2010, report in Chinese) have also studied the correlation between coal cleaning and coal blending. Work at the Huainan PAN1 mine in China is ongoing to develop a non-linear programme to optimise the maximum clean coal yield through a combination of manipulating both the separation density and the blending ratio during coal washing.

In Iran, the Zirab plant used to fire coals from different mines in the area without any control on the weight percentage of the blending. Studies on the washability and blending of the Kiasar, Lavidj and Karmodz coal were carried out at the Alborz Markazi coal washing and processing plant to optimise the recovery rate of washed coal. The ash contents of these coals are 36%, 32.6% and 17% respectively. The optimum mix for washing and coal recovery (95% at 12% ash) was shown to be 10% Kaisar, 20% Lavidj and 70% Karmodz. The optimum blend was discovered by testing different mixes in practice rather than by using any spreadsheet or modelling tools (Zahra and others, 2011).

5.2 Blending during transportation/at a centralised stockpile

The growth in energy demand worldwide means that many stockyards are facing growing demands on available space. Stricter regulations on noise and dust emissions also promote the use of centralised facilities to co-ordinate larger production rates of commodities such as coal and coal blends (Lieberwirth, 2012). The use of stockyards allows the 'buffering' of material flow – allowing deliveries at different times from different sources and in different volumes to feed into a large single handling facility reduces waiting times for the majority of customers. This approach also allows for more consistent blending and homogenising of materials.

As noted by Woodbine (2011), the future of coal is assured in many locations worldwide. However, the economics requires considerable focus not only on high efficiency power plants but also on the logistics of coal transport from the mine sites to the generators, including the rail and port facilities in between. Blending before transportation can be a means to keep coal costs lower for those plants which do not have facilities or space to create facilities for coal blending on site. Blending at a centralised location can be ideal for a number of individual mines located in a catchment area. The coals from each mine can be delivered to a central processing area by truck or overland conveyor and then treated in bulk to produce a saleable blend. Large stockpiles can be created at these purpose-built sites, allowing layering in combination with continually operating equipment such as radial and luffing booms to create a relatively homogenous stockpile, as discussed in Chapter 4.

As mentioned above, coal processing at a centralised stockpile can provide buffering for periods when deliveries become intermittent or stop completely. Nkuna (2009) describes the development of an online analysis system to measure the ash in the coal as it starts its 20 km journey from the Mooikraal shaft at the Sigma mine to the blending station which provides coal to the Infrachem boilers at Sasol, in Sasolburg, South Africa. The ash content is reported to the blending station in advance of the coal arriving and the stockpiling and blending arranged accordingly. The coal is sorted into three piles depending on the ash content – low (<30.5% ash), good (30.5–31.5% ash) and high (>31.5% ash). Blending is achieved by controlled hopper feed through a vibrator feeder onto the belt. A computer system was developed to control the feed rate and thus the blend as required. Figure 22 shows the flow chart for the system for the occasions when the coal mine was not in operation.

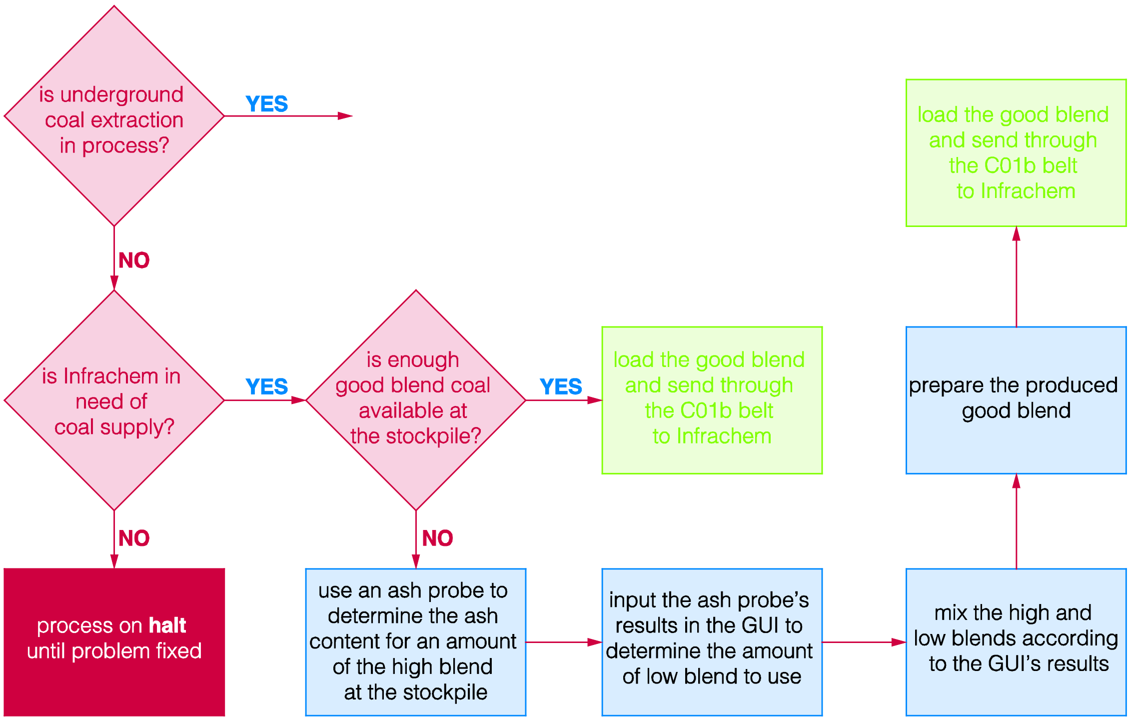

Figure 22 System implementation for mine production downtime (Nkuna, 2009)

When coal is not currently being delivered from the mine, the system will determine how best to maintain the existing coal flow to the power plant based on available stockpiles. Nkuna (2009) calculated that the project had the potential to save the plant R 8,195,000 per year (around $773,000) and the payback period on the investment would be five years.

Ports are excellent locations to facilitate co-ordinated and centralised blending as coals arrive from different countries can be stockpiled for blending to customer requirements. For example, coal in Nova Scotia now arrives via two strategic ports which then distribute the coal to the various plants by road or rail. Further blending may be performed at the individual units, as required (Campbell, 2014).

The coal company EMO in the Netherlands operates a coal blending facility at the port of Rotterdam which makes coal blends from coals being delivered from all over the world. The delivered coal is placed into silos (6–8 kt capacity each) and then blended in carefully calculated proportions to produce a 'combustion-ready' mix that meets the client's specifications. The port supplies the Maasvlakte Power Plant as well as many plants in the Ruhr Valley region of Germany. The coal blending facilities were developed by KEMA based on many years of research into coal blending (Roggen, 2007).

In 2006, KEMA were approached by Petrocom in China to produce a similar project in China. KEMA provided information on what blends could be produced from the coals sourced in China and Indonesia to suit the power plants to be supplied. A blend was proposed for each plant based on plant characteristics and modelling. Full-load trials were then carried out to confirm that the prescribed coal blend was indeed suitable or whether modifications were needed. Depending on the success of this first blending site, twenty further sites across China were proposed, handling 10 Mt/y of coal each (Roggen, 2007).

According to Lieberwirth (2012) Indonesian Adaro coal group has formed Coaltrade Services International to handle the blending of Adaro's Indonesian coal with other coals for 'value added purposes'. This involves blending the low sulphur 'Envirocoal' produced by Adaro with other coals of lower quality to provide larger quantities of coal with high blending efficiency at a centralised stockyard.

The Port of Koper in Slovenia has a specially designed coal terminal. This terminal takes large shipments from large vessels and splits these down into barge-sized volumes for local users. The longitudinal coal pile allows for the storing different grades of coals at different locations. The rail-mounted, bucket-wheel system can then reclaim coal from specified areas of the pile at a rate of 2200 t/h. The relatively simple bucket system means that the characteristics of the coal can be very varied and lower grade or wet coals, which may block a more sophisticated system, can be handled. This system is cost effective for the large volumes of coal passing through the terminal (Oberrisser, 2008).

Dominion Terminal Associates (www.dominionterminal.com) operates one of the major coal shipping and storage facilities on the east coast of the USA in Virginia. The port receives trains delivering coals from eastern US coal mines and can store up to 1.7 Mt of coal. Barges taking up to 177 Mt (dry weight) can be loaded to deliver coal nationally or internationally. The site has two stacker/reclaimer units with 200 ft (61 m) booms which can each stack 5900 t/h or reclaim 6800 t/h. There are twin silos (4000 t each) with variable speed vibrating feeders which can precisely blend coals from multiple coal piles. Further blending can be achieved when loading the coal into the vessels. Mechanical samplers, outbound and inbound, are operated by a third party to ensure independent verification of quality (DTA, 2014)

Using a top down approach, large coal or utility companies who buy coal in significant quantities from numerous suppliers around the world have the opportunity to co-ordinate the delivery of different coal types to permit blending requirements to be met during coal shipping. So, by defining the coal mix required in advance and ordering coal accordingly, the mix required for the coal blend can be delivered together and, in some cases, some of the blending can occur during this process.

Stacking blending can be achieved at the Dominion terminal by controlling the delivery of trains of the different coal types and layering these as required. Reclaiming from piles can also be co-ordinated to produce layered blends in outbound silos. As many as eight separate coal piles can be used to create a blend. Programmable logic controllers are used to adjust the flow rates from outbound silos depending on the blend rates required and the weights can be controlled using the electronic belt scales (DTA, 2014).

For large companies who are trying to produce different blends for different plants, the ordering of coal and the co-ordination of delivery requirements becomes more complex. Liu (2008) describes an impressive blending and inter-modal transportation model to deal with this coal distribution problem. In addition to streamlining coal deliveries and orders, the model is also reported to reduce costs significantly. Figure 23 shows the network of transport between several coal mines and several power plants via the transport seaports, from international to domestic transport. Liu (2008) explains that the model must consider the transport restrictions, such as the size of the port and the type of vessel which can access it – Handy-size (<20 kt), Panamax (<65 kt) or Cape-size (<110 kt). The model also considers the demands for coal characteristics. The chemical variables such as sulphur, ash, calorific value, volatile matter and nitrogen are considered additive and can be taken into account by a calculation. Coal attributes such as grindability and moisture content are not additive and are therefore not combined, rather shipments are prohibited if they exceed of the qualities is exceeded. The model therefore takes into account:

- number of trips made by each transport ship;
- number of coal sources;
- number of coal users;
- available seaports;
- plants which do and those which do not have blending facilities on site;
- cost of shipping;
- limits for sulphur, nitrogen, calorific value, volatile matter and ash;
- acceptable grindability index; and
- percentage moisture permitted.

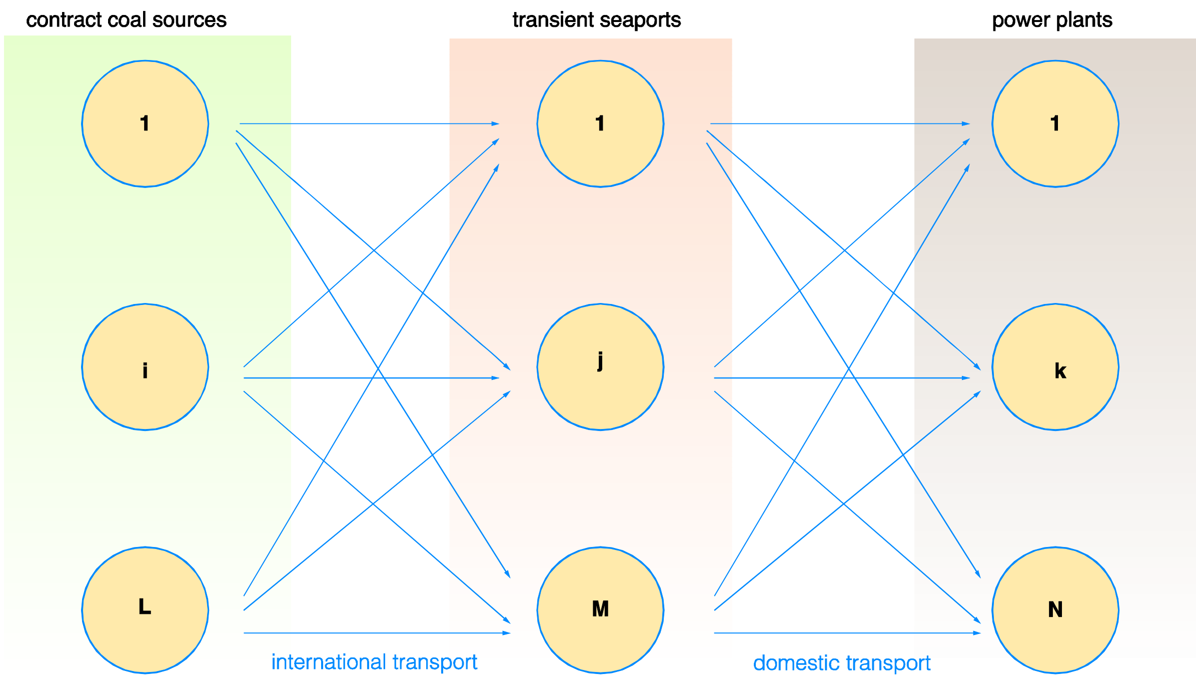

Figure 23 Coal blending and intermodal transportation network (Liu, 2008)

The overall calculation is outlined in detail by Liu (2008) and is based on a commercial software package known as AMPL/CPLEX.

An earlier study by Lui and Sherali (2000) reported on the development of a model to calculate an optimum shipping and blending process for the Taiwan Power Company (TPC). The TPC is the only electric utility company in Taiwan which relies heavily on coal imports from overseas. The model had to take into account:

- the supply quantity, quality and price from each contract coal source;
- the demand and quality requirement of each power plant;
- the transportation costs along all possible routes from contract coal sources to power plants through transient seaports; and
- the available shipload fleet capacity.

At the time of the study by Liu and Sherali (2000), coals arrived into Taiwan from numerous coalfields in Australia, Indonesia, Canada, South Africa and the USA. The coal was delivered via either Panamax or Cape-sized vessels into one of four different seaports (Su-Au, Keelung, Taichung or Kaohsiung). Some of the coal plants had blending on site but others did not. There were six coal storage and blending fields available to receive and process the coals – Northern, Kin-Kao, Middle, Taichung, Shin-da and Ta-Lin. Coal from these fields were then delivered to six selected coal-fired power plants – Shen-Au, Lin-Kao, Taichung, Shin-Da and Tai-Lin, each of which have at least two separate boilers.

The model had to take into account the coal parameters required by each of the coal plants and balance these with the characteristics of the coals available. For example, the plant requirements ranged from as narrow as 0.45–0.65% sulphur to as wide as 0.8–1.2% sulphur. The available coals varied from 0.45% to 1.1% sulphur. Most plants had a maximum ash limit of 13.5–16%, although one plant had a 7.5% maximum. The ash contents of the available coals varied from 4.51% to 15.0%. These and other variables had to be taken into account within the model. However, the ultimate aim of the model was to minimise the total cost, including the freight-on-board cost of the fuels, the shipping cost and the inland delivery cost. The model used was based on a mixed-integer zero-one programming model and is explained in detail in the original reference. According to Liu and Sherali (2000) the top management of the Taiwan Power Company were satisfied with the model. However, there is no further information available to confirm whether the model has been adopted into practice in Taiwan.

The paper by Liu and Sherali (2000) was itself an update on some work started in 1993 which, at that time, concentrated on developing an ‘inventory theory’ model to control the import of coal into Taiwan. It was intended that coal blending would avoid the need for the installation of FGD systems for sulphur control in at least some of the plants (Lyu and others, 1993). The annual demand for coal in Taiwan in 1990 was over 6 Mt which means holding over 2 Mt in reserves, in order to meet the Taiwanese Government requirement that the country hold one-third of the total national annual demand of coal as a ‘safety reserve’. The initial challenge was to optimise the delivery of the coals at lowest cost, whilst taking into account constraints in delivery and supply. According to Liu and Sherali (2000), the probability that a ship would actually carry out its quarterly schedule was only 30%. This was the value for during the 1970s and, hopefully, would be improved by now. However, it is likely that coal management systems must still take into account some level of unpredictability in coal delivery and this is significantly improved with a well-designed coal management system.

5.3 Stockpile blending at the coal plant

Coal blending at the coal plant adds extra cost and space requirements but allows the flexibility for plants to alter the blend of coals very quickly. This is ideal for plants that are required to adjust output rapidly to cope with grid demand or for plants that switch coals to ensure that emissions comply with legislated limits (*see* Section2.4). Blending on site also allows plants to manage their own coal purchase and buffer supply as required.

With respect to keeping the coal plants adequately stocked, McCartney (2006) recommends that the relative size of the coal piles should be comparable to the relative burn rates of the coal. Stock should keep up with coal burn rate but not necessarily exceed it in any significant quantity. This is an important consideration when dealing with coals such as PRB and others that are prone to spontaneous combustion. These coals should be reclaimed on a first-in first-out basis. Coal delivery rate should also be controlled in the same way. Active coal piles are normally defined as three day's requirements of coal at the maximum burn rate of the plant that can be reclaimed without the use of mobile equipment.

The blending methods used at any site will be, to some extent, determined by the available space and equipment. The stockpiling and blending systems outlined in Chapter 4 are all suitable for on-site plant use, depending on the space and equipment available, For example, for smaller plants with little storage space and only one hopper/bin, the coal mix may be dozed into the hopper at the same time, in the required proportional quantities to create the blend. A more accurate method would involve a dozer trap for the first coal type and a conveyor reclaim system for the second coal type. If two hoppers are available then each can contain a separate coal type and the feeder can then be used to withdraw the coal at the required ratio. Larger plants are likely to have more space for storage and a greater number of silos/piles and more hoppers to allow more co-ordinated blending.

The main methods for coal blending used on-site at coal-fired power plants are summarised in Table 3.

Table 3 Blending methods – advantages and disadvantages (Arora and Banerjee, 2013)

Method	Description	Location of blending	Advantage	Disadvantage
Beds/stockpiles	stacking of two or more coals in layers	on the conveyor belt homogenisation at transfer point	only one system required relatively inexpensive	all coal must be stacked before blending not possible to change the blending ratio
Silos	coal in one silo is dropped onto a conveyor below carrying a second coal	on the conveyor belt homogenisation at transfer point	accurate blending ratio ratio can be varied	high capital cost
Ground hopper	first coal is bulldozed into the hopper, second coal is added via wagon or other source	at common transfer point homogenisation at transfer point	ground hopper is an additional source/stock for reclaiming	feeding rate is not accurate
Blending on moving belt	two types of coal are stacked in two yards and gathered by separate stacker/reclaiming systems	at common transfer point homogenisation at transfer point	blending ratio can be changed at any time	all coal must be stacked first
Blending on moving belt (imported coal reclaimed and domestic coal from track hoppper	imported coal is reclaimed from the coal yard and domestic coal is fed from the track hopper/wagon	at common transfer point homogenisation at transfer point	blending ratio can be changed at any time only imported coal needs to be stacked, other can come in as delivered	lower blending accuracy than silo blending

Many of the advantages of on-site blending relate to the flexibility of the blend to be sent to the boilers. The disadvantages generally relate to practicalities such as cost and the co-ordination the stockpiles and blending activities.

For many blends, the majority of the determination of the blend mix, in terms of proportion of each coal type, is achieved during the placement of the coals onto the same stockpile or into the hopper. However, the actual physical mixing of the coals happens as the coal is reclaimed from the pile or hopper. This has to be carried out in such a way that the coals from different layers within the stockpile are mixed and, as much as possible/required, homogenised before the final delivery to the boiler.

Figure 24 shows the stacker/reclaimer system at the longitudinal coal pile at the 192 MW Plomin coal-fired plant in Croatia. The coal plant next to the power plant could no longer meet the plant's demand for coal and so coal was imported from overseas. This meant tripling the capacity of the coal yard from 32 kt to 114 kt and quadrupling the stacking speed of the reclaimer serving the coal pile from 350 t/h to 12,000 t/h. The plant also needed a new 6000 ft long (1830 m) conveyor to deliver the coal from the jetty to the yard (Oberrisser, 2008). A boom of 135 ft (41 m) is required to be able to access and reclaim from the full width of the pile (Oberrisser, 2008).

Figure 24 Stacker/reclaimer at the coal pile at the Plomin Power plant in Croatia (Oberrisser, 2008)

The Ho Ping Power Plant, Hualien, Taiwan has two 660 MW pulverised coal fired units. The plant has two circular stockpiles, each storing over 270 Mt of coal – these are two of the largest circular coal piles ever built. Two 3500 t/h radial stackers receive conveyed coal from ships and add this into the existing pile using a 105 ft (32 m) boom. At the moment the system is relatively simple as the plant does not fire blended coal. However, the space and equipment available means that this is an option for the future (Oberrisser, 2008).

Space constraints at the W H Sammis Plant in Stratton, Ohio, means that coal has to be unloaded into a 300,000 t pile at the train-unloading site that is 2350 feet from the coal yard reclaim area. Four hoppers with vibratory feeders reclaim the pile and feed the coal onto a 1000 t/h transfer conveyor which travels 1900 ft (580 m) to a stacking tube forming a 15,000 t pile in the coal yard reclaim area. This transfer allows an almost buffering effect between coal delivery and coal use at the plant. Multi-hoppers and radial stackers co-ordinate to provide custom coal blends as required for each of the plant's coal-fired units (McCartney, 2006).

As mentioned in Section 2.3, in general, Indian coals are low in moisture (7–8% at most mines and 10–12% for a few mines). However problems arise when rain causes coal to swell and, in extreme situations, form slurries. This problem can be limited by ensuring that the coals and stored and piled appropriately. Washed coal is fed to more efficient units and is generally not stockpiled. Although the mixing of washed or imported coal with raw coal could help reduce coal handling problems in the rainy season, many stations are not practicing coal blending or mixing. Blending of coals could also help plant performance during the rainy season where the combination of raw coal (gross calorific value, GCV, 14.5 GJ/kg) with washed coals (GCV 17.5 GJ/kg) or imported coals (21 GJ/kg) that have been stored in the rain does not lead to clinkering problems that may have been encountered through dry coal blends. Bhatt and others (2010) suggest that techniques for blending of washed coal with indigenous coal under wet conditions should be developed. They suggest that coal yard blending methods, using bulldozers and similar equipment, are inefficient but that blending inside the boiler (tier blending by injecting washed coal from one bunker-mill-firing port exclusively) does not give good combustion control. Conveyor blending methods, where the coals are blended just prior to entry into the bunker, could be optimised.

Canada has relatively stringent emission control requirements for all major pollutants – particles, SO_2 and NOx – but also has province-specific requirements for mercury reduction. This has required significant investment in pollution control technologies and, in some cases, fuel blending or switching (Sloss, 2009). Campbell (2014) describes the work involved in changing fuels for several 150 MW units of Nova Scotia Power in Canada following the closure of local mines. Detailed computerised fluid dynamic modelling was carried out at some of the units along with analysis and testing at laboratory scale. The company developed their own software model to study the different coal and coal blends. Full-scale testing with these coals was then performed to calibrate the model to the existing units over a four-year period. The model was modified to take into account restraints on air emissions (SO_2, NOx, CO_2, Hg and opacity) as these emerged during this period. This work is seen as ongoing and the model will continue to develop as more data become available from additional coals and from further testing. The model will allow the plant to predict how best to blend the coals in order to cope with changes in coal characteristics of available coals into the plants without compromising performance or risking non-compliance with emission legislation.

A report on the development of on-site blending at the B L England Station has been produced by Russell and others (2013). The plant comprises two separate boilers, one fitted with FGD sulphur reduction and both fitted with SNCR (selective non-catalytic reduction) for NOx control. Unit 1 (138 MW gross) comprises three cyclones whilst Unit 2 (170 MW gross) with FGD installed, has four cyclones. Both units operate with similar efficiencies and heat rates and are generally cycled to the same minimum load during evening hours. However, Unit 2 uses around 10% more fuel than Unit 1 on a daily basis. Since Unit 1 does not have an FGD system installed, it still fires a low sulphur blend, as described in the previous paragraph. Initially, the lower sulphur fuel was blended off-site with PRB at a normalised delivered fuel cost of $1.22. The contract coal alone had a delivered fuel cost of $1.00 and thus the blend, as delivered, was more expensive. However, on-site blending was shown to come in at only $1.06, significantly lower than the off-site blend and only slightly more expensive than contract coal alone. In order to facilitate this, the site had to upgrade the coal handling area to allow unloading, stack-out and storage of two different coals. The two coals are loaded in appropriate percentages onto a conveyor belt system and the mixing that occurs at the crushers and through transition points on the conveyor system were shown to provide sufficient blending of the coal before it reaches the boiler. This minimises the need for an on-site blending system. This system proved to be the least costly approach (<$800,000 for all modifications) and, based on the lower costs of the on-site blending, the capital costs of the fuel switch have a payback period of less than two years.

It is interesting to note that the majority of the literature relating to coal management on site relates to advanced control systems. This is perhaps a reflection on what is regarded as interesting for publication. In reality, many plants do not use such complex blending methods and, instead, achieve adequate coal blending using existing coal moving equipment. For example, the Longannet Plant in Fife, Scotland, blends coal largely for volatile content (mainly Indonesian and Columbian coals) and have had problems with spontaneous combustion prior to the fuel entering the furnace. Three of the four 600 MW units at the plant have FGD systems whereas the fourth unit relies on low sulphur coal (<0.5%) for compliance with emission limits. This low sulphur is achieved through blending. The NOx emissions are also controlled through blending, with South African coals, having a higher nitrogen content, having to be used to a lower extent. Although the plant relies on coal blending to meet both performance and emission requirements, it does not have a blending facility as such and, instead, achieves blending through the existing coal movement machinery (such as bulldozers) (Dickson, 2013).

5.4 Blending just before or during combustion

An alternative to delivering blended coal to the boiler is to feed different coals into the boiler at a pre-determined ratio. This avoids the need for pre-mixing and means that coals can be stockpiled separately at the plant (Stasiuk and Whitt, 2010).

Stasiuk and Whitt (2010) discuss the upgrading of a coal blending facility (site unspecified) at an underground coal reclamation site feeding blended coal to a local plant. Initially the blending was achieved by basic control of feed rates. The plant operators determined that the plant performance, including pollution control, would be improved by using a particular coal blend. The existing system was not able to provide the consistency of blending required by the plant. The site was upgraded with new feeders to provide a more consistent coal flow and was fitted with a control system comprising:

- remote set-point control for each of the feeders;
- advanced control software to monitor coal weight and flow rate at the reclaim tunnel and to provide consistent coal delivery;
- improved alarm system to notify operators when the blend does not meet required specifications;
- tracking and storage of historical data on coal delivery and performance that can be directly correlated with boiler performance.

Prior to the system upgrade the coal blend flow rate fluctuated from 340–450 t/h and this improved to a more consistent 330–380 t/h, which matched neatly with the target demand. The new system could also change from one blend mix to another, remotely, automatically and almost immediately, if required.

Blending can be performed through the mill control. On-belt coal blending can be achieved using a PLC along with a DSC (distributed control system) to control the rate of feed of different coal types onto the conveyor and through to the mill. Coal blending software and on-belt analysers allow mass balances to be more accurately calculated, tracked and developed. This also allows changes to be made to the blend composition at the last minute (Stasuik and Whitt, 2010).

For blending within the furnace, each type of coal can be injected into the boiler from a separate burner with no prior mixing. This method can be used to control burn-out rates and promote the complete combustion of fuel through fuel-staging. Lee and others (2012) cite data from studies showing that this form of in-furnace blending can be used to reduce both unburned carbon and NOx emissions. Lee and others (2011, 2012) carried out studies in a bench-scale entrained flow reactor (EFR) furnace (60 cm long with a 7 cm internal diameter). The system set up allowed for the variation of feed coals and the variation in mixing time between binary coals. One coal was fed into the side of the injection probe and another coal was fed into a centre tube installed with a cooling system. Bituminous (Yagutugol) and subbituminous (Adaro) coals were blended. As expected, in-furnace blending of the coals resulted in improvement of the unburnt carbon fraction and a further reduction in NOx emissions, exceeding what could be achieved by blending the coals prior to combustion. Controlling the levels of excess air could achieve similar reductions in coals blended outside the boiler. Lee (2011) also showed that the combustion efficiency of the blend could be improved by creating a swirl effect within the boiler but that the overall result was dependent on the primary gas ratio. The in-furnace blending method showed potential for improving the combustibility of the fuel and reducing NO emissions in real power plants. Numerical modelling was developed which could ‘reasonably’ predict the unburned carbon and NO emissions from the bench-scale study (Lee and others, 2011). However, Lee and others (2012) stress that the practical application could be limited due to the complexity of the arrangement of the boiler required and that their finding should be verified, possibly with a more extensive model, before testing a larger scale.

Dynamic blending is becoming increasingly popular for a combination of reduced fuel costs improved combustion stability and improved environmental performance. Because of the complex, non-additive behaviour of coal blends, dynamic blending uses neural network processing – regression equations within computer optimisation algorithms, to predict and produce the optimum blend to meet requirements.

Zhao and Xiong (2011) tested HuoLinHe lignite and Hulunboir lignite blends in laboratory conditions to compare the actual blend performance against that predicted by dynamic blending calculations. Regression analysis was used to correlate the ‘goodness of fit’ of the results. Although the paper is translated from Chinese, it would appear that the results indicate that dynamic blending systems can improve upon predictions based on plant design and coal characteristics.

5.5 Comments

There are many methods for creating coal blends. Blends can be produced at almost any stage of the fuel chain, such as the mine, washery, transport hub, storage yard and even as it is delivered to the boiler. Each of these methods has its own advantages and disadvantages, many of which depend on the circumstances of the situation and location – there is no one best approach to suit all. Each plant will have to determine which method is most appropriate for them and this will depend on how the coal is delivered and in what quantities, how much space is available, what blend is required and how flexible the blending process must be and, of course, cost. However, it is often the case that, although the construction and outfitting of a coal blending facility is a great expense, the cost is often justified in the savings that can be made in terms of long-term coal costs.

6 Conclusions

Coal blending is becoming increasingly valuable as a means to extend plant operational life and maintain performance at times when coal supply and consistency can be an issue. This may be due to a number of reasons such as loss of indigenous/local fuel supply, cost issues, and increasingly stringent emission control requirements. Since most plants were designed to burn a specific coal type, switching to alternative coals can cause significant plant problems such as efficiency reduction, reduced availability, or slagging and fouling damage.

Coal is a complex mix of physical and chemical characteristics, many of which are understood but many are not. Some of the behaviour of a coal blend may be predicted from what is known about the individual coals but much remains guess work. Numerous systems, from simple excel spreadsheets to advance computer modelling systems are available which aim to predict the behaviour of coal blends in practice. Some of these systems can be integrated with online analysis systems at coal plants to provide real time control of coal blend mixes to required specifications.

Coal blending offers a means for coal plant operators to try to balance the characteristics of the coals available with the combustion performance required by the plant. In many cases, this balance cannot be achieved fully and so there must be decisions made on which characteristics are necessary and which can be worked around. For example, a coal may have a higher moisture than desired but its low ash content will be an advantage. Although the characteristics of a blend can be estimated or predicted to some extent, in most cases, it is full-scale testing and operational experience that will prove whether a blend will work or not.

Blending can be achieved almost anywhere in the coal chain. Some coal mines can produce blends on site or will perform rudimentary blending to provide a more consistent supply of coal. Any point where coal is resting, such as stockyards and ports, can be a site for blending. By piling coal in an organised manner in layers or groups and then reclaiming it in a co-ordinated manner, blends can be created to order. Mixing is achieved as the coal is reclaimed from piles or silos, some with vibrating conveyors, and transferred to the plant or for further storage. Coal processing facilities are often located at ports and/or rail yards where coal supplies converge. These facilities can create blends to order and can maximise the use of cheaper coals, that may otherwise be unsaleable, to sell at a profit.

Plant operators must make the decision as to whether to buy in more expensive blends or to perform coal blending on site. This decision will often be pre-determined by the space available to the plant for such blending and/or by the investment required. Coal blending can be expensive. However, on-site blending allows blends to be created and altered to suit the plant with far more precision than may be achieved with a bought in blend. It also allows for quick changes, for example from low calorific stock to high calorific stock when demand peaks or from high sulphur coal to low sulphur coal during periods where emissions must be lowered.

Perhaps one conclusion which must be made is to emphasise that this report represents a review of the literature and, as such, can only present data which have been published. In many cases, this will be material produced by those who wish to advertise work that has been done, much of which is commercial. The average plant operator does not publish on the general day to day operation of a coal plant. And so, although this report provides information on the state-of-the-art with respect to coal blending methods and equipment, it may not fully represent what is actually being carried out at the average coal-fired power plant. Several papers alluded to the fact that coal blending is almost an 'art' and that most plants achieve the blend they require based on operator experience. This kind of information is often considered commercially sensitive and will remain unpublished. Further, it is known that many plants are not fitted with the on-site blending equipment that is discussed in Chapter 4. Rather, they make do with the simple coal moving equipment they have available to them and are managing to operate their plants and their coal blending effectively and efficiently.

And so it would seem that although coal blending is a relatively complex issue, most plants manage to adjust to coal blending requirements through a combination of outside expertise (specially designed blending systems, or blends modelled), trial and error, and judgments made by a qualified on-site expert.

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