Coal beneficiation

Dr Ian Reid

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Preface

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

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

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, China, the European Commission, Germany, India, Italy, Japan, Poland, Russia, South Africa, Thailand, the UAE, 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.

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Abstract

Up till now the power industry has largely met the demand to increase efficiency and reduce emissions by improving boiler technology and post combustion emission treatment. However, feedstock quality is a key element to improve coal power plant performance. The preparation of coal to remove inert matter and reduce contaminants can benefit every aspect of power plant operation. This report reviews a broad range of technical developments in coal beneficiation covering conventional, physical dense-media and dry coal treatment, upgrading technologies using thermal, chemical and bio-oxidation, coal blending, and applications for the use of ultrafine coal and waste streams.

Lignite power generation normally utilises raw feedstock resulting in significant energy and reliability penalties; the report discusses energy efficient technologies that reduce moisture and ash levels.

The direct injection coal engine (DICE) may have the potential to compete with diesel fuel as a source of compact flexible power generation, offering a rapid response to complement intermittent renewable energy generation. Suitable coal sources and preparation methods are discussed for the production of micronised refined carbon (MRC) fuels, with specific formulations that overcome issues associated with coal water slurry fuels.
**Acronyms and abbreviations**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADMFB</td>
<td>air dense-media fluidised bed</td>
</tr>
<tr>
<td>ARA</td>
<td>Amsterdam-Rotterdam-Antwerp</td>
</tr>
<tr>
<td>AUSC</td>
<td>advanced ultrasupercritical steam system</td>
</tr>
<tr>
<td>CCS(g)</td>
<td>Clean Combustion System gasifier</td>
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<td>CGA</td>
<td>coal grain analysis</td>
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<tr>
<td>CIF</td>
<td>cost insurance and freight</td>
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<td>CPP</td>
<td>coal preparation plants</td>
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<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation (Australia)</td>
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<tr>
<td>CWS</td>
<td>coal water slurry</td>
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<td>CWF</td>
<td>coal water fuel</td>
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<tr>
<td>DICE</td>
<td>direct injection carbon engine</td>
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<tr>
<td>DMC</td>
<td>dense-media cyclone</td>
</tr>
<tr>
<td>D&amp;R</td>
<td>drain and rinse</td>
</tr>
<tr>
<td>DSI</td>
<td>dry sorbent injection</td>
</tr>
<tr>
<td>US$/GJ</td>
<td>dollars per Giga Joule (note: 1 GJ = 0.948 million Btu = 9.48 therm)</td>
</tr>
<tr>
<td>Ep</td>
<td>particle efficiency in coal separation</td>
</tr>
<tr>
<td>ESP</td>
<td>electrostatic precipitator</td>
</tr>
<tr>
<td>FGD</td>
<td>flue gas desulphurisation</td>
</tr>
<tr>
<td>GCV</td>
<td>gross calorific value</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas</td>
</tr>
<tr>
<td>HELE</td>
<td>high efficiency low emission</td>
</tr>
<tr>
<td>HHS</td>
<td>hydrophobic-hydrophilic 2-liquid separation</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>LNG</td>
<td>liquefied natural gas</td>
</tr>
<tr>
<td>mPa.s</td>
<td>millipascal-second (viscosity)</td>
</tr>
<tr>
<td>MPa</td>
<td>megapascal, 1 MPa = 10 bar pressure</td>
</tr>
<tr>
<td>MRC</td>
<td>micronised refined carbon</td>
</tr>
<tr>
<td>Mtce</td>
<td>million tonnes carbon equivalent</td>
</tr>
<tr>
<td>NaOH</td>
<td>sodium hydroxide (caustic soda)</td>
</tr>
<tr>
<td>NGM</td>
<td>near gravity material</td>
</tr>
<tr>
<td>NMP</td>
<td>N-methyl-2-pyrrolidone</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PRB</td>
<td>Powder River Basin (USA)</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
</tr>
<tr>
<td>rpm</td>
<td>revolutions per minute</td>
</tr>
<tr>
<td>ROM</td>
<td>run-of-mine coal (raw supply)</td>
</tr>
<tr>
<td>REE</td>
<td>rare earth elements</td>
</tr>
<tr>
<td>SBC</td>
<td>screen-bowl centrifuge</td>
</tr>
<tr>
<td>SC</td>
<td>supercritical</td>
</tr>
<tr>
<td>SCR</td>
<td>selective catalytic reduction (NOx)</td>
</tr>
<tr>
<td>SNCR</td>
<td>selective non-catalytic reduction (NOx)</td>
</tr>
<tr>
<td>SSC</td>
<td>screen-scroll centrifuge</td>
</tr>
<tr>
<td>SG</td>
<td>specific gravity</td>
</tr>
<tr>
<td>t/h</td>
<td>tonnes per hour</td>
</tr>
<tr>
<td>UCC</td>
<td>ultra-clean coal</td>
</tr>
<tr>
<td>UHV</td>
<td>useful heat value</td>
</tr>
<tr>
<td>USC</td>
<td>ultrasupercritical</td>
</tr>
<tr>
<td>WHT</td>
<td>internal waste heat utilisation</td>
</tr>
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1 Introduction

The worldwide coal power industry must rise to the challenge imposed by more stringent environmental regulations; typically, higher performance targets are achieved by the adoption of high efficiency low emission (HELE) technologies that raise plant efficiency and lower pollutant emissions. Internationally traded coals are prepared to achieve a uniform coal standard; substitution by inexpensive, minimally prepared high ash indigenous coals impairs power station performance, affecting every aspect of an installation. The quality of the coal directly influences the selection and optimal implementation of the latest high performance boiler technologies. The impact of coal properties is now of greater significance due to the introduction of carbon dioxide emission targets.

Overall the energy content of coal resources is gradually declining. The average gross calorific value (GCV) of coal consumed in the USA has steadily fallen from 28 MJ/kg to 20 MJ/kg over the last 50 years; most USA coal supplies are now of low-sulphur subbituminous grade mined from the Powder River Basin, Wyoming. Similarly, in India the GCV of coal has fallen from 24.7 to 14.7 MJ/kg in the same period (Mills, 2016). The reduction in coal quality impacts upon power station performance inhibiting efforts to maximise energy efficiency.

In the coal mining industry ‘beneficiation’ is any process which removes minerals from coal, to produce a higher-grade product (concentrate) and a waste stream (tailings). Power stations that use beneficiated coals can obtain practical, environmental and economic benefits over those plants that use minimally processed or sized coal. A cleaner, more concentrated fuel will lead to improved boiler operation by the reduction of ash formation in the boiler which in turn minimises fouling, ash handling and disposal. High ash and water content in coal lowers the overall plant efficiency, necessitating a larger, more expensive installation with increased fuel handling and consumption. Beneficiation processes partially remove the pollutant precursors that lead to particulates, sulphur and mercury; beneficiation may ultimately return significant cost savings in emissions control equipment. A prepared coal typically lowers greenhouse gas emissions by about 5% when compared to the combustion of untreated, run-of-mine (ROM) coal. Economically, significant cost savings are obtained from the improved coal handling and transport of beneficiated coal (Zamuda, 2007).

However, the industry continues the commercial use of indigenous, untreated coal that may contain up to 50% ash which lowers the energy content of the coal leading to a dramatic impact on plant efficiency, reliability and emissions. While the use of these indigenous, low-cost feedstocks offers significant energy security, these coals require beneficiation to achieve international performance standards. As an example, a specification for an internationally traded coal that is imported to Rotterdam (termed ARA) is attached as Appendix 1; the coal is processed to achieve a water content of 12–15% and ash content in the range of 11–15% to meet the set energy standard (globalCOAL, 2016).

A number of barriers prevent the widespread introduction of coal beneficiation in developing economies. A major issue is to ensure that the cost of beneficiation may be recovered so that the process is economically
worthwhile. For example, in India the current coal classification system possesses wide banding; thus, a cleaned coal may remain in the same band as the original raw coal, resulting in a loss in value for the beneficiated coal. The Indian grading system is under revision; the adoption of a greater number of calorific value bands will distinguish between the values of raw and prepared coal which possesses higher energy content (Dipu, 2016).

Plants designed to use untreated coal may not fully benefit from switching to a prepared coal; the resultant reduction in operational flow rate may lead to a departure from optimal design parameters. The boiler plant, including the feed and burner systems, would require modification to adapt to the lower feed rate.

The improvements in operability and efficiency derived from beneficiated coal are more apparent for stations employing advanced technologies than for more basic subcritical stations. Beneficiated coals are necessary to optimise HELE plants: steam boilers operate with higher surface temperatures and hence have an increased sensitivity to ash fouling. Beneficiating the coal may produce thermal efficiency gains that are much greater (up to 50%) than for a subcritical plant, while the reduction in contaminants from prepared coal alleviates the demand on complex emissions control technologies.

There are over 3000 coal preparation plants in operation treating approximately a third of the global coal production. Coal beneficiation can be broadly divided into physical, thermal and chemical methods. The focus of new physical beneficiation methods is to increase recovery of smaller coal particles to improve efficiency in processing coal resources and simultaneously reduce environmental waste. During the current treatment of thermal coals, the ultrafine fraction is often rejected as waste due to the additional cost of recovery. Physical separation methods can employ wet dense-media or dry technologies; the international problem of water scarcity is leading to increased adoption of dry methods, which are lower cost but reject more carbon matter. These dry methods have proved effective for coarse particles but need to be extended over a broader size range.

Thermal, chemical and bio-oxidation methods offer more intensive cleaning of coal, removing sulphur from both the organic and inorganic fractions. The adoption of chemical and bio-processing systems has been limited due to higher costs and the formation of waste streams. However, these techniques may be applicable to cases where coal and mineral matter are finely interspersed and less tractable to physical separation techniques. Thermal processing is practised in the preparation of coking coals but involves high temperatures that require significant energy input, while new technologies that process coal under intermediate temperature conditions may be attractive to produce uniform and stable thermal coal.

The blending of coals to achieve a suitable boiler feedstock is well established to maximise the use of a low-quality inexpensive feed to achieve acceptable plant operability. Bio-feedstocks and fuel additives may be fed with raw or beneficiated coal to modify boiler emissions.

The preparation of a micronised refined carbon (MRC) fuel for use in an internal combustion engine is based upon a slurry fuel that is formulated from low ash and sulphur coal. The MRC fuel can be achieved
by chemical processing, but a less restrictive fuel specification has been adopted which requires less expensive physical methods.

This report reviews the status of coal preparation, extending earlier IEA Clean Coal Centre studies on: Coal upgrading to reduce greenhouse gas emissions (Couch, 2001); Losses in the coal supply chain (Baruya, 2011); Direct injection carbon engine (Nicol, 2014) and Low quality coals – key commercial, environmental and plant considerations (Mills, 2016).
2 Projected coal demand 2016 to 2040: implications for new coal preparation facilities

Coal production currently remains close to the high level observed from 2010, approaching 8 Gt in total, with indications that future production will continue to rise, albeit at a more modest rate. This trend is despite the contraction in coal generation observed in OECD member states where 2300 GW of capacity is expected to be withdrawn during the period 2016 to 2040.

The trends in OECD coal consumption are attributed to: substantial rise in renewable energy sources with an additional 3000 GW capacity projected by 2040; competition from low-cost natural gas in the USA; general domestic and industrial efficiency improvements; and reductions in coal demand arising from utilising new clean coal technology in thermal plants.

However, the closure of older stations in mature economies is predicted to be more than offset by the rise in coal use in Asia, particularly India, while the consumption of coal may have peaked in China, currently the largest global coal producer and consumer (IEA, 2016). Overall, despite a temporary reduction in coal demand during 2015, new coal stations proposed for India indicate that coal consumption is likely to gradually increase at a rate of +0.4%/y over the next 25 years (IEA, 2015a). A more detailed breakdown, using selected data extracted from the IEA World Energy Outlook is shown in Table 1.

The need for new coal preparation plants (CPP) depends on how thermal coal generation capacity is likely to change over the next 25-year period. There are currently two opposing trends in coal demand which will have consequences for new investment in CPP: significant capacity contraction in mature OECD economies driven by climate change policies that may lead to plant closure (UN/COP21, 2016); and a substantial increase in thermal coal power capacity in rapidly developing countries, notably in India where only a fraction of coal is currently pre-treated (IEA, 2015a). Announcements on the addition of new thermal coal power capacity mostly for supercritical (SC) or ultrasupercritical (USC) technologies suggest this trend is set to continue. Plants using higher severity steam conditions can be designed to operate on ROM coal supplies, but benefit more from using higher quality fuels than do subcritical plants. The construction of additional large subcritical stations is not expected and in a number of countries the intent is to decommission aged stations and replace them with new coal HELE technology.
Projected coal demand 2016 to 2040: implications for new coal preparation facilities

Table 1  Coal demand by region 2013-2040 under the New Policies Scenario, Mtce (IEA, 2015a)

<table>
<thead>
<tr>
<th>Region</th>
<th>2013, Mtce</th>
<th>2040, Mtce</th>
<th>Change, Mtce</th>
<th>CAAGR (compound average annual growth rate), %</th>
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</thead>
<tbody>
<tr>
<td>Global</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>World prediction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World</td>
<td>5613</td>
<td>6306</td>
<td>692</td>
<td>0.4%</td>
</tr>
<tr>
<td>Main thermal coal regions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>617</td>
<td>398</td>
<td>-220</td>
<td>-1.6%</td>
</tr>
<tr>
<td>EU</td>
<td>409</td>
<td>145</td>
<td>-264</td>
<td>-3.8%</td>
</tr>
<tr>
<td>China</td>
<td>2932</td>
<td>2826</td>
<td>-106</td>
<td>-0.1%</td>
</tr>
<tr>
<td>India</td>
<td>488</td>
<td>1334</td>
<td>846</td>
<td>3.8%</td>
</tr>
<tr>
<td>South East Asia</td>
<td>130</td>
<td>446</td>
<td>315</td>
<td>4.7%</td>
</tr>
<tr>
<td>Africa</td>
<td>148</td>
<td>259</td>
<td>111</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

Note: The IEA ‘new policies scenario’ is the central scenario of the ‘World Energy Outlook 2015’, and assumes modest implementation of announced government measures that introduce energy efficiency measures, supports low carbon fuels and renewable energy, and prices carbon dioxide. The alternative policies are considered less likely and assume that either there is little change from current activities leading to significantly enhanced coal consumption or alternatively there are stringent de-carbonisation measures to limit CO₂ to 450 ppm, which are to be implemented by a larger set of countries.

Coal demand in China has previously risen dramatically but a decline is now anticipated due to an intensive state programme to raise overall coal power efficiency and to introduce extensive renewable energy resources. In contrast, India faces severe power shortages on a daily basis, and has limited alternate energy resources to supply a rapidly expanding population. Thus, the Indian government plans to add 900 GW of thermal coal capacity by 2035. The construction programme includes plans to introduce supercritical steam technology, rather than the currently dominant subcritical coal power plant fleet (Barnes, 2016; Banuya, 2016). Introduction of new coal power stations provides an opportunity to add new CPP facilities and a number of potential projects have been announced. The intended replacement of imported coal by a one third increase in domestic production during 2017 means that these indigenous coals would require extensive treatment to be of a comparable standard. Current domestic supplies are generally blended with imported coal to improve the feed characteristics (Goyal, 2016).

Indian coals have proved hard to beneficiate due to the presence of a fine matrix of minerals within the coal structure. It may be particularly advantageous to intensively prepare these coals to encourage the installation of the latest HELE power plant technologies. A higher quality feed would help attain both the new AUSC efficiency target of 49% (LHV) set by the Indian Government national power programme and the recent emissions legislation controlling major pollutants (Adams, 2016).
Figure 1  IEA near-term global coal demand by region (historical and forecast) for the period 2000-2020 shows the rise in demand due to published information from India (IEA, 2015b)

The modest growth rate in coal consumption over the next five-year period as shown in Figure 1 is predicted to result in steady coal feed prices. The trend is attributed to coal mine overcapacity, with projected prices of approximately 50 US$/t coal (IEA, 2015b).

The implication of the IEA projections is that coal is likely to remain competitive with other resources in Asia where there are limited options for alternative low-cost energy (Baruya, 2016). For example, despite recent low crude oil prices, the current price ratio of fossil fuels in China (coal 1: petroleum 8.3: natural gas 3.2) strongly favours coal despite the requirement of enhanced emissions control systems (Zuo, 2016).

In the medium term, in the absence of state subsidy for renewable energy, coal will continue to be the lowest cost option for electricity generation in China. A sudden rise in coking coal prices from 78 US$/t to 260 US$/t during the third quarter of 2016, attributed to reduced Chinese production to adjust the steel market, has also temporarily impacted thermal coal import prices, but is expected to recede with prices settling above 40 US$/t (The Times, 2016).

Globally due to the issues of greenhouse gas emissions and localised urban smog, the coal power industry is under regulatory pressure to reduce emissions and improve performance. The quality of coal is an important factor in achieving these goals and for countries expanding the use of coal, an increasing concern is that the energy content of coal supplies is falling. High ash and water content impact on overall plant efficiency, particularly if inexpensive untreated lignite fuel is used as the feedstock.
3 Coal blending and feedstock additives

In a well-established practice, low-quality feedstock can be enhanced by blending with another fuel or by introducing a fuel additive. The fuels and chemicals which may be included are higher quality coals, additives which moderate emissions or bio-feedstocks that possess lower GHG emission ratings. Blending is also used to control the size distribution of the coal feedstock to optimise the proportion of fine particles. This section provides a limited introduction to coal blending and feedstock additives with further detail available in reports published by the IEA CCC (Sloss, 2014; Mills, 2013).

3.1 Coal blending

Coal blending using higher-grade imported coal is practiced where the indigenous coal supply is of low quality and where few upgrading facilities are available (Mills, 2016). The main benefit of using a coal blend is to maximise the use of inexpensive feedstock while limiting the negative impact of the low-cost fuel on the performance of the plant. The coal blend regulates slag formation in the boiler to improve operability and reliability. In addition, the higher fuel energy density obtained by blending improves plant efficiency by lowering ash content. Raising the feed quality reduces demand on emissions treatment systems such as ESP and flue gas desulphurisation (FGD) systems. Coal blending has been extensively practiced in India, particularly as the quality of indigenous mined coal has gradually declined. The latest Indian Government targets aim to encourage the use of domestic supplies; however, the plants continue to rely upon coal blending to permit reliable operation on this low-quality feedstock.

3.2 Coal feedstock additives

The upstream addition of minerals to coal to lower emissions is an alternative technique to post combustion effluent treatment. For example, lime may be combined with coal in fluidised bed combustors to form sulphates in the reactor and thus reduce sulphur dioxide emissions. Lime addition with coal under an oxygen deficient atmosphere forms a removable molten sulphide upstream of the boiler, as an alternative to upgrading post combustion emissions control equipment.

A new metal oxide additive has been developed to influence the coal combustion mechanism to lower NOx emissions (Ottolini, 2016). The metal oxide acts as a cracking catalyst to improve the combustion of coal through enhanced pyrolysis which enriches the initial effective fuel stoichiometry influencing nitric oxide formation. Performance data obtained from a live trial at the Wilton Power UK station, in 2015, showed the benefits of the addition of finely milled iron alumina silicate (present at 3.4 vol% in coal). The additive led to a 10% reduction in raw NOx emissions (from 550 to 500 mg/m³), improved ash burnout with lower carbon content, with an added benefit of reduced corrosion of the boiler. Fine milling is considered a key factor in the preparation of the additive and coal feed, as it improves miscibility between the reagent and coal particles. The technology is considered applicable to plants using selective non-catalytic NOx reduction (SNCR) as a result of reduced nascent NOx formation; the mineral additive equates to a corresponding reduction in ammonia addition.
Coal blending typically involves the addition of a higher-grade coal to raise overall fuel quality and achieve reasonable plant operability. A number of coal-fired plants in Europe, if the policies are favourable, cofire biomass, to improve their carbon footprint. Most of the biomass cofired in Europe is pelletised wood, which is from forestry residues. More cofiring is planned in China, largely using agricultural waste to save CO₂ emissions and to avoid local pollution from the open burning of waste. Unless the existing fuel is low grade then the addition of raw biomass is likely to reduce the quality of a mixed fuel impacting plant efficiency. Generally, biomass has high moisture content and possesses a high degree of partial oxidation that lowers the overall energy content of the fuel. An alternative strategy is to add biomass which has been previously heat treated to form a fuel that is closer to bituminous coal in character. Although at the early stage of commercialisation, such torrefied biomass fuel may be utilised together with a low-quality coal feedstock, to improve both the overall feed quality and lower resultant station carbon emission (Torftech, 2016; Bayar, 2016).
4 Wet and dry coal physical separation technologies

The method selected to process coal is determined by the raw coal classification, the specification required of the product and the availability of water resources. Hard coals are either processed in coal washeries or destoned in air jigs, while low rank coals are upgraded using drying technologies.

Most hard coals are separated by wet processing techniques that form coal-water slurries; separation of fractions is achieved by specific gravity methods. In 'dry-shaling' methods coal is segregated using air tables (Section 3.2) and is applicable in regions with a constrained water supply. Low rank coals are dewatered utilising low or waste energy resources (Section 4.1).

The extent of ash removal required depends on both the percentage and mineral composition present in the raw coal. The content of ash in coal is highly variable but typical mineral content of coal supplies of relevance to India, which is currently seeking to replace imported coal with indigenous supplies, are: India indigenous 39%; Indonesian 14%; South African 17%; and Australian export coal at less than 15% ash (Platts, 2016).

In a typical coal the main non-combustible impurities consist primarily of quartz SiO₂, termed ‘gangue’, together with aluminium oxide Al₂O₃, ferric oxide Fe₂O₃, calcium oxide CaO and magnesium oxide MgO. These metal oxides are present in the form of clays, dolomites, ankerites, calcites, and carbonates. Table 2 lists the main ash components for some international coals.

<table>
<thead>
<tr>
<th>Compound (%)</th>
<th>India</th>
<th>Australia</th>
<th>Canada</th>
<th>South Africa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>57.0</td>
<td>59.0</td>
<td>53.0</td>
<td>49.0</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>27.0</td>
<td>28.5</td>
<td>30.5</td>
<td>30.1</td>
</tr>
<tr>
<td>Ferric oxide</td>
<td>10.0</td>
<td>3.6</td>
<td>4.8</td>
<td>6.9</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>1.7</td>
<td>1.4</td>
<td>3.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>0.6</td>
<td>0.8</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Sodium oxide</td>
<td>0.4</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Sulphur trioxide</td>
<td>0.6</td>
<td>0.9</td>
<td>2.5</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Indigenous Indian coals contain a higher quantity of ash (around 41%) compared to these typical imported coals at less than 17% ash yield, but as shown by Table 2 the main compositional difference of the ash is the high iron content. While the presence of iron can beneficially promote the oxidation of mercury to facilitate extraction (Lee, 2001), the main impact is detrimental as iron lowers ash fusion temperatures leading to operational problems in the boiler (Hatt, 1990). Of the coals in Table 2, the typical Indian one possesses the lowest percentage alumina content, which may increase the propensity to fouling, making it more beneficial to remove the ash.
The qualitative advantages of a prepared coal include: reduced wear and tear in the grinding section of coal mills, reduced erosion of coal nozzles and pipelines; improved furnace reliability; improved heat rate, and improved operation of electrostatic precipitator (ESP) units and induced draught (ID) fans.

The results from a study to quantify the benefits of coal washing when applied to a typical subcritical Indian power plant are shown in Table 3 (Zamuda, 2007). Based on practical experience from typical coal washeries, the study assumed that the ash content of ROM indigenous Indian coal is lowered from 41% to 30% ash. The benefits are expressed in terms of lower costs, energy efficiency and reduced greenhouse gas emissions.

### Table 3  Benefits of coal washing – replacing ROM coal (41% ash) with prepared coal (30% ash) (Zamuda, 2007)

<table>
<thead>
<tr>
<th>Transportation of coal</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in transportation cost</td>
<td>For a 1000 km distance, reduce transport costs by 7.5%</td>
</tr>
<tr>
<td>CO₂ emission reduction associated with transport</td>
<td>For a 1000 km distance, 15% reduction in CO₂ emission</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power plant site</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease in auxiliary power</td>
<td>10% reduction in power use equates to a 10% reduction in ash content</td>
</tr>
<tr>
<td>Decrease in auxiliary fuel consumption</td>
<td>50% decrease in fuel required corresponds to 10% ash reduction</td>
</tr>
<tr>
<td>Improved thermal efficiency</td>
<td>10% ash reduction equates to 3% rise in thermal efficiency on a typical plant</td>
</tr>
<tr>
<td>Improved plant load factor</td>
<td>10% improvement corresponds to 10% lower ash</td>
</tr>
<tr>
<td>Reduction in operation and maintenance (O&amp;M) costs</td>
<td>2% cost reduction corresponds to 10% ash reduction</td>
</tr>
<tr>
<td>Lower capital investment for new power plant</td>
<td>8% reduction for a plant using washed coal (30% ash)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmental</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction of ash disposal</td>
<td>12% reduction in land required for disposal</td>
</tr>
<tr>
<td>Lower water use</td>
<td>12% reduction in water consumption</td>
</tr>
<tr>
<td>Lower CO₂ emission</td>
<td>Washed coal leads to 2–3% lower CO₂ emission</td>
</tr>
<tr>
<td>ESP efficiency improvement</td>
<td>1% improvement (98% to 99%)</td>
</tr>
</tbody>
</table>

Table 3 shows that the use of a higher quality fuel of greater energy density will produce various benefits which combine to provide a substantial improvement in overall plant performance and resultant emissions. For example, a 10% ash reduction corresponds to: transport cost savings of the order of 7.5%; a 3% rise in thermal efficiency, and at least 3% lower carbon dioxide emissions. The 12% reduction in water use could be particularly significant in drought affected regions; in 2016, there were occasions where affected stations were forced to temporarily cease operations due to water shortages. The economic and environmental advantages outlined in Table 3 relate to subcritical power plants; benefits would be even larger for HELE coal plant implementing advanced steam systems and utilising the latest pollution control technologies.
4.1 Coal washery methods

A coal washery carries out four main processes using a range of methods: comminution (crushing), sizing, separation, dewatering and waste disposal (see Table 4). Crushing technologies that reduce coal to under 60mm diameter include: rotary breakers which use gravity and agitation; roll crushers and impact crushers such as hammer mills or ring granulators. The most common type of preparation plant involves a 3-step water-based dense-media method. This is relatively inexpensive, but new developments seek to improve recovery of ultrafine coal particles whilst minimising both water consumption and the formation of waste streams.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Size classification</th>
<th>Solid separation</th>
<th>Dewatering</th>
<th>Waste disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse (&gt;10 mm)</td>
<td>Grizzly vibrating screens</td>
<td>Dense-media vessel (DMV), large diameter dense-media cyclone (DMC)</td>
<td>Drain and rinse (D&amp;R) screens</td>
<td>Waste pile/co-disposal</td>
</tr>
<tr>
<td>Intermediate 10–1mm</td>
<td>Vibrating screens</td>
<td>DMC, jigs</td>
<td>D&amp;R screens centrifugal dryers</td>
<td>Waste pile/co-disposal</td>
</tr>
<tr>
<td>Fine 1–0.15 mm</td>
<td>High frequency screens</td>
<td>Spirals, Teeter bed separators, Reflux classifiers Water only cyclones Enhanced gravity separations, Enhanced gravity, Shaking tables</td>
<td>Screen-bowl centrifuge, Vacuum filters</td>
<td>Thickener, impoundment, Underground injection Co-disposal</td>
</tr>
<tr>
<td>Ultrafine &lt;0.15 mm</td>
<td>Classifying cyclones</td>
<td>Flotation</td>
<td>Screen-bowl centrifuge, Vacuum filters, Thermal dryers, Recessed plate press</td>
<td>Thickener, Impoundment, Underground injection Co-disposal</td>
</tr>
</tbody>
</table>

The design of the separation process selected for a coal washery will depend on a range of factors (Couch, 2002):

- coal washability assessment of the raw feedstock;
- percentage fines content of the ROM coal, which is dependent on the extraction technique, and results in carbon losses;
- assessment of coal quality over a 10-year period;
- market, regulatory and taxation environment;
- capital and operating costs for the selected coal preparation plant (CPP) design;
- projected value of the separated coal products;
- projected value for carbon containing waste streams to be used locally; and
- cost of waste treatment and disposal.
Characteristics of the coal (ash content and hardness) and the physical size separation of particulates determine the efficiency of operation of a coal washery. A partition (Tromp) curve can predict how effective certain coal washery processes will be in recovering the coal. The partition coefficient obtained using float analysis is plotted as a function of specific gravity to predict the separation efficiency for a particular feedstock (Kohmuench, 2000). Bituminous grade coal is the preferred feedstock for coal washeries, but issues of supply, sulphur content and feed cost mean that increasingly lower rank coals are required to be treated. The main separation techniques used in coal washeries are summarised below.

Coal preparation plants consist of a series of processing steps, each designed for a specific particle size range. Inefficiencies arise where the particle size does not fall within the intended range for that circuit. Water based cleaning processes for the preparation of internationally traded coal aim to divide the raw coal into the following three categories: clean coal with an ash content of 7–9 wt%; ‘middlings’ with an ash content of 25–30 wt%; and lastly ‘rejects’ containing an ash content of 65–70 wt%.

Figure 2, schematically depicts the flow of coal through the sizing, cleaning and dewatering processes in a typical coal preparation plant which can treat the full range of particle sizes. Four cleaning circuits treat the crushed raw coal; coarse, medium, fine and ultrafine particles are treated in separate units, ending with froth flotation to isolate an ultrafine coal fraction (Luttrell, 2009).

![Figure 2 Flowsheet for a typical US coal preparation plant (Luttrell, 2009)](image-url)
and only contributes a few percent of the final coal product; however, on a large installation (25 Mt/y) this can amount to several hundred thousand tonnes of coal.

A small fraction of coal is unrecovered and passes out of the plant in waste streams; in this way, a high efficiency coal preparation plant typically loses approximately 10% of the original energy content (Luttrell, 2009). The processing of less tractable composite coals, where the coal and minerals are closely interlaced, results in higher rejection levels. Such losses can exceed 15% of the heat value of the raw coal feed to achieve the required coal quality.

A coal washery at Mugla, Turkey (Figure 3) shows a modern CPP layout with process units using dense-media (DM) separation: DM vessels for coarse coals, dewatering screens (yellow), a DM cyclone (red) for middle-sized fractions, and a thickener for fine coal waste slurries. This washery possesses two heavy-media vessel circuits: a Drewboy wheeled DM vessel (0 + 50 mm) for coarse coals and a Larcodem DM 1–18 mm) small coal separator (Altincelep, 2014).

![Image of a coal washery](image_url)

**Figure 3** Example of a heavy media-based coal washery, Mugla, Turkey (CWP, 2016)

The recently announced Kusmunda CPP plant located at Korba, Chhattisgarh, India is scheduled to process 25 Mt/y of raw coal. The plant has adopted a coal jig preparation strategy that is specifically designed for high ash Indian coal to achieve an ash content of 33.5 wt% from the original 41 wt% ROM coal. The plant operates twin coarse coal jigs with double deck dewatering, twin small coal jigs with basket centrifuges, classifying cyclone and spiral concentrator and thickener with pressure filtration (CMPDI, 2015).

A detailed summary of the range of worldwide coal preparation methods is available in an earlier IEA Clean Coal Centre report (Baruya, 2012).
4.1.1 Coal comminution (crushing) and sizing

Unprocessed coal is first conveyed below suspended magnetic separators which remove tramp iron (roof bolts, ties, wires, and cutting bits) from mining activity. This unit is generally located after coal breakers but prior to a screen-crusher. The magnets are suspended over the conveyor or at the head pulley; self-cleaning electromagnets are required for large quantities of tramp iron (Norrgran, 2016; Colorado Air Pollution Control, 1998).

Subsequently coal is crushed to a suitable processing size before treatment in the washery. A crusher utilises the softness of coal relative to the hard mineral matter; crushing causes fractures along fissures within the coal structure requiring minimal application of mechanical force. Crushing equipment normally comprises rotary breakers and roll crushers, although impact crushers such as hammer mills or ring granulators may also be used (Kumar, 2012; Eck, 2007). A rotary breaker is generally used to crush and screen the feedstock to a particle size, typically smaller than 50 mm, which can pass through the breaker apertures, while the harder shale particles remain unchanged and are rejected.

An advantage of a 50 mm top size is that the coarse coal circuit which includes the dense-media vessel (DMV) unit shown in Figure 2, may be eliminated in favour of a dense-media cyclone (DMC), simplifying the coal washery plant (Yoon, 2017). In certain cases, larger diameter DMC can accept coarser coal sizes reducing crusher energy consumption.

The ease with which a coal sample can be crushed is measured on the Hardgrove Grindability Index. The sample is assigned a value relative to a standardised coal (value 100); internationally traded coals typically have an index value in the range 45–70, while harder, less tractable, high ash coals have a lower index value (GlobalCOAL, 2016).

After crushing, coal is partitioned by size before entering the appropriate coal separation circuit. Typically, the screen size ranges used are: coarse: larger than 10 mm; intermediate: 1 mm to 10 mm; and fines: less than 1 mm. Size separation in water-media screening uses single or double deck vibrating screens for coarse particles although the vibratory derrick sizer screen can have up to five decks stacked one above the other; multi-slope, double-layered banana screens separate the intermediate fractions; and classifiers segregate fine coal particles (Bethell, 2007). Roller screens that resist clogging may be utilised for high moisture content coal.

**Stack sizer**

In comparison to a single deck screen, a compact stack sizer™ unit offers a larger useful screen area for the same equipment footprint. As the majority of coal slurry passes through the screen openings near the inlet, the stack sizer optimises this separation zone by enhancing the effective screen width. The screens are manufactured from durable urethane with screen openings typically set at 45 to 75 microns. A flow control device meters a suitable coal slurry flow to each feed box attached to five stacked screens arranged in a parallel flow formation. The under-size and over-size streams are combined and diverted to appropriate
separation circuits. A multi-feed point machine arranged in this way may provide up to twice the capacity of a comparable single feed screen possessing a comparable screen area (Valine, 2009).

**Reflux™ Classifier**

A Reflux™ Classifier unit can enhance segregation rates of dense mineral particles and improve conveying of low density coal particles. The process unit consists of a fluidised bed which is located below a system of inclined channels. In a Reflux™ Classifier the fluidised coal suspension passes up through the inclined channels formed by a network of plates fixed at a 70-degree angle and at a spacing of 6 mm, specified to optimise particle separation. Separation of fine coal is enhanced by an emphasis on particle density properties. Faster settling particles segregate on the sloping surfaces where there is a lower stream velocity boundary layer, and slide back down to the fluidised zone where dense matter is withdrawn (Galvin, 2005). Slower settling coal particles in the size range 0.125–2 mm pass through to overflow launders. The actual particle size range that may be processed in the Reflux™ Classifier can be varied to suit the coal supply but is governed by a top-to-bottom size ratio limitation of 8:1. The device offers a higher throughput than would be possible for a fluidised bed alone, possessing a greater hydraulic capacity and offering improved separation of dilute feedstock (Orupold, 2014).

**Hydraulic separators**

Hydraulic separators such as the teeter bed, a type of fluidised bed separator, are used for particle size classification and gravity concentration of coal but performance may be affected by variations in feed composition. Alternate hydraulic separator designs include the CrossFlow and Hydrofloat separators that are intended to improve both throughput and the quality of separation.

The Crossfloat design differs from conventional teetered beds by adding a transition feed box to avoid the high velocity injection of the feedstock slurry into the fluidised region. The revised feed system enables the coal slurry to be added tangentially across the full width of the separator minimising turbulence. The advantage of this injection procedure is that it minimises the effect of the slurry solids composition on the separation process and a constant velocity is maintained across the chamber. This differs from a teeter bed where the velocity profile varies and increases above the feed injector location. Modifications of the fluidising water injection system combined with the low turbulence feed addition method improve the separation, allow higher throughput and reduce distributor blocking while lowering energy and water requirements (Luttrell, 2006).

The Hydrofloat separator is intended to process a feedstock possessing a broader size and density range than a Crossflow separator, including coarse coal particles. The feedstock is treated with a collector to improve the hydrophobicity of the coal particles and added to an adapted fluidised teeter bed. Compressed gas present as fine bubbles is injected to aerate the bed and requires a frother agent to be added to the fluidisation water. Light bubble-particle aggregates rise to the top of the denser teeter bed and are collected as the overflow from the separation chamber, while the dense mineral particles descend to be discharged as a high solids stream. The Hydrofloat separator has characteristics of both a teeter bed and a flotation cell. When compared to a flotation cell the device offers increased throughput in a compact volume and is
intended to recover coarser coal particles. The device improves bubble-particle contacting, benefitting from the upward flow of elutriation water which lifts larger particles into the product chamber. The Hydrofloat device should offer significant energy savings due to the absence of mechanical agitation that is needed in conventional floatation cells (Luttrell, 2006).

### 4.1.2 Coarse coal cleaning – dense-media

Coarse coal (exceeding 10 mm) cleaning is normally undertaken using a dense-media bath or vessel; coal and impurities (ash) are separated using specific gravity (SG) methods. The SG of coal is normally in the range 1.3–1.5, compared to rock with an SG exceeding 2.2; a separation point is selected at an SG of typically 1.6–1.65. A dense-media vessel processes a slurry of coal, magnetite (iron oxide mineral Fe₃O₄, SG >4.9) and water; the less dense, particles with a high carbon content float to the surface while the rocky particulates containing sulphur, ash and mercury, sink to the base of the vessel.

The potential effectiveness of wash operations on an unprocessed, powdered coal may be assessed by a laboratory float/sink analysis, whereby coal float and rejects are separated in a series of flasks containing organic solvents of gradually increasing density. The float from the lowest density liquid (SG=1.3) may constitute up to half of the original coal sample dependent on coal characteristics. This fraction would possess a low ash yield, with subsequent vessels showing a higher ash yield at each stage. The optimum SG separation point is in the region of 1.6, a compromise between minimal ash and maximum carbon recovery.

The separation medium is a slurry mixture of magnetite in water that is circulated through the DMV. The coal added to this mixture floats to the surface and overflows into a collection screen, while the higher density waste rock sinks to the base of the vessel to be collected by scrapers or flights. Optimum separation is achieved where the particle size is greater than 10 mm, as there is insufficient time for the settling of fine matter; fines content is generally limited to <2 wt% in order that the refuse carrying capacity of the vessel is not affected (Jain, 2016). Both the washed coal and waste are passed over drain and rinse screens. Magnetite flows into a magnetic circuit fitted with a mounted steel drum containing an interior fixed magnet for magnetite recovery and reuse (Norrgran, 2016). The dense-media washing process typically rejects about 20–40% of the ROM coal feed.

### 4.1.3 Intermediate coal cleaning – dense-media cyclone

A dense-media cyclone method is used to treat the medium-size fraction of coal (10 to 1 mm) separated by a deslime screen; a static DM vessel is unsuitable since medium particles would take too long to settle. The cyclone consists of a conical vessel cast in high chrome cast iron or from steel lined with either ceramic tiles or nickel based alloys to protect the outer vessel (see Figure 4). The medium coal feed fraction combined with finely ground magnetite in water (termed pulp) is pumped tangentially at optimum pressure into the inlet pipe of the cyclone, swirling to create a vortex.
4.1.4 Fine coal treatment – spirals

Dense-media techniques, are unsuitable for fine particles as long treatment times would be required, and coal recovery inefficient. A method that utilises both density and hydrodynamic particle properties is more appropriate. A wet spiral method treats the fine coal fraction (0.15 to 1 mm) using a flowing film passing over a corkscrew shaped column to effect separation. As depicted in Figure 5, water flows down a spiral channel and the more dense mineral particles remain in the centre of the spiral, while the lighter coal particles, which experience less drag forces, are drawn by centrifugal force to the outer surface where they can then be collected.

Figure 4  DM intermediate coal cyclone arranged at a 15° angle (Parnaby, 2016)

The centrifugal effect draws higher density rock and ash downwards to pass out of the spigot (apex) as rejects or middlings, while lighter carbon particles are carried in an upward flow and exit as clean coal through the cyclone overflow outlet. The cyclone design features a spigot outlet that is too small to accommodate the entire flow, forcing a fraction of the flow containing lighter coal particles to exit at the top, at the vortex finder. The denser media are drawn to the surface of the cyclone while an inner spiral of lighter matter flows in the counter direction. While the operation of a cyclone requires minimal maintenance due to the absence of moving parts, the unit is prone to occasional jamming that is detected by changes in operating pressure (Gluskoter, 2009).

Figure 5 Spiral concentrator schematic (adapted from Osborne, 2013) and a compound Krebs 2-stage spiral bank fitted (FLSmidth, 2017a)
Two stage spiral circuits are used to maximise coal recovery. The first stage produces a reject stream, while a second stage produces a clean coal product and reject. The middlings produced from the second stage are recycled back to the inlet of the spiral circuit for reprocessing (Yoon, 2017). Table 5 shows an example of the distribution of coal from compound spirals per specific gravity fractions.

<table>
<thead>
<tr>
<th>SG Fraction</th>
<th>Coal product, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6 float</td>
<td>97.3</td>
</tr>
<tr>
<td>1.6 x 1.8</td>
<td>1.05</td>
</tr>
<tr>
<td>1.8 sink</td>
<td>1.03</td>
</tr>
<tr>
<td>Dense matter (heavies)</td>
<td>0.56</td>
</tr>
</tbody>
</table>

The device employs a density separation method, and optimum conditions are achieved when particle fractions are of near uniform size, which also facilitates the hydrodynamic flow effect. Inefficiencies arise from the introduction of a wide range of particle sizes or material exceeding the design range. Optimal spiral operating conditions are met by utilising a coal feed slurry that contains up to 30% solids with a particle size range of 1 to 0.15 mm.

4.1.5 Fine or ultrafine coal circuit – flotation and agglomeration

Coal flotation is widely practiced on higher quality coal supplies to clean coal that is of less than 600 microns (preferably 0.15 to 0 mm). Flotation cells make use of the hydrophobic property of coal particles and the method is suitable for ultrafine particles that cannot be separated by density techniques. The hydrophobicity of the coal is enhanced by the addition of chemical reagents termed frother or collector that are premixed with water and then added to the fine coal–water slurry prior to entering a flotation cell. In practice a minimal excess of chemical reagents is applied to optimise coal recovery (Bulatovic, 2014).

A schematic of a mechanically agitated flotation cell is shown in Figure 6; the rotor draws the fine coal slurry through the stator and expels it to the side, creating a partial vacuum that draws air down the shaft of the stator to aerate the slurry. Alternate designs such as Outotec and Dorr-Oliver cells use pressurised air blowers, while stackcells offer a compact design that utilises a pre-aerated high shear feed chamber for bubble particle contacting (Jones, 2011). Air bubbles are dispersed throughout the slurry and contact the hydrophobic coal particles that are then drawn by the air bubble buoyancy to form a surface froth. The froth layer flows over the discharge lip either by gravity or by using froth scrapers.
Wet and dry coal physical separation technologies

![Simplified schematic of a mechanically agitated cell and image of a flotation cell fitted with a Wemco Drive](Darling, 2011; FLSmith, 2017b)

Column flotation cells operate using a similar principle but the agitator used to mechanically mix air and particles is replaced by a static microbubble sparger that generates a rising bubble field of more uniform bubble size. The column flotation system also has the advantage of requiring less maintenance than a mechanical cell.

A limitation of flotation technology is that modest volumetric flow rates mean that a number of flotation cells may be required in a typical beneficiation plant, impacting on the economics of fine coal recovery. The maximum gas flux through a flotation cell is constrained to avoid a condition termed ‘flooding’. This restriction impacts on the bubble size that can be utilised; although small bubbles of about 0.3 mm are preferred for efficient separation, providing enhanced particle collision efficiency, the typical bubble size found in conventional flotation cells is larger, at up to 1.5 mm. Furthermore, in a conventional cell, finer bubbles may be entrained into the tailings stream and lost. The Reflux Flotation cell has the capability to operate at higher throughput and use a finer bubble size improving coal particle recovery. An adapted flotation cell would have a network of inclined plates located below the bubbly bed with a high shear rate downcomer to promote fine bubble formation. The inclined channels are intended to enhance bubble liquid segregation reducing the loss of fine bubbles to tailings. The reflux of bubbles back into the bubbly bed has a dramatic impact on the capacity of the flotation device; typical values for the bubble surface flux in a mechanical flotation cell of up to 36/s compare to trials with the reflux flotation cell that show a surface bubble flux approaching 600/s at a gas flux of 0.055 m/s, a consequence of the fine bubble diameter that can be used in this device (Dickinson, 2013).

Frother reagents used in coal flotation collect at the gas-water interface, stabilising the froth. They include: short, branched chain alcohols such as methyl isobutyl carbinol (MIBC), creosotes, pine oil and polypropylene glycol ethers that are effective for larger particles. Suitable collector reagents such as
No 2 fuel-oil and kerosene are added after the frother reagent to enhance the hydrophobicity of the coal particles.

Oil agglomeration is an alternative separation method for fine particles, where high sheer forces are applied to coal slurry that is mixed with an agglomerating liquid such as diesel fuel, fuel oil, heptane or pentane. At high shear rate the water is stripped from the coal particle to be replaced by the agglomerating agent that acts to separate the coal from the mineral matter, and avoids a subsequent dewatering step. There are a number of technology variants that include: a ‘spherical agglomeration process’ which has a compacting step; a ‘shell pelletising separator’ that forms 3 cm pellets and reports a high recovery of coal (95%) and high ash rejection (to 95%); an ‘Olifloc process’ using 15% fuel oil; and the ‘SFRI process’ that uses a combination of diesel and heavy oil for less tractable coal (Bulatovic, 2014).

4.1.6 Dewatering

Water is removed from processed coal at the end of each treatment circuit to reduce the overall mass, improve the energy content (calorific value, CV) and to avoid stockpile run-off. Coarse and medium coal is typically dried by dewatering screens or centrifuges, whereas fine coal dewatering requires filtration (using belt or vacuum filters). To remove the ash from lower quality, high ash coals it is necessary to crush the feedstock to a fine particle size, which often results in increased moisture levels in the clean coal. An area of processing concern is the loss of ultrafine coal particles which accumulate in the thickener and are lost in the waste stream.

**Coarse coal (>10 mm)**

The dewatering of larger coal particles is normally achieved by using drain and rinse (D&R) screens. Solids are captured and exit from the base of the screen, while water passes through fissure grids to discharge via the screen slot. The durability of the screen equipment to resist abrasion has a significant impact on the overall operating costs of a coal washery (O‘Bryan, 2016).

In practice, some plants combine the streams of coarse and intermediate-sized wet coal particles prior to dewatering; a vibrating centrifuge is employed, the coal is conveyed by vibratory action into the centrifuge at rates approaching 300 t/h. The vibratory centrifuge method for coarse coal separation has high efficiency and low operational costs (Eraydin, 2016).

**Intermediate coal (1–10 mm, 18 mesh)**

Although the intermediate coal fraction may be combined with coarse coal for separation in a vibratory centrifuge, an option is to use a screen-scroll centrifuge which can operate at higher velocity, to improve dewatering efficiency. Although a more efficient method, the higher mechanical forces of the scroll design can result in the unit suffering from increased maintenance costs due to wear and tear. The screen-scroll centrifuge can reduce the water content of the coal stream by approximately 5% more than the vibratory device.
Fine coal contains a higher level of moisture than coarser grades. After treatment in the fine particle cleaning circuit which uses a spiral separator, tilted bed unit or reflux classifier the resultant coal slurry may possess up to 80% moisture. The slurry enters a fine coal centrifuge which is generally either a screen-scroll centrifuge (SSC) or a screen-bowl centrifuge (SBC). These machines are designed to process 80 t/h of fine coal slurry and can achieve moisture levels of 40 to 60%. The slurry is pre-processed through desliming cyclones and sieves to ensure that the very fine matter is less than 5% of the solid content to optimise efficient operation of the centrifuge.

The Somerset SUB325 centrifuge has extended the recovery range down to 44 microns (325 mesh). The revised design uses a hydraulically-driven solid-bowl centrifuge that can achieve coal recovery of almost 95%. At the same time the water content is reduced from 80% to about 50%, to achieve less than 20% moisture once recycled coarser coal is included (Somerset, 2016). The redesign of the SUB325 centrifuge (see Figure 7), involves optimisation of the G-force (force obtained by acceleration) and torque (force causing rotation). A new hydraulic, variable speed drive permits optimisation of the rotational difference between the rotating bowl and the centrifuge helical scroll.

The equipment can process up to 25 L/s and has recently completed a 4-month commercial trial.

The centribaric centrifuge from Decanter Machine has improved upon performance from centrifugation alone by using gas pressure to increase moisture reduction. The unit is a combination of pressure filtration that employs a filter cloth and centrifugation in one device. The processing conditions include air pressures of up to 0.25 MPa and the application of centrifugal force of approximately 2000G (Asmatulu, 2005). The centribaric centrifuge can achieve less than 25% moisture from a mixture of 50% 325 mesh screen-bowl effluent and 50% <0.5 mm screen drain (Yoon, 2017).

These methods enable a smaller particle range to be collected, which leads to more efficient operation of a flotation cell bank and a substantial reduction in the chemical demand required for the thickener.
Ultrafine coal (<0.15 mm)

Advances in centrifuge technology are significant in extending the range of particle size that can be recovered by high-volume and low-cost methods. Currently, ultrafine coal is dewatered by filtration, but the high cost means that this is normally employed for metallurgical coal applications. For belt presses, flocculants are added to form coal agglomerates that allow water to drain easily through filter cloths at low pressure. Other filtration techniques, such as ‘plate and frame’ and ‘filter presses’ use systems that require 10 bar (1 MPa) of differential pressure. Hyperbaric filtration that applies a greater pressure differential is used to further lower the water content. Whichever method is adopted, addition of shear resistant chemicals at minimal practical dosage rates can enhance the moisture reduction efficiency. The addition of surfactants raises particle hydrophobicity; these reagents combine to improve filtration kinetics resulting in significantly enhanced moisture reduction to meet specifications of between 7–8.5% water content. In addition, where further water removal is required, the vacuum filtered coal then undergoes thermal drying (Eraydin, 2016).

Waste streams

New rigorous environmental standards mean that it is increasingly inappropriate to discharge CPP tailing streams to slurry impoundment for subsequent disposal. The coal industry is seeking acceptable methods of handling the waste streams; these include recovering ultrafine coal from tailings using the latest techniques and removal of water from tailings to form a recycle water stream. This approach also addresses increasing concerns about water conservation.

After the tailings slurry is dosed with flocculants it passes to a thickener. A thickener is a large circular tank of up to 40 m diameter that is equipped with slowly rotating rakes used to settle out the solid material from the water in the feed slurry. Plate and frame filters or belt presses can be used in this part of the process to dewater the settling fine refuse. The formation of a ‘filter cake’ within these devices, effectively performs the filtration duty; the separated water is clarified and reused as process water in the CPP (Klima, 2015). The inclusion of waste slurry treatment in the CPP plant can reduce the fresh water requirement of the plant by 60%, although care must be taken to avoid overloading the coarse coal circuit with fine matter.

4.2 Dry coal beneficiation

Dry coal separation, also termed pneumatic cleaning or air table destoning, is of growing relevance due to the emerging shortage of water supply to manufacturing and thermal power industries. The water requirement for a subcritical thermal power station is approximately 2 t/MWh (for example 1000 t/h for a 500 MW station), but this excludes the water consumed in the preparation of the coal.

China is the largest coal producer and consumer and 70% of the coal reserves are located in arid regions, where not only is there significant competition for fresh water, but there are also harsh winters, which can prevent the application of wet coal preparation techniques (Zhao, 2014). In response, the power industry is exploring the use of alternative water sources such as extracted mine water, municipal wastewater and seawater from desalination. In times of water shortage, if an alternative supply is not available, thermal coal stations in India had to cease operations. Indeed, the situation is becoming more critical as
The consumption of fresh water is predicted to rise by 50% in the period 2016 to 2050; this resource constraint is likely to impact all aspects of the coal supply chain including the coal preparation technology. More information on the management of water resources in the power industry is available in a series of reports prepared by the IEA Clean Coal Centre (Carpenter, 2015 and 2016).

Historically, dry separation methods were considered to be little better than the simple destoning of coal and therefore much inferior to wet processing technologies. However, dry separation methods are much improved although not as effective as comparable dense-media separators for medium and coarse coal (Colorado Air Pollution Control, 1998; Zhao, 2014).

The effectiveness of a coal separation method may be assessed by examining the particle efficiency (Ep) value; this provides a measure of the particle density difference at 25% and 75% coal partition. Lower Ep values indicate a more efficient separation and low ash content (Zhao, 2014). The particle efficiency (Ep) is defined by the following equation:

$$Ep = \frac{(\rho_{25} - \rho_{75})}{2}$$

Wet separation Ep values are normally in the range 0.01–0.05, while for dry methods the reported range of 0.07–0.25 particle efficiency indicates an incremental rise in the ash content of the cleaned coal at the higher end of the scale. If applied to a suitable coal feedstock, dry processing technology can result in a similar quality coal product to that obtained by wet preparation methods.

Dry processing offers several potential advantages including: an improved coal energy content due to reduced water content; ease of plant construction; capital cost reduced relative to comparable sections of a wet beneficiation plant; and a reduction in waste slurry water (Korte, 2014). However, operation under dry conditions requires extensive gas and dust handling infrastructure for safe management of the operation.

Dry separation techniques are under development to exploit different aspects of coal particle properties that include: coal density, particle shape, friction, electrostatics, and magnetism. The current dry beneficiation methods for coarse and fine particle sizes are described below:

For coarse particles:

- Air dense-media fluidised bed separation (ADMFB) – vibration energy is applied to a mixture of powdered coal and magnetite present as the separating medium, utilising the density/sink-float principle (Luo, 2002).
- Fluidised bed separation – similar to ADMFB omitting the use of magnetite, agitation of particles releases coal from denser mineral matter (Yang, 2013).
- Compound dry separation – air table separation that exploits several coal properties: particle friction, shape and density. This category dominates commercial dry separators and includes air jigs and the FGX dry separator, described in the next section.
For finer particles, not yet commercialised:

- **Tribo-electrostatic separation** – fine particles (200 mesh) are charged by dust charging mechanisms, passed through an electric field that deflects particles according to magnitude and sign of the particle charge. Coal becomes positively charged; quartz kaolin, pyrite and calcite negatively charged, allowing separate collection of cleaned coal and reject (Zhang, 2009).

- **Magnetic separation** – the difference in magnetic properties enables the separation of the coal and mineral matter passed through a powerful magnetic field (Subba Rao, 2016).

The lowest cost dry separation methods, and consequently the most deployed technologies use air jigs and of these the commercial leader is the FGX separator. The fluidised bed technology loses a greater fraction of material to middlings reducing coal recovery, while the ADFMB method suffers from the cost of magnetite recovery and associated losses. Due to the higher cost involved, the techniques outlined for fine coal particles are restricted to specialist applications rather than steam coal. The following section examines the widely-used air table technology in more detail.

### 4.2.1 Air jigs and FGX Dry Separator

The dry-cleaning jig operates using a similar separation mechanism to that of a wet cleaning jigger machine but water is replaced by compressed air. Figure 8 shows an Allair pneumatic jig that is an adaptation of an earlier wet jig design which can process a wide range of coal feedstocks. Raw coal is fed into the jig from a hopper and subjected to a combination of vibration and air pulses applied through a perforated table. The material on the deck becomes loosened and stratified according to the material density.
Heavier mineral matter sinks to the bottom of the bed and is then rejected, while lighter matter consisting of coal rich particles, floats to the top of the bed. Gradually a steady state is achieved and a material bed is formed which aids the separation through inter-particle agitation. Allair jig units can process up to 100t/h of a full range of coals from brown to bituminous grade.

The FGX separator developed in China (Zhao, 2014) was designed for the treatment of coarse coal sizes; it is the most widely used dry coal cleaning unit with over 2000 FGX installations in operation. Most of the units are in China, but have been installed in the majority of coal-producing countries.

An FGX dry beneficiation plant consists of a coal feeder, separating compartment, air blower, draught fan, and two-stage dust collecting system. The separating compartment includes a perforated deck, vibrators, air chamber, and hanging mechanism (Figure 9).
The FGX system can be optimised by adjusting a number of parameters, for example the deck vibration frequency, deck angle, feeder and fluidisation air rate and the baffle plate height. The main technical advantage of the FGX over earlier systems is the addition of riffles on the deck to perturb the coal bed and also improve dust control (Figure 9). Heavy mineral particles stay on the base of the bed and due to contact with the deck surface they are moved forward by the combined action of vibration and riffles to the narrow exit of the bed. The lighter coal particles rise to the surface of the accumulated, fluidised bed, and as they are not in direct contact with the deck, these particles are less affected by the vibrating surface and move to the discharge lip of the angled table. Three streams of coal, middlings and rejects are obtained. There is the option of recycling the middlings to improve coal recovery.

The FGX can be designed to process up to 480 t/h in dual systems, separates at typical relative density of 1.8 to 2, and, while the efficiency of separation does depend on the coal quality, shows Ep values of 0.2 to 0.3 (Korte, 2014).

Trials on US Illinois coal showed a more efficient Ep separation value of 0.17, rejecting up to 70% of inert rocky matter (Zhao, 2014). In practice, operational problems arise if there is a sudden change in particle size with a higher proportion of coal fines, which may lead to overloading of the air table and of the dust control equipment.
Dry separators are normally restricted to the processing of coarse coal in the 6–80 mm size range. The new TFX-8 air jig extends the range of coal particles that can be dry-separated to include smaller coal particles (0.2–10 mm). The TFX-8 has a 2-stage vibratory bed to produce a coal, middlings and two reject streams, and is capable of processing 130 t/h of feed ROM coal with an Ep value of 0.2 which is comparable to an FGX unit. Previously, ash rejection from small coal separators has been poor, whereas, TFX-8 separation data for a high-ash Indian thermal coal shows the following streams (Tangshan, 2016):

- **Clean coal**: ash reduction from 42% to 27% at 59% yield;
- **Middlings**: ash content 55% at 22% yield;
- **Rejects**: 73% ash content at 19% yield.

### 4.2.2 X-ray sorting

The Technical University of Delft developed an x-ray sorting method to separate coal on a piece-by-piece basis. Raw coal falls from a conveyor past an x-ray source to one side and detector to the other; each particle is scanned and the extent of x-ray absorption measured (Figure 10). Mineral shale particles absorb x-ray radiation more effectively and show as a dark image, whereas less dense coal particles have a lighter image. The images are processed in ‘real-time’ and a set of air nozzles activated to send a compressed air jet to move coal to the collector while heavier mineral matter is rejected (Kiser, 2005).

![X-ray ore sorting device DriJet™](image)

**Figure 10 X-ray ore sorting device DriJet™** (Kumar, 2014; Kiser, 2005)

Isambane Mining, SA trialled the x-ray sorter and found the coal could be cut at a relative density of between 1.8 to 2.1. This is similar to the performance of an FGX separator, but shows a slightly improved Ep value of 0.15–0.2. The x-ray sorter proved most efficient on coarse coal particles exceeding 30 mm; smaller coal sizes could be sorted if the feed rate was reduced below the intended 100 t/h. A suggested application of the Drijet™ x-ray sorter is that it might be operated in conjunction with an FGX air bed separator and used to improve processing of the middlings fraction, improving the overall recovery rate (Korte, 2014).
4.3 Hydrophobic hydrophilic 2-liquid separation (HHS) for ultrafine coal slurries

Hydrophobic-hydrophilic separation (HHS) is a novel process for the separation of ash from ultrafine coal particles to improve the recovery of coal and reduce tailings rejects. The process has been developed in a partnership between Virginia Tech and the Minerals Refining Company, both in the USA (Gupta, 2016; Yoon and others, 2016). The process uses the disparate surface chemistry properties of coal and ash to separate and dewater fine and ultrafine coal (to 325 mesh) from clay and moisture. Pilot plant trials assessed the effectiveness of the technology separating US bituminous coal waste slurry; this process reduced the water content from over 30% to below 4%, while the ash content was reduced from 65% to less than 5%. The specification of the dry, cleaned coal product lies well within that of internationally-traded coal (Table A1).

![Diagram of Hydrophobic-hydrophilic separation process](Gupta, 2016)

A coal-waste feed slurry derived from reject streams taken either from screen-bowl centrifuges or desliming cyclones is separated from water and ash-forming minerals by combining the slurry with a hydrophobic liquid (Figure 11). The two liquids are first mixed and then phase separated, leaving the water and hydrophilic ash-forming minerals (such as clays) in the aqueous phase, while the hydrophobic (organic) coal is dispersed into the hydrophobic liquid phase. A suitable hydrophobic liquid could be a short chain alkane such as pentane or a light oil distillate. The coal immersed in hydrophobic liquid is passed to an upgrading unit (termed Morganizer) where emulsions are destabilised to release the coal particles, with water and waste matter collecting at the base. The coal particle immersed in the hydrophobic liquid retains no surface moisture. The coal particles can be separated from the hydrophobic liquid by conventional filtration while any residual hydrophobic liquid left on the coal surface is stripped off by vaporisation and condensation. Selection of low boiling point, non-hydrogen bonded liquids requires minimal vaporisation energy, much less than for equivalent water evaporation technologies, with the recovered liquid reused in the process.

In comparison to conventional froth flotation, HHS is considered to offer a superior performance on ultrafine particles. Froth flotation would require a longer retention time, larger vessels and additional cleaning and scavenging stages. The HHS process eliminates the need for costly final dewatering of the
collected coal product. The difficulty in separating water from ultrafine particles is one reason that much of the ultrafine product is typically lost to waste streams.

### 4.4 Coal preparation in India

Indian coals (Gondwana coal) are characterised by a high-ash content and impurities embedded in the coal matrix; the coal seams may have been deposited by accumulative (drift) rather than in situ mechanisms. The distribution of ash throughout the coal results in a high level of rejection of near gravity material (NGM) >30%. In India, currently less than 20% of indigenous coal is beneficiated in CPP plants, largely limited to coarse and small coal cleaning (Gupta, 2016; Osborne, 2013). As fine coal is not separated, the reject streams retain a significant amount of coal content and are commonly sold for local use.

New washeries are designed to extend the range of coal processed to include fine particle separation. Table 6 shows the technical specifications for the most recent Indian washeries (Bharat Coking Coal Ltd); the plants may operate ‘deshaling cyclones’ for coarse coal and ‘teeter bed separators’ for fine particles.

### Table 6: New coking coal washeries (Venugopal, 2016; CMPDI, 2015)

<table>
<thead>
<tr>
<th>Washery name</th>
<th>Capacity, Mt/y</th>
<th>Coarse coal technology</th>
<th>Small coal technology</th>
<th>Fine coal technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jharkhand, East India</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Madhuband</td>
<td>5</td>
<td>Deshaling cyclone</td>
<td>Heavy media cyclone</td>
<td>Teeter bed separator/flotation</td>
</tr>
<tr>
<td>Patherdih</td>
<td>5</td>
<td>Jig</td>
<td>Heavy media cyclone</td>
<td>Flotation</td>
</tr>
<tr>
<td>Dahibari</td>
<td>1.6</td>
<td>Deshaling jig</td>
<td>Heavy media cyclone</td>
<td>Cyclone/spirals</td>
</tr>
<tr>
<td>Kusmunda</td>
<td>25</td>
<td>Jig</td>
<td>Jig</td>
<td>Spiral</td>
</tr>
</tbody>
</table>

The plants listed have all introduced fine coal technologies, generally adopting spiral and flotation systems. In a new initiative, the Madhuband washery is to use a deshaling cyclone and teeter beds designed for Indian coals.

Finer grinding is required to reduce the maximum particle size to under 6 mm and to access the minerals within these coals. Fine grinding is not normally performed in Indian washeries resulting in higher rejection rates, lower mine recovery efficiency and consequently low coal yield from the plant (Venugopal, 2016).

### 4.5 Coal washery costs

The cost of preparing coal rises with the number of processing steps included in the preparation plant. For PC plants, physical coal treatment would normally be limited to fine coal separation accepting a higher degree of carbon rejection at coal washeries; separation of ultrafines is restricted to the preparation of high value coking coals. However, with increased focus on reducing washery waste, more efficient coal recovery has been introduced in thermal coal treatment.
Table 7 provides a guide to the cost of coal beneficiation, rising with the targeted level of ash removal (Osborne, 2016). The coal cleaning options described cover the full range of wet techniques and dry beneficiation methods, shown as Level 2, ‘coal destoning’.

<table>
<thead>
<tr>
<th>Level of cleaning</th>
<th>Description</th>
<th>Treatment processes</th>
<th>Cost US$/t (7000 h/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sizing only</td>
<td>ROM coal</td>
<td>2.25</td>
</tr>
<tr>
<td>2</td>
<td>Coal destoning</td>
<td>Dry cleaning using FGX; removal of rock &gt;75 mm</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>Coarse coal cleaning</td>
<td>ROM dry screened coal with 10 mm dense-media (DM) bath</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>Coarse and small coal cleaning, no fine coal cleaning</td>
<td>DM baths and DM cyclones to size 0.5 mm Includes draining, dewatering and desliming</td>
<td>5.5</td>
</tr>
<tr>
<td>5</td>
<td>Coarse and small coal cleaning with treated fines added</td>
<td>Coal 60mm to 0.25 mm fine coal DM cyclones; spirals/TBS with drain/dewater/deslime</td>
<td>6.5</td>
</tr>
<tr>
<td>6</td>
<td>Total coal cleaning</td>
<td>As for level 5 with 4 or 5 flotation cells or columns and added dewatering</td>
<td>7.5</td>
</tr>
<tr>
<td>7</td>
<td>Deep cleaning – more intensive treatment of coal middling fraction</td>
<td>Additional milling to reduce maximum size below 5 mm With focus on fine coal cleaning</td>
<td>9.5</td>
</tr>
</tbody>
</table>

As the coal recovery rate rises by adding dense-media cyclones, spirals and flotation cells to the plant then the cost of preparation increases and this is categorised as a cleaning level of 1 to 7 in the table. Dry beneficiation methods at Level 2, are effectively coarse cleaning and lead to significant carbon rejection. Thermal coals are normally processed by wet methods to Level 5, although procedures are now changing to include flotation cells shown as Level 6. The preparation of slurry fuels for a piston engine that requires a finer particle size would need more intensive cleaning to Level 7. The extent of coal preparation can raise the price of ROM coal by 2–10 US$/t covering the full range from minimal coal sorting through to deep coal cleaning. For reference, a pre-prepared imported coal is currently priced at approximately 50 US$/t, a price that is predicted to be maintained through to 2020 (IEA, 2015).

In the case of a 600 MWe PC plant consuming 440 t/h (based on 20 MJ/kg bituminous coal) the additional cost of cleaning the coal to level 5 which includes dense-media gravity separation with spirals for the finer coal fraction would be US$12 million a year, if the CPP facility operates for 7000 h/y. More advanced cleaning involving flotation cells or columns, normally limited to metallurgical coals, would add a further US$3 million per year.

### 4.6 Overall trends in physical separation methods

Dense-media separation remains the most commonly used technology operated in coal preparation plants. Wet preparation remains the most efficient method for coarse and small coal particles. However, there is a trend to adopt dry separation methods in regions affected by drought or harsh weather conditions, with the additional benefit that this technique avoids wet waste disposal. The separation efficiency difference
between wet and dry methods has substantially reduced and dry techniques are now extended to include small coal sizes.

The focus of industry development is on the recovery of fine and ultrafine particles to improve recovery efficiency, partly driven by a period of high coal prices, but primarily to reduce waste and ease waste disposal. Increasingly CPP facilities are introducing froth flotation separation methods to thermal coal preparation, and advances in dewatering techniques recover fine particles rather than lose them to tailings. New methods such as 2-liquid hydrophobic-hydrophilic separation may offer an alternative to froth flotation for recovery of a dry fine coal product.

Given the coal consumption trends, it is probable that the greatest demand for new CPP facilities will occur in India, where there is a pressing need to improve the quality of the indigenous coal. Indian coals are resistant to physical separation methods and produce coal with residual ash levels of about 30%. Based on coal separation assessments and experience, the technologies adopted are based on coal jigs, dense-media cyclones and include fine coal recovery in new facilities.
5 Thermal coal beneficiation (coal refining)

Coal preparation plants treat raw coal to remove mineral matter but organically-bound sulphur and mercury are not removed by such methods. The following section describes recently implemented thermal coal technologies that access the volatile components in coal to reduce contaminants. The processes include: a 3-stage drying process to produce low moisture, stabilised coal suitable for long distance transport; technology that combines pyrolysis and fractionation recovering a liquid product; a thermal beneficiation module immediately upstream of the boiler to prepare coal for gasification accompanied by desulphurisation under fuel rich combustion conditions; and a hydrothermal coal drying technique.

5.1 Thermally stabilised coal

The Pristine-M™ process is under development in the USA. It is designed to treat high moisture subbituminous or lignite coal supplies by moderate heating to remove moisture, pollutant precursors and other volatiles. The result is a thermally stabilised fuel which is cleaner and has an enhanced energy content (Eves, 2016).

In a conventional thermal coal coking plant, coal passes through three temperature regimes: initial decomposition of the coal occurs at 375–475°C; devolatilisation of gaseous components followed by re-solidification is completed at 475–600°C, and coke stabilisation is achieved at 600–1100°C, before the final pushing and quenching of the coke.

In comparison, the thermally stabilised coal treatment described here is a process conducted below 450°C that is intended to partially dry and devolatilise coal. The process conditions are roughly comparable to the first stage of coal decomposition in a coking plant.

The overall process, shown in Figure 12, first removes gas and liquid volatiles (<7% of the mass) during initial heating of the coal in an inert atmosphere, prior to a drying phase that takes place at 121°C using Carrier dryers. The degree of drying is set to match boiler requirements for the feed which is normally specified at 10% moisture content. At lower throughput 5% water content may be achieved by increasing the residence time the coal spends within the dryer. A second process step treats coal at 400–450°C to devolve gases. Non-condensable gases, such as methane, are used to fuel the process avoiding the need for a separate fuel resource and the gas is treated with an amine stripper to remove hydrogen sulphide, lowering the sulphur content of the feedstock. Condensable volatiles are collected and may be extracted as a separate chemical product stream. The heat is recovered to conserve energy. In a third stabilisation and vapour deposition phase, part of the condensable volatile matter is reabsorbed into the pores of coal from which the moisture has been driven off. Re-absorption of the organic volatiles lowers reactivity by minimising the surface area which enhances coal stability and reduces the hazard of auto-ignition during transport and storage of the cleaned coal product.
Table 8 shows the effect of thermal processing a range of coals to demonstrate the applicability of the process to a wide range of feedstocks including Powder River Basin (PRB) subbituminous coal and lignite of varying moisture and ash content. The results show significant reductions in the volatile and moisture content of the coal leading to substantial increases in the GCV of the test coals. Notably the high moisture and ash lignite obtained from Greece shows the most dramatic change improving the GCV by a factor of 2.

The earlier version, termed Pristine, only implemented the first steps to remove moisture and volatile matter, producing a higher efficiency, cleaner thermal coal that was restricted to local use. This differs from Pristine-M™ which partially returns condensable volatiles to the coal to reduce permeability lowering reactivity for transport and storage.

The Pristine-M™ process is based on a commercial module designed to process 30 t/h of 30% moisture ROM coal which would produce up to 175,000 t/y of dry coal. A 1 Mt/y plant would be comprised of six modules. The process is continuous with mean residence time estimated to be about 15 minutes, depending on the degree of moisture removal and the inherent moisture in the coal. Operation at atmospheric pressure and with process temperatures achieved by using gases released from the coal feedstock to fuel the process, leads to relatively low running costs.
The existing 3 t/h Pristine-M™ demonstration plant (1/10th scale) is to be relocated from Oklahoma to a new permanent site to evaluate the process using a wider range of US coals prior to commercial deployment following recent granting of the US patent (Hunt and others, 2017); a pilot-scale project is utilised to optimise process conditions specifically for PRB coals, prior to construction of a 30 t/h commercial plant (Eves, 2016).

In addition, the preparation of fuel for gasification, which has a lower moisture specification, is a promising application for Pristine-M™ that can provide a uniform low volatile feedstock.

### 5.2 Thermal cracking and fractionation

Coal pyrolysis has a significant history in the production of liquid coal products, and a novel technology from Frontier Applied Science combines mild thermal cracking, dewatering and liquid hydrocarbon fractionation in a single, fluidised bed reactor (McKean, 2014). The FASForm™ or Solid Carbon Fractionation reactor is initially externally fired by natural gas establishing a rising temperature gradient as coal descends the column. At steady state, a fuel gas product is generated that provides the energy for the ongoing process. The feedstock which is preferably low ash-yielding coal is dewatered and the low-pressure process also removes volatile components to achieve a significant reduction in sulphur, mercury and nitrogen content. For pulverised coal power generation, the removal of the thermal load of evaporation and higher boiler efficiency from the upgraded fuel heat content results in improved GHG characteristics, even though ash components are retained in the fuel.

The low pressure solid-vapour reactive fractionator process will produce approximately 1.5–2 barrels of liquid products per tonne of coal or lignite, and these are segregated into propane/butane, naphtha, kerosene and diesel streams which are suitable as refinery feedstocks which can be upgraded to meet fuel specifications.

Except for the liquid fuels fractionation, the separate features of the process have been demonstrated in other technologies but not combined in a single, continuously fed reactor. A modular reactor is due to commence pilot-scale testing in 2017 processing 10 t/d of low ash-yielding feedstock to confirm the fractionation technology and affirm laboratory trial data on syncrude and dry coal product quality (Pitts, 2017).

### 5.3 Beneficiation module of a retrofit hybrid gasifier

There are several coal gasification technologies under development that include the Kemper County transport integrated lignite gasification (TRIG™) technology which commenced electricity generation in January 2017. Castle-Light’s hybrid gasification technology differs in that it incorporates coal beneficiation and is intended as an upgrade to retrofit existing under-performing plants.

Re-engineering a pulverised coal boiler to incorporate a gasification reactor fitted with a coal beneficiation module offers a means to remove sulphur and other contaminants prior to steam generation in the boiler. The retrofit technology is intended as a replacement for existing boiler firing equipment and to avoid...
installation of new SCR and FGD treatment plant, with testing currently performed at their Cold Lake test site in Alberta, Canada (Moore, 2016).

The hybrid gasification technology consists of coal gasification combined with sulphur removal together with drying and devolatilisation in a reactor configuration that is located upstream of a conventional steam boiler (Howard, 2016). The process possesses two coal beneficiation stages: coal devolatilisation in a thermal step within the beneficiation module; followed by sulphur removal in a reducing atmosphere. The first thermal treatment stage removes volatile gases and liquids, including water that will not progress into the boiler. The second step consists of ‘fuel-rich’ gasification where sulphur is removed within the gasifier and results in a cleaned syngas that then passes to the original boiler where final air-rich combustion takes place. Thus, the retrofit hybrid reactor adaptation of a boiler comprises a beneficiation module, the add-on gasifier and the original boiler.

The main features of the gasifier plant that includes the coal preparation module are shown in Figure 13. The first stage is to prepare the coal for gasification in the beneficiation module: the process heat supply to the coal mill is obtained from boiler exhaust gas at a temperature of 400°C that is diverted upstream of the air preheater; surface moisture and other volatile components are then driven from the fuel to raise the heating value. The use of a low reactivity, hot gas stream that is taken downstream of the main heat transfer tube banks reduces the risk of auto-ignition and the energy load of the beneficiation module when compared to conventional lignite preparation designs.

![Schematic of the coal preparation stage as a gasifier retrofit to a PCC](Moore, 2016)
Following a partial separation of mercury and ash from the coal, the fuel then passes to a baghouse where volatiles including water vapour are removed before passing the fuel to a pulveriser that feeds coal combined with limestone to the gasification reactors.

The gasification section of the clean combustion system is intended as a ‘bolt on’ addition with the boiler retained as a secondary oxidation reactor and steam generator. The gasifier creates ‘fuel-rich’ reaction conditions through partial combustion of the fuel avoiding the formation of nitric oxides formed from fuel nitrogen that requires ‘air-rich’ conditions. Injection of limestone intimately mixed with the coal or lignite feed directly converts sulphur to calcium sulphide in the vitiated air atmosphere, which can then be removed as a molten slag prior to the main boiler. Thus, the add-on combustor section acts as a sulphur removal step. The pre-mixing of coal and lime avoids the high reagent consumption of typical dry sorbent injection DSI technology that is mixing dependent and carried out under milder conditions. The formation of removable molten calcium sulphide in the gasifier reduces the load on ESP and baghouses located downstream.

Within the gasifier reactor, nitrogen compounds present in the coal form nitrogen gas rather than nitric oxide (NO), carbon is partially oxidised to carbon monoxide rather than CO₂, while sulphur is converted to sulphide and removed as part of the molten slag from the reactor base. The reducing atmosphere in the gasifier section also prevents the formation of SO₃, a significant potential source of corrosion in steam boilers.

Hydrogen is formed from hydrocarbons present in the fuel and from water gas-shift chemistry equilibrating CO and H₂. The syngas product then passes to the boiler where it is partially cooled, the combustion process is completed with hydrogen oxidised to water and carbon monoxide to carbon dioxide. Air admission through the original burner ports is staged to control the peak temperature and thermal NOx, to provide a final gas composition and gas flow rate to match the original boiler design conditions.

In practice, with primary combustion relocated to external gasifiers, the existing boiler is re-configure with access ports cut through the water wall, while original burner ports are sealed or converted to supply over fire air to complete combustion.

The emission reduction demonstrated by the combined gasifier – steam boiler, which is an adapted 1940s stoker furnace, shows performance data comparable to that achieved by a conventional boiler fitted with an SCR and wFGD treatment plant. Hybrid gasification technology offers an alternative and potentially lower-cost route to achieve NOx and SOx levels of approximately 100 ppm, when compared to retrofitting an SCR/wFGD plant. The removal of molten slag prior to the boiler means that the boiler will be maintained in a much cleaner state and so the technology may be of particular interest for stations currently processing high sulphur coals with out-of-date emissions control technology.

Current demonstration trials on an adapted Stoker furnace are at 30 MW-scale utilising 15 t/h of hard coal (2.5% S). The concept is a modular one and so a single gasifier would be suitable for each 100 MW of capacity. Thus, for a 600 MW scale plant, six gasifiers, each containing four burners and associated with
one coal beneficiation module, would be installed into the base of the pre-existing boiler. The total project time to modify an existing boiler is estimated at 1.5 to 2 years, with about 4 months required to install the gasification module, during which time the plant would be offline. The cost of the device is estimated to be equivalent to a retrofit SCR unit for any given scale of boiler (Moore, 2016).

5.4 Turbulent air and hydrothermal drying

A new process designed by Coomtech based in Kent, UK (Coomtech, 2017) applies high air turbulence to dry coal or biomass particles. First, coal is supplied to a tube using high velocity low pressure unheated air. A high-pressure air jet then creates turbulence in the tube stripping off the water. This process is termed ‘surface moisture removal’.

A second thermal process termed inherent moisture removal (IMR) uses uniform heating in a pressurised chamber to hydrothermally extract moisture contained within coal particles. The continuous hydrothermal process forms a hydrophobic product that resists moisture re-absorption. The process is currently at the demonstration stage, evaluating the performance and benefit of the technology on a range of coal feedstocks that include Columbian coal.
6 Chemical digestion and bio-oxidation

Chemical pre-treatment can be used to prepare a coal which is ultra-low in ash and sulphur making it an optimum feedstock for thermal power generation. Sulphur present in ash may be readily removed by gravity separation techniques, while chemical and biological desulphurisation methods are required to remove sulphur organically-bound within coal particles. Chemical and biological beneficiation processes are complex with potentially high energy demand and the resultant increased fuel cost has restricted the technology to niche applications. In an environmental context, consumption of chemical reagents in the digestion of coal means that a life-cycle analysis is required to demonstrate the benefits of chemical cleaning. Given new emission control legislation it is worth revisiting a technology that can remove sulphur and reduce ash content of coal to below 1% to enable maximum power plant performance.

6.1 Chemical digestion and leaching

Chemical reagents suitable for the desulphurisation of coal have been extensively investigated and encompass a wide range of powerful oxidation or digestion chemicals that include: calcium fluoride in sulphuric acid; anthracene oil; sulphuric acid; copper and iron salts; hydrochloric acid; sodium hydroxide (caustic soda); hypochlorite, potassium permanganate; and N-methyl-2-pyrrolidone (NMP)/ethylene dioxide mixtures (Sato, 2004; Chaudhary, 1996; Saha, 2013). However, high processing costs have prevented these technologies from entering general commercial service, and the majority of information on chemical treatment was obtained more than 20 years ago. More recently, the ultra clean coal (UCC) caustic process has completed a 10-year demonstration programme in Australia producing ultra-low sulphur and ash coal to meet the specifications for the direct injection carbon engine (DICE) programme.

The UCC technology is a caustic leach process, an analogue of the Bayer caustic acid process for refining Bauxite invented in 1887 (International Aluminium Institute, 2012), and a development of the Gravimelt process (Siwiec, 1994). The UCC pilot facility processed 350 kg/h of coal for the preparation of micronised carbon slurry fuel. Commissioned in 2002, the plant operated continuously until 2012, and the technology was acquired by Yancoal of Japan in 2009 (Yancoal, 2016).

The UCC process feed of coarsely milled coal (1.2 to 2 mm diameter) allows sufficient contact of reagents with the sulphur contained in the coal particles. Earlier chemical leaching technologies specify an optimum size of less than 500 microns to improve contact between the chemical and the coal. Milling to 500-micron fineness adds significantly to the processing cost of chemical coal preparation.

The UCC reagents are caustic soda (NaOH) and sulphuric acid; caustic soda is regenerated in the process. Ash consists mainly of quartz (silica or gangue) which is digested by caustic soda into a soluble form. Other clays present in the coal particle are dissolved by subsequent sulphuric acid washing, ‘acid soaking’. The clean coal is recovered by filtration (hydrothermal washing), while the waste products of gypsum and calcium alumina silicates are recovered for sale or disposal after precipitation from the waste solutions. This leaching process can reduce ash content of the coal product to below 1%.
The one-hour chemical demineralisation process shown in Figure 14 consists of the following 3-stage treatment process:

- Formation of crushed coal particle slurry in a caustic soda solution with coal forming about one third of the slurry. The slurry is heated to 250°C and maintained at elevated pressure (10–20 MPa) to prevent boiling.
- Separation of the alkali-sed coal and spent leachate by centrifuge, prior to adding acid to form acidified slurry at pH 0.5 to 1.5.
- Separation of the acidified slurry into coal and liquid fractions followed by hydrothermal coal washing using methanol or citric acid prior to filter press drying.

The resultant chemically treated coal would be attractive to improve the performance of any plant. However, where an existing facility cannot meet new emission legislation then the use of ultra-low ash coal may be an alternative to the addition of enhanced emission control systems. The elevated reaction conditions and consumption of inorganic reagents and methanol are the major contributors to the process operating cost. Further details on the relative cost of chemical cleaning are outlined in Chapter 7.

A life-cycle analysis (LCA) has been conducted to determine the environmental benefit of a caustic chemical treatment plant compared to a physical coal washery applying dense-media cleaning (Ryberg, 2015). The study assessed the overall benefit of burning a cleaner fuel taking into account the chemical cleaning of the coal.

The process benefits include:

- reduced airborne emissions from the power plant;
- reduced content of hazardous metals (Sb, As, Cd, Cr, Co, Cu, Hg, Pb, Mn, Ni);
- improved power plant thermal efficiency due to reduced ash content;
- increased plant lifetime due to reduced furnace slagging; and
• reduction of coal transport energy consumption.

The increased environmental demands are identified as:

• additional heat and electricity for chemical cleaning to achieve 250°C;
• chemical production: NaOH, acids (H₂SO₄ or HCl), methanol CH₃OH, and higher water use;
• waste water impact, as partial solvent recovery; and
• overall greenhouse gas emission (furnace efficiency increase offset by energy consumption from cleaning).

The study assumed a 5% ash content in the coal product as typical from historical data on chemical leaching; however, this may not represent the full benefit of the UCC process that can deliver ultra–low ash coal. It was concluded that the chemical process appears less suitable for low ash feedstock, but if the ash content is substantial and finely distributed throughout the coal matrix, then chemical cleaning is beneficial (Ryberg, 2015).

The chemical extraction method has the side benefit of reducing the levels of heavy metals, which are of increasing environmental concern. Most existing PC plants are not fitted with mercury adsorption units and so removal of mercury and other elements at source would be advantageous.

Production of a chemically cleaned coal possessing <1% ash is one of the two technology options for the preparation of micronised refined carbon (MRC) fuel for the DICE. The fuel produced by the UCC process has been successfully tested in a coal slurry modified 1 MWe two-stroke, six-cylinder diesel engine, and trials on an adapted gas turbine showed ash production at less than 0.2% operating on the MRC slurry fuel (Dicenet, 2016) (see Chapter 9)

6.1.1 New developments in chemical leaching

The caustic process can produce coals that are low in ash content, but requires relatively high energy input and produces liquid wastes that may require further treatment. Recent research explores chemical methods that employ benign reagents which can de-ash and desulphurise coal under mild conditions.

In comparative laboratory trials to test the efficacy of solvents to de-ash coal, a number of potential reagents were tested: N-methyl-2-pyrrolidone (NMP), furfural, aniline, acetic acid and toluene. Of these solvents, promising results were obtained using a high ratio of NMP solvent to high-ash coal in a vessel at ambient pressure and 120°C; this procedure led to an ash reduction of 72% which is significant at these mild conditions (Saha, 2013).

A desirable feature of NMP is that while it is thermally and chemically stable it is also recyclable and biodegradable. In this example, recovery of NMP was carried out by mild thermal distillation followed by hot air drying of the coal dust product.
As an alternative to fine milling, the action of solvent leaching chemicals may be further enhanced by using ultrasound for intensive mixing of coal and reagents. Similarly, microwave heating can augment the breakdown of larger coal particles through steam formation within the particles.

In the power industry, the future of chemical digestion technology will depend on the cost benefit of using a low ash coal product to achieve performance and emission targets.

6.2 Bio-desulphurisation

An alternative to chemical oxidation or solvent digestion is the use of a biological agent for bio-depyriritisation, where the biocatalyst facilitates oxidation of sulphur. Biological separation was extensively studied in the 1990's with significant success achieved with a range of bacteria and fungi, achieving near complete removal of organic sulphur from coal (Siwiec, 1994). The barrier to technical implementation has been the long residence times required that may exceed one months' duration resulting in the need for a large preparation facility. The intractability of coals possessing interlaced coal and ash has led to renewed interest in these techniques as an alternative to physical methods.

The proposed mechanism for oxidation of sulphur to sulphate catalysed by the extensively studied bacterium *Thiobacillus ferroxidans* uses an 'indirect mechanism', which is then followed by an aeration step (Prayuenysong, 2002).

The bacterium acts primarily by promoting the oxidation of ferrous iron in the pyrites content of coal. In addition, the bacteria catalyses the formation of sulphate ions, and also the oxidation of elemental sulphur. As in the case of chemical treatment, the action of the bacterium is limited by physical access into the microporous structure of the coal, and so is influenced by the milling size.

The major process parameters identified in the bacteria catalysed desulphurisation, and applicable to the bio-depyriritisation plant depicted in Figure 15, include:

- micro-organism selection;
- particle size (in common with chemical leaching);
- initial pyrite content;
- nutrient composition;
- solution pH – acid alkali adjustment;
- temperature (30–80°C) and residence time;
- aeration (O2/CO2); and
- reactor design (plug flow or multistage).
The plant in Figure 15 shows a multistage bioreactor taking a coal slurry supply from a coal washery to be treated with a bacterium in a nutrient rich solution containing acid or alkali to adjust pH. Each cell is aerated to supply oxygen for the process with temperature held between 30°C to 70°C. The remainder of the plant shows product slurry neutralisation and dewatering. Available operating costs are rather dated and depend on the plant scale but adjusting for inflation, are considered to lie between 30 US$/t (8000 t/d) to 80 US$/t (300 t/d) (Klein, 1998).

Although sulphur and ash removal remains an important target, increasingly the focus of research has shifted to other potentially harmful elements in coal. In a recent research study using a bacterium isolated and grown from indigenous bacteria in Rajmahal coal, *Pseudomonas mendocina strain B6_1*, coal samples were treated for a period of 30 days at ambient conditions. The resultant treated samples show promising demineralisation activity for trace elements including calcium, potassium, sodium, manganese; selenium, lead, zinc, and nickel. However, reduction in ash content using this bacterium was limited in these trials, ranging from only 3% to 7% for the Gopinathpur coal samples (Singh, 2016). The technical challenge is to reduce the reaction residence time while retaining the metals reduction capability and substantially reducing the ash content.

In a study investigating fungal leaching from subbituminous coal, the analysis of bio-leached coal treated by *A.niger* fungi showed complete removal of sulphur from coal after 10 days exposure (Manoj, 2013).

Biological preparation requires a residence time of many days to effectively treat coal, which compares to the one hour chemical leaching process. While the plant size must be substantially greater due to slow bio-kinetics, reagents are less expensive, process conditions are close to ambient, and reagents pose less
Chemical digestion and bio-oxidation

potential impact on the environment. As the need to lower sulphur and heavy metal emission gathers pace these technologies may offer a means to produce ultra-low sulphur coal.

6.3 Chemical and bio-desulphurisation costs

Chemical cleaning has not been adopted by the thermal coal industry as less expensive physical cleaning has proved sufficient to meet legislative standards. An analysis of earlier chemical treatment plants dating to 1980 indicated that the chemical cleaning cost would be of the order of 100 US$/t. This figure is based on an adjustment of the original costing of about 40 US$/t of coal (an average of several plants priced at 30–50 US$/t) to account for inflation between 1980 and 2016 (Cooper, 2013). Clearly chemical cleaning costs are substantial and indicate that implementation of a chemical cleaning process is likely to be reserved for specialist niche applications. As the UCC ultra-low ash coal plant has not been developed to full commercial scale then it is not possible to evaluate the specific additional cost of this unit.

As for chemical cleaning, while biological methods have the potential to achieve low ash content in coal, the technology has not been commercially implemented. The energy demand is likely to be lower than for chemical cleaning, and the reactor would be designed for milder operating conditions close to ambient. However, the most significant issue is that the process requires large inventories of coal slurry due to the long reaction time (exceeding ten days), compared to chemical treatment (one hour), which is a scale factor increase of 240. An estimate of bio-processing cost is likely to exceed 30 US$/t (Klein, 1998), corresponding to a throughput rate of 8000 t/d.

6.4 Overview of chemical and biological methods

Earlier studies on chemical and biological digestion failed to produce a cost-effective alternative to physical separation methods. The cost of reagents, waste handling, and additional processing stages to separate reagents for chemical digestion and the long treatment times required for biological processing made these technologies less attractive.

However, since that time the regulatory environment, the life-cycle analysis of coal supply, and a focus on maximising efficient coal plant performance means that these technologies may potentially offer a route to ultra-low ash coal feedstocks. The gradual decline of coal quality in the intervening period is also relevant; this is particularly evident in India where the coal type is less tractable to conventional methods and retains relatively high ash content after treatment.

New research initiatives seek to develop processes which are simpler, more environmentally benign and which use lower-cost reagents for chemical digestion. Progress on biological methods has shown promising heavy metals recovery but still needs to reduce processing time to avoid large inventories of coal. These technologies are the only means to reduce ash levels below 1% which is relevant to certain high value applications such as DICE.
7 Lignite drying and demineralisation

Lignite has a low calorific value, high moisture content and often a high ash content. The attractiveness of indigenous lignite as a feedstock is its ease of extraction via opencast mining and hence it’s relatively low cost compared to imported coal supplies. Thermal power plants are generally located close to the lignite mine to avoid transporting low GCV fuel, and lignite is normally milled and burned in its raw state.

Improvement of the fuel quality by drying and removal of ash is one means to meet legislated plant heat-rate targets; this has the added benefits of improving boiler reliability and reducing plant and effluent treatment costs.

7.1 Drying technologies

Most lignite boilers currently use raw lignite feed and accept the accompanying loss of efficiency and higher capital cost associated with the use of low-quality fuel. The presence of water that must be evaporated using hot furnace gases is a source of inefficiency in lignite plants. Despite numerous research initiatives the implementation of lignite pre-drying technology has a limited number of full scale commercial applications due to the additional cost of dryers, and the ensuing need to adjust boiler operation (Zhu, 2012; Dong, 2014; Reid, 2016). However, the changing legislative environment means there is growing pressure on the industry to adopt fuel drying technology to achieve enhanced plant heat-rate targets, meet tighter emissions legislation and comply with international COP21 carbon dioxide targets.

In the processing of raw lignite, water evaporation and high-ash heat capacity combine to place a significant thermal load on lignite power plants which typically utilise high temperature streams diverted from the boiler to dry the feed. Switching to dry feed reduces the total volume of raw lignite mined and transported due to improved boiler efficiency. The dried fuel is friable and easily milled, lowering energy use and maintenance associated with fuel preparation. For new plants, using dried lignite feedstock reduces total gas flow through the boiler when compared to raw lignite fuel, leading to smaller boilers and lower cost downstream equipment. For retrofit projects, the installation of new stack gas treatment such as NOx SCR and mercury abatement units add to the plant parasitic load, making independent options to raise efficiency much more attractive.

In selecting suitable drying technology, the heat source utilised for drying is critical, as only low-grade or waste heat streams can provide an efficiency benefit to the plant. A substantial research effort has led to the development of various lignite drying methods including rotary, mechanical, microwave, high velocity air, hydrothermal and fluidised bed dryers. They have been reviewed in recent IEA CCC reports (Zhu, 2012; Dong, 2014). Of these methods, fluidised bed pre-drying technologies have been commercially developed at full scale and are capable of continuously processing ROM lignite using low-grade heat streams. Established plants at RWE Technology International (RWE), Germany, and Great River Energy (GRE), USA, have successfully operated drying systems for over five years, with individual commercial dryers sized at 115–200 t/h. The GRE plant uses two sets of three dryers, with each set supplying 500 t/h of lignite to a 900 MWe plant.
The two fluidised bed drying plants use different strategies; the most appropriate technology is dependent on the moisture and ash composition of the lignite feed. The RWE dryer technology described as ‘internal waste heat utilisation’ (WTA), is designed for processing German lignite containing 60% water, and can reduce the moisture content to 12%. The capital cost of the RWE (200 t/h) pre-drying plant is likely to be approximately US$50 million, and currently it is used to process 30% of the feed supplying a lignite boiler (Dong, 2014). The GRE dryer (Dryfining™) designed for US lignite containing 30% water, removes less moisture but additionally separates a proportion of dense mineral matter, potentially alleviating effluent treatment to remove SOx and mercury. The base equipment cost of a GRE (115 t/h) dryer unit is approximately US$10 million (Bullinger, 2016).

As the two systems are designed for different degrees of moisture reduction and one also includes gravity segregation, direct comparisons are not straightforward. The technical and operational details of these two fluidised bed drying technologies are discussed in the following sections, with key features summarised in Table 9.

### Table 9  Key features of WTA and DryFining™ fluidised bed lignite dryers

<table>
<thead>
<tr>
<th></th>
<th>Particle size, mm</th>
<th>Fluidising medium</th>
<th>Moisture reduction, %</th>
<th>Ash removal</th>
<th>Processor scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWE</td>
<td>1</td>
<td>Steam at 0.11MPa</td>
<td>60–12</td>
<td>No ash reduction</td>
<td>200 t/h ROM lignite</td>
</tr>
<tr>
<td>DryFining™</td>
<td>6</td>
<td>Air and water vapour</td>
<td>39–29</td>
<td>Partial removal of iron pyrite and mercury</td>
<td>115 t/h (bank of 6 units for 1000 t/h)</td>
</tr>
</tbody>
</table>

The WTA dryer uses fine milled raw feedstock heated by moderately pressurised, superheated steam (110°C) to remove up to 60% of water from the raw lignite. Operating under milder and hence potentially more efficient conditions, with coarser feedstock, DryFining™ uses fluidising air with hot water heating to remove a quarter of the water present while a proportion of dense mineral matter is also extracted.

Modern pre-drying processes are expected to raise efficiency by up to 1.7% when retrofitted to a typical US lignite-fired power plant (Cichanowicz, 2014). Following an extensive plant modernisation programme to optimise the whole process using dried feedstock, GRE report a 3.4% efficiency improvement at the subcritical Coal Creek Station, USA (Bullinger, 2016). The main operational concern is the reduction in mass flow-rate through the boiler when water is extracted from the fuel, as this can lead to reduced heat transfer in the convection bank. In a retrofit application, operators can compensate for reduced flows and increased reaction temperatures by recirculating part of the flue gas flow back to the burner level. In the absence of any modification to the boiler, the overall gas flow-rate is lower and sets a limit on the practical extent of moisture reduction.

The Dryfining™ process, originally designed to reduce water content by up to 10% points (for example 35% to 28% water), has since been adapted to extract more water to suit East German and Australian lignite supplies. As the degree of drying increases, the Dryfining™ technology requires higher energy steam resources using an adapted final (hybrid) drying stage. Using these techniques, the dryer may be tailored to Indonesian, Indian, and Chinese lignite. North American lignite was further treated to lower moisture...
levels from 40% to 10% to supply a Siemens dry-feed gasifier. Gasification with combined cycle generation offers higher efficiency operation on lignite fuel when compared to a conventional power plant, with larger efficiency gains possible from dried feedstock.

Lignite beneficiation using low energy dryers is a potential means to lower emissions per MWh, which may be an important measure for power generator groups in the USA seeking to retain low-cost lignite generation in an overall energy strategy. The most beneficial retrofit improvements to a typical lignite boiler were assessed to be the upgrading of aged steam turbines refitted into original casings, and the beneficiation of lignite feed using low energy streams to raise efficiency (Cichanowicz, 2014; Reid, 2016).

**Summary of lignite beneficiation**

Despite significant research and development initiatives on lignite drying technologies, the majority of lignite continues to be used in a raw state to avoid the additional cost of processing. However, the need to raise performance is particularly important in lignite power generation as it is the least efficient of fossil fuel generators. Suitable drying techniques must use low-energy or waste-heat streams to raise overall plant efficiency, replacing the use of hot furnace gases.

The prepared lignite fuel is more easily milled which saves energy and the initial removal of inert matter and water reduces the overall consumption of lignite. Two fluidised bed drying technologies have been implemented at commercial scale, one treats high moisture lignite, and the other is designed to remove moisture and ash content by incorporating a gravity segregation module. Unlike hard coal, lignite is not normally transported over long distances and so these facilities may be best located at the plant to optimise heat integration. As the industry moves to adopt HELE technologies lignite preparation will become increasingly important to achieve performance levels and avoid excessive effluent treatment costs.
8 Micronised fuel for a direct injection carbon engine (DICE)

Coal and lignite fuels may be utilised to power a specially-adapted internal combustion engine for flexible power generation. Replacement of diesel fuel by coal and water mixtures can provide flexible power production at a fraction of the fuel cost for a comparable diesel-fuelled engine. Historically, coal water slurry mixtures have been used in conventional burner equipment but attempts to combust these fuels in an engine proved unsuccessful due to abrasion and deposition in the engine (Kakwani, 1993). Developments in coal processing have led to a re-formulation of the fuel so that it is in a suitable form to be directly fed into a diesel engine. Key advances in coal slurry preparation methods involve specific criteria for fuel viscosity, ash content and particle size.

DICE is being developed to compete with diesel engine generators, support conventional pulverised coal combustion by offering small-scale flexible power generation and offer an alternative to gas power generation with long-term cost benefits. DICE may be suited to balance intermittent rapidly fluctuating renewable energy sources (Wibberley, 2013). DICE has a potential thermal efficiency advantage over conventional boiler systems due to direct use of combustion energy, avoiding losses associated with heat transfer within a boiler.

DICE combusts a micronised coal water slurry in a minimally modified, large capacity, diesel engine, such as an adapted marine engine, to generate electric power, as shown in Figure 16. Individual DICE units, termed modular generators, could form part of a distributed power network providing grid stability and security, complementing renewable energy resources. The micronised slurry fuel is intended to replace diesel, and in appropriate cases, to displace natural gas as the generating fuel. Developers anticipate that DICE may be installed as a flexible module alongside a conventional USC coal power plant of 500 to 1000 MWe capacity; DICE power may offer incremental generation steps to match demand allowing the main plant to operate more optimally in a variable power environment.

A 10 MWe marine engine is the currently preferred commercial-scale unit for DICE, shown in Figure 16. It is operated at moderate revolutions of approximately 500 rpm to allow sufficient residence time to ensure coal particle burn out. For larger-scale applications, it may be suitable to generate 80 MWe in an engine consisting of 14 cylinders of 0.956 m bore. Although the MRC fuel is composed of particles suspended in water, the particles are sufficiently small that the fuel possesses similar characteristics to a fuel oil.
The technology is currently at the demonstration stage, focused on delivery of successful operation of a 1 MW engine and optimisation of DICE fuel preparation that overcomes technical barriers associated with feeding particulates. A full history of the development of coal water slurry (CWS) combustion and DICE has previously been reported by the IEA Clean Coal Centre (Nicol, 2014), and this study will focus on preparation of the MRC fuel, revisiting suitable feedstocks and considering optimisation of the MRC fuel.

8.1 Suitable coal resources for micronised refined carbon fuel

An ideal coal for the preparation of MRC fuel by physical and/or chemical techniques would be a high volatility, low-ash coal that is easily milled, that is with a high Hardgrove Grindability Index. However, a practical approach has been adopted to obtain the best feedstocks for MRC preparation from currently available resources, of particular relevance to an Australian application:

- Ultrafine coal fractions are normally lost to waste in typical coal washeries, and an MRC preparation plant could be introduced as a new separation circuit to collect ultrafine coal particles.
- Brown coal in Victoria, Australia possesses a high moisture content but low ash (<4%) and sulphur (<1%) levels. Lignite is unsuitable for export and local demand for the fuel is in decline, leading to its availability as a raw feedstock for MRC. Techniques developed for partial lignite drying that increase coal friability and lower ash content may also be of interest for these feedstocks (Section 7.1).
- Coal tailings are a waste stream that consists of ultrafine coal mixed with ash. MRC preparation is one potential solution to reduce accumulation of tailings ponds formed as a result of preparing coal for export. The coal in tailings is already in a finely divided form and may be tractable to MRC physical separation techniques.

The coal tailings application is especially topical given the vast accumulation of tailings in some regions and the developing environmental legislation relevant to coal preparation and tailings ponds (Szczepanski, 2012).

An important attribute in selecting suitable coals is its mineral composition. The abrasion by particulates in the injection system and combustion cylinder represent the most practical difference between the
Micronised fuel for a direct injection carbon engine (DICE)

Combustion of diesel and MRC fuel. Coals possessing a lower content of harder minerals such as quartz and pyrite are preferred for this application.

Considering regions where coal use is set to expand, the Indian Gondwana coals are among the most difficult to prepare as there is a fine matrix of ash interspersed with coal particles. Bespoke preparation plants for these high ash coals to remove a portion of the ash are being developed for standard pulverised coal furnaces. Although a relatively expensive option, fine milling to enable the liberation of coal particles could form part of an MRC production plant, producing a higher value fuel capable of replacing diesel engine generation which remains prevalent in India.

## 8.1 Coal grain analysis method

The method developed to assess whether a coal or coal tailings can be successfully processed to form MRC fuels is termed coal grain analysis (CGA) and examines coal particle distribution in a sample. Standard coal analysis focuses on the physical and chemical properties of coal samples:

- elemental composition (C, H, S, N, O);
- sulphur forms (chemically bonded sulphide/sulphate/organic sulphur);
- moisture;
- ash and ash fusibility;
- volatile and carbonaceous content;
- trace element analysis; and
- density distribution which affects gravity separation methods (Speight, 2015).

These analyses are relevant to assess coals for MRC, but the specific particle petrography analysis developed for an MRC feedstock determines the mineral distribution and maceral composition within coal samples. The vitrinite/inertite/liptinite maceral content influences the volatilisation of coal within a piston engine, and the mineral/maceral distribution affects the particle surface properties and hence the efficacy of micro-flotation separation methods.

The CGA optical microscopic imaging technique provides an assessment of the coal liberation efficiency and potential yield from a given sample. From a benchmark of coal samples the lowest potential ash value can be determined using Jameson cell preparation, assuming all entrained minerals are removed from the coal, and the likely fuel yield at a given ash removal level. The technique is most accurate for ultrafine milled material where there is the maximum access to the mineral content of the coal (O’Brien, 2011). The analysis thus provides an assessment of the yield and cost of MRC preparation from any coal resource.

## 8.2 Preparation of MRC fuel

The preparation of MRC fuel requires most of the ash to be removed from the coal which may be achieved by physical processing methods employing micro-flotation techniques, by chemical preparation methods, or by separation of fine coal particulates based upon coal chemical properties such as hydrophobic-hydrophilic 2-liquid separation.
Ideally the mineral content of fuels suitable for MRC would approach less than 2% on a dry coal basis (Arthur D Little Inc, 1995), an important fuel attribute when intended for use in combustion engine equipment normally fuelled by low viscosity liquids such as diesel. Chemical cleaning, discussed in Chapter 6, can achieve near-complete removal of ash but is relatively expensive due to multistage processing and the consumption of up to three chemical reagents. In addition to the high cost of chemical leaching the process has a significant environmental impact due to chemical production, energy use and liquid waste disposal.

Figure 17 illustrates the processing cost benefit of applying a mineral target of 2% dry basis ash content for MRC that enables physical separation methods.

![Figure 17](image)

**Figure 17** Comparison of the processing cost as a function of ash content (dry basis) dependent on ROM coal beneficiation techniques (Wibberley, 2013)

The cost competitiveness of MRC fuel may be improved by setting a target of 2% ash that is shown to achieve sufficiently low abrasion and deposition characteristics. Chemical cleaning of the coal remains the most technically effective solution to minimise mineral content and remains an option for replacement of more expensive diesel fuel. The cost of chemical cleaning is shown to be a factor of five times higher than physical preparation of fuel that can achieve 2% ash content.

The preferred MRC fuel production method for DICE is to feed fine particles, either from ultrafine milling, or derived from the spiral circuit of a CPP plant, to a Jameson cell to separate the coal from ash. The method has been successfully demonstrated and is detailed in Section 8.2.1.

A new hydrophobic-hydrophilic 2-liquid separation method HHS (see Section 4.3) may also be applicable. The technique depends on hydrophobicity differences and initial trial data indicate that an ash content of less than 2% dry basis is achievable, which would make this process potentially suitable for MRC preparation (Gupta, 2016).
Conventional coal washeries cannot produce the low-ash content fuel essential for applications such as DICE, and aim for an ash content of typically 10–15%. The higher quality, low mineral product produced by chemical preparation would offer an extended operational lifetime in engine applications and an additional benefit of reduced heavy metal content of the fuel. However, by opting for a process target of 2% ash yield MRC can maintain a more modest production cost of 1 US$/GJ (approximately 20–40 US$/t depending on coal quality) while producing a practical fuel for a large-scale, low-speed DICE application.

8.2.1 Preparation of MRC from ROM coal and tailings – the Jameson Cell

The Jameson cell, shown in Figure 18, is the current process selected for MRC production. For a typical MRC installation, a Jameson Cell would be added to a conventional coal washery plant; after the fines removal, the flotation cell would process the ultrafine coal fraction to produce MRC. The Jameson Cell method may also be applied as a standalone plant to process ROM coal that has first been subjected to fine milling to produce particles of sub 325 mesh size. The Jameson Cell uses a flotation technique, similar in principle to that described in Section 3.1.5, but with a number of technical differences to improve coal recovery and reduce separation costs. The design avoids the need for agitators, blowers or compressors, promoting the formation of fine bubbles and intense mixing between an air stream and a coal slurry jet.

![Jameson Cell diagram](image-url)

Figure 18 Jameson Cell, a high-intensity froth flotation cell for the separation of ultrafine coal, with detail of the downcomer air entrainment device (Glencore, 2016)

Specifically, for the Jameson cell design, the particle bubble contact occurs within a multiple set of downcomers while the remainder of the tank is used to perform froth-pulp separation (Glencore, 2016). Within the downcomer high pressure jets shear and entrain atmospheric air into the slurry. As air is drawn into the jet, a liquid column is drawn upwards and the jet then plunges into that liquid which results in the
formation of fine air bubbles that contact with the coal and ash particles. The various zones in the ‘downcomer’, as depicted in Figure 21, include:

- a free jet entrains air into the slurry;
- an induction trumpet channels air into the slurry jet base;
- a plunging jet shears air into fine bubbles;
- a mixing zone of recirculating eddies; and
- finally, a pipe flow zone, a downward moving fluidised bed.

The high interfacial surface area and intense mixing promotes particle attachment to the air bubbles, raising the efficiency of ultrafine coal recovery. A recycle system in the Jameson cell enables multiple passes for rejects, reducing waste and is essential where the initial feed has high ash content. This feature is of specific relevance to the handling of tailings feedstock.

The process yields an MRC fuel with particle size of approximately 10 microns, and an ash content of less than 2%. The final coal content of the slurry product is set depending on actual mean particle size and the intended application for the slurry, but higher levels exceeding 60 wt% carbon are targeted for DICE applications.

8.2.2 Viscosity modification – MRC fuel transport, storage and atomisation

Diesel or heavy fuel oil are homogenous liquids and can be stored indefinitely. Coal water fuels are more sensitive as there is a tendency for the slurry to destabilise and form sludge. Other fuel handling issues include the abrasive wear of pumps, instability of the stored fuel and possibility of blockages. In practice these problems are prevented by recirculating and stirring the fuel, and by the addition of additives to disperse and stabilise the fuel leading to somewhat more complex formulations.

In a conventional fuel, low viscosity results in finer atomisation which promotes efficient combustion and leads to lower particulate emissions. Diesel fuel atomisation shows similar atomisation characteristics to water, with low viscosity leading to small droplets in narrow size distributions, optimised in the latest high-pressure fuel injector designs (Jankowski, 2002). Comparable atomisation of heavy fuel oil would result in a larger Sauter mean diameter droplet size due to the higher viscosity of the fuel, producing a wider size range distribution and leading to increased soot levels. Thus, it would be expected that a low viscosity MRC fuel would be preferred for diesel engine applications. However, researchers report that a somewhat higher viscosity is preferable for fuel handling and atomisation in diesel injectors, compared to the low viscosity fuel of typical commercial coal slurry burners (Wibberley and Dryer, 2015).

Where the MRC fuel is prepared to meet low viscosity criteria then the coal content of the fuel is reduced to less than 50% carbon, and storage of the fuel requires greater use of additives such as polystyrene sulphonate, to maintain the dispersal of coal particles in water. Low viscosity coal slurry fuels are also prone to destabilisation, particularly at low loading levels, requiring addition of compounds such as xanthan gum, accompanied by continuous recirculation to prevent sludge formation. Allowing a higher viscosity alleviates these problematic issues found in coal slurry fuels, and permits higher coal content in
the slurry while minimising the additives package. Improved transport and storage properties for MRC fuel is a key attribute for commercial application of the technology.

Higher viscosity was expected to impair combustion of the MRC fuel, but in practice this has not been the case; the better than expected performance was attributed to greater shear forces applied in diesel injectors compared to typical coal water slurry (CWS) fuel injectors (Wibberley and Dryer, 2015). The high shear rates exceeding 750/s of diesel injectors permits the viscosity to increase to about 1 Pa/s, while conventional CWS applications require a viscosity of approximately 0.3 Pa/s; the high shear rate counteracts higher viscosity in the atomisation process.

The impact of adopting higher viscosity MRC fuel on particulate combustion has proved to be minimal, and the slurry coal content can be increased from 45 wt% to at least 60 wt% or higher, dependent on the mean particle size in the slurry. In addition to the benefit to fuel stability discussed above, the higher coal content results in higher thermal efficiency, of critical importance where the environmental performance of the fuel is closely scrutinised. The MRC fuel has the potential for lower NOx emissions than diesel due to the suppression of peak temperatures by the presence of water, but clearly particulate emissions will be higher due to the initial ash content of the fuel.

### 8.2.3 Abrasion and erosion

Micronised refined carbon fuels are designed to overcome the abrasive properties of conventional coal water slurry (CWS) fuels. MRC is processed to achieve a low mineral content, with sulphur and mineral content at less than 1/10th of a typical prepared coal and coal particles in the micron size scale. The particulate size in CWS is typically 75 microns which is unsuitable for a diesel engine design, whereas for MRC the particulate size is less than 10 microns. The MRC water content is typically 25% to 40% and contains an additives package to modify the fuel rheology consisting of dispersants, surfactants, neutralisers and stabilisers forming up to 1% of the fuel (Williams, 2013).

The practical concern in using CWS fuel is the potential deterioration of the diesel engine combustor parts; injector erosion impairs atomisation leading to increased soot production, and piston wear caused by particulate accumulation can eventually lead to jamming of the piston ring. Although superior to CWS due to the finer particulate size, MRC is less effective than diesel liquid fuels at lubrication of injection parts; development has focused on replacing vulnerable materials with alumina or tungsten carbide injector parts, the main engine alteration required to use MRC instead of diesel fuel.

Accumulation of particles on the walls within the engine cylinder can lead to excessive erosion and it is likely that MRC fuels will produce more abrasive particles than diesel fuels. Engines fuelled by diesel produce hollow particulates derived from the fuel, termed cenospheres (Williams, 2013). The size of these carbon rich particles varies but can be up to 3% of the original diesel fuel droplet mass, an accumulation of particles can cause the size to increase to 10% (Jankowski, 2002). The micronised fuel droplet is intended to be less than 10 microns in diameter and hence of comparable size to some particles produced from diesel. However, it is the hardness of the particles which is the most significant property, and the mineral content
of these particles means they will be more abrasive. Tests show that a modified diesel engine can accept MRC particulates, even though these would be more numerous and abrasive than in petroleum fuels.

### 8.3 MRC fuel summary

The DICE requires a coal slurry fuel of low ash content, and the replacement of certain engine injection components to avoid excessive wear. Suitable coal supplies can be assessed using a bespoke coal grain analysis method which can predict the efficacy and cost of the separation technique. The technology is currently sourcing feedstock from existing CPP fine coal circuits or from processing waste tailings streams. Adoption of an ash content specification of 2% enables the use of a physical separation method rather than the earlier, costlier chemical digestion technique.

The 2% ash yield specification showed promise in early trials, and when combined with a higher viscosity formulation resulted in improved fuel storage and handling. A long-term proving trial in a large-scale engine is needed to demonstrate the applicability of a 2% mineral content. The effluent from the engine should show a reduction in NO content compared to diesel fuel due to effect of water suppressing peak temperatures, however, the increase in ash content of the revised fuel specification will result in a requirement for effluent dust control.

The technology competes with natural gas turbines to offer a flexible power product of typically 10 MW-scale as an add-on to conventional power plants to rapidly respond to power fluctuation from intermittent alternative sources such as wind. The economics of the DICE is based upon the stable pricing of coal feedstocks. In Asian markets the current low natural gas price reduces the commercial benefit of the DICE technology, but the price of natural gas is historically highly variable. The DICE can achieve efficiency comparable to diesel fuelled engines, may exceed the potential efficiency of subcritical power plants, and competes favourably with distributed diesel electric generation.


9 Conclusions

In response to tightening environmental legislation thermal coal plants are required to update emissions control treatment. Improving the quality of coal feedstock reduces pollutant emissions at source and improves boiler performance. The use of beneficiated coals is one option available to operators to achieve greenhouse gas emission targets. High quality coals provide the optimal feedstock for HELE thermal coal plants that are sensitive to coal characteristics; treated coals may offer an alternative to introducing emission control systems on outmoded plants.

Preparation of coal to meet international trading standards covering ash, moisture and energy content is long established, but the actual quality of coal fed to thermal stations has often been of lower quality based on inferior indigenous supplies. There is a general global trend of using inferior feedstock, due to the reduced availability of quality coal. Generation using low quality, low sulphur coal means that installation of enhanced FGD systems can be postponed although impaired reliability and thermal performance may have to be accepted. This strategy is incompatible with new legislative limits and raising coal quality may now be a more practicable means to meet performance and environmental targets.

New coal preparation plants are planned in developing countries which intend to significantly increase their thermal power capacity. Coarse and small coal beneficiation is generally practiced and new developments in coal washeries are focused on fine and ultrafine coal treatment to reduce waste, and the tailoring of treatment technologies to coals that possess finely interspersed mineral and carbon content.

Dry separation of coal using riffling tables is taking an increasing share of the market due to concerns over water shortages. Although potentially less expensive, dry treatment is also less efficient than dense-media technologies. Recent developments show that dry air table methods can be extended to include small coal sizes, and there is an option to use wet methods in an adjoining circuit dedicated to recovering fine particulates.

The environmental impact from washery tailings ponds necessitates new solutions to reduce waste streams. In the dewatering stage, centrifuges have extended the range of recoverable ultrafine coal particles, and increased application of froth flotation in thermal coal preparation improves coal recovery and reduces the quantity of waste to be disposed. A new method employing the hydrophobic property of coal particles, hydrophobic-hydrophilic 2-liquid separation (HHS) seems to be an efficient means to recover fine coal particles and achieve low sulphur specifications. These technologies may have applications in reprocessing existing wet waste contained in slurry coal ponds.

Coking coals are prepared at high temperature, but new thermal coal refining methods operating at intermediate temperatures of up to 450°C may offer a superior, cleaner coal compared to that prepared by physical methods. This thermal treatment can substantially reduce pollutants such as sulphur and mercury, and form stable and uniform coal supplies permitting more optimum boiler operation.
The chemical treatment of coal has proved to be more expensive than physical methods, and there are concerns over control of wastes and energy consumption. Recent research on chemical digestion seeks to employ benign leaching agents that are effective under moderate processing conditions. Chemical cleaning provides a method to produce ultra-low sulphur and ash content that would be of interest in specialist, higher value applications. Chemical treatments are most suitable when processing fine or ultrafine coals where the coal particles can be accessed more easily to leach out mineral components. The comparable bio-oxidation of coals has yet to gain commercial acceptance due to the long reactor residence times, although the moderate processing conditions potentially mean that biological methods may be able to compete economically with chemical leaching.

Conventional dense-media and dry coal preparation costs vary from 1 to 10 US$/t depending on the degree of preparation which ranges from minimal sorting through to total coal cleaning using froth floatation techniques. The cost of chemical digestion or bio-oxidation is higher but offers a route to ultra-low ash content of less than 1 wt%, with optimised physical methods capable of achieving an ash content of 2 wt%.

Lignite coal processing developments have centred on drying methods as the water and ash levels in lignite affect the overall performance of a station. Plants have operated at commercial scale using fluidised bed reactors that harness waste energy streams. In addition to drying lignite, these systems can be configured to remove dense mineral matter. These methods are increasingly relevant to improve boiler efficiency and reduce sulphur and mercury emissions enabling efficient power generation from low cost, locally available fuel. Lignite gasification plants, striving to maximise efficiency, have much to gain from using beneficiated lignite.

DICE uses a coal water slurry fuel that may have the potential to offer a flexible power option which can replace diesel power generation; the rapid response method is especially suited to balance the output from intermittent renewable energy resources. A coal slurry fuel has been formulated that is suitable for use in a minimally modified marine diesel engine, equipped with dust control measures. A Jameson flotation cell is the preferred fuel production method separating coal drawn from the fine fraction of a coal preparation plant, or alternatively from a tailings waste stream.

Coal beneficiation is a mature technology that is being re-examined in response to new legislative initiatives. Currently, coal preparation plants must tackle the issues of water use, ash content, coal recovery and liquid waste. Legislators are demanding higher efficiency and lower emissions from coal power generation. The industry has responded primarily by improving boiler technology and adding more sophisticated effluent treatment. However, improving the quality of coal at source alleviates a number of reliability issues, reduces the energy associated with coal transport, reduces the amount of coal processed in the plant, and eases effluent treatment and waste disposal. It may be as cost effective to improve the quality of coal as it is to introduce new technologies.

For an existing power plant, where the technology cannot easily be modified, improving fuel quality is the most significant option available to raise performance. This is particularly relevant where new emission control equipment is required and hence there is additional plant parasitic energy demand. Feedstock
strategies need to reduce both water and ash content, but technologies that remove other contaminants such as heavy metals are gaining importance. Where there is a desire to use low quality indigenous feedstock which impairs power plant performance, the installation of new coal beneficiation facilities could approach international performance standards.
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Appendix: Internationally traded beneficiated coal specification

Platts CIF ARA 6000 NAR is a daily 15–60 day forward price assessment for thermal coal shipped from Colombia, Russia, South Africa, Poland, Australia or the US to the northwest European trading hub of Amsterdam, Rotterdam and Antwerp (ARA) (Platts, 2016). The term ‘6000 NAR’ refers to the net calorific value (heating value) of the coal in kilocalories per kilogram and CIF refers to cost, insurance and freight charges.

CIF ARA 6,000 NAR is a coal price assessment, reflecting the spot price of industry standard 6,000 kcal/kg NAR quality coal bought mainly by European utilities which is eventually barged from the ARA region via a network of rivers and canals to inland power plant in Belgium, the Netherlands, Germany and France.

Table A1  Coal specification ARA (globalCOAL, 2016)

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<th>Australia</th>
<th>Columbia</th>
<th>Poland</th>
<th>Russia</th>
<th>South Africa</th>
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<td>Total moisture, % maximum (as-received)</td>
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<td>14</td>
<td>14</td>
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<td>Volatile matter, % (as-received)</td>
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<td>25–2</td>
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<td>27–35</td>
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