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BROWN COAL INNOVATION AUSTRALIA

LIGNITE DRYING STATUS REPORT

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BACKGROUND AND METHODOLOGY

This study was commissioned by the Electric Power Research Institute (EPRI), an independent, non-profit organization which conducts research, development, and demonstration projects, on electricity generation, delivery, and use, for the benefit of the public in the United States and internationally.

This study involves a review of lignite drying technologies undertaken by Brown Coal Innovation Australia (BCIA) on behalf of EPRI. It provides an overview of the lignite drying technologies that are currently available and offered by commercial vendors. It also includes some novel technologies that are not yet at commercial offer stage. The evaluation of these technologies is more limited and reflected in the Technology Readiness Level (TRL) ascribed to them.

The study was based on feedback provided to a survey questionnaire provided to known proponents of lignite drying technologies and supplemented with public domain information sourced by BCIA and commentary based on BCIA's experience.

The reference coal used for the study is Victorian lignite from Australia, specifically coal located in the Gippsland Basin. This coal was chosen due to its high moisture content and the familiarity to BCIA. The efficacy of coal drying is best measured against the most challenging of lignites to dry. Victorian lignite is high in moisture (~60% to 65%) and presents as a dry solid due to the majority of the moisture being held in macro and micro pores in the coal structure. Very little moisture is held as 'free water'.

The requirement to remove water from around 60% to 15% (roughly atmospheric moisture levels) provides a challenge to coal drying technologies and enables observations to be made as to the efficiency of different coal drying technologies. This gives a benchmark for assessment for each of the different technologies. It should be noted that the benchmark is general in nature and some technologies may perform better or worse with lower moisture coals or coals with a different physical and chemical structure.



GLOSSARY OF TERMS

ALDP	Advanced Lignite Demonstration Program	GTLE	GTL Energy Pty Ltd	
	(a Victorian Government initiative)	HTD	Hydrothermal dewatering	
bbl BCB	Barrell Binderless Coal Briquetting (White Energy	IDGCC	Integrated drying gasification combined	
ВСВ	Company)		cycle	
BTU	British Thermal Unit	IER	Ignite Energy Resources Pty Ltd	
Cat-HTR	Catalytic Hydrothermal Reactor (Ignite	KIER	Korea Institute of Energy Research	
	Energy Resources Pty Ltd)	LRC	Low rank coal	
CBR	Compact Bed Reactor (Torftech Group)			
CCGT	Closed cycle gas turbine	MTE	Mechanical thermal expression	
CHTD	Continuous Hydrothermal Dewatering	NCV	Net calorific value	
	(Exergen Pty Ltd)	NSENGI	Nippon Steel & Sumikin Engineering Co.,	
COMB	Counter Flow Multi Baffle (KIER)		Ltd.	
CSIRO	Commonwealth Scientific and Industrial	ROM	Run-of-mine coal	
	Research Organisation	SECV	State Electricity Commission of Victoria	
CV	Calorific value	tpa	Tonnes per annum	
DICE	Direct injection carbon engine	TRL	Technology readiness level	
EBR	Expanded Bed Reactor (Torftech Group)	UBC	Upgraded Brown Coal (Kobe Steel)	
ECT	Environmental Clean Technologies Pty Ltd	WTA	Wirbelschicht Trocknungmitinterner	
GCV	Gross calorific value		Abwarmenutzung (Translated as 'Fluidized bed drying with internal heat	
GHG	Greenhouse gas		utilization')	





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1. Executive Summary

Lignite is a major international coal resource that is often underutilized because it has a high moisture content and consequent low calorific value on a per tonne basis. It has a propensity for spontaneous combustion when dry, making it difficult to handle and store in raw form if it is not held under low oxygen conditions. The moisture in lignite is distributed throughout in a gel-like state, stabilized by oxygen-containing surface functional groups and ionic species. Moist lignite shrinks as it dries, becoming brittle and producing dust and the risk of explosion. Effective use of lignite requires it to be efficiently dried in a safe manner and, if long-distance transport is required, to be briquetted for reduced risk of spontaneous combustion.

The high moisture content and low calorific value has meant that utilisation of lignite has generally been restricted to mine mouth applications unless beneficiation occurs. Mine mouth application has usually been electricity production from large-scale power plants. As the drive for greater efficiency from lignite developed and also the imperative to provide the capacity to transport and use the resource for products other than electrons, the need to efficiently dry the coal became essential. This led to a technology expansion from the early 20th century to around the 1990's.

Over the past century a broad range of lignite drying technologies have been developed, but with the passage of time and the global shift toward renewables, many technologies have fallen into disuse and are no longer commercially available. In their place, newer technologies are being developed in an attempt to convert lignite into valuable products.

Consequently, a diverse range of lignite drying technologies is available, including a range of evaporative and non-evaporative approaches, as well as innovative combinations of both that span the technology development curve from the lab bench to fully commercial offerings.

This report provides a comparison of contemporary drying technologies that could be considered for projects seeking to utilize dried or briquetted lignite. In order to appreciate the relative merits of each drying technology, it is necessary to understand the way that moisture is held within a particle of lignite, and to recognise how drying affects the lignite structure and surface chemistry. This study provides a brief introduction to these topics, with a particular focus on Victorian lignite as a benchmark 'worst case' (i.e. highest and most tightly bound moisture) example.

In the compiling of this report, current information was sought from all known lignite drying technology vendors. As a basis for comparison, each vendor was requested to provide data for a facility capable of producing 1 million tonnes per year of dried Victorian lignite (i.e. drying from 65% to 15% moisture). Not all vendors responded and not all responded in full, and it appears that some are no longer in business. Where this was unable to be verified, the best available contact details have been provided. It should be noted that the report does not purport to cover every technology provider but considers at least one from each of the main forms of drying processes to enable the reader to obtain a perspective of each technology.



For comparative purposes, each of the prospective drying technologies was considered in relation to a number of key characteristics, including technological maturity, energy efficiency, greenhouse gas intensity and cost considerations, as well as the safety and handling properties of the dried product. This provided some useful insights into the relative advantages and disadvantages of each technology.

However, this information is not sufficient to identify the 'best' drying technologies, as the definition of 'best' is application-specific. In particular, production of binderless briquettes requires the dried lignite to have a relatively broad particle size distribution, while use as a gasifier feedstock would require a finely powdered product. Hence, the drying technology must be fit for the intended application.

For producing dried lignite suitable for binderless briquettes, the most energy-efficient processes were RWE's WTA fluidized bed dryer and GTL Energy's pressing and tubular steam drying process. If a suitable source of waste heat is available for drying, ECT's Coldry process would also be appropriate. Other drying technologies that may also be suited to this application are those from Drycol Australia, Kumera, Great River Energy, NSENGI and KIER, although each would need to be validated through a program of pilot trials.

For producing a finely-powdered product, the most suitable process would be Torftech's TORBED drying system. The Ahrko and Cartwheel processes also have potential but are at a lower stage of technology readiness. In addition, fine powder could be produced by milling coarse product from any of the other drying technologies.

From the information available, it was not possible to rank the relative cost-effectiveness of the lignite drying technologies. In general, it may be expected that the capital cost will be greater for processes that require multiple processing modules and greater space. Another consideration is that energy-saving measures, such as vapour recompression, will lower the operating cost but increase the capital cost. The ready availability of a source of waste heat would also significantly impact on the process costs.

In order to progress beyond this report and select the best candidate for a specific application, it would be necessary to provide funding to a short-list of vendors to do the work necessary to provide an indicative quote for a drying plant at the intended site where the availability of waste heat, steam, etc. is clearly defined.

This report will allow EPRI and its members to obtain an oversight of technologies and the types of drying and to consider what technology may be best suitable for any particular application. The report does not, nor can it, make definitive recommendations on a single drying technology. In the case of drying technologies there is no silver bullet but lots of silver buckshot.



2. Introduction

Lignite is a geologically young form of coal, intermediate between peat and sub-bituminous coal. Under the international classification system, lignite and sub-bituminous coals are referred to as 'brown coal', while in Australia 'brown coal' refers only to lignite.¹ In this report, 'lignite' is regarded as synonymous with 'brown coal'.

It has been estimated that nearly half of the world's total proven coal reserves are made up of lignite and subbituminous coal. Under the Australian classification system, it is estimated that Australia holds approximately 22.6% of the world's recoverable economic demonstrated resource of lignite. The largest deposits of lignite in Australia are located in the Gippsland Basin in Victoria, where sequences (>400 m) containing seams up to 100 metres thick were deposited during the period from the Eocene to the Miocene (~43–14 Ma) (Holdgate et al. 2009). Victorian lignite is characterized by its high moisture content (ranging from 45% to 65%), low level of mineral impurities, and high reactivity. The economically accessible reserve of this resource is estimated at around 34 billion tonnes.²

Despite its abundance and geographically wide distribution, lignite finds limited use worldwide, due primarily to its high moisture content and the attendant low calorific values, as well as its propensity for spontaneous combustion. As-mined lignite is uneconomical to transport over long distances, and so is used primarily by local power utilities and industries close to the mine sites (Kopp 2016).

There is a range of industrial uses for lignite, e.g. briquetting, gasification, liquid fuel synthesis, fertilisers, and others. In each case, the lignite must be dried and presented in a form suitable for the intended application (e.g., as powder or briquettes), each of which may require a different optimum moisture content and different drying conditions. Consequently, there is no 'one size fits all' lignite drying technology. The drying process must be fit-for-purpose for the intended application.

A broad range of lignite drying technologies have been developed over the past century. One of the fundamental incentives for innovation in lignite drying is the energy penalty involved in overcoming the latent heat of vaporisation of water. Over many years, researchers have sought ways to minimise energy costs while balancing the need for safety and reliability. Lignite drying technologies have been the subject of numerous reviews in recent years (e.g. Karthikeyan et al. 2009, Jangam et al. 2011, Osman et al. 2011, Nikolopolous et al. 2015, Rao et al. 2015, Violidakis et al. 2017).

This report is not intended to simply repeat the information already available in previous reviews. Instead, this report focuses on those technologies that are currently being offered as commercially prospective by potential vendors. The objective is to provide a comparison of contemporary drying technologies that could be considered for commercial projects seeking to utilize upgraded lignite.

¹ http://www.australianminesatlas.gov.au/aimr/commodity/brown_coal.html

² Ibid.



The structure of this report is as follows:

Section 3 describes the current understanding of the way that moisture is held within a particle of lignite, and the changes to the lignite structure and surface chemistry that occur during drying. This provides a context to understand the rationale adopted in each of the drying technologies under consideration.

Section 4 provides a general introduction to the range of technological options available for use in lignite drying.

Section 5 provides details on each of the contemporary drying technologies that are available for commercial consideration. As a basis for comparison, current drying technology vendors were contacted and requested to provide data for an installation that could produce 1 million tonnes per year of dried Victorian lignite (i.e. drying from 65% to 15% moisture). This section provides information on the background of each technology, flowsheets, mass and energy balance, an estimate of CO₂ emissions, technology readiness level (TRL - see Appendix for definitions), and the likely plant footprint. In each case, additional commentary is provided by BCIA, based on its experience in the sector.

Section 6 addresses the likely effect of the drying process on the propensity for spontaneous combustion of the dried lignite, and the implications for safe handling and transport of the product. A tentative ranking of the technologies is provided, based on the scant comparative information in the published literature.

Section 7 provides a synthesis and evaluation that summarises the available information and assesses the comparative merits of each drying technology. Insight is provided into the relative advantages and disadvantages of each process, affording the information needed to develop a short-list of lignite drying technologies that would be appropriate for any particular drying application.



3. Fundamentals of Lignite Drying

3.1. THE MOISTURE CONTENT OF LIGNITE

The lignite deposits in Victoria's Latrobe Valley, in the Gippsland Basin, represent an enormous accumulation (up to 400 m thick) of organic matter approximately 14–43 million years old. Victorian brown coal is very low rank: it passed through the rotting and humification stages of coalification, but was not subjected to the higher temperatures and pressures needed to convert it into higher rank coal.

During the early stages of coalification, microbial activity selectively degraded cellulosic components while preserving lignin-like components, transforming plant material into an aqueous suspension rich in highly oxygenated humic material, containing a variety of degradation-resistant plant remnants such as spores, resins, waxes and primary cell walls. As coalification continued, the chemical composition became more uniform and the cells coalesced under compaction. Consequently, bed-moist lignite is in a gel state, with physico-chemical and mechanical properties intermediate between those of a suspension and a solid, i.e. a gel. The gel structure is stabilised by the hydrophilic carboxyl and hydroxyl groups on the solid surfaces (Woskoboenko et al. 1991).

As-mined Latrobe Valley lignites typically exibit moisture contents ranging from 60 to 70%, depending on the location and depth of burial (see Table 1 below). Freshly mined lignite has the appearance of a dry, brittle solid and can be readily broken into pieces by hand. However, under shear the macropore structure is disrupted and water is liberated. Fully sheared Latrobe Valley lignite has a plasticine-like consistency, in which the liberated water acts as a lubricant for the particles to move past one another. This shear-dependence results in poor storage and flow properties, which must be accounted for in industrial operations such as converying, milling, screening, bunker storage, drying, press dewatering and extrusion (Woskoboenko et al. 1991).



	Typical moisture contents			
Field	% as-received	kg H ₂ O/kg dry coal		
Yallourn, Victoria	66.7	2.03		
Loy Yang, Victoria	62.6	1.67		
Morwell, Victoria	60.9	1.56		
Anglesea, Victoria	46.6	0.88		
Leigh Creek, South Australia	31.0	0.45		
Lower Rhine, Germany	56.0	1.27		
Fort Union, Nth Dakota, USA	37.2	0.59		

Table 1: Moisture contents of lignites, as received and dry basis (Allardice et al. 2004)

The water in lignite is an integral component of its structure and its removal results in the irreversible loss of the gel structure. When lignite is air-dried (10 -15% moisture) the volume shrinks by 20-50%, depending on the petrographic composition of the sample. When dried lignite is re-exposed to water it swells but does not regain its original volume.

The high moisture content of Victorian lignite is the largest barrier to its commercial utilisation. Virtually all potential uses for lignite require it to be dried in a cost-effective manner, which requires an understanding of the way that water is held within the lignite structure.

3.2. CHARACTERISATION OF THE WATER IN LIGNITE

Much research has been done to understand the nature of the water held within Victorian lignite. It has been found that about 60% of the water is contained in macropores, about 30% in the large and small capilleries, and about 10% in mono- and multilayers, possibly hydrogen bonded to functional groups in the coal structure (Allardice 1991; Allardice & Evans 1971).

Only a portion of the water in Victorian lignite behaves like bulk water. Differential Scanning Calorimetry (DSC) measurements have distinguished three forms of water in lignite: (a) *free water*, which freezes at about 0 °C and behaves essentially like conventional (bulk) water; (b) *bound water*, which freezes in the region -28 to -36°C; and (c) *non-freezable water*, which is so intimately bound to the coal structure that it is not able to crystallise (Norinaga et al. 1998).



Free water is water that fills the intraparticle space and larger pore voidage, without chemical interactions with coal components.

Bound water is water held by capillary forces within narrow, slit-like pores that are estimated to be approximately 2nm wide (Hayashi et al. 2001). The bound water has been attributed to water held in the capillaries with increased potential for hydrogen bonding compared to free water and hence a lower vapour pressure (Fei et al. 2005).

Non-freezable water is currently poorly defined, but is understood to be water that is affected by the chemical composition of the pore surface and is a function of the total surface area. Analytically, it is quantified as the difference between the total water content and the sum of the free and bound water components. Part of the non-freezable water is comprised of a monolayer of water (0.083 kg/kg dry coal) that is attached to the coal by hydrogen bonding at suitable polar functional groups, representing about one twentieth of the total water present (Allardice & Evans 1971). Adjacent to this is another layer of water, known as the multilayer, made up of clusters of 10 or so molecules of water for each strongly bound water molecule in the monolayer (Allardice et al. 2004).

Monolayer and multilayer moisture are primarily stabilised by metal carboxylates, carboxylic acids and phenolic hydroxyls in the coal structure. The equilibrium moisture content is also dependent on the type and amount of cations present, varying in the order $Fe^{2+} > Mg^{2+} > Ca^{2+} > Cu^{2+} > Ba^{2+} > Al^{3+} \sim Fe^{3+} \sim Na^{+} > K^{+}$ (Schafer 1972).

The three different forms of water are progressively more tightly held within the lignite structure, requiring increasing energy for their removal during drying. For the free water, the isosteric heat of desorption (i.e., the difference between the partial molar enthalpies in the vapour and adsorbed phases) is approximately equal to the heat of vaporisation of bulk water, at water contents down to about 0.6kg/kg dry coal. To remove the bound water, down to about 0.15kg/kg dry coal, the heat of desorption increases gradually as water is liberated progressively from smaller capillaries or pores. To remove non-freezable water, at water contents below 0.15kg/kg dry coal, the heat of desorption increases steeply, as water held by various chemical interactions is progressively removed (Allardice & Evans 1971). This information is summarised in Figure 1 below.

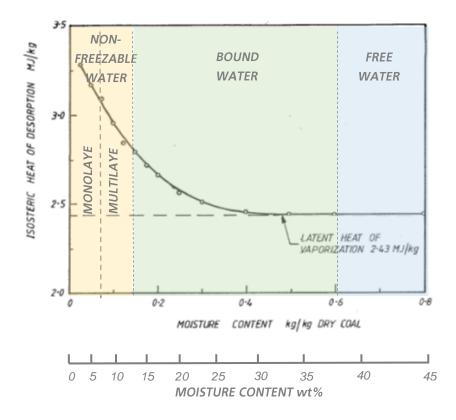


Figure 1: Isoteric heat of desorption of Yallourn lignite as a function of moisture content (Adapted from Allardice 1991)

In a study using pressurised steam drying of Loy Yang Low Ash lignite (62% bed moisture), Bongers et al. (1998) found that free water was removed with only 2–3°C of superheat. As the degree of superheat was increased, bound water was progressively removed from smaller and smaller pores, reaching an equilibrium moisture content of 10% with 5°C of superheat. Much higher levels of superheat were required to remove the multilayer non-freezable water, while the strongly bonded monolayer water could not be removed with even 40°C of superheat for 65 hours.

3.3. EFFECTS OF DRYING UPON LIGNITE STRUCTURE AND SURFACE CHEMISTRY

During the drying process, progressive removal of water from the gel-like lignite structure causes the pore structure to collapse irreversibly. This leads to shrinkage of the lignite particle. As water is progressively removed by evaporation the large pores empty first, followed by the larger capillaries, but collapse of the lignite structure is initially relatively small because of the ordered arrangement and structural rigidity of the



coalified vegetable macrostructure. Further removal of bound and multilayer non-freezable water leads to collapse of capillaries and significant shrinkage. For Yallourn lignite, maximum shrinkage occurs at a moisture content of 0.16kg/kg dry coal, producing the most stable and strongest structure possible. Further loss of water causes the structure to swell (Evans 1973).

The shrinkage observed during lignite drying is not fully reversible upon rewetting. As bound water and multilayer non-freezable water are evaporated, capillary pressure causes the mesopores and nanopores to collapse. Crosslinking reactions then seal a proportion of the pores or otherwise limit their ability to expand during water readsorption. The net effect is that a portion of the pore structure becomes inaccessible to rewetting, so the lignite cannot recover its original volume or water-holding capacity. The net loss in accessible internal volume increases with increasing drying temperature (Salmas et al. 2001).

The surface chemistry of lignite is also affected by the temperature employed for drying. Carboxylic acid groups on the lignite surface are decomposed at drying temperatures between 60°C and 120°C. Phenolic and carbonyl groups start to break down at 150°C and alcoholic groups decompose at temperatures above 200°C (Murray & Evans 1972).

The loss of carboxylic acid and phenolic hydroxyl groups during drying cause the lignite surface to become more hydrophobic, making it harder for water to enter and fill the collapsed pores. In addition, the cation-binding capacity of the surface is reduced, which decreases the affinity for binding non-freezable water through chemisorption (Schafer 1972).

Feng et al. (2016) have confirmed these effects in a drying study with Zhaotong lignite. The loss of surface hydroxyl and carboxyl groups was observed to increase linearly with drying temperature, between 100°C and 500°C. The total pore volume within the lignite was found to increase at higher drying temperatures, while the average pore diameter fell. The moisture holding capacity of the lignite decreased with increasing drying temperature, which was mainly attributed to the reduced concentration of hydroxyl and carboxyl groups on the lignite surface.



4. Overview of Lignite Drying Technologies

A broad variety of dryer configurations have been developed for use with lignite, which can be classified according to (i) the type of drying, (ii) the controlling heat transfer mechanism, (iii) the heating medium, (iv) operating pressure and (v) the heat source. The range of options available is summarised in Table 2 below.

Parameter	Alternatives		
Drying method	Evaporative or non-evaporative		
Heat transfer mechanism	Direct or indirect		
Heating medium	Flue gas, hot air, steam, hot water or solvent		
Pressure	Atmospheric, vacuum or high pressure		
Heat source	Dryer burners, boiler (flue gas or steam), recovered waste heat or electrical.		

Table 2: Types of dryer configuration (adapted from Nikolopoulos et al. 2015)

These drying options create opportunities for a wide variety of drying technologies, in the pursuit of reduced costs and economies of scale. They can be broadly classified as evaporative or non-evaporative, or a combination of the two.

The majority of lignite drying processes are based on evaporative drying. In general, evaporative drying involves heating the moisture within the lignite to its boiling temperature, causing liquid water to be converted to vapor. This change of state requires an input of energy to overcome the latent heat of vaporisation, plus additional energy to overcome heat and mass transfer limitations. In simple drying operations the latent heat of vaporisation cannot be recovered, representing an energy penalty equivalent to about 20% of the energy content of the dry lignite. The challenge for innovation in evaporative drying processes is to minimise the energy penalty with the goal of reducing the overall cost of drying.

Accordingly, a wide range of evaporative drying technologies have been developed, which can be classified as (i) rotary drying, (ii) flash drying, (iii) fluidized bed drying, (iv) screw conveyor drying, and (v) microwave drying.



- Rotary drying is one of the oldest forms of lignite drying technology and has been the principal drying process used for briquetting operations worldwide. This represents the benchmark against which newer drying processes are assessed.
- Flash drying refers to processes in which lignite particles are dried whilst entrained in a flowing stream of hot air, steam or combustion gases. In general, flash drying has low capital cost, involves minimal handling, is very rapid and is inherently safe when the lignite dries in a co-current manner, surrounded by an inert atmosphere or water vapor. The main disadvantage of flash drying is that it allows no option to recover the latent heat of evaporation of the moisture removed, so it is relatively energy-intensive. A range of flash drying variants have been developed, which can be classified as (i) mill flash drying, (ii) attrition flash drying, (iii) pneumatic flash drying, and (iv) countercurrent flash drying.
- Fluidized bed drying involves suspending a bed of lignite particles in an upwardly-flowing stream of fluidising material that can range from hot gas to steam, allowing for relatively efficient drying.
- Screw conveyor drying is a recent development, in which lignite particles are dried during passage through a heated auger.
- Microwave drying is another recent development, in which lignite particles are heated uniformly using microwave energy, generating an internal pressure that drives moisture out of the pores.

In non-evaporative drying, moisture is removed in liquid form by the application of pressure, either at ambient or elevated temperatures. The objective is to remove moisture without the energy penalty involved in converting water from liquid to gaseous form. A range of non-evaporative drying techniques have been developed for lignite, which can be classified as (i) press dewatering, (ii) thermal dewatering, (iii) mechanical thermal expression, (iv) hot oil immersion drying, and (v) solvent extraction drying. Not all of these processes can produce a fully dry product and are usually referred to as 'dewatering' processes.

Despite this, partial dewatering can play a valuable role in reducing the energy load in subsequent drying operations, or for converting the lignite into a feedstock for further upgrading processes. Hence, some processes have been developed that utilize a combination of non-evaporative dewatering following by evaporative drying, to strike an optimum balance between drying efficiency and cost.

Table 3 below provides a brief summary of the relative advantages and disadvantages of each drying method, and lists the commercial vendors associated with each. Development of a number of these processes have been discontinued and are either no longer available for new lignite upgrading projects or they have not progressed beyond the research stage. The subsequent focus of this report will be on drying technologies that are currently offered by their developers and are prospective for new lignite upgrading projects. In each case, extensive efforts were made to contact the vendors for comparative information.



Dryer type	Advantages	Limitations	Commercial offerings
a) EVAPORATIVE DRYERS			
Rotary	Stable operation; robust design; attrition produces fines	Relatively slow throughout	Keith Engineering; Davenport; GEA; ZEMAG; Kumera
Mill-type	High throughput, potentially rapid drying	Abrasive wear; high maintenance	Loesche; Mitsubishi Hitachi
Attrition flash	High throughput, rapid drying	Mostly experimental; high proportion of fines	Windhexe; DevourX; Cartwheel Resources; Torftech Group
Pneumatic flash	Simple construction, rapid drying	Requires small particle size for rapid drying	HRL; Lignite CRC; White Energy; Ahrko System
Countercurrent flash	Compact design; utilizes waste heat	Potentially higher risk of spontaneous combustion; large particles reduce drying efficiency	KIER
Fluidized bed	Good mixing; high heat transfer	High pressure drop; attrition produces fines	AMAX; Western Syncoal; Great River Energy; Nippon Steel; Lurgi; RWE; Vattenfall; MHI; Tian
Screw conveyor	Stable operation; robust design; enables torrefaction	Relatively slow throughout; largely unproven	Torreco
Microwave	Volumetric heating; energy-efficient	Local hotspots; fire hazards; small scale; expensive to scale up	DryCol Australia; CoalTek
Evaporative solvent	Rapid drying, stabilised product	Solvent contamination of product	NBCL; Kobe Steel
o) NON-EVAPORATIVE DRYE	RS		
Steam dewatering	Water released as a liquid	Batch process, relatively slow throughput	Voest-Alpine; KHI; Evergreen Energy
Hydrothermal dewatering	Water released as a liquid; opportunity for energy recovery; continuous process	Partial dewatering, wastewater treatment is expensive	Exergen; Ignite Energy Resources
c) COMBINED EVAPORATIVE	AND NON-EVAPORATIVE DRYERS		
Densification and drying	Efficient drying	Relatively slow throughput	ECT; Latrobe Lignite Developments; GTL Energ

Table 3: Overview of drying technologies



5. Contemporary Lignite Drying Technologies

This section describes the lignite drying technologies that are available for commercial consideration, which are either being offered by vendors worldwide or have been developed for use with Victorian lignite at a suitable scale but are not actively being pursued. The rationale for the focus on Victorian lignite is that it is one of the world's wettest and most difficult to dry; technologies that are successful with Victorian lignite are likely to be broadly applicable. The inclusion of technologies that have been developed for Victorian lignite but have been mothballed is intended to illustrate the full range of options available, which might be worth investigating for particular drying applications.

The information provided in this section is based on feedback from current drying technology vendors, who provided details on the background of each technology, flowsheets, mass and energy balance, an estimate of CO₂ emissions, technology readiness level (TRL; see Appendix for definitions), and the likely footprint of a drying plant producing 1 million tonnes of dried Victorian lignite annually. In each case, additional commentary is provided by BCIA, based on its experience in the sector.

5.1. ROTARY DRYING

Rotary drying involves lignite particles falling through a stream of heated air or gas as they pass along the length of a rotating tube set at a slight incline or flow through heated tubes surrounded by a steam jacket. There are two main variations on this theme:

- a) In rotary *drum* drying, the dryer consists of a single large tube, or drum, fitted with many lifting flights on the interior of the chamber. As the drum rotates, the flights pick up material from the bed, carry it over, and drop it through the drying gas, maximizing the transfer of heat to the moist particles. There are two types of rotary drum dryers:
 - Direct heat rotary drum dryers pass a stream of hot gas (air steam or combustion gas) through the drum to contact the particles directly. The drying gas is directed in either a co-current flow (flowing the same direction as the material), or counter-current flow (moving in the opposite direction of the material).
 - Indirect heat rotary drum dryers transfer heat into the chamber through either an outer heated jacket on the drum or steam tubes inside the drum.
- b) In rotary *tubular steam* drying, the solids pass through a series of tubes that pack the drum. The tubes rotate along with the drum, causing the solid particles within to tumble and shower as they are moved down the incline. Steam flows over the outside of the tubes, transferring heat as it condenses.



Rotary dryers are often described as the workhorses of the thermal processing industry. They are simple, robust and versatile, produce a uniform product and often last for decades. They are also commonly used for drying materials such as sand, limestone, gypsum, potash and mineral ores (Kelly 1995).

5.1.1 Keith Engineering

Keith Engineering, based in Sydney, specialises in the design, manufacture and installation of processing equipment for the rendering and abattoir industries. Keith Engineering is part of the Pinches Group, based in Melbourne, which owns and operates a number of manufacturing and engineering supply companies.

Keith Engineering has developed a process called Airless Drying, which utilizes *direct heat rotary drum drying* with superheated steam as the drying medium instead of conventional hot air. The major benefit of Airless Drying is that superheated steam has heat transfer properties superior to air at elevated temperatures. The removal of oxygen from the drying process reduces odour and minimises the risk of explosion and fire.

Keith Engineering has constructed a pilot scale superheated steam rotary drum dryer system, shown in Figure 2 below. The dryer has a drum diameter of 0.37m and a length of 3.0m, with an evaporation rate of 125kg/hr.



Figure 2: Pilot scale superheated steam rotary drum dryer (© Keith Engineering (Australia))

Researchers at Monash University have evaluated the feasibility of drying Loy Yang lignite in this system. The lignite had a moisture content of 61% (1.56g/g dry basis) and an average particle size of 8mm. Superheated



steam at 230°C was passed through the dryer co-currently with the lignite, at a velocity of 1.5m/s. Superheated steam exiting the dryer was passed through a cyclone to remove lignite fines, then through a heater to boost the temperature back to 230°C, and returned to the drum through the action of a fan. A proportion of the steam, equal in mass to the amount evaporated from the lignite, was removed from the system via a condenser.

Operation of the dryer at a rotation speed of 0.05 sec⁻¹ and a lignite feeding rate of 10kg/hr resulted in an average residence time of about 30 minutes. The dried lignite product had a moisture content of 11% (0.13g/g dry basis), demonstrating that more than 90% of the moisture could be removed from Loy Yang lignite by this method (Clayton et al. 2007).

Monash University researchers subsequently utilized this system to successfully dry anaerobic digester sludge using lignite as a drying aid (Hoadley et al. 2015), and to produce a slow release nitrogen fertiliser by simultaneous granulation and drying of urea with lignite (Rose et al. 2016).

Keith Engineering is interested in applying its Airless Drying technology to lignite at commercial scale.

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5.1.2 Davenport Dryer

Davenport Dryer, a division of Doerfer Companies in the United States, manufactures a range of rotary drying equipment including steam tube dryers, direct fired dryers, water tube coolers and air coolers. Davenport dryers have been used with grains, minerals, sludges, aggregate, powders, coal and chemicals, and have established a reputation for quality, durability, and dependability.

Davenport steam tube dryers (shown in Figure 3 below) are a form of indirect heat rotary drum drying, utilizing conduction as the heat transfer method. Rotary steam tube dryers dry at a lower temperature, are resilient and can tolerate process upsets.





Figure 3: Davenport steam tube dryer (© Davenport Dryer) 3

BCIA contacted Davenport Dryer to contribute to this report, knowing that Davenport steam tube dryers were utilized in GTL Energy's demonstration plants in North Dakota and New Zealand (see Section 5.9.2). While a response was promised, nothing was forthcoming before this report was finalised.

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5.1.3 Kumera Corporation

5.1.3.1 Process description

Kumera Corporation, of Finland, is the global market leader in drying of non-ferrous metal concentrates. The Kumera Steam Dryer is its leading technology for water removal, with a solid reputation based on its minimal need of maintenance, low operational expenses and minimum impact on the environment.

³ http://www.quad-citydryerworks.com/index.htm



The Kumera Steam Dryer is based on the *indirect heat rotary drum drying* principle. It was originally developed for nonferrous metal concentrates, using steam from waste heat boilers as the heating source. Internationally, there are currently 26 Kumera Steam Dryer reference plants for drying of non-ferrous (mainly copper) smelter concentrates, with feed rates ranging from 30 to 240 tonnes/hr.

The patented design (Räsänen & Tiitu 1999), shown in Figure 4 below, utilizes an arrangement in which the steam tubes are divided into individual maintenance-friendly heating element modules. The modular construction makes drying capacities easily adjustable and increases the availability to 98% or higher.

To improve the efficiency of its steam drying process, Kumera Corporation captures a significant part of the latent heat of evaporation in a separate Heat Recovery Dryer. It is claimed that the use of the Heat Recovery Dryer reduces the energy required in the drying process by 30-40%.⁴

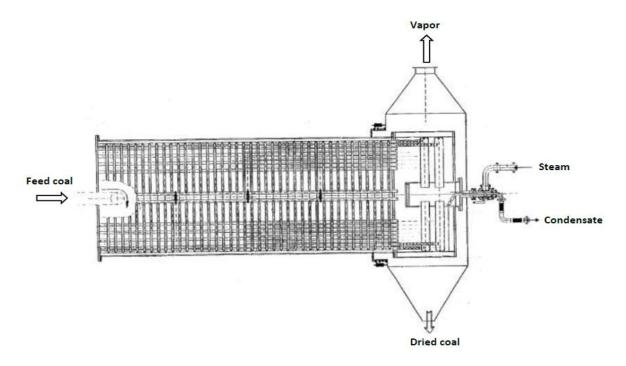


Figure 4: Concept of Kumera rotary drum steam dryer (Räsänen & Tiitu 1999)

5.1.3.2 Flow diagram

A Kumera Steam Dryer system for drying of lignite would comprise the following items:

- Wet lignite feeding system to dryer
- Steam Dryer

⁴ http://www.kumera.com/newsletter-03-2017.html



- Heat recovery dryer utilizing latent heat, thus minimizing the amount of thermal heat for drying
- Steam and condensate control system
- Dry lignite discharge system
- Exhaust gas handling system
- Inert gas conditioning systems for safety
- Safety extinguishing system
- Instrumentation and process control

5.1.3.3 Lignite preparation specifications

For optimum drying efficiency, lignite should be crushed to a top particle size of 6mm, although larger particles can be handled.

5.1.3.4 Mass balance

Energy requirement = ≈ 0.97 t_{steam}/tonne H₂O, or ≈ 0.62 MWh/tonne H₂O, or ≈ 2.23 GJ/tonne H₂O evaporated.

On a dried product basis:

Drying from 60% moisture to 15% moisture produces 0.889 tonnes product for each tonne of water evaporated.

Energy requirement = $2.23 \text{ GJ/t H}_2\text{O} \times (11 \text{ H}_2\text{O}/0.889 \text{ t product}) = 2.51 \text{GJ/tonne product}$

5.1.3.5 Plant footprint @ 1.0 million tpa dried lignite

For this capacity it would be necessary to use a four line Kumera plant, which would require a space of less than 1ha. The overall area requirement will depend on the selected ancillary equipment and the layout for material handling and storage.

5.1.3.6 Services required

Electricity, Steam and reuse of secondary condensates for tree plantations or water treatment plant.

5.1.3.7 CO₂ emissions per tonne of finished product

Typical steam drying produces 0–0.6tonne CO_2 /tonne product, depending on the CO_2 emissions of the steam source. Emission is 0 t CO_2 /t product, for example when using excess heat to make steam. Excess heat is defined as pure waste heat, or sun energy, or wind energy, etc.

For heat recovery steam drying, GHG emissions are estimated as 0–0.13tonne CO₂/tonne product.



5.1.3.8 Is the technology capable of capturing CO₂ emissions?

The drying process does not in itself generate CO2, however the heat source in whatever form is likely to.

Conventional amine capture technologies may be used if the heat source is a boiler, or CO2 emissions may be avoided altogether if waste heat is available from steam generation.

5.1.3.9 TRL estimate

Kumera Steam Dryers are at TRL 9 for mineral concentrate applications.

Kumera Corporation has established a pilot plant for its steam drying with heat recovery process at Kangasala, Finland. Pilot tests have been conducted with lignite from Germany and sub-bituminous coal from Indonesia, but a full scale plant has not yet been built. For Victorian lignite, a program of testing at pilot scale would be required.

TRL = 5 for Victorian lignite.

5.1.3.10 Commercialization pathway

Kumera Corporation is prepared to develop a full-scale lignite drying plant for a commercial customer.

5.1.3.11 Reference plants

26 steam dryer references, feed range 30 to 240t/hr. Descriptions of 11 of the earlier reference plants can be found in Talja et al. (2011).

One pilot plant reference for heat recovery drying of any coal quality is situated in Kangasala, Finland, feed range 0.1 to 1t/hr.

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5.1.4 ZEMAG

ZEMAG (formerly Zeitzer Eisengießerei und Maschinenbau AG) was a German mechanical and plant engineering company based in Zeitz, Saxony-Anhalt. From the 1870s, ZEMAG was the leading supplier of equipment for briquette factories, especially coal mills, coal dryers and briquette presses, with reference plants in Germany, South Africa, Norway, India, Ukraine, Australia and China.

For lignite drying, ZEMAG manufactured *rotary tubular steam dryers*, which provide a large drying surface and high evaporation rates. ZEMAG tubular steam dryers have proven to have long working lives, with a dryer installed in 1937 at Mitteldeutsche Braunkohlengesellschaft (MIBRAG) still in operation (Anon. 2011). In Australia, ZEMAG dryers were used at the Morwell briquette factory, in Victoria's Latrobe Valley, until the factory was closed in 2014.



Figure 5: ZEMAG rotary tubular steam dryer at Morwell briquette factory (Allardice 2015)

ZEMAG increasingly ran into financial difficulties from the 1970s, due to the closure of many coal mines and associated briquette factories around the world. It experienced a series of closures and restarts under new names.⁵

Its latest incarnation, ZEMAG Clean Energy Technology GmbH, is a subsidiary of the Chinese company Shanghai Zemag Mindac Machinery & Equipment Co., Ltd. The business activities of ZEMAG Clean Energy

⁵ https://de.wikipedia.org/wiki/ZEMAG



Technology consist of project planning, design, manufacture, supply and the installation of turnkey-ready-plants for processing lignite and potash as well as complete lignite-briquette factories and coal-drying plants. ZEMAG Clean Energy Technology also supplies gasification equipment based on the BGL fixed-bed gasification process.⁶ Most recently, ZEMAG tubular steam dryers have been installed to support BGL gasification processes in China, for coal-to-olefins and coal-to-ammonia projects (APEC 2013).

Efforts were made to contact ZEMAG Clean Energy Technology for additional information through its website (www.zemag-zeitz.com) and listed phone number, without success. Efforts to contact Shanghai Zemag Mindac Machinery & Equipment Co., Ltd were also unsuccessful. It is unclear whether ZEMAG rotary tubular steam dryers are still available for new lignite processing projects.

BCIA comments

Rotating steam dryers are a very reliable form of drying. The technology is robust, reliable and proven. Throughput is relatively low but the technology is one that commercial operators can have confidence in.

Kumera steam dryers are similar to Davenport dryers, which have been proven to be effective with lignite. A potential customer for lignite would need to undertake a program of pilot testing at Kumera's pilot plant in Finland to develop the necessary design data.

ZEMAG dryers are proven over more than a century of operation in the coal space. For customers who wanted the confidence of reliable coal drying capability both these dryers hit the mark. The critical question would be do ZEMAG still supply?

5.2. ATTRITION FLASH DRYING

Attrition flash drying refers to drying devices of novel design in which lignite is dried in a high velocity hot gas stream, with attrition of particles through impact. In this class, Windhexe and DevourX were the subject of previous reviews (e.g. Nikolopoulos et al. 2015), but these technologies are no longer available.

5.2.1 Cartwheel Resources Pty Ltd

5.2.1.1 Process description

Cartwheel Resources Pty Ltd developed a novel process for combined milling and drying of lignite, called the Intense Gas Vortex dryer. As shown in Figure 6 below, the Intense Gas Vortex dryer comprises two fans, one at the inlet and one at the outlet, to generate a strong airflow in the main body of the reactor, the vortex

⁶ http://gasification2017.missionenergy.org/presentation/ZEMAG.pdf



tube. A venturi section at the end of the vortex tube further intensifies the process, and a comminution screen at the solids exit breaks down larger particles (Gomez 2013).

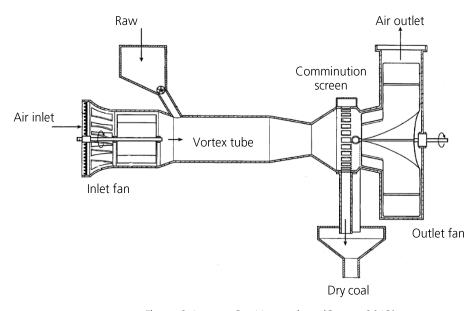


Figure 6: Intense Gas Vortex dryer (Gomez 2013)

It is claimed that lignite is simultaneously milled and dried through a combination of (a) intense shearing and centrifugal forces inside the vortex, which separates free moisture, (b) acoustic energy generated by the fan impeller, (c) the negative pressure generated by the venturi, and (d) impact with the comminution screen. Further drying can be achieved by directing microwave energy into the vortex tube (Gomez 2013).

Cartwheel Resources tested a prototype 300kW Intense Gas Vortex dryer in 2009 using Loy Yang lignite. The feed lignite had a moisture content of 31.9%, (it is not clear why the coal was at 31.9% moisture when run of mine coal is ~63%) with more than 80% of the particles passing through a 2300µm screen. After a single pass through the machine, the moisture content was reduced to 18.1%, with more than 80% of the particles passing through a 40µm screen. It was suggested that two passes would be needed to achieve a moisture content of 10–15% (Gomez, personal communication). [Note, however, that as-mined Loy Yang lignite has a moisture content of 61%-63%.]

Cartwheel Resources subsequently built four 1000kW Intense Gas Vortex dryer units, each with a nominal lignite capacity of 150 tonnes/hr. Development for a demonstration site at Loy Yang power station was begun, but subsequently put on hold when Cartwheel Resources was unsuccessful in obtaining financial support from the Victorian government under its Advanced Lignite Demonstration Program (ALDP).



Cartwheel Resources continues to seek financial support to build a demonstration plant of its Intense Gas Vortex dryer.

5.2.1.2 TRL estimate

TRL = 4. While a 300kW pilot system was constructed, insufficient work has been done at that scale to establish an engineering basis for design of a larger system.

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BCIA COMMENTS

This technology appears to have some potential but has not yet been developed beyond initial proof-of-concept testing. A full program of pilot plant testing is required to demonstrate satisfactory performance.

The dried product from this process would be very fine and dusty, and probably unsuitable for binderless briquetting. It is potentially suitable as a feedstock for pulverised fuel injection into a boiler or an entrained flow gasifier.

5.2.2 Torftech Group

5.2.2.1 Process description

Torftech Group produces reactors for use in processing of biomass, minerals, foods, catalysts, sludge wastes and off-gases. Its TORBED technology uses high speed gas streams to intensify processes that require gassolid contacting. In contrast to other technologies, TORBED systems contain the reaction within the reactor by utilising patented gas swirl patterns and process chamber shape. The high gas velocities used in the process result in much enhanced heat and mass transfer but without the penalty of high pressure drop. Processes can thus be pushed beyond limits that are imposed by conventional technology, allowing for very fast and intense process regimes.

TORBED reactors were originally conceived in 1981 and first commercialized in 1985; since that time over one hundred and eighty reactors have been installed worldwide, combining for more than five million operating hours.



The TORBED Compact Bed Reactor (CBR) is a unique gas-solid contacting system that achieves efficient heat and mass transfer in a compact unit. The operating principle of the TORBED CBR is illustrated in Figure 7 below. The CBR itself has no moving parts and no resident bed, setting itself apart from most conventional drying technologies. The hot inlet gas stream passes through a stationary set of blades that direct the airflow. This directed flow interacts with the feed material to form a spinning bed of material. As the gas velocities through the blades is high it facilitates very high mass transfer and efficient processing as it impacts the bottom of the resident bed. The material stays in the bed until it is discharged, either through elutriation in the gas stream or through a purpose-built discharge port (Dodson 1985).

Over the past 10 years, Torftech Group has carried out extensive test work and completed studies on upgrading many types of coal, including Latrobe Valley lignite. This has included drying the coal as well as upgrading the coal through de-volatilisation, to produce several different products.

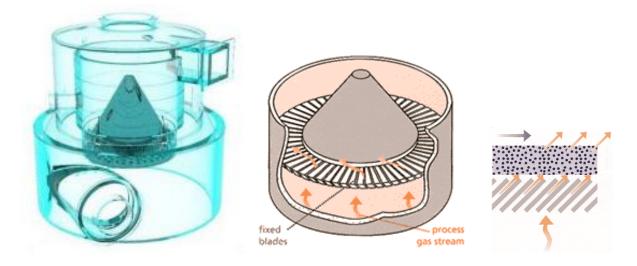


Figure 7: Operating principle of TORBED compact bed reactor (© Torftech)

Drying of lignite would be accomplished using a series of modules, each using a stack of three TORBED CBR dryers. This would increase the total residence time of the lignite, which is necessary given the high moisture content of the feed. It would also facilitate a consistent and on specification dried lignite.

The TORBED CBR reactor can be utilized to process as-mined lignite, provided that the maximum particle diameter is no more than 10mm. No further preparation is needed. Coal fines are also processed without difficulty in the TORBED CBR. Depending on the final design some of the fines will be elutriated from the reactors and collected in a bag filter. This can be blended back with the main stream of dry coal or it can be kept separate as a fine dry coal stream if there is benefit in doing so.



The TORBED dryer system also has low pressure drop, allowing for the recycling of process gases, thus further increasing the total plant efficiency. The recycled dryer exhaust gas displaces some of the fuel, lowering total CO₂ emissions and, if using dried coal as the fuel, reducing the total required throughput of the plant.

5.2.2.2 Flow diagram

Torftech Group proposes to use another of its patented technologies, the Expanded Bed Reactor (EBR), as the hot gas generator for use with lignite. A portion of dry coal would be combusted in the EBR to provide the heat required for drying the raw lignite.

The TORBED EBR (shown in Figure 8 below) is a high gas velocity, high intensity gas-solid contacting device. The coal is circulated as an expanded bed by a hot inlet gas steam, forming a spinning bed of material that fills the height of the EBR chamber. TORBED combustors can operate at precisely controlled temperatures to ensure thorough conversion of carbon from the feed material without any sintering of ash, optimising combustion efficiencies.

Torftech envisages a modular drying system approach, with a heat generation plant associated with each stack of dryers, as shown in Figure 8 below. This modularisation would allow standardisation of design as well as operational flexibility. The fuel for each heat generation system would come directly from the dryer associated with it, providing a self-contained system to be integrated in the wider plant.

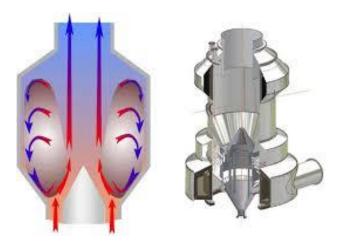


Figure 8: Operating principle of TORBED Expanded Bed Reactor (© Torftech)



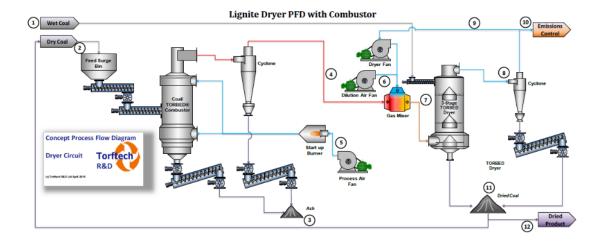


Figure 9: Proposed lignite drying circuit using TORBED CBR and EBR reactors (© Torftech)

5.2.2.3 Lignite preparation specifications

Lignite should be crushed and sieved to a maximum size of ~10mm. This would produce dried coal with at least 90% below 1mm particle size.

5.2.2.4 Mass balance

The mass balance for the proposed lignite drying circuit is shown in Table 4 below. A total of eight drying circuits would be required to produce 1 million tpa of dried lignite.

No.	Line	Throughpo kg/hr	ıt per unit tpa	Total for 8 units tpa
1	Raw coal input	47,000	350,683	2,805,468
2	Dry coal fuel	4,135	38,853	246,821
3	Ash	125		
4	Combustor exhaust	94,493		
5	Combustor air input	90,484		
6	Dilution air input	154,990		
7	Dryer inlet gas	554,483		
8	Dryer exhaust	580,594		
9	Dryer recycle gas	305,000		
10	System exhaust	275,594		
11	Total dry coal	20,888	155,853	1,246,821
12	Product coal	16,753	125,000	1,000,000

Table 4: Mass balance for TORBED lignite drying circuit



Energy requirements:

a) Energy from coal combustion

Heat value of fuel = 18.41MJ/kg (NAR)

Energy produced = 18.41MJ/kg x 4,135kg/hr = 76,125.35MJ/hr = 21.15MW

b) Energy from electricity

Electrical input per module = 1.3MW

c) Energy intensity

Total energy requirement = 21.15 + 1.3 = 22.45MW

Energy intensity of product = 22.45MW / 20.888t/hr = 1.07MWh/t = 3.87GJ/t product

Water in feed coal = $47,000 \text{kg/hr} \times 0.62 = 29,140 \text{kg/hr}$

Water in dried coal = 20,888kg/hr x 0.15 = 3,133kg/hr

Water evaporated = 29,140 - 3,133 = 26,007kg/hr

Energy intensity of evaporation = 22.45MW / 26.007t/hr = 0.863MWh/t = 3.11GJ/t

5.2.2.5 Plant footprint @ 1.0 million tpa dried lignite

Each proposed drying module will require a space 18m x 30m x 23m high.

Production of 1 million tpa will require 8 modules, i.e. 72m x 60m x 23m high.

5.2.2.6 Services required

All utility requirements will be identified fully as the project develops.

Gas is required for start-up. The annual consumption will vary based on the operating parameters of the client.

Ash disposal will need to be carried out in the system using combustion.

Approximate installed power requirement = 1.3MW/module x 8 modules = 10.4MW

5.2.2.7 CO₂ emissions per tonne of finished product

327kg CO₂-e/tonne Gross product or 408kg CO₂-e/tonne Net product



5.2.2.8 Is the technology capable of capturing CO₂ emissions?

Yes. Additional capital can be invested in oxy-combustion and indirect heating of the dryers that will facilitate CO_2 capture.

5.2.2.9 TRL estimate

Generally, TORBED dryers and combustors are at TRL 9.

Specifically, Latrobe valley lignite drying and combustion are at TRL 6–7 (a large number of successful pilot trials).

5.2.2.10 Commercialization pathway

Torftech has a significant track record in successfully commercialising projects. The standard project implementation of a TORBED system includes pilot trials as part of an initial engineering package. Prototyping is also typical when significant scale up, or a novel innovation, are envisaged in making the best possible final plant.

There are a large number of processes that have successfully taken TORBED technology from pilot trials to commercial solutions, including:

1. Flue gas scrubbing in the aluminium industry (Comalco)

Project duration to commercial plant implementation – four years

Year of project implementation – 1995 and 1997

Scale up factor – 1st stage 10x, 2nd stage 35x

2. Torrefaction of biomass to bio-char (RWE and Vattenfall)

Project duration to commercial plant implementation – four years

Year of project implementation – 2008 and 2011

Scale up factor from pilot plant trials – 250x

3. Drying of sludge in the pulp and paper industry (Sappi)

Project duration to commercial plant implementation – one year

Year of project implementation – 2004

Scale up factor from pilot plant trials – 100x



4. Catalyst regeneration (Shell Oil)

Project duration to commercial plant implementation – two years

Year of project implementation – 1997 and 1999

Scale up factor from pilot plant trials – 80x

5. High temperature calcination of clay (Imerys)

Project duration to commercial plant implementation – 10 years

Year of project implementation – 2001

Scale up factor from pilot plant trials – 45x

If required, on a case-by-case basis, Torftech undertakes major projects with larger partners, generally from the process engineering and contracting industry. This is to enhance the financial strength of its credit and completion obligations and increase its implementation capacity during the commercialisation phase.

5.2.2.11 Reference plants

The table below shows a partial listing of relevant reference plants.



Client	Country	Application	Diameter, mm	Date	Status
Krex	Poland	Wood Drying	4500	2018	Commissioning
Biomasa P'ners	Poland	Wood Drying	4500	2018	Commissioning
Dupont	Spain	Carob Flour Drying	1250	2018	Operating
Meral	Poland	Chicken Litter Drying	4500	2017	Operating
B&P Dev.	Poland	Sawdust Drying	4500	2017	Operating
Cedrus	Poland	Biomass Drying	3500	2017	Operating
Banpong	Thailand	Starch Drying	3000	2017	Operating
Miwan	Indonesia	Starch Drying	4500	2017	Operating
FNS	Poland	Sawdust Drying	4500	2016	Operating
Daesang	South Korea	Starch Drying	2000	2016	Operating
Earthpak	New Zealand	Starch Drying	1000	2015	Operating
FerMinOre	South Africa	Coal Dryer	1000	2012	Operating
ABC	Cambodia	Rice Husk Combustion	2500	2011	Operating
MZEC	Poland	Biomass Gasification	1000	2010	Operating
Topell	Netherlands	Torrefaction	3000	2010	Mothballed
Topell	Netherlands	Biomass Dryer	4500	2010	Mothballed
Topell	Netherlands	Biomass Combustor	2500	2010	Mothballed
Sappi	Netherlands	Paper Sludge	4500 (Triple)	2004	Operating
KMC	Denmark	Potato Starch	4500 (Twin)	2003	Operating
Comalco	Australia	Gas Scrubbing	6000	1997	Operating
NZAS	New Zealand	Gas Scrubbing	6000	1995	Operating

Table 5 List of reference plants for TORBED dryers

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BCIA comments

Torftech Group has undertaken extensive pilot-scale testing of the TORBED reactor with Victorian lignite, and additionally has considerable experience in construction of large-scale drying systems. It has established a versatile engineering capability that could readily be applied to the design of a lignite drying plant using existing know-how.

One of the advantages of the TORBED system is that it has a relatively low bed volume and high throughput, so that start-up and shut-down times are relatively short. This would make it easier to integrate the TORBED system with other unit operations.

The drying circuit shown in Figure 9 above lacks a cooling circuit after the dryer. This would perhaps be appropriate if the dried lignite is to be used immediately in another application, e.g. as gasifier feedstock. Otherwise, cooling is required to reduce the risk of spontaneous combustion.

The TORBED system would produce dried lignite with a small particle size, which would make a good feedstock for a gasifier but would probably be unsuitable for binderless briquetting and subsequent transport.

5.3. PNEUMATIC FLASH DRYING

Pneumatic flash drying involves drying of finely milled lignite particles in a co-current stream of superheated steam, combustion gas or syngas. In principle, hot air could also be used, but the high risk of dust explosion makes this impractical. This is a relatively simple, effective and versatile method, and there have been a number of recent efforts to develop this as a commercial process for lignite.

5.3.1 HRL Holdings Pty Ltd

HRL Holdings Pty Ltd developed a gasification process specifically for high moisture lignites, called Integrated Drying Gasification Combined Cycle (IDGCC), which incorporated a pressurised entrained flow dryer with an air blown fluidized bed gasifier, as shown in Figure 10 below.



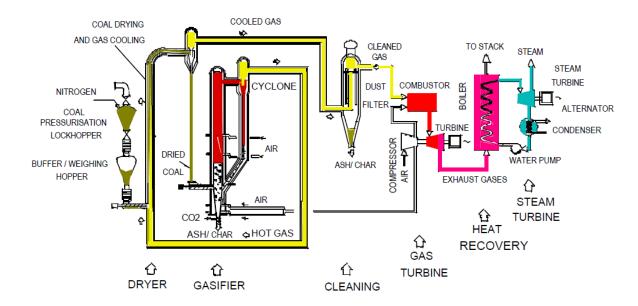


Figure 10: IDGCC process diagram (Johnson 2003)

The novelty of this system was that it used the heat generated during gasification to dry the raw lignite, achieving full integration between the two processes. The feed lignite was pressurised in a lock hopper system and then fed into the dryer where it was entrained in the hot gas leaving the gasifier. The heat in the gas was used to dry the lignite whilst evaporation of water from the lignite cooled the gas, eliminating the need for expensive heat exchangers. The lignite dryer was smaller and cheaper to build than conventional lignite dryers because it operated under pressure (Johnson 2003).

The water vapor from the lignite became part of the product gas, which was used to fuel a gas turbine combined-cycle power generation plant. Although the heating value of the fuel gas was reduced by the additional moisture, it could still be combusted in commercial gas turbines fitted with appropriate burners and gas control equipment. Although the heat of vaporisation was lost, the added moisture expanded in the gas turbine and increased its power output (Johnson 2003).

HRL successfully demonstrated the IDGCC process at 10MW scale at its Coal Gasification Development Facility in Morwell (shown in Figure 11 below) during 1996-97. The facility had a throughput of up to 10 tonnes/hr of raw lignite, at a pressure of 2.5MPa. Full operation of the integrated system, including operation of the pressurised lignite feed system and dryer, and combustion of coal gas in the gas turbine, was achieved over 14 runs. The integrated dryer reportedly operated well, giving the correct level of gas cooling with sufficient drying of the lignite to give stable gasifier operation. These demonstration trials showed that drying could be successfully integrated with gasification, and the feasibility of the IDGCC concept (Johnson 2003).



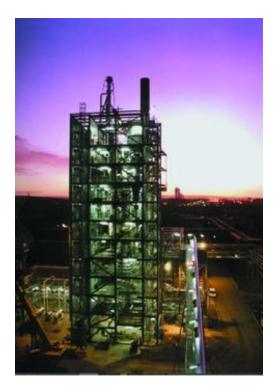


Figure 11: HRL's 10 MW IDGCC demonstration plant at Morwell (Johnson 2003)

HRL had plans to commercialise the IDGCC technology through its Dual Gas subsidiary, but was blocked by a ruling of the Victorian Civil and Administrative Tribunal (VCAT) in 2012. The VCAT ruling meant that Dual Gas could not build its proposed 600MW plant until after an equivalent amount of higher greenhouse-gasemitting electricity generation had been retired. This condition was not met until the closure of the 1,600MW Hazelwood power station in 2017. In the interim, HRL went into receivership and most of the staff associated with the Dual Gas project were lost.

It is likely that the know-how associated with the pressurised entrained flow dryer and lock hopper feeder systems is still available to the current incarnation of HRL, and could be revived on a consulting basis if required.

5.3.2 White Energy Company

White Energy Company is the worldwide licensee of a patented technology, developed in conjunction with CSIRO, known as the binderless coal briquetting (BCB) process. The BCB process involves crushing, drying and briquetting of high moisture lignites, resulting in a reduction of the moisture content and an increase in the calorific value of the lignite.



At the heart of the BCB process (shown in Figure 12 below), is a gas recycle flash dryer. The moist lignite feed is injected into a flash heating riser tube, where it is partially dried in a hot gas stream. The gas stream with entrained lignite particles passes through a cyclone arrangement, where the partially dried lignite is recovered. The separated gas stream is partially recycled through a heater to the gas recycle flash dryer, with excess gas being vented. A key feature of the BCB process is that the lignite is allowed to dry further during feeding into the briquetting apparatus, while any residual moisture is condensed under pressure during briquetting (Meakins et al. 2004).

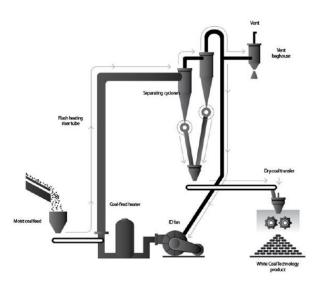


Figure 12: White Energy's BCB process (Godfrey 2010)

White Energy operated a pilot plant of the BCB process at Cessnock, NSW and a process development plant at Collie, WA. Victorian lignite was successfully dried and briquetted in the pilot plant, although no details were made public.

White Energy subsequently entered into a joint venture partnership with PT Bayan Resources Tbk. of Indonesia, known as PT Kaltim Supacoal, which established a 1 million tpa BCB lignite upgrading plant at Bayan's Tabang mine in East Kalimantan (shown in Figure 13 below).

The PT Kaltim Supacoal plant successfully commenced operation in 2009, but was halted in 2011 when the partners fell out over the costs charged by Bayan for the lignite feedstock. White Energy commenced litigation proceedings against Bayan, and in July 2017 the Singapore International Commercial Court found in its favour on substantially all of the matters considered. Bayan subsequently appealed this decision.⁷

⁷ http://member.afraccess.com/media?id=CMN://2A1062364&filename=20180131/WEC_01946192.pdf





Figure 13: PT Kaltim Supacoal plant at Tabang, Indonesia (© White Energy Company)

5.3.3 Ahrko Systems

5.3.3.1 Process description

It is possible to increase the effectiveness of pneumatic flash drying systems by imparting a swirling motion to the flow, which can be done with the use of tangential slots, propeller type swirl generators, honeycomb structures, or inserts of twisted tapes, wires or tubes mounted within the inlet to a pipe section. Development of a swirling motion increases the turbulence of the drying medium, which can improve heat and mass transfer and reduce power consumption (Fokeer et al. 2009). Detailed mathematical modelling has shown that a swirling motion enhances the drying process (Ibrahim et al. 2015), and allows use of a smaller dryer (Bombino Matos et al. 2017).

Ahrko Systems (www. arkhosystems.com) is a Melbourne-based, private unlisted company that has developed a unique Swirling Pipe Coal Dryer technology for use with Victorian lignite. In this system, swirling is induced by combining air flow from two tangential pipes, and drying is affected via variable temperature air-driven vortexes and a specially designed separation cyclone.

Working in collaboration with the University of Melbourne, it has developed a computational fluid dynamics (CFD) model of the drying process, which has been validated at full scale with Yallourn lignite.

The business model of Ahrko Systems is to produce 100 tonne/hr modular drying systems, which it intends to lease rather than sell. Additional lines are simply added in parallel to increase volume.

A conceptual view of a single module is shown in Figure 14 below.





Figure 14: Artist's impression of the modular Ahrko swirling flow coal dryer (© Ahrko Systems)

Ahrko has built a full scale prototype (shown at https://player.vimeo.com/video/144192336), which is currently being fine-tuned for lignite in collaboration with the University of Melbourne. BCIA has supported a portion of this work, which showed that the moisture content of lignite could be reduced by 5% per run using ambient air as the drying medium. Further developmental work will include optimisation of air heating to improve the drying performance.

5.3.3.2 Flow diagram

Not available.

5.3.3.3 Lignite preparation specifications

Experimentation has shown that drying performance is improved when the product is smaller and uniform in size i.e. around 1mm minus. As such, AHRKO have also developed a pre-crushing / milling system that can be integrated with the AHRKO drying system.

5.3.3.4 Mass balance

Not available

5.3.3.5 Plant footprint @ 1.0 million tpa dried lignite

The "engine room" of a typical 100t/hr system can be accommodated within a 40-foot container. Overall footprint including discharge pipe and cyclone is around 5m W x 35m L x 5m H. This increases slightly when a crusher is added.



A drying plant producing 1 million tpa of dried Victorian lignite would process \sim 300 tonnes/hr, thus requiring 3 x 100t/hr modules.

The combined area of 3 modules is $15m \times 35m = 525m^2 = 0.05ha$

5.3.3.6 Services required

Three phase 400V electrical, mains or LPG gas supply and water for cooling (when product is heated).

5.3.3.7 CO₂ emissions per tonne of finished product

Not specified.

5.3.3.8 Is the technology capable of capturing CO₂ emissions?

No

5.3.3.9 TRL estimate

The drying process is being refined using commercial-scale equipment.

Satisfactory drying of lignite to 12-16% moisture content has not yet been demonstrated at pilot scale.

TRL = 4.

5.3.3.10 Commercialization pathway

The business model of Ahrko Systems is to produce 100 tonne/hr modular drying systems, which it intends to lease rather than sell.

5.3.3.11 Reference plants

Not available

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BCIA comments

Development of the Ahrko drying process originated in the observation that drying often occurs in pneumatic solids transport systems. Ahrko has taken the approach of working with the University of Melbourne to develop mathematical model of the process, for use as a design tool. Using ambient air as the drying medium, the process has been able to reduce the moisture content of Victorian lignite by about 5%. In order to achieve a sufficient degree of drying, it will be necessary to provide extra energy for drying, in which case the process will evolve toward a flash drying system. If the extra energy is provided from a waste heat source, then this could be a cost-effective drying system.

The Ahrko system would produce dried lignite with a small particle size, which would make a good feedstock for a gasifier but would probably be unsuitable for binderless briquetting and subsequent transport.

5.4. COUNTERCURRENT FLASH DRYING

This entrained flow process involves moist lignite being dried as it falls under gravity through a rising stream of hot drying gas. In the usual co-current flash drying scenario, the lignite particles are enveloped in a progressively denser cloud of water vapor as drying proceeds, creating a resistance to further evaporation. In contrast, countercurrent involves the driest particles contacting the hottest and driest gas stream, producing a greater driving force for heat and mass transfer. This is a recent development for drying of lignite, developed by the Korea Institute for Energy Research (KIER).

5.4.1 Korea Institute for Energy Research

5.4.1.1 Process description

The Counter flOw Multi Baffle (COMB) drying technology consists of a vertical series of inclined baffle plates which increase the residence time and mixing of the lignite as it descends. Hot combustion gas is used as the heating medium. Depending on the temperature of the gas, COMB can be used for either drying lignite or torrefaction of biomass (Lee 2017).

During COMB operation, the solid and gas flow counter-currently such that the contact efficiency is high while the temperature gradient, the driving force for drying, is maximised over the length of the column. This configuration means that the incoming moist solids are first heated with the lowest-temperature gas exiting the system, while the driest solids (containing multilayer moisture) are heated against the highest temperature gas. A typical temperature gradient in the COMB dryer is shown in Figure 15 below.



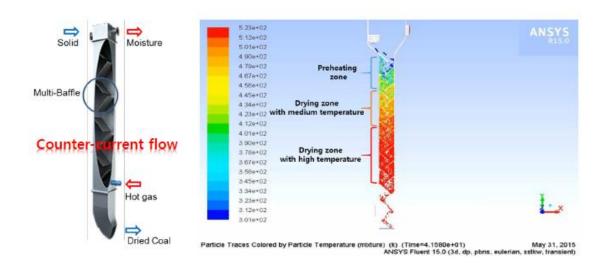


Figure 15: Schematic view of COMB column and typical temperature gradient of particles

Depending upon the nature of the solids to be dried, the shape and arrangement of the inner baffles can be adjusted to maximise contact efficiency, as shown in Figure 16 below. In addition, depending on the density of the solids, the residence time of the solids can range between three to 10 minutes. The COMB drying technology is both simple and flexible in operation.

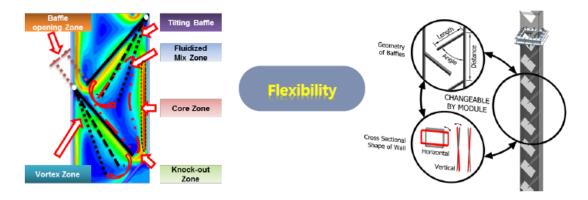


Figure 16: Examples of baffle structures that can be adjusted to the density and shape of particles

KIER has established a 1 tonne/day pilot plant COMB dryer at the Dangjin power plant owned by the Korea East-West Power Company. It is operated by Samyang Eco-energy Co., with research support provided by KIER. The COMB drying plant uses hot flue gas for drying, to mimic the low temperature flue gas widely available as waste heat in power stations.



The COMB drying technology has been successfully tested at pilot scale with a range of different lignites. In each case, the inlet gas temperature was 210°C and the outlet was 135°C, and the lignite was milled to 3–6mm size. Under these conditions, a Chinese Inner Mongolia lignite was dried from 36.0% to 11.2% moisture, an Indonesian sub-bituminous coal was dried from 25.0% to 7.2% moisture, and a Victorian lignite was dried from 62.2% to 11.0% moisture. The residence times in the dryer ranged from 90 to 245 seconds. The dried coals were found to be stable for two weeks without any increase in moisture content (less than 3%) or spontaneous combustion.

5.4.1.2 Flow diagram

A schematic of the COMB drying process is shown in Figure 17 below.

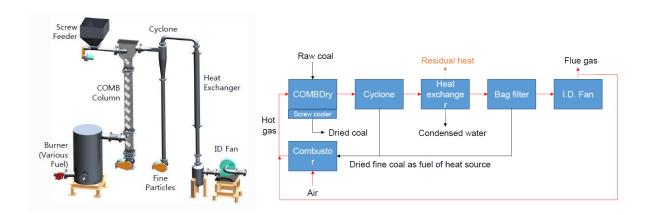


Figure 17: Schematic of COMB drying process (© KIER)

5.4.1.3 Lignite preparation specifications

A particle size of 3–6mm is suitable for the 50kg/hr COMB pilot plant.

5.4.1.4 Mass balance

It is assumed that the COMB drying system will be modularised into units capable of drying 100 tonnes/day of Victorian lignite containing 62% moisture. A portion of the dried coal is used as fuel to produce the flue gas used for drying. Each module produces 34 tonnes/day of coal containing 13.6% moisture. The mass balance for a single module is shown in Figure 18 below.

In order to produce one million tpa of dried coal (assuming 24/7 operation for 310 days/year), 95 of these modules would be required.



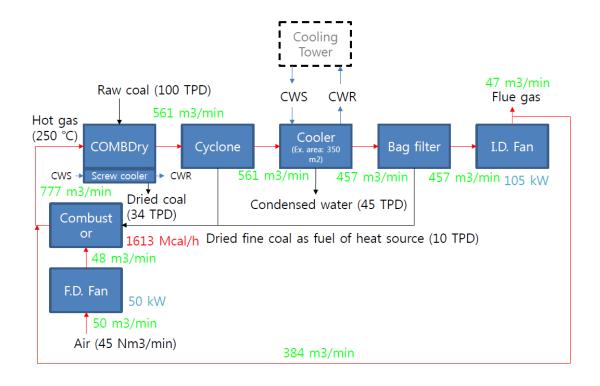


Figure 18: Mass balance for drying Victorian lignite using COMB technology

Feed = 100t/d feed at 62% moisture: solids = 38t/d, water = 62t/d

Dried coal = 44tpd at 13.6% moisture: solids = 38t/d, water = 6t/d

Water evaporated = 56t/d

Energy required to dry coal:

Combustion of coal: 1613MCal/hr = 1.875MW

Electricity = 160kW = 0.16MW

Total energy = 2.035MW

Energy intensity = $2.035MW \times 24h/d / 44t/d dried coal = 1.11MWh/t = 4.00GJ/t coal$

 $= 2.035MW \times 24h/d / 56t/d H₂O = 0.872MWh/t H₂O = 3.14GJ/t H₂O$

5.4.1.5 Plant footprint @ 1.0 million tpa dried lignite

The COMB unit is modularised to process 100ton/day of Victorian lignite. The demand for higher capacity is satisfied by constructing additional units in parallel.



Each 100 tonne/day module is $23.7 \text{m x } 15.8 \text{m} = 374.46 \text{m}^2$

95 modules would require 35,573m² = 3.6ha

5.4.1.6 Services required

For each 100tonne/day module:

Cooling water: 50m³/hr

Electricity: 200kW

Ash disposal: 0.2t/day

Condensed waste water: 45t/day

For 95 modules:

Cooling water: 4,750m³/hr

Electricity: 19MW

Ash disposal: 19t/day

Condensed waste water: 4,275t/day

5.4.1.7 CO₂ emissions per tonne of finished product

Based on mass balance for one module:

a) Combustion of dried coal at 10t/day

Heat value of fuel = 18.41MJ/kg (NAR)

Energy produced = $18.41MJ/kg \times 10,000kg/d = 184,100MJ/day$

Carbon emission factor for lignite = 27.6 t C/TJ (source: IPCC8) = 1.012x10⁻⁴ t CO₂/MJ

 CO_2 emission = 184,100 MJ/day x 1.012x10⁻⁴ t CO_2 /MJ = 18.63 t CO_2 /day

b) Electricity generation

Assume CO₂ emissions from electricity generation are accounted for at source.

c) Specific CO₂ production rate

 CO_2 emission rate = 18.63 t CO_2 /day / 44t/day product = 0.423 t CO_2 /t product

 $^{^{8}\} https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_1_CO2_Stationary_Combustion.pdf$



5.4.1.8 Is the technology capable of capturing CO₂ emissions?

Yes. Typical CO₂ capture technologies (such as amine scrubber) could be utilized.

5.4.1.9 TRL estimate

TRL 4-5

5.4.1.10 Commercialization pathway

Current status

- ▶ 2018: 1ton/day BSU operation: drying of coal with high water content, drying and torrefaction of biomass
- ▶ 2019: Construction and operation of 5ton/day pilot plant in Bandar Lampung, Indonesia (funding is secured)

Demonstration plant for commercialization

- The unit capacity of a commercial plant will be ~100ton/day, which will be modularized to cope with commercial scale capacity via its parallel installation
- In order to apply COMB to Victoria lignite in a stable manner with minimized risk factors for scale-up (~100ton/day commercial plant), 10–20ton/day demonstration test is required

5.4.1.11 Reference plants

- ▶ 1ton/day COMB system in Samyang Eco-energy Co. (Korea, 2015~present)
- 1ton/day COMB system in Harbin Institute of Technology (China, 2015~2016)
- ▶ 1ton/day COMB system in Lampung university (Indonesia, 2017~present)
- ▶ 5ton/day COMB system in Lampung University (Indonesia, under construction)

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BCIA COMMENTS

The COMB drying process is still at an early stage of development. Unlike other drying systems, the countercurrent nature of the COMB systems means that the driest lignite comes into contact with the hottest gas stream, creating a high risk of spontaneous combustion. Very close control of the oxygen content in the gas stream would be necessary to mitigate this risk.

It is likely that the COMB process would produce a dried lignite suitable for binderless briquetting and subsequent transport, a more extensive pilot plant program is required to demonstrate the performance and safety of the system.

5.5. FLUIDIZED BED DRYING

5.5.1 Principle of fluidized bed drying

Fluidized bed dryers utilize the principle that a bed of solids can take on fluid-like properties when it is suspended in an upward gas stream flowing at a suitable velocity. Fluidization of solids allows the entire particulate surface area to be exposed, increasing the drying efficiency relative to a packed bed. The general concept of fluidized bed drying is illustrated in Figure 19 below.

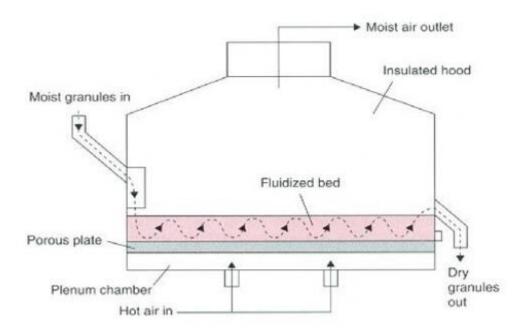


Figure 19: General concept of fluidized bed drying (Choudhary 2015)



The principal advantages of fluidized bed drying in comparison with other drying methods are (Hovmand 1995):

- The even flow of fluidized particles permits continuous, automatically controlled, large scale operation with easy handling of feed and product.
- The rapid exchange of heat and mass between gas and solid particles.
- High heat transfer rates between the fluidized bed and heating surfaces.
- The rapid mixing of solids leads to nearly isothermal conditions, providing uniform heating and more reliable process control.

Some possible disadvantages are:

- Optimally suited only for fine-grained materials to around 4mm.
- Sensitivity to abrupt changes in the solid material particle sizes, moisture content and throughput rate or to cut-out of the drying air.
- Relatively high electrical energy requirement.
- > Significant effort and expense involved in commissioning and parameter optimisation.

There are three main types of fluidized bed dryers, classified by their flow behavior (Hovmand 1995):

- Stationary or bubbling fluidized bed, where the gas flow is at relatively low velocity and fluidization of the solids is relatively stationary, with some fine particles being entrained.
- Circulating fluidized beds (CFB), where the gas flows at a higher velocity, entraining larger particles which are recirculated via an external loop back into the reactor bed. Depending on the process, the particles may be classified by a cyclone separator and separated from or returned to the bed, based upon particle size
- Vibratory fluidized beds are similar to stationary beds, but use a mechanical vibration to fluidise the solids at lower air flow. These are used for solids that are difficult to dry because of (a) wide particle size distribution; (b) low particle strength; (c) stickiness of particles; or (d) pasty properties of wet feed.

Fluidized beds have been utilized successfully for drying lignite, lignite and sub-bituminous coal, using either combustion gas or superheated steam as the fluidising and drying medium. Examples of each of these are discussed below.

5.5.2 Combustion gas or air as the drying medium

Fluidized bed drying became widely used in the United States during the 1960s. Early fluidized bed dryers used hot flue gas, generated by burning lignite fines, as the drying medium. The hot flue gas, having a low oxygen content, contacted a bed of lignite in a dryer at a high velocity causing the lignite to flow like a fluid.



The heat in the gas evaporated water from the lignite and elutriated dust from the dryer. Evaporation of the water from the surface of the lignite prevented the temperature of the lignite from rising, but the temperature rose rapidly once the lignite had dried. Upsets in the system, such as a temporary interruption in the flow of wet lignite into the dryer, resulted in hot gas with a higher than normal oxygen content contacting the lignite, often resulting in fires and explosions. Consequently, special safety equipment, such as sprinkler systems, blowout doors and automatic fail-safe shutdown devices, were necessary (Merriam 1993).

5.5.2.1 Great River Energy

Great River Energy owns and operates Coal Creek Station, a 2 x 600MW mine mouth lignite-fired subcritical power station near Underwood, North Dakota. During the 1990s, the company's engineering staff investigated options for improving the efficiency of the power station and reducing emissions. In 1997 a decision was made to utilize waste heat to partially dry the lignite feed using fluidized bed drying.

5.5.2.1.1 Process description

The DryFining[™] fuel enhancement process uses waste heat and gravitational separation to dry and refine low rank coals to improve plant efficiency and reduce emissions of sulphur, mercury, nitrogen oxides and carbon dioxide. The DryFining system comprises a two-stage fluidized bed drying process, as shown in Figure 20 below.

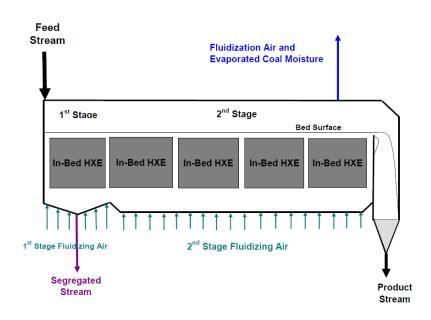


Figure 20: Schematic of DryFining process (© Great River Energy)



Fluidization and heating of coal and removal of coal moisture is accomplished using hot fluidization air. In the first stage, higher-density rocks and mineral impurities are segregated at the bottom of the dryer and are discharged. The discovery that impurity-rich dense materials could be separated out in the fluidized bed dryer resulted in a series of patents (Bullinger et al. 2013a;b;c). Separation of pyrite at this stage removes about 30% of the sulphur and mercury from the coal. The lower density beneficiated coal then flows to the second stage, where it is dried. In-bed heat exchangers are used to supply additional heat to the dryer (Sarunac et al. 2007).

Development of the DryFining process was executed in three stages (Bullinger et al. 2010):

- (1) A feasibility stage, in which a 1.8 tonnes/hr fluidized bed pilot plant was installed at Coal Creek in 2002. Testing confirmed that the dryer performed satisfactorily. It was also observed that the fluid bed segregated the solids on the basis of density, leading to the separating of heavier ash components containing sulphur and mercury.
- (2) Phase 1, in which a nominal 100 tonnes/hr demonstration fluidized bed was installed in 2006.
- (3) Phase 2, in which 8 commercial-scale fluidized bed modules of 115 tonnes/hr capacity were installed in late 2009. Design throughput of the full-scale plant is 6.8 million tonnes/year.

Using this system, the moisture content of the feed lignite was reduced from 38.5% to 29%, while the heat content was increased from 6,200 to 6,850BTU/lb. This has reduced the fuel input to the power station by 9.5wt% (purchased fuel savings) and into the boiler by about 14wt% (efficiency improvement plus water removal), and increased the overall plant efficiency by 3.5%. The reduction of impurities in the lignite has reduced wear in the mills and conveying lines, and has reduced stack emissions: SO_2 and mercury by more than 40% each, NOx by more than 20%, and CO_2 by more than 4% (Brehm 2010).

The eight DryFining modules have been operating continuously since December of 2009 and, as at the end of 2017, had successfully dried and refined more than 50 million tons of wet coal. The operating cost of the dryers is US\$0.38/ton wet lignite, which has resulted in a net saving of more than US\$18 million per year in direct operating and maintenance costs.

In addition to producing beneficiated lignite for power generation at Coal Creek Station, the eight DryFining modules also produce additional 7,100BTU/lb fuel for use at Spiritwood Station, east of Jamestown, North Dakota. The dried lignite is transported over 240km in enclosed rail cars to prevent moisture reabsorption. At full capacity, Spiritwood Station uses approximately 610,000tons of DryFine coal annually.

The DryFining process was originally developed as a low-temperature drying process to prevent oxidation of dried lignite. Advanced designs of the dryer have been developed, operating at higher temperature to reduce size (and cost) of drying equipment. To prevent oxidation of lignite, the high-temperature lignite dryer can be fluidized by an inert fluid (nitrogen from an Air Separation Unit (ASU), or low pressure CO₂ stream). This is especially important for reactive lignites which are prone to auto-ignition. A number of lignite drying



configurations have been developed to accommodate different configurations of the power plant equipment, and different sources of waste heat (Sarunac et al. 2009).

5.5.2.1.2 Flow diagram

The DryFining fuel enhancement process is custom designed for each application, therefore each mass and energy balance and process flow diagram is proprietary to each application.

5.5.2.1.3 Lignite preparation specifications

Raw lignite is crushed and screened to 6mm or less before it is processed through the fluidized bed dryer.

5.5.2.1.4 Mass balance

Not supplied. In each application, the design will depend on the quantity and quality of available waste heat.

5.5.2.1.5 Plant footprint @ 1.0 million tpa dried lignite

Each DryFining module is expected to be able to dry about 30 tonnes/hour of lignite from 60% to 15% moisture, and will require an area approximately 6m wide x 18m long.

A drying plant producing 1 million tonnes/yr of dried Victorian lignite would process ~300 tonnes/hr, thus requiring 10 DryFining modules.

The combined plant footprint would be approximately 324m², or 0.03ha.

5.5.2.1.6 Services required

The DryFining system requires fluidizing air fan(s), pumps for heat exchangers, motor for crusher and compressed air for air jig and dust collectors. Less than 1% of fuel mass is ultimately rejected as solid waste.

Estimate 7KWh/short ton of raw coal input to operate DryFining.

5.5.2.1.7 CO₂ emissions per tonne of finished product

N/A – The DryFining process does not produce any CO_2 .



5.5.2.1.8 Is the technology capable of capturing CO₂ emissions?

No, but efficiency improvements from dried coal yield a commensurate reduction in fuel consumption and CO_2 emissions (estimated at 3.5% improvement in Higher Heat Value)

5.5.2.1.9 TRI estimate

Currently TRL = 8 for processing Coal Creek lignite (38% moisture).

No test work has been undertaken with Victorian lignite, so TRL = 5 at best.

5.5.2.1.10 Commercialization pathway

The DryFining process is fully commercial at Coal Creek Station. Great River Energy is now licensing the use of its DryFining technology for other coal beneficiation applications.

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BCIA COMMENTS

The performance of the DryFining system with Victorian lignite is currently unknown. The mineral content of Victorian lignite is predominantly in the form of ionic species associated with charged groups on the coal surface, with minimal sand, pyrite and clay, so little beneficiation would be expected. The process may be expected to generate a large amount of dust, so a good dust collection system would be necessary, along with a useful application for the dust recovered.

Since the DryFining system is designed to be heated using waste heat from a nearby process, the efficacy of the drying process will be dependent on the quality of the waste heat available. A lower temperature will have a lower drying efficiency and will reduce the capacity of the dryer.

An extensive test program would be required to determine the performance characteristics of DryFining with lignite before a system could be specified with confidence.



5.5.2.2 Nippon Steel & Sumikin Engineering Co., Ltd.

Nippon Steel & Sumikin Engineering Co., Ltd. (NSENGI) has extensive expertise in coal drying technologies, through Nippon Steel's development of drying processes for coking coal since the 1980s. Nippon Steel has developed coal moisture control (CMC) systems for coke production using three different drying technologies: steam tube dryers, coal in tube dryers and fluidized bed dryers.

In a NEDO-funded project in partnership with Kyushu Electric Power Co., Inc. and Tokyo Electric Power Company Holdings, Inc., NSENGI is using its coal drying expertise to develop technology for upgrading low rank coals for use as a fuel for electricity generation in Japan (Igarashi et al. 2018). The upgrading process involves the development of novel coal drying and carbonisation technologies, leading to production of low-cost, high energy briquettes from Victorian lignite for export to Japan. A combination of drying, pyrolysis, and briquetting processes is used to modify the lignite to improve the calorific value and combustion performance, and reduce the propensity for spontaneous combustion (Sekimoto et al. 2018).

5.5.2.2.1 Process description

The novel drying technology developed by NSENGI is an adaptation of its fluidized bed coal dryer for use with high-moisture lignite. Incorporation of indirect heating steam tubes within the fluidized bed has effectively doubled the evaporative capacity of the dryer, halving the bed area that would normally be required. This innovation also allows the use of lower-temperature fluidising gas, thus reducing the risk of spontaneous combustion (Sekimoto et al. 2018).

During 2015-2017, NSENGI developed the primary drying process from bench scale through to operation of a 700 kg/hr pilot plant. Pilot-scale drying of Victorian brown coal was demonstrated at the design capacity was achieved, using a drying temperature of under 60°C to reduce the risk of spontaneous combustion (Sekimoto et al. 2018).

Combustion tests of the reformed coal were conducted during 2016-2017. It was shown that reformed brown coal containing 16–33% volatile matter produces less NOx under ultra-supercritical combustion conditions than bituminous coal. Testing of the reformed coal for gasification will be undertaken in 2018 (Igarashi et al. 2018).



5.5.2.2.2 Flow diagram

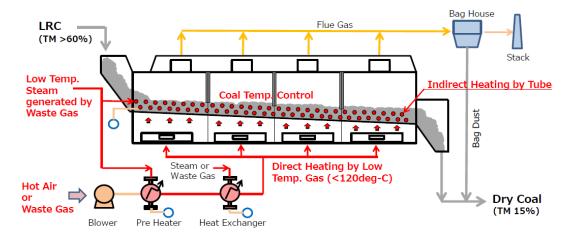


Figure 21: Low temperature fluidized bed dryer (© NSENGI)

5.5.2.2.3 Lignite preparation specifications

The lignite should be crushed prior to feeding into dryer, to a maximum diameter of 10mm (average diameter 2mm).

5.5.2.2.4 Mass balance

Not available.

5.5.2.2.5 Plant footprint @ 1 million tpa dried lignite

Dryer: $7.3 \text{m x } 26 \text{m x } 4 \text{ sets} = 759 \text{m}^2$

Baghouse: $19.1 \text{m x } 9.1 \text{m x } 4 \text{sets} = 695 \text{m}^2$

Total area = 1,454m² = 0.145ha

Other facilities depend on plant layout arrangement



5.5.2.2.6 Services required

The following numbers are for one plant of 250,000tpa finished product.

Gas (hot air) * : 334,100 Nm³/hr @120°C

* hot air can be heated by utilising low-temperature exhaust gas

Steam for drying: 25.3t/hr @125°C

Steam for tracing: 570kg/hr @0.5MPa

Industrial water: 7.2m³/hr @0.2MPa

Nitrogen: 1,110Nm³/hr@ 0.5MPa

Electrical power: 1,800kW

Multiply by four units

5.5.2.2.7 CO₂ emissions per tonne of finished product

None. It is assumed that hot waste gas is available for heating the fluidising air and to generate the steam used in the drying process. CO_2 emissions associated with the hot waste gas and electricity supply are attributed to those service providers.

5.5.2.2.8 Is the technology capable of capturing CO₂ emissions?

Not applicable.

5.5.2.2.9 TRL estimate

The TRL of fluidized bed drying for coke oven coal moisture control systems is \sim 9.

Proof of concept of the FB dryer incorporating indirect heating steam tubes for drying Victorian lignite has been shown in a 700 kg/hr process development plant, but only to a moisture content of 30%. More work is required to demonstrate that the dryer can produce 15% moisture lignite reliably at a significant scale, so TRL = 5.



5.5.2.2.10 Commercialization pathway

NSENGI has supplied a fluidized bed coal dryer without steam tube at Maanshan Iron & Steel Co., Ltd., with a drying capacity of about 1 million tpa bituminous coal. The new fluidized bed dryer with steam tube is an improvement on this design, with increased efficiency as demonstrated by repeated 700 kg/hr test plant.

NSENGI is now ready to supply commercial drying plant for use with Victorian lignite.

5.5.2.2.11 Reference plants

Fluidized bed coal drying reference plants, without the addition of indirect heating steam tubes:

- 1) Coal throughput 91 dry-t/hr, water evaporation 11.9t/hr, Japan
- 2) Coal throughput 167 dry-t/hr, water evaporation 7.4t/hr, China

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BCIA COMMENTS

NSENGI is a very capable engineering company with extensive experience in drying bituminous coals. There is no doubt that it has the capability of delivering a commercial scale fluid bed dryer for Victorian lignite, given sufficient incentive.

To date, the fluidized bed dryer has only been used to dry Victorian lignite to a moisture content of 30%, as part of a research program aimed at producing briquettes from lignite char. Significantly more pilot plant testing would be required to establish the conditions needed to run the dryer as a stand-alone process producing lignite at 15% moisture. This, in turn would depend on the quality of the heat source available.

The process may be expected to generate a large amount of dust, so a good dust collection system would be necessary, along with a useful application for the dust recovered. It is likely that this technology would be a suitable front end to a dry entrained gasifier.



5.5.2.3 Clean Coal Technologies, Inc.

Clean Coal Technologies, Inc. (CCTI), based in New York, is an emerging coal upgrading company that is developing a drying process for lignite and sub-bituminous coal, known as Pristine-MTM. The Pristine-MTM process was developed as an economical way to de-water high moisture (30%–60%) coals.

Pristine-M™ is a continuous process that is comprised of three separate stages. The first stage involves drying using a Carrier-type fluidized bed dryer. Drying takes place at 120°C, with the final moisture content being a function of residence time, bed depth and temperature.

In the second stage, a small portion of the feed coal (typically less than 7%) is devolatized by heating to 800°C, producing gases that are used for process heat as well as to stabilize the dry coal. Process parameters are optimized so as to produce only enough volatile gases for these purposes. Excess devolatized coal is blended back with the dry and stabilized coal at the end of the process.

In the third stage of the Pristine-M[™] process, the volatile matter is absorbed into the pores of the dried coal. This renders the coal impermeable, structural integrity is maintained, and moisture readsorption is inhibited. The Pristine[™] coal does not have a tendency to break in transport and has a reduced propensity for spontaneous combustion.

Pristine-MTM is designed to remove fines at various stages of the process, making them available for combustion (process heat), if desired. The few fines that enter the third phase of the process tend to agglomerate and harden on the surface of the dry and stabilized coal.

Pristine-M™ is a modular process. It is based on a commercial module designed to feed through 30 tons per hour that, handling 50% moisture coal, would produce about 160,000 tons of dry coal per year. A one million ton per year plant would be comprised of 6 modules. The process is continuous with a residence time of about 15 minutes.

A pilot plant of the Pristine-MTM process has been operated in batch mode at a coal fired power plant in Alabama. A continuous version of the process is being commissioned in Wyoming, where it will be operated 24/7 on Powder River Basin coal (27% moisture) (Horner 2018). CCTI anticipates that its Pristine-MTM technology will be commercial in Q4 2018⁹.

⁹ http://www.cleancoaltechnologiesinc.com/about-us/overview



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5.5.3 Superheated steam as a drying medium

5.5.3.1 Principle of superheated steam drying

The goal in all lignite drying processes is to produce the dried product at lowest cost for the required purpose. To achieve this, energy efficiency is a key consideration. A disadvantage of simple evaporative drying processes is that there is no opportunity to recover the energy used to evaporate the moisture in the lignite, which represents about 20–25% of the energy content of the lignite.

This problem can be overcome by using superheated steam as the drying medium instead of hot air or combustion gas. When steam is heated to temperatures above its saturation point, making it supersaturated, it becomes a very useful drying medium. The basic principle of superheated steam drying is illustrated in Figure 22 below. The superheated steam is continuously recirculated, minimising the amount of drying medium needed. The moisture evaporated from the lignite becomes part of the superheated steam, which can be diverted to a heat exchanger where its latent heat can be recovered and reused. The energy lost in the main steam circuit through drying is topped up with a heater to maintain the superheated steam temperature. Any volatile organic carbons driven off from the lignite can be condensed along with the purged steam, eliminating atmospheric emissions, however this would then require the installation of a water clean-up system.



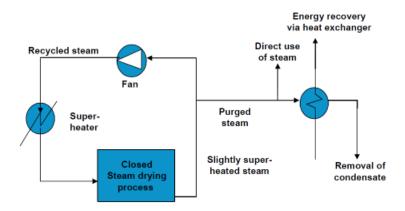


Figure 22: Principle of superheated steam drying (Godfrey 2010)

Superheated steam drying has some significant advantages over air drying. Since the specific heat capacity of steam is more than twice that of air, it can transfer more than twice the amount of heat for the same mass flow. Also, the viscosity of steam is about half that of air at the same temperature, enhancing its ability to penetrate into moist lignite particles. As a result, the drying rates with superheated steam are significantly higher. In addition, superheated steam drying has a lower net energy consumption, provides an inert, non-oxidising environment and does not create airborne emissions (Sehrawat et al. 2016).

In principle, any drying technology can be adapted for operation using superheated steam. To date, there have been two large-scale examples of superheated steam drying of lignite in Victoria. One was Keith Engineering's superheated steam rotary drum dryer system, discussed in Section 5.1.1 above. The other was a steam-fluidized bed drying system developed by Lurgi and Rheinbraun, which was an ancestor of the WTA drying system currently offered by RWE.

5.5.3.2 Lurgi GmbH.

The concept of steam-fluidized bed drying was first developed by Professor Owen Potter at Monash University in the 1970s. This work attracted German interest, leading to construction of pilot plants at Zeithain (1 tonne/hr) in 1981 and Borna (10 tonnes/hr) in 1986. Monash University subsequently licensed the technology to Lurgi GmbH., which designed two commercial demonstration steam-fluidized bed drying plants, each with an output of 20 tonnes/hr (150,000 tonnes/year) of dried lignite. The first (shown in Figure 23 below) was built by Lurgi at Loy Yang power station in Victoria, in association with Australian Char and with the cooperation of the State Electricity Commission of Victoria (Potter 1992). The second was built in association with Rheinbraun AG (now RWE Power AG) at the Wachtberg briquette factory near Frechen in Germany. The principal difference was that the Loy Yang plant was supplied with live steam from the Loy Yang A power station, while the Wachtberg plant included energy recovery with vapor recompression. In the



latter case, the only external energy supply was from electric motors for the steam compression (Allardice et al. 2004).



Figure 23: Steam fluidized bed drying plant, Loy Yang (Allardice 2015)

The steam-fluidized bed dryer at Loy Yang had an operating temperature of 107°C and produced dried lignite containing 12-15% moisture (Schmalfeld & McKensie 1993). Water evaporated from the lignite was used as the fluidising medium, with additional heat provided by high pressure steam flowing through pipework within the bed of lignite (Nikolopoulos et al. 2015). The wet lignite was initially processed in a size range of 1mm to 6mm. This technology became known as a coarse grained drying. The dry lignite was cooled to under 45°C then ground to dust in vibration mills, with 75% < 90µm. The dust was stored in an intermediate facility with a capacity of more than 2000 tonnes before it was pneumatically transported through a pipe to the nearby Loy Yang B power station for use as a start-up and auxiliary fuel (Schmalfield & Twigger 1996). The drying plant operated successfully from 1992 to 2003, but was subsequently moth-balled when Loy Yang B was converted to natural gas as an auxiliary fuel (Allardice et al. 2004).

5.5.3.3 RWE Power AG

5.5.3.3.1 Process description

The steam-fluidized bed dryer installed at the Wachtberg briquette factory near Frechen was based on a technology developed by Rheinbraun AG, known as Wirbelschicht Trocknungmitinterner Abwarmenutzung (WTA), or 'fluidized bed drying with internal heat utilization'.

WTA technology utilizes a stationary fluidized bed dryer (as shown in Figure 24 below), where milled raw lignite is continuously fed onto the top of the fluidized bed, and dry lignite product is continuously drawn



from the bottom of the fluidized bed. Heating is provided by a set of tube bundles immersed on the fluidized bed, containing slightly superheated low-pressure heating steam (3–4 bar abs) from a variety of steam sources. During drying, the raw lignite equilibrates with a slightly superheated pure steam atmosphere at approximately ambient pressure. Under these conditions, the residual equilibrium moisture in the coal is only a function of the drying temperature. For typical lignites and operating conditions, residual moistures of 8-15% can be achieved. The WTA process is inherently safe, because the hot, dry lignite is dried in an oxygen-free environment (smouldering limit for hot lignite is 2% oxygen). The dry lignite after removal from the dryer is rapidly brought down to a sufficiently low temperature for safe handling in air.

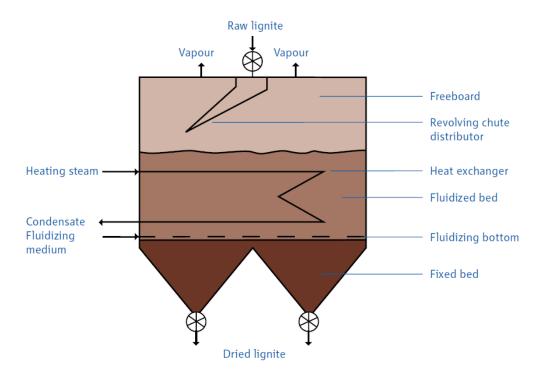


Figure 24: Schematic of the WTA fluidized bed dryer (© RWE)

The volume of the fluidized bed is chosen such that residence time of the lignite in the dryer exceeds the time required to reach equilibrium. The equilibration time, and with it the dryer size, depends strongly on the grain size of the raw coal. The WTA plant normally comes with one or two double rotor hammer mills (in series), producing either raw lignite of 0–6mm (coarse-grain) or 0–2mm (fine grain). The fine-grained dryer system will normally be more economical, since the capex for the second coal mill is more than compensated by the smaller dryer size. For a given evaporation rate, a fine-grain dryer will be about 50% the size of a coarse grain dryer in all linear dimensions, i.e. 12.5% of the volume of the corresponding coarse-grain dryer.



The WTA-1 demonstration plant at Wachtberg operated reliably for 20,000 hours between 1993 and 1999. It had an evaporative capacity of 25 tonnes/hr, and was fitted with a novel vapor recompression system, and could process 53 tonnes/hr of raw lignite with a grain size of 0–6mm (Klutz et al. 2010).

Based on this experience, RWE Power AG (formerly Rheinbraun AG) developed an improved process, known as the fine-grained WTA process, using raw lignite with a grain size of 0–2mm. This provided better heat transfer and allowed lower fluidization velocities, with greater overall efficiency. RWE built a test plant, called the WTA-2 plant, directly next to the WTA-1 plant in Frechen in 2001. The capacity of this plant was increased progressively to a raw lignite throughput of 28.7 tonnes/hr and a water evaporation capacity of 13.1 tonnes/hr (Klutz et al. 2010). In late 2014, the WTA-2 plant was called out of "hot conservation" into commercial service at short notice to provide additional drying capacity for about three months.

Based on that experience, RWE Power AG decided to refurbish the WTA-1 plant (it had been cannibalized a bit to build the WTA-2 plant on a shoe string budget) and reactivate it to expand drying capacity in Frechen. The WTA-1 plant has been in commercial operation since 2015.

Based on the experience from operating the WTA-1 and WTA-2 plants, RWE developed a commercial-scale WTA plant, which was installed at the Niederaußem power station between 2006 and 2008. The plant (shown in Figure 25 below) was designed as a production plant with industrial-type process control system and safety features. It has a design capacity of 210 tonnes/hr of raw lignite throughput, 110 tonnes/hr dry lignite output and an evaporation capacity of 100 tonnes/hr (Klutz et al. 2010). It was operating smoothly by January 2011 and remained in trial operation until the end of 2014. It has been operating commercially since the beginning of 2015, providing dried lignite for approximately 30% of the furnace thermal rating.¹⁰



Figure 25: WTA fine-grain drying plant at Niederaußem power station (Klutz et al. 2011)

¹⁰ http://www.rwe.com/web/cms/en/88182/rwe/innovation/power-generation/fossil-fired-power-plants/fluidized-bed-drying/



5.5.3.3.2 Flow diagram

As shown in Figure 26 below, the WTA system offers several options for recovering the heat of evaporation. The heat of evaporation can be utilized by either (a) by recompressing the vapor to about 0.35MPa-a and letting it condense inside the heat exchanger tubes of the WTA dryer, thereby recycling the heat of evaporation back into the process, or (b) heating water in a vapor condenser to ~95°C (e.g. the first stage of a power plant feedwater heater line). The choice of heat recovery system, if any, depends on the capex and the availability of suitable heat sinks outside the WTA process.

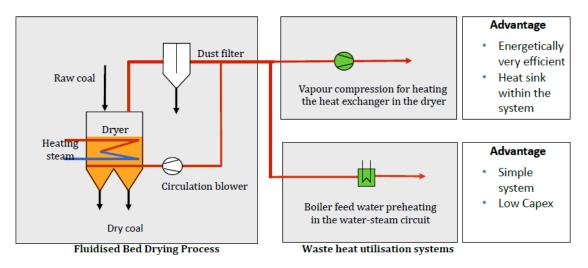


Figure 26: Waste heat utilization options with WTA technology (© RWE)

Figure 27 below shows a process flowsheet for a WTA system using vapor recompression, which would be suitable for use with a gasifier or lignite dust plant.



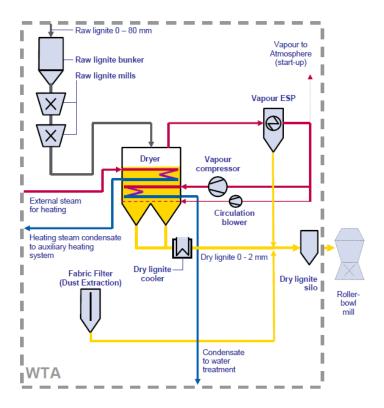


Figure 27: WTA using Vapor Recompression (© RWE)

Due to the necessity to synchronize the coal flow throughout the drying process, WTA plants are designed by RWE with all necessary internal lignite coolers, trace steam heating, de-dusting systems, internal dry lignite buffer silo, dry lignite remix system, etc. and the system battery limits are from the raw coal intake to the dry lignite outlet to the next downstream process.

Lignite does not come into contact with the heating steam, hence the heating steam condensate remains clean and can be recycled to the heating steam source.

Vapor condensate will have very low dissolved solids (nearly "distilled water") and some dissolved short-chained organic acids from the entrained coal dust after the dust filter, and will be moderately acidic (pH ~4). Biological cleaning (algae in a carbon bed) is very effective in reducing the COD in the vapor condensate to levels commensurable with ambient streams. Exact figures will depend on the coal and would have to be determined experimentally.

5.5.3.3.3 Lignite preparation specifications

The WTA plant normally comes with one or two double rotor hammer mills (in series), producing either raw lignite of 0–6mm (coarse-grain) or 0–2mm (fine grain).



Input: Raw lignite crushed to 0-80mm, free of stones and foreign matter

Output: Dried lignite (8–15wt.-% moisture), 0–2mm (fine-grain WTA) or 0–6mm (coarse-grain WTA).

A secondary hammer mill can be integrated, reducing the output grain size to 0–1mm, which would be suitable for use in a power plant. Any finer product, e.g. for entrained-flow gasifiers, will require a separate bowl-roller mill plant after the WTA.

5.5.3.3.4 Mass balance

The Mass /Energy balance will depend on the raw lignite and dry lignite moisture. Assuming a WTA plant with 1 million tpa product at 12% moisture and a raw lignite moisture of 60% operating for 7500hr/yr, the mass and energy balance are:

Input: 134t/hr raw coal (60% moisture)

Output: 61t/hr dry coal (12% moisture)

Evaporation: 73t/hr

Variant:	Recompression	Condensation
Electricity (MW)	7.1	1.3
Heating Steam (t/hr)	10	90
Condensate Recovered (t/hr)	73	58

Consider the vapor recompression option:

a) Electrical energy requirement

Electricity consumption = 7.1MW

Product rate = 61t/hr Intensity = 7.1MW/61t/hr = 0.116MWh/t = 0.419GJ/t product

Water removed = 73t/hr Intensity = 0.350GJ/t water

b) Steam energy requirement

Assume steam @ 180°C, condensate @ 175°C

Enthalpy of steam @ 180° C = 2777.82MJ/t



Enthalpy of water @ 175° C = 741.255MJ/t

Power delivered in steam = $2777.82MJ/t \times 10t/hr \times (1 h/3600 s) = 7.716MW$

Power removed in condensate = 741.255MJ/t x 10t/hr x (1 h/3600 s) = 2.059MW

Heat consumed in dryer = 7.716 - 2.059 = 5.657MW

Product rate = 61t/hr Intensity = 0.334GJ/t product

Water removed = 73t/hr Intensity = 0.279GJ/t water

c) Total energy requirement

Energy intensity of product = 0.419 + 0.334 = 0.753GJ/t product

Energy intensity of water removal = 0.350 + 0.279 = 0.629GJ/t product

5.5.3.3.5 Plant footprint @ 1.0 million tpa dried lignite

Allow for a $35 \text{m} \times 75 \text{m}$ area (i.e. $2625 \text{m}^2 = 0.26 \text{ha}$), which includes also the necessary access and lay-down space for service and repair work.

5.5.3.3.6 Services required

Electricity: See above.

Heating Steam: See above (3–4 bar abs, slightly superheated)

Waste: Solid raw coal from wash water (occasionally)

Lignite Dust: Completely disposed with product

Nitrogen: Only for start-up and shut-down

Cooling Water: For compressors for pneumatic coal transport

5.5.3.3.7 CO₂ emissions per tonne of finished product

No inherent CO₂ emission by the WTA process as such.

The CO_2 emissions attributable to WTA lignite drying would have to be determined from the CO_2 emitted by the external supplies of heating steam and electricity.



5.5.3.3.8 Is the technology capable of capturing CO₂ emissions?

No

5.5.3.3.9 TRL estimate

TRL 8-9 (first commercial operation)

5.5.3.3.10 Commercialization pathway

WTA Technology is in commercial operation.

5.5.3.3.11 Reference plants

- Fine-grain WTA, 110t/hr dry lignite (design capacity), attached to 1000MW Unit K of lignite fired power plant Niederaußem, Germany: Co-combustion of dry and raw lignite. Commercial operation: since 2015.
- Coarse-grain WTA, 30t/hr dry lignite, lignite beneficiation plant Frechen, Germany: Dry lignite production for dry lignite dust. Built 1993, refurbished 2014, in commercial operation since 2015.

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solutions/wta-technology/

BCIA COMMENTS

The WTA process is currently operating at commercial scale with German lignite, and has undergone extensive testing with Victorian lignite. It is commercially mature, and would be available from RWE with process and performance guarantees. RWE is a large reputable company with significant financial reserves. This is important in assessing the value of any performance and process guarantees.

The WTA process is highly energy efficient when operated with vapor recompression, but this is expensive. However, lower cost options are also available.



The dried lignite produced by the WTA process would be suitable for binderless briquetting and subsequent transport. A further milling step of the dried coal would make this technology suitable to provide feedstock for a gasifier.

5.5.3.4 Shandong Tianli Drying Technology and Equipment Co., Ltd.

5.5.3.4.1 Process description

Shandong Tianli's novel internal heating fluidized-bed drying technology is illustrated in Figure 28 below. The internally-equipped heat-exchanger provides more efficient drying for a given amount of fluidising gas flowrate (Ma et al. 2005).

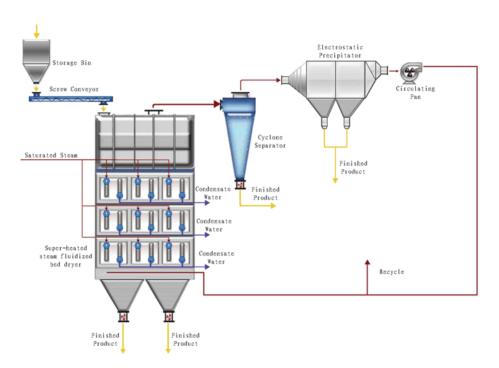


Figure 28: Shandong Tianli super-heated steam internal heating fluidized-bed dryer11

The advantages claimed for this technology are:

- ▶ Reduced heat loss, with drying efficiency > 82%
- ▶ Safe and reliable operation in an oxygen free environment
- ▶ Energy efficient, with recovery of heat of evaporation

¹¹ http://en.kytl.com/product/product.aspx?ProductID=36



- Ability to recover and reuse water removed from lignite
- ▶ Reduced greenhouse gas emissions
- The technology for large scale equipment is mature and the processing capacity of single unit is large. The equipment investment is low.

5.5.3.4.2 Reference plants

2001: 50t/hr coal drying system, China University of Mining & Technology

2005: Coal powder drying system, deep dewatering with inert gas protection, Henan Dengfeng Power Plant

2011: 150,000tpa Lignite Upgrading & Briquetting Project, Shanghai Electric Power Co., Ltd.

2011: 3,000,000tpa Lignite Upgrading for carbocoal production, design general contract, Xinwen Mining(group) Co., Ltd.

2011: Pilot plant for coal mine in Indonesia, Kobe Steel, Japan

2013: Coal drying system for Yitai-Huadian Ganquanbao 5,400,000 tpa (1,800,000tpa for stage 1) Coal Polygeneration Project, Inner Mongolia Yitai Group

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NOTE: The News section of the website has not been updated since 2012, and attempts to contact via phone

and email have been unsuccessful.

5.6. MICROWAVE DRYING

5.6.1 Principle of microwave drying

Industrial-scale microwave processing is an emerging field, with some existing applications in the areas of ceramic/ceramic matrix composite sintering, powder processing, polymers and polymer-matrix composites processing, minerals processing and food processing. The first large-scale commercial application was for



vulcanisation of rubber, where microwave processing brought about increased throughput, reduced operating costs, product uniformity, improved control, and environmental compatibility (Ku et al. 2002).

During microwave processing, microwave energy penetrates through the material, where it is absorbed and converted to heat. This raises the temperature of the material such that the interior is hotter than the surface, as the surface loses more heat to the surroundings. This characteristic allows the potential to heat large sections of the material uniformly. The advantages of this are that materials can be rapidly heated; there may be a reduction in surface degradation because of lower surface temperature; gases are removed from porous materials without cracking; and there may be improvement in product quality and yield. On the other hand, microwave heating carries the risk of formation of hot spots and cracking (Ku et al. 2002).

Microwave drying of lignite has been found to be one to two orders of magnitude quicker than conventional thermal drying at 80 °C. This was attributed to "liquid pumping" of the convective fluid flow, created by build-up of vapor pressure within the particles (Standish et al. 1988). Microwave energy is preferentially absorbed by the water molecules over the dry coal matter, so the internal temperature is higher than on the surface. This creates a build-up of vapor within the particles, and the resulting internal vapor pressure forces out the moisture in liquid form. This is less energy-consuming than moisture evaporation (Salomatov et al. 2012). Besides increasing the heating efficiency, microwave drying keeps the temperature of the lignite low enough to avoid combustion or oxidation (Drozd & Learey 2007).

5.6.2 CoalTek, Inc.

CoalTek, based in Tucker, Georgia, has developed a process for drying low rank coal using microwave energy (Weinberg et al. 2011). The CoalTek process was developed, tested, and proven over eight years by Dr. Jerry Weinberg, the company's co-founder, along with chief geologist Neil Ginther.

CoalTek opened its first commercial processing facility in Calvert City, Kentucky (shown in Figure 29 below) in 2006. The plant is used to dry sub-bituminous coal from the Powder River Basin, and has a capacity of 100,000 tpa (Taulbee et al. 2012).





Figure 28: The 100,000 tpa CoalTek microwave facility (Taulbee et al. 2012)

In 2011, CoalTek announced a joint venture deal with Yijian Group Co., Ltd of China, to build a clean coal processing facility in Inner Mongolia. The US\$350 million deal was planned to transform 10 million tpa of low-grade lignite into high-thermal value coal.¹² This partnership subsequently collapsed, apparently through an inability of the Chinese partner to raise the necessary funds.

In 2018 CoalTek entered into a new partnership with Guangdong Yi Jian Investment Co., also to build a 10 million tpa coal-treatment facility in Inner Mongolia. ¹³

No further details are available on the operational status of CoalTek. The contact details available are:

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CoalTek

945 Concord Street, Framingham, MA 01701

Phone: 1-508-620-5322

Website: www.coaltek.com (not functional)

¹² http://www.businessinsider.com/chinas-clean-coal-game-2012-2/?r=AU&IR=T

¹³ http://www.seacliffcap.com/hfen/info.php?tid=160



5.6.3 Drycol Australia Pty Ltd

5.6.3.1 Process description

Drycol Australia Pty Ltd (Ashgrove, Queensland) has developed a continuous microwave lignite drying process, called the Drycol process (Drozd & Learey 2007), based on a standard 3MW single microwave conveyor platform.

A 20 tonnes/hr demonstration plant for the Microwave concept has been established near Calvert City in Kentucky, USA, where it is operated commercially (by Coaltek) to dry Powder River Basin coal from 28% moisture to 12%.



Figure 30: Drycol microwave drying plant, Calvert City (© Drycol Australia)

During the process, the lignite is maintained at a temperature lower than 90°C to avoid loss of volatiles and minimise the risk of fires by spontaneous combustion (Graham 2007). Figure 31 below shows dried coal emerging from the microwave dryer.





Figure 31: Microwave dried coal emerging from the drying zone (© Drycol Australia)

The throughput of the 3MW platform is dependent on the type of coal and its structure. Performance data with Victorian lignite has yet to be established. However, it would be considered not too dissimilar.

5.6.3.2 Flow diagram

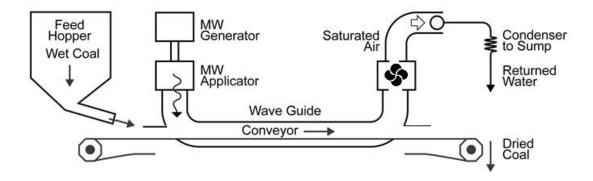


Figure 32: Schematic of Drycol microwave drying process (© Drycol Australia)

5.6.3.3 Lignite preparation specifications

Lignite feed for the Drycol process should be crushed and screened to a size of 20mm or less. The absence of fines is desirable, to minimise the risk of dust build up.



5.6.3.4 Mass balance

Based on an Excel spreadsheet model provided by Drycol Australia:

1,000,000tpa product at 15% moisture requires 1,817784tpa feed at 60% moisture.

Assuming continuous operation 22hours/day, the amount of moisture to be removed is 101.9 tonnes/hr.

The amount of energy required = 0.55kWhr/kg moisture (variable based on test work)

= 0.55MWh/t = 1.98GJ/t H₂O

1 t lignite at 60% moisture produces 0.4706 t product at 15% moisture and 0.529 t water

Energy required = $1.98GJ/t H_2O \times 0.529/0.4706 = 2.23GJ/t$ product

The total amount of microwave energy required = 56.03MWhr.

@ 3MWhr/platform = 19 platforms required

Assume a cost of electricity to industry of $$85/MWh^{14} = $0.085/kWh$

Estimated OPEX = \$31.56 per tonne of raw coal = \$57.38 per tonne of product

Likely CAPEX ~ US\$190 million (order of magnitude)

5.6.3.5 Plant footprint @ 1.0 million tpa dried lignite

A standard 3 MW platform requires an area $45m \times 20m = 900m^2$

Total area for 19 platforms = $17,100m^2 = 1.71ha$

5.6.3.6 Services required

60W HV connection, water, wash-down water control.

5.6.3.7 CO₂ emissions per tonne of finished product

None

¹⁴ https://www.aer.gov.au/wholesale-markets/wholesale-statistics/quarterly-base-futures-prices



5.6.3.8 Is the technology capable of capturing CO₂ emissions?

Not applicable

5.6.3.9 TRL estimate

A single full-scale 3MW module is operating near Calvert City, Kentucky, processing Powder River Basin coal for commercial customers. Larger installations would be a multiple of the same module, enabling the system to be scalable.

Currently, TRL = 8.

For Victorian lignite, TRL = 5 at best. It is unclear whether the dusty nature of Victorian lignite would present an unmanageable risk. Test work would be required.

5.6.3.10 Commercialization pathway

Manufacturing partnership facility established.

5.6.3.11 Reference plants

Calvert City plant 3MW (Converting PRB coal 28% moisture to 12% moisture - into high price bracket).

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BCIA COMMENTS

The Drycol process has not yet been proven with Victorian lignite. The friability of Victorian lignite is cause for concern, since the dust produced would increase the risk of hot spots and spontaneous combustion.

The Drycol process has a high requirement for electrical energy, but uses this for drying in an efficient manner. While there is minimal greenhouse gas production directly attributed to the drying process, that associated with electricity production would need to be accounted for in a lifecycle analysis. An advantage of this process is that the electricity could be sourced from a renewable source.

The Drycol process has been developed in the form of 3MW modules, with the intention of scaling up in parallel. A hypothetical factory producing 1 million tpa of dried Victorian lignite would require 19 such modules, presenting a significant materials handling logistical challenge.

An advantage of the Drycol process is that it can process lignite crushed to a size suitable for briquetting, and so could potentially be used for making a product suitable for export. However, a significant testing program would be required to validate the viability of this process with lignite.

5.7. SCREW CONVEYOR DRYING AND TORREFACTION

A screw conveyor dryer consists of a stationary, jacketed trough enclosing a rotating shaft mounted with a helical screw flight. As the screw rotates, material heaps up in front of the advancing flight and is pushed through the trough. A heating medium, such as steam or hot water, is passed through the jacket and possibly a hollow shaft, and solids are heated as they are swept over the exposed surfaces. The conveyor usually has a closed top and may be swept with air, combustion gases or superheated steam to carry off the evaporated moisture, or may operate under partial vacuum (Waje et al. 2006).

Some of the advantages of screw conveyor dryers are (a) their applicability for indirect heating, (b) their small size compared to other systems, (c) their very high heat transfer area-to-volume ratio compared to other dryers, (d) the ability to operate in counter-current drying mode, and (e) their potential to be used for either heating or cooling. They can be utilized as a pre- or post-treatment for other drying systems, and can be configured as multistage drying systems (Nikolopoulos et al. 2015).

5.7.1 Screw conveyor drying of lignite

Hydrocarbon Research, Inc. (now HTI, http://www.hti-hcat.com/about), developed a process for drying lignite using a three-stage screw conveyor drying system. In the first stage, lignite (milled to a particle size smaller than about 5mm) was heated by direct contact with $120 - 150^{\circ}$ C air at atmospheric pressure, to remove free moisture. With North Dakota lignite, this stage reduced the moisture content from 38% down to 8 - 12%.



The lignite then passed to a second screw conveyor, which was maintained at an elevated pressure of 34kPa and 120°C, with the gas vent rate controlled to maintain the wet bulb temperature at about 70°C. The slower drying rate in the second stage served to remove the bound moisture without excessive cracking of the particles. It also permitted a gradual wicking up of internal hydrocarbons and resins to directly coat and seal the pores. In the third screw conveyor section, water was circulated through the jacket to cool the product for safe handling. This process was claimed to produce dried lignite containing about 5% moisture that was not subject to moisture readsorption or spontaneous combustion (Comolli 1981).

It is understood that this screw conveyor drying process was intended to form part of Hydrocarbon Research's 'H-Coal' coal liquefaction technology (Hoertz & Swan 1979), but it is unclear whether it ever progressed beyond pilot scale.

5.7.2 Screw conveyor torrefaction of lignite

Torrefaction is a thermochemical process in which carbonaceous material is heated to 200 – 300°C in the absence of oxygen. This is somewhat harsher than typical drying conditions, but has the advantage that some of the volatile organic components are driven off along with the water. Typically, the material loses about 30% of its mass while the energy content only decreases by 10%. The torrefied solid is a dry, blackened material which is hydrophobic, i.e. water repellent, brittle and is easy to grind into powder with little energy, with a high energy content (Nachenius et al. 2015). The process can be operated at high process energy efficiency; typically 96% thermal efficiency and 92% net process efficiency (including internal electricity consumption) (Bergman et al. 2005).

Figure 33 below illustrates a typical torrefaction process. The screw reactor is heated indirectly, driving off water vapor and volatile hydrocarbons. This creates an inert environment, eliminating the risk of combustion. The evaporated gas can subsequently be burned to produce the energy needed to heat the reactor and sustain the drying process.



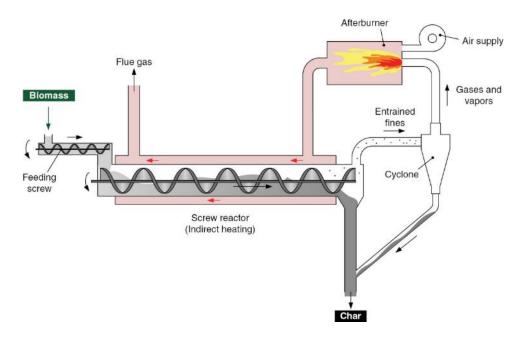


Figure 33: Conceptual continuous torrefaction process (Ronsse 2016)¹⁵

Currently, most interest in torrefaction is directed toward its use for upgrading biomass as a fuel for co-firing in coal power stations. While there is a lot of commercial interest, there are no large scale operations in existence using screw conveyor technology.

To date, there has been limited work done on torrefaction of lignite. Ibeto et al. (2017) showed that torrefaction of Nigerian lignite at 200°C for 20 minutes could reduce the moisture content from 30% to 5%. In the process, the higher heating value (HHV) was increased from 15,300 to 23,800kJ/kg.

Park et al. (2017) demonstrated that torrefaction of a Russian lignite resulted in the removal of hydrophilic surface functional groups, an increase in heating value, and a reduction of both surface area and pore volume. Torrefaction at 200–300°C for 1 hour reduced the moisture content to 0.42 – 0.48%. Torrefaction upgraded the lignite to a sub-bituminous coal. Similar upgrading was achieved with sub-bituminous coals.

In Victoria, Torreco Pty Ltd is in the process of scaling up a proprietary screw conveyor torrefaction process. Initially, Torreco used a 50kg/hr prototype torrefaction reactor to demonstrate that lignite and a range of biomass materials can be dried to near-zero moisture content, making them amenable to milling and granulation.

As a route to commercialization, Torreco is developing a range of organic fertiliser products, which include a proportion of lignite for its binding and soil improvement properties. It has recently installed a pilot-scale

¹⁵ © Cambridge University Press, used with permission



continuous torrefaction reactor at its fertiliser plant at Bacchus Marsh, as shown in Figure 34 below. The reactor can process 750 kg/hr of biomass containing 50–55% moisture, reducing the moisture content to < 10% in 5–8 minutes.



Figure 34: Pilot-scale torrefaction reactor (© Torreco)

While Torreco has expressed interest in developing a torrefaction process for producing dried Victorian lignite, only preliminary proof-of-concept work has been done using its small prototype reactor. While the pilot-scale torrefaction reactor has shown that Victorian lignite can be dried in combination with organic waste materials, a program of pilot scale trials would be necessary to define the operating conditions for Victorian lignite alone. Current TRL for Victorian lignite = 4–5.

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5.8. HYDROTHERMAL DEWATERING

In the early 1970s, researchers at the University of Melbourne developed the concept a continuous lignite dewatering process, which involved heating lignite in water under sufficient pressure to prevent evaporation (Evans & Siemon 1971). This process, known as hydrothermal dewatering (HTD), was an extension of the earlier Fleissner drying process, in which lump lignite was heated in the presence of steam. The HTD process decomposes the oxygen-rich functional groups on the lignite surface, increases its hydrophobicity and produces a harder lignite product with lower moisture and porosity.

The HTD process was initially investigated in a 90kg/hr pilot plant during the 1980s at the University of North Dakota Energy Research Center (Baker et al. 1986). During the 1990s, the State Electricity Commission of Victoria (SECV) operated a HTD pilot plant with a capacity of up to 1 tonne/hr at 325°C (Anderson et al. 1992). The SECV pilot plant demonstrated that the moisture content of brown coal could be reduced to about 50–55% by treatment at temperatures of 275–325°C. About 1% of the dry coal mass was lost soluble organics in the water, along with some of the inorganic constituents, particularly sodium (Saripalli et al. 1993).

Waste water from HTD process contained significant amounts of organics along with inorganic salts. A range of water treatment processes were evaluated to clean up the effluent water, with limited success, including flocculation/filtration, membrane filtration, reverse osmosis, electrodialysis, aerobic and anaerobic biological digestion and adsorption onto feed coal or char (Allardice et al. 2004). Treatment of the waste water with membrane separation technologies such as reverse osmosis and electro-dialysis were found to be impractical because of rapid fouling of membranes by the organics in water. Biological treatment of the waste water using anaerobic or aerobic digestion was successfully used to reduce the organic levels, but the slow kinetics of the process made the technology expensive. Concentration of waste water in brine concentrators with subsequent incineration of waste brine was one of the potentially feasible options (Saripalli et al. 1993).

5.8.1 Exergen Pty Ltd

5.8.1.1 Process description

Exergen Pty Ltd (Exergen) is a privately owned Australian company that formed in 2001 to develop a high efficiency continuous vertical autoclave technology for HTD that incorporates heat and pressure recovery. Exergen's patented process (Nicklin & Tait 2002) is known as Continuous Hydrothermal Dewatering (CHTD) technology.

In the CHTD process, low rank coal is crushed and mixed with water to create a pumpable slurry. The slurry is heated in Exergen's CHTD autoclave, which consists of concentric pipes placed in a deep mine shaft or borehole, allowing the weight of the column of slurry in the autoclave to provide enough pressure at the bottom to prevent boiling at elevated temperature. The concentric pipes act as a heat exchanger, passing heat from the inlet stream travelling down the autoclave to the outlet stream returning to the top of the



autoclave. While the slurry can reach a temperature of nominally 300°C and pressure of 100 bar at the bottom of the autoclave, the surface temperature and pressure are relatively low. This design is very energy efficient, using about 2% of the energy content of the coal for the overall process.

At 300°C an exothermic decarboxylation reaction takes place, causing changes to the composition and structure of the low-rank coal, rendering it relatively hydrophobic and collapsing its porous structure, forcing out water. The exothermic nature of the reaction reduces the need for external heat input. After the slurry cools and exits the autoclave, these changes to the coal allow a large portion of the coal moisture to be efficiently removed from the coal in the liquid state. The whole process is extremely energy efficient and has very low carbon dioxide emissions. Carbon dioxide generated is in a near pure form and sequestration ready. In the CHTD process, output coal is also rendered relatively hydrophobic, thus enabling its transport (as a slurry) by pipeline before final dewatering using mechanical pressure.

A variety of technologies can be used to dewater the treated coal slurry, including centrifugation, filtration and mechanical expression. Mechanical dewatering can be supplemented with thermal evaporation to achieve very low moisture content as required. Commercial membrane filter press technology has been proven for dewatering the pilot plant CHTD treated coal to 30–35% moisture (62+% raw coal), and is claimed to be the best existing technology for achieving a low moisture content. Bench-top mechanical expression trials and preliminary dewatering roll press trials have shown improved potential for dewatering CHTD coal. Other dewatering equipment, including vacuum filters, centrifuges, thickeners and pressure filters have been tested by various equipment vendors. Koeppern, a world renowned manufacturer of briquetting equipment, has also demonstrated in trials commissioned by Exergen, that CHTD treated Latrobe Valley lignite can be further dried and briquetted to form a 10% moisture product with a calorific value of over 5700 kcal/kg.

At its Pilot Facility and in collaboration with CSIRO, Exergen has also demonstrated that it can produce stabilised CHTD coal and water slurry that can be stored for long periods without settling and be transported safely by pipeline and tanker vessels. The water-based CHTD slurry has also successfully fuelled a DICE (Direct Injection Carbon Engine) test engine at CSIRO's premises in Newcastle.

Some of the claimed key advantages of the CHTD process are:

- high energy efficiency
- moisture removed as a liquid avoiding the thermal energy required for evaporation
- low carbon footprint and can reduce carbon emissions from power generation. Carbon dioxide from the CHTD process itself is in a near pure form, facilitating capture and storage
- increases the energy content of the coal through removal of water and improves the energy density of the dry coal mass
- changes the nature of the coal so that it can be economically transported as a slurry by pipeline or tanker vessels
- transportation and shipping as a slurry avoids the danger of spontaneous combustion



- water can be removed from the slurry by efficient mechanical means at a convenient point in the logistics chain
- can be linked with commercially available technologies to create valuable products tailored to individual customer needs

5.8.1.2 Flow diagram

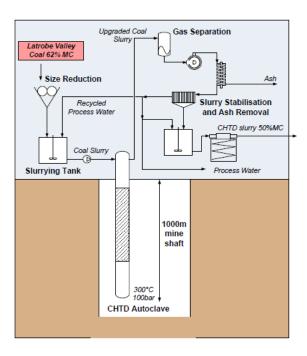


Figure 35: Schematic of CHTD process

5.8.1.3 Lignite preparation specifications

Standard crushing and slurrying process using commercially available equipment.

5.8.1.4 Mass balance

Based on Pilot Plant data, Exergen has developed a computerised process model.

Detailed mass and energy balance calculations based on pilot plant performance show that typically process inputs comprise 50 tonnes/hr of raw Latrobe Valley lignite (@ 62% moisture), 0.5 tonnes/hr liquid oxygen and 986kW of electricity, while process outputs comprise 27 tonnes/hr of CHTD treated product (@ 50% moisture), 1.7 tonnes/hr of process gas (carbon dioxide) and 22 tonnes/hr of process water.



Apart from an electrical and oxygen supply, the CHTD process does not require any external source of energy. Based on this mass balance it is anticipated that the CHTD process will only consume energy equal to less than 2% of the total energy in the raw coal. To achieve the same result through traditional thermal evaporation techniques would consume up to 20% of the coal's energy.

Energy intensity:

a) Product basis

Energy input = 0.986MW

Product @50% moisture = 27t/hr

Intensity = 0.986MW/27t/hr = 0.036MWh/t = 0.13GJ/t product

b) Moisture removed basis

Energy input = 0.986MW

Water in feed = $0.62 \times 50 t/hr = 31 t/hr$

Water in product = $0.5 \times 27t/hr = 13.5t/hr$

Water removed = 17.5t/hr

Intensity = 0.986 MW/17.5 t/hr = 0.056 MWh/t = 0.20 GJ/t water removed

5.8.1.5 Plant footprint @ 1.0 million tpa dried lignite

As the CHTD autoclave is suspended in a 1,000m deep shaft or bore, the actual plant footprint is more defined by the layout of the balance of plant items and storage requirements. Overall footprint will be very small compared to other technologies.

5.8.1.6 Services required

- HV electrical connection
- Liquid oxygen
- Water
- Waste disposal (depending on anticipated or desired use for the waste water)

5.8.1.7 CO₂ emissions per tonne of finished product

Approximately 0.037 tonnes CO₂/tonne CHTD product (dry mass basis).



5.8.1.8 Is the technology capable of capturing CO₂ emissions?

CO2 is liberated from the lignite under hydrothermal processing conditions and is separated from the treated slurry by depressurization. The purity of the CO2 stream has not been determined; this would be evaluated at the next stage of scale-up. In principle, the liberated CO2 can be purified by absorption using a conventional amine solvent.

5.8.1.9 TRL estimate

The CHTD technology has been proven using a 4 tonnes/hr pilot plant which was established at the Beaconsfield gold mine in Tasmania. In an 8-year Pilot Phase costing in excess of \$30m, Exergen has successfully upgraded a range of low rank coals including from the Latrobe Valley, Bacchus Marsh, Anglesea and Indonesia, and has proven that CHTD can be integrated with other proprietary and commercially available equipment to successfully dewater the upgraded product. The moisture content of the coals successfully tested ranged from 35% to 65% and, following CHTD treatment and dewatering, delivered a final product with moisture content ranging from 10% - 25%.

The next stage of development would be to scale up the process by a factor of 12, in a proposed 50 tonnes/hr Pre-Commercial Demonstration Plant.

The TRL of the CHTD process is assessed to be 6. The TRL of the dewatering process is likely to be five to six, depending on the technology chosen. Note that even commercial dewatering technologies have not been validated using CHTD upgraded coal slurry at full scale.

5.8.1.10 Commercialization pathway

Exergen's business plan centres on leveraging the company's technology into resource development through a range of commercialisation pathways, including:

- Stabilised, water-based, CHTD slurry that can be safely pumped, stored, transported by ocean tanker and mechanically dewatered at a customer's power station overseas, at carbon dioxide emission intensity levels around 800kg CO₂ per MWh sent out.
- ▶ 10% moisture content CHTD briquette that can be safely stored and transported overseas using bulk handling and shipping methods, for power production in Asia and produced at a cost that allows it to compete with Newcastle black coal on a CV and quality adjusted basis.
- ▶ 25% moisture content CHTD filter "Cake" that can be safely stored and transported overseas using bulk handling and shipping methods, for power production in India. This is a "mid-range" CV product that can compete with similar CV Indonesian coal, without the high production costs and increased energy requirement of 10% moisture briquettes.



- Many lignite conversion processes such as coal to liquid, coal to gas, coal to chemicals and fertilizer and partial pyrolysis, rely on a feed of dewatered coal. Exergen will develop technology integration partnerships in order to participate in the commercial development of such processes.
- In the seven to 10 year time horizon, Exergen expects that high efficiency and low emission Direct Injection Combustion Engine (DICE) options will emerge for domestic and overseas lignite based power generation. Using Latrobe Valley lignite, Exergen will develop a low-ash, low-silica, CHTD / water based DICE fuel that will allow Exergen to market liquid fuel in Asia to compete with LNG or potentially will facilitate Exergen to enter the domestic power generation market with a technology and fuel that will compete with gas-fired CCGTs.

Exergen secured its first coal resources in Bacchus Marsh (exploration licence, 1.6 billion tonnes) and has now secured a mining licence at Driffield in the Latrobe Valley (500 million tonnes).

Exergen is now positioned to advance to the next stage of commercialisation through the funding and development of a Pre-Commercial Demonstration Plant. This plant is required to prove the scale up of the operations at the 50 tonnes/hr level. The demonstration program will include:

- Validation of autoclave scale up, mass and energy balances, materials of construction and water treatment systems.
- Proving a series of process design advancements over those at the Pilot Facility, including multiple downcomers, extended depth to 1000m, alternative heating source, a new heat exchange profile and new start-up systems.
- Trials of oxygen injection and foam management systems and development of further processes for secondary dewatering, briquetting and product storage.

The Pre-Commercial Demonstration Plant will also demonstrate (to bankable feasibility study standards), that CHTD technology and processed lignite (and sub-bituminous coal) can be integrated with other, commercially available technologies and Exergen developed technologies, to produce at least one commercially viable product or application from a number of current commercialisation opportunities.

Exergen is seeking to raise funding to construct a 50 tonnes/hr pre-commercial demonstration plant and position the Company for commercial production.

5.8.1.11 Reference plants

4 tph pilot plant at Beaconsfield in Tasmania.



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BCIA Comments

The Exergen CHTD process is based on a novel countercurrent heat exchanger configuration that is sunk 1000m below ground level. Its advantages are that the hydrostatic pressure developed at this depth is sufficient to prevent boiling at the hydrothermal reaction temperature of 300°C, and its heat recovery is such that very little additional heat input is required. It can reduce the moisture content of Victorian lignite from 62% to 50%, halving the energy requirement for a subsequent drying step.

In order to achieve this energy saving, the CHTD reactor must be placed in a 1km deep shaft, which would seem to be an expensive option. It is unclear whether the benefits of the process would outweigh the additional capital cost involved, especially since only half of the water in lignite would be removed. This technology would need to be measured against other technologies in consideration of any commercial application.

5.8.2 Ignite Energy Resources Pty Ltd

5.8.2.1 Process description

Ignite Energy Resources (IER) developed a variant of the HTD process, in which a slurry of lignite or biomass is mixed with a stream of supercritical water in the presence of an oxidising catalyst (Humphries 2009). This Catalytic Hydrothermal Reactor process, known as 'Cat-HTR', is illustrated in Figure 36.



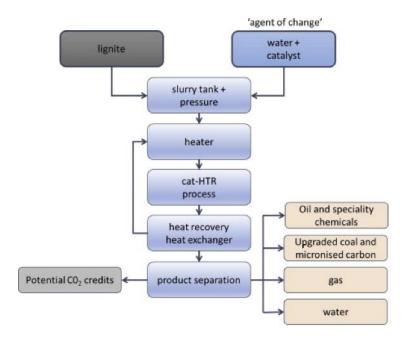


Figure 36: Cat-HTR process (Godfrey 2010)

The Cat-HTR process is more aggressive than conventional HTD, and rapidly converts lignite in a water slurry into an oily coal which can be separated into two high energy products:

- Synthetic crude oil (syncrude) that can be processed in existing oil refineries to produce an array of fuels, including gasoline, kerosene, and diesel; and
- Micronised upgraded coal that can be used in the manufacture of steel (as a PCI-type coal) and loweremissions coal power generation.¹⁶

Independent economic modelling by the University of Sydney has suggested that syncrude and upgraded coal could be produced by the Cat-HTR process at a cost comparable to the cost of production of conventional oil.¹⁷

Cat-HTR uses the water held in lignite as the main change agent to produce upgraded coals and syncrude. The hydrothermal transformation is accomplished by using a combination of near-critical water and low-cost, readily available homogeneous catalysts to break some of the carbon-oxygen bonds that form part of the polymeric structure of lignite.

In parallel, radical reactions occur that further transform the partially depolymerized materials. In case of the syncrude, cascade reactions are induced that lead to a further reduction in oxygen content. In the case of the

¹⁶ http://www.igniteer.com/technology/

¹⁷ http://www.igniteer.com/ier-signs-a30m-investment-with-pt-bukit-asam/



non-depolymerised fraction, fused aromatic rings are formed, leading to an accelerated coalification reaction and ultimately to the upgraded coal product.

The resulting coal product is more hydrophobic than the lignite and is, therefore, more easily dewatered. The oil product is initially adsorbed onto the coal, but once separated it is a high-quality syncrude that can be readily upgraded under conventional mild hydrotreating conditions to fully fungible fuel blendstocks.

Cat-HTR removes oxygen from the lignite mainly as carbon dioxide, much of it via decarboxylation of carboxylic acids. This has the advantages that the syncrude is low in acidity and retains as much hydrogen as possible from the lignite. Hydrogen transfer from water is also possible. This latter gives the syncrude a volumetric energy content on a par with that of petroleum crude.

The technological advantages of the Cat-HTR process can be summarized as follows:

a) General technical advantages

- A highly controllable terrestrial chemical process that delivers consistent product quality.
- ▶ Highly upgraded coal and high quality synthetic crude oil products in one chemical transformation step.
- No external hydrogen or other reducing gas required for the process.
- ▶ Lower carbon footprint due to a relatively low reaction temperatures (~300°C) unlike other applications such as pyrolysis (~500°C) and gasification ~1000°C).
- Run of mine lignite of any water content may be used as feed.
- Inexpensive, homogeneous catalysts.
- Certain minerals in the lignite help to catalyse the process (i.e. turning a problem into an opportunity).

b) Specific upgraded coal advantages

- The upgraded coal is produced by relatively low temperature chemical process when compared to either pyrolysis or gasification and as such has a lower carbon foot print.
- ▶ The upgraded coal is produced in a micronized form coated with the Synthetic crude oil which immediately lends itself to pumping and bulk shipping (similar to mineral slurries) giving access to conventional transportation options.
- As the upgraded coal is produced in a micronized form it can with little to no additional processing be used as direct feed into a modern supercritical boiler with thermal efficiencies in the region of 45% compared to existing Lignite fuelled boilers running at a circa ~22% efficiency leading to a lower carbon footprint.



- The micronized coal has also been shown to be a fuel of choice in the Direct Injection Carbon Engine ("DICE") running at 50% plus thermal efficiencies.
- ▶ The upgraded coal produced is hydrophobic so it can be easily dried.
- Extremely high energy density ~30 GJ/tonne.

c) Specific Synthetic crude oil advantages

- Synthetic crude oil produced is very low in Oxygen content (~8% by weight) compared to pyrolysis oil (>30% by weight). Can drop straight into a conventional refinery with little to no pre-processing.
- The Synthetic crude oil has shown promise in being able to be directly blended into marine diesel fuels
- Extremely high energy density ~ 38GJ/tonne
- The Synthetic crude is near neutral pH while the oil produced by pyrolysis is acidic. This translates that the IER Synthetic crude can be handled in conventional vessels while the pyrolysis oil requires special materials and much higher cost logistics.

IER has demonstrated the Cat-HTR process with both lignite and biomass at its pilot plant at Somersby, north of Sydney, shown in Figure 37 below.



Figure 37: Cat-HTR pilot plant at Somersby, NSW (© Ignite Energy Resources)



In 2014, IER secured a AU\$20 million grant, under the Victorian government's Advanced Lignite Demonstration Program, for the design, construction and operation of a commercial-scale lignite upgrading plant in the Latrobe Valley.

In the same year, IER entered into a collaborative partnership with PT Bukit Asam (Persero) Tbk., which is the largest and most profitable coal company in Indonesia, with 7.3 billion tonnes of coal resources (almost half being lignite). IER had shown that it could successfully upgrade Bukit Asam's low-rank coal in its pilot plant to synthetic crude oil and metallurgical-grade coal.

In 2016, in response to significant unforeseen site permitting obstacles, IER withdrew from the ALDP and decided to construct a demonstration project in Canada instead.

IER's focus is now on the more prospective markets in North America and Europe, particularly in the field of renewables.¹⁸

5.8.2.2 Flow diagram

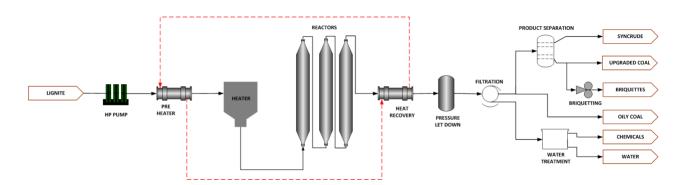


Figure 38: Schematic of CAT-HTR process

5.8.2.3 Lignite preparation specifications

Lignite is prepared by crushing and sieving to 5mm or less to enable slurry production.

5.8.2.4 Mass balance

Cat-HTR produces two products from lignite (assuming 65% moisture).

2.8 tonnes of as-mined lignite produces 1 bbl (42 US gallons) syncrude and 0.75 tonne upgraded coal.

¹⁸ http://www.igniteer.com/update-on-iers-advanced-lignite-demontstaion-program-aldp-project/



The process uses the water in the lignite and other catalysts to upgrade (no pre-drying required)

Best of breed energy efficiency and carbon emissions as only 15% of energy residing in the coal is used for conversion.

5.8.2.5 Plant footprint @ 1.0 million tpa dried lignite

15ha

5.8.2.6 Services required

All services can be included in a greenfield plant build. However if available at a brownfield site gas, water, water treatment, and 415V electrical services could be utilized to reduce cost.

5.8.2.7 CO₂ emissions per tonne of finished product:

Total GHG emissions = 162kg CO₂-e / dry tonne of lignite processed.

Proportioning GHG emissions based on the energy content of the syncrude and upgraded coal products gives:

GHG emissions associated with upgraded coal = 194kg CO₂-e / tonne coal product

GHG emissions associated with syncrude = 245kg CO₂-e / tonne synthetic crude oil

5.8.2.8 Is the technology capable of capturing CO₂ emissions?

As the technology uses decarboxylation to remove oxygen from the lignite it produces a high purity CO_2 stream which is suitable for addition to a carbon capture and storage network.

5.8.2.9 TRL estimate

TRL 6

5.8.2.10 Commercialization pathway

Ignite Energy Resources is currently constructing a commercial scale Cat-HTR project for hydrothermal processing of biomass, through its wholly-owned subsidiary Licella Holdings Ltd. The facility is being built in the North East of England, Wilton Industrial complex, and will be on line in 2019.



5.8.2.11 Reference plants

IER has successfully operated a small pilot plant (SPP) located in Somersby, NSW from 2008 to 2011 with a nominal processing capacity of 1000 tonnes per annum of process slurry. Also located at the same facility, and operational on various feedstocks since 2011, a 10 times scale up large pilot plant (LPP) with a nominal capacity of 10,000 tonnes per annum of process slurry. This facilitates a nominal processing capacity in excess of 7,500 ROM tonnes of lignite when coupled with a direct heating methodology.

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BCIA comments

Strictly speaking, the Cat-HTR process is not a lignite drying process, but rather a process for converting lignite into both a refinable oil and an upgraded coal. The upgraded coal would be suitable as a feedstock for gasification, but could not be briquetted without a binder.

While the Cat-HTR is an interesting process, IER's main focus is on the syncrude product, particularly from biomass. In principle, operating the plant as a conventional hydrothermal treatment process for lignite dewatering may be a possibility, but is no longer the commercial focus of IER. The technology would best be utilised in a co-production environment where the syncrude could be refined and the upgraded coal be used as a source of fuel for an entrained gasifier.

5.9. COMBINED EVAPORATIVE AND NON-EVAPORATIVE DRYING

This class of process involves an initial lignite dewatering step, in which liquid water is mechanically forced out of the pores, followed by a typical evaporative drying step to achieve the final target moisture content.



5.9.1 Environmental Clean Technologies Ltd

5.9.1.1 Process description

During the 1980s, researchers at the University of Melbourne developed a method for transforming run-of-mine lignites into a dense, dry, hard product (Johns et al. 1989). The researchers found that raw lignite could be comminuted in a kneader to break down the coal structure, releasing water to form a paste-like material. The paste could be extruded to form pellets which, when dried at or near ambient conditions, formed a hard briquette-equivalent product. It was found that the product strength could be improved with the addition of pH modifiers (Johns et al. 1984; Harvey et al. 1986a,b).

The densification phenomenon was shown to be the result of gelification of the colloidal lignite particles liberated under shear, which subsequently form hard, glassy structures under the capillary stresses of contraction during drying (Christie & Mainwaring 1995). However, for maximum strength, it was important that the pellets were dried slowly at near-ambient temperature, otherwise the structure was weakened by stress-induced cracking (Johns et al. 1989).

The intellectual property rights to the University of Melbourne's densified lignite process were acquired by the Calleja Group around 1994. The Calleja Group owned the Maddingley lignite mine at Bacchus Marsh, and was exploring the possibility of utilising densified lignite as a fuel and reductant for smelting mill scale to metallic iron. By 2003 they had successfully demonstrated key aspects of the lignite densification process via batch scale at increasing capacities.¹⁹

In 2004, the Calleja Group invested in a 16,000 tonne/year pilot plant at Bacchus Marsh. In 2005, what had become known as the 'Coldry process' was acquired by Environmental Clean Technologies Ltd (ECT), which expanded and improved the pilot plant to demonstrate the process.

The Coldry process, shown in Figure 39 below, was designed to reduce the moisture content of lignite at low temperature and low pressure. This is achieved through a unique combination of lignite densification and waste heat utilization.

¹⁹ http://www.ectltd.com.au/david-wilson-1934-2013/





Figure 39: Overview of Coldry process (© ECT)

ECT developed a specialised dryer to dry the moist pellets, designed to use low-grade waste heat to facilitate slow drying at temperatures of less than 80°C (Wilson 2005). Slow drying is necessary to allow time for the pellets to shrink uniformly and maintain the strength of the pellets (shown in Figure 40 below).



Figure 40: ECT's extruded densified brown coal pellets and dryer design (© ECT)

The Coldry process is designed to be integrated with host applications that feature waste heat streams, directing that heat toward the evaporative drying of the pellets, thereby minimising 'paid' energy input. It has applications in the power industry where it can be used to upgrade low-quality coal, reduce CO₂ intensity,



increase the efficiency of existing coal-fired power plants (retrofit) or enable the deployment of new high efficiency, low emissions (HELE) power plants for low-rank coal resources. The Coldry process is an ideal feed preparation stage for downstream coal upgrading processes, enabling higher-value utilization of lignite in coal conversion technologies (liquids, gas & derivatives, hydrogen). It has also been designed for use in iron and steel making via ECT's Matmor process, in which pellets are produced from lignite and iron oxide bearing material (e.g. iron ore, mill scale, nickel tailings) and subsequently retorted to produce iron metal.

The Coldry technology involves the following process stages:

- 1. **Sizing**: ROM lignite is sized to < 8mm
- 2. **Mechanical Shearing**: The majority of the physically trapped moisture is released via destruction of the porous structure of the coal, which is achieved via specific application of mechanical shear, resulting in a coal slurry of suitable consistency for extrusion.
- 3. **Extrusion**: The slurry is extruded to form pellets of optimal dimension for subsequent drying.
- 4. **Drying**: Waste energy from a co-located power station (or another low-grade 'waste' energy source) is utilized to cost-effectively evaporate the mobilised water within the pellets, delivering a finished product with less than 15% moisture.

The Coldry process has impressive benefits in comparison to the traditional drying processes, including;

- Zero CO₂: No direct gaseous emissions (including CO₂, NOx, and SOx)
- Significant energy uplift compared to the raw lignite (200% increase in net calorific value)
- Net energy uplift overall
- Thermally stable finished product, with reduced spontaneous combustion profile
- Where commercially desirable, there is also the option to harvest evaporated moisture

The Coldry product, made from various Victorian lignites, has the following indicative specification range:

Source	M (%)	GCV (MJ/kg)	NCV (MJ/kg)	Ash (%db)	S (%db)	Particle Size
Range	11.3-12.3	22.1 - 26.2	21.5 - 22.1	1.6 – 2.3	0.26-0.45	<50µm
Average	12.4	25.7	21.9	2.0	0.4	17µm

Table 6: Typical composition of Coldry pellets produced from Victorian lignite



5.9.1.2 Flow diagram

As indicated in Figure 39.

5.9.1.3 Lignite preparation specifications

ROM lignite is sized to < 8mm.

5.9.1.4 Mass balance

A given Coldry plant design can vary in potential throughput based on:

- 1) Desired output product specification:
 - a) Finished moisture content
 - b) Pellet hardness
- 2) Available volume and temperature of the waste heat of the host application:
 - a) Higher temperature = high throughput with lower pellet hardness suitable for front-end feed preparation to a co-located process.
 - b) Low-moderate temperature = lower throughput suitable for pellets destined to be transported or exported.
- 3) Ambient conditions:
 - a) Temperature
 - b) Relative humidity

5.9.1.5 Plant footprint @ 1.0 million tpa dried product

The Coldry process is modular, with each module notionally designed to output 23 tonnes/hr, or 170,000 tpa finished product under Latrobe Valley ambient conditions (40-45°C base scenario). Figure 41 below shows a conceptual sketch of a Coldry plant comprising two such modules.



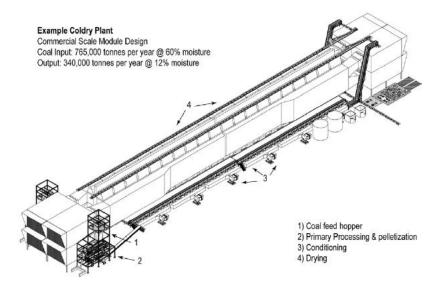


Figure 41: Concept sketch of two Coldry modules in parallel (© ECT)

A Coldry plant deployed on a 40-45°C basis to an existing lignite power station would require ~6 x 170,000 tpa Coldry modules to deliver 1.0 million tpa of finished product under Latrobe Valley ambient conditions.

A nominal 1.0 million tpa plant footprint is ~200m x 120m, or 2.4ha.

5.9.1.6 Services required

- Electrical (HV) Total requirement dependent on scope of host application and level of integration.
- Gas not required.
- Waste disposal not applicable.
- ▶ Water minimal requirement, not a major process input.

5.9.1.7 CO₂ emissions per tonne of finished product

Nil.

The Coldry process has been developed to utilize the large volumes of waste heat typically generated by a lignite -fired power station. Most industrial scale processes that utilize coal, and indeed that intend to use dried lignite, will have a substantial waste heat source. Coldry can be tightly integrated with a co-located host application, minimising or eliminating auxiliary cooling requirements.



5.9.1.8 Is the technology capable of capturing CO₂ emissions?

Not applicable.

5.9.1.9 TRL estimate

6 - Prototype system: tested in intended environment close to expected performance.

5.9.1.10 Commercialization pathway

In 2018, ECT entered into a collaborative agreement with the Indian government to construct a large scale integrated Coldry and Matmor pilot plant, capable of producing 2 tonnes of metal per hour.²⁰ The pilot plant will be constructed at NLC India, at Neyveli, southwest of Chennai in the state of Tamil Nadu. This will be India's largest ever (~AU\$35m) government backed joint R&D Project with an Australian company.

Additionally, ECT is part way through a Feasibility study for a commercial scale Coldry demonstration plant (~170,000 tpa / single module) in the Latrobe Valley, to be located at Yallourn power station.

5.9.1.11 Reference plants

Coldry high volume test facility Bacchus Marsh, Victoria Australia, with a capacity up to 30,000 tpa.

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²⁰ http://www.ectltd.com.au/news-investor-relations/



BCIA comments

The Coldry process would be an efficient way to dry lignite if a suitable source of waste heat is available. It could potentially provide a lower cost option for feedstock for direct injection into boilers or for gasification.

The finished product is not structurally strong, and evidence has not been seen to suggest that the risks associated with dust generation during handling have been adequately mitigated. It is understood that the Coldry product produces significantly more dust during each handling step than a stamp press briquette. This is not an issue if utilisation of the product is in close proximity to the coldry production process.

5.9.2 GTL Energy Ltd

5.9.2.1 Process description

GTL Energy Ltd (GTLE) is an Adelaide-based company that has developed a proprietary process for drying lignite using a mechanical compaction process to dewater the lignite before drying in an indirect rotary steam tube dryer. GTLE's proprietary technology uses mechanical energy to liberate contained water present in the unexposed pores and interstices of the coal before drying. High mechanical pressure (compaction) releases most of the internal moisture held in the pores (or void spaces) of coal, allowing increased rate of evaporation enabling use of low temperatures (French et al. 2013; 2014; 2016). Using a GTLE proprietary roll design, compaction physically alters the coal, such that the crushed particles are forced together under high pressure which in turn significantly improves the strength, competency and quality of the product.

Trials with lignite have shown that mechanical compaction can reduce the moisture content from 63% to 46% (French et al. 2013). Figure 42 below presents the drying curves of compacted versus uncompacted lignite at 40°C, showing that a target moisture content can be achieved much more quickly after compaction.



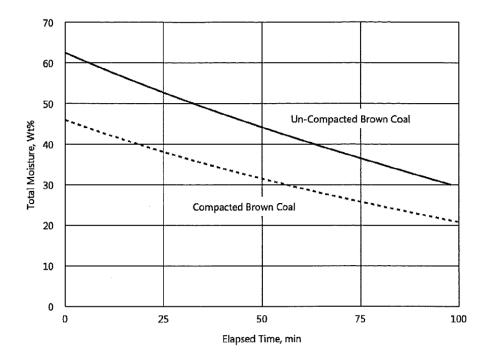


Figure 42: Effect of compaction on drying at 40 oC (French et al. 2013)

Following the compaction, the lignite is dried in an indirect steam rotary dryer at 40–60°C to a moisture content of 14–16% (French et al. 2014). After this, the upgraded lignite can be briquetted without the use of binders (French et al. 2016). Alternatively, the dried product could be direct fed to a power plant (or gasifier) without briquetting.

The GTLE briquette product, unlike products from alternative thermal upgrading technologies, has a low propensity to reabsorb moisture and low pyrophoric tendencies (spontaneous combustion), principally due to the permanent collapsing of the pore space.

Over the last decade, GTLE has constructed two separate facilities, using full scale equipment and commercial layouts. The first commercial scale demonstration plant was constructed near South Heart, North Dakota and commissioned in 2010. This 250,000tpa test facility has successfully been used for large volume trials with coals from the US, New Zealand and Indonesia. The Indonesian product was subsequently burned in a test run at a Minnesota Power & Light facility, demonstrating superior performance vis-à-vis its Illinois design coal.

A video presentation of the South Heart facility can be seen at:

https://www.dropbox.com/s/lebhyt9lbvgpw5h/GTL Technology%20Final%202012-11-1.wmv?dl=0.



This facility was recently sold to an Indian firm for relocation to Indonesia. Once re-installed, commercial operations data will be available using local Indonesian sub-bituminous coals. The unit may also be available for limited testing of other unique coals.

The second facility, a 100,000tpa nameplate facility in Mataura, New Zealand was constructed and owned by Solid Energy New Zealand Limited (SENZ), a local utility and lignite producer. The plant, shown in Figure 43 below, was commissioned in 2013 and ran successfully for several months, producing briquettes from Southland lignite for customer combustion trials.





Figure 43: Briquette production at the SENZ facility in Mataura, NZ (© GTLE)

The original intention for the Matura plant was to supply the local industrial market with briquette fuel and provide a raw material for upgrading to other products. However, the commissioning of the plant coincided with low lignite prices and mounting debt within SENZ, causing the company to abandon its plans for upgrading lignite.²¹ SENZ went into voluntary administration in 2015 and was liquidated in March 2018. GTLE has subsequently acquired the Mataura facility and is in the process of offering the unit for sale and relocation to a more commercially attractive location.

5.9.2.2 Flow diagram

GTLE's high level process flow diagram is shown in Figure 44 below.

²¹ https://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=10867047



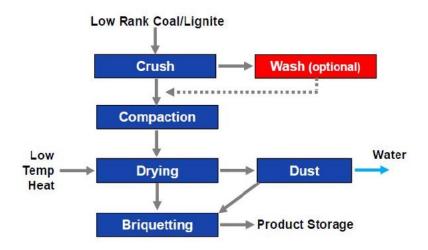


Figure 44: Schematic of GTLE process

Inputs to the GTLE Process are raw coal and low pressure steam heat. The crushing stage converts the raw coal (typically sized to less than 50mm) to a fine material less than a nominal 6mm mesh. Size distributions are dependent on type of coal used.

The crushed coal is mechanically compressed by a double-roll press to destroy and collapse the small pores that are integral to the lignite internal structure. The rolls are a unique GTLE design to maximize pore reformation and moisture condensation.

The low temperature drying or moisture evaporation (coal does not exceed 60°C) ensures that negligible volatile organic compounds are produced as a waste stream, and prevents the coal from becoming brittle as is common with high temperature coal drying alternatives.

The dried, compacted material is then briquetted without binders to produce a relatively stable, non-dusty product compared with raw lignite or high-temperature-dried lignite. Any residual fines from the briquetting process (from webbing) are screened out and recycled into the process or used in a boiler for producing required steam.

Outputs are low moisture coal briquettes (multiple sizes and geometries are possible), water vapor from the dust collection stack and emissions from the dryer steam source. Coal briquettes have a moisture content of 12–16%, depending on the coal characteristics. Substantially all of the dust or fines created during the process can be collected in the dust collectors and recycled into the GTLE Process ensuring near full utilization of the resource.

Water vapor released from the coal through the GTLE Process can be captured and condensed to reduce the overall fresh water needs of energy conversion plants. Tests on the water vapor released from drying coal at low temperature have proven that it is non-toxic.



Because the GTLE process uses conventional industrial equipment in a relatively simple configuration, the process is relatively robust and reliable and can be scaled up to commercial size without developing specialized equipment.

5.9.2.3 Lignite preparation specifications

The crushing stage converts the raw lignite (typically sized to less than 50mm) to a fine material less than a nominal 6mm mesh. Size distributions are dependent on type of lignite used.

5.9.2.4 Mass balance

An analysis of the energy consumption associated with the GTLE process is contained in a life cycle analysis study prepared by consultants Black & Veatch (2012).²²

Assuming a feed of 1 tonne raw Victorian lignite at 60.6% moisture, producing 0.46 tonne at 14.0% moisture:

a) Electricity requirement

Electricity required = 56.7kWh/tonne product²³ Intensity = 204,120kJ/tonne product

b) Steam requirement

Steam required = 618.0kWh/tonne product²⁴ Intensity = 2,224,679kJ/tonne product

c) Energy required for evaporation of water

Total water removed = $[(1 \text{ tonne } \times 0.606) - (0.46 \text{ tonne } \times 0.14)] / 0.46 \text{ tonne product}$

= 1.177 tonnes H₂O/tonne product

Energy required = 618.0kWh/tonne product + 56.7kWh/tonne product

- = 674.7kWh/tonne product
- = 2.429GJ/t product

Energy required = 2.064GJ/tonne water removed

²² Black & Veatch (2012). Life cycle analysis of greenhouse gas emissions. Prepared for GTL Energy, 17 December 2012.

²³ Ibid.

²⁴ Ibid.



5.9.2.5 Plant footprint @ 1.0 million tpa dried lignite

 $90m \times 300m = 27,000m^2 = 2.7ha$

5.9.2.6 Services required

Electricity and low pressure steam heat.

5.9.2.7 CO₂ emissions per tonne of finished product:

a) GHG emissions from steam production

GHG emissions from steam production = 163.6kg CO2-e/MWh = 101.1kg CO2-e /tonne product

b) GHG emissions from electricity production

Assume that electricity is produced using upgraded briquettes as fuel:

Black & Veatch (2012) state that power station production of 5,613GWh/yr requires 2,281,000t/yr lignite and produces 5.6 x 109kg CO2-e/yr.

Thus, GHG emissions from electricity production = 998kg CO2-e/MWh

Electricity required = 56.7kWh/tonne product

Therefore, GHG emissions from electricity production = 56.6kg CO2-e /tonne product

c) Total GHG production

Total GHG emissions from GTLE process = 101.1 + 56.6 = 157.7kg CO2-e /tonne product

The life cycle analysis performed by Black & Veatch indicated that the Victorian lignite upgrading process would result in a GHG emissions saving of approximately 2.9% over the Baseline power generation process.

5.9.2.8 Is the technology capable of capturing CO₂ emissions?

Assuming no associated steam co-generation alternative, the only CO_2 emission from the facility is from the steam generation section – either a coal or natural gas boiler. So, CO_2 can be captured if the boiler system flue gas can be scrubbed.



5.9.2.9 TRL estimate

Given that the GTLE process utilizes commercially available process equipment and has been implemented in two commercial demonstration operations at scales to 250,000tpa, so it can be considered to have achieved a TRL of 7.

The drying and briquetting demonstration work in New Zealand was conducted with Southland lignite, which has a moisture content of 41–64% (Suggate & Isaac 1990) and is a close analogue to Victorian lignite. In addition, preliminary trials have been undertaken with Victorian lignite, using commercial equipment.

As such, the TRL of this process is 6–7 for Victorian lignite.

5.9.2.10 Commercialization pathway

GTLE is seeking partners and customers with an interest in developing projects with full commercial capabilities, based on an existing 1 million tpa reference plant design.

5.9.2.11 Reference plants

GTLE's first commercial scale demonstration plant was a 250,000tpa facility near South Heart, North Dakota, commissioned in 2010. This facility was successfully used for large volume trials with coals from the US, New Zealand and Indonesia. It was recently sold to an Indian firm for relocation to Indonesia, where it will be used commercially to produce briguettes from Indonesian sub-bituminous coals.

The second commercial facility was a 100,000tpa briquette factory in Mataura, New Zealand, constructed and owned by Solid Energy New Zealand Limited (SENZ). This has since been reacquired by GTLE and is under negotiation for relocation.

5.9.2.12 Product Development and Testing

Since its inception, GTLE has worked closely with Hazen Laboratory, Golden CO, to develop and test products made using the GTLE process. Over time, dozens of coals from around the world have been processed using smaller, commercial scale equipment, then evaluated using standard industry quality testing methods. While each coal demonstrated varying characteristics for production, the GTLE process was shown to work effectively in most instances.

Third party testing has also been completed on several sample products with similar success. Of particular interest was a very detailed combustion study performed by the ACIRL labs in Australia for the SENZ development program.



A commercial scale test burn has also been completed at the Laskin Power Plant of MP&L. An Indonesian coal processed at GTLE's South Heart plant was successfully burned in a test run lasting several hours with a 4 MW increased power production versus the design coal from Illinois. No handling or other combustion issues were noted.

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BCIA comments

The GTLE process has been proven to produce good quality briquettes from Victorian lignite in preliminary trials. The technology has been demonstrated in North Dakota at 250,000 tpa scale, and could be scaled up in parallel with minimal technical risk. The base technology is robust with a proven drying medium (Davenport dryer) and briquetting machines (Komarek) adapted for both compaction and briquetting. The briquette circuit could be removed if only dried coal was a desired outcome and output would be increased.

This is a potentially good prospect for commercial implementation.



6. Effect of drying process on spontaneous combustion and transportability

Dried lignite is unstable in the presence of moisture and oxygen, and has a tendency to spontaneously combust. In the absence of moisture, atmospheric oxygen reacts with hydrogen groups in the lignite structure, liberating heat. At low temperatures, the reaction rate is slow and the heat generated is insufficient to initiate combustion. In the presence of humid air, however, dried lignite will readsorb moisture, releasing the heat of vaporisation. Under the right conditions, this can raise the temperature enough to accelerate the exothermic oxidation reaction and initiate combustion. This is a major risk associated with the storage and transport of dried lignite.

The propensity for spontaneous combustion of dried lignite, also known as its 'reactivity', is influenced by the following factors:

- a) Surface area for moisture readsorption, which involves:
 - i. Particle size small particles present a much larger accessible surface;
 - ii. Pore size distribution mesopores (diameter 2–50nm) present a larger surface area than macropores (diameter > 50nm) and are more accessible to water vapor than micropores (diameter < 2nm); and
 - iii. The presence or absence of oily components which can block the pores and prevent moisture readsorption.
- b) The surface concentration of hydrophilic hydroxyl and carboxyl functional groups, which provide sites for moisture readsorption.

The difference between moisture content of the lignite and the equilibrium moisture content – more initial moisture means a lower driving force for readsorption (note that this is one reason for the target moisture of dried coal as being between 12% and 15%, which roughly equates with atmospheric moisture conditions).

- c) Mineral composition of the lignite, including:
 - i. Alkaline earth metals and pyrite promotes spontaneous combustion; but
 - ii. A high proportion of mineral matter will dilute the heat generation and inhibit spontaneous combustion.

Each lignite drying process will influence these factors in different ways. For example:

- Vacuum drying has the least effect on surface chemistry and pore structure, and produces a highly reactive dried coal.
- Drying at high temperature can reduce the concentration of surface functional groups. In addition, volatile components may be (i) partially mobilised and reform as tars to block pores, or (ii) volatilised to leave a carbon-enriched solid.



- Hydrothermal or mechanical-thermal extraction (MTE) dewatering can reduce the concentration of mineral components.
- Pressing and briquetting can collapse internal pores and produce large chunks with relatively low surface area
- Solvent drying, such as Kobe Steel's Upgraded Brown Coal (UBC) process, stabilises lignite by blocking the pores with a film of heavy oil.

While there have been a number of published studies which have examined the reactivity of lignites dried by various means, there is very little data to inform a direct comparison between the effectiveness of various drying methods. With the current state of knowledge²⁵, only a crude comparative ranking is possible. Assuming similar particle sizes, the reactivity of dried lignite produced by different drying technologies is listed below, from most reactive to least:

- Vacuum drying
- Hydrothermal dewatering (when fully dry but not at 50% moisture)
- Steam drying and briquetting
- MTE (when fully dry but not at 50% moisture)
- Flash drying / Mild microwave drying
- Air drying
- Fluidized bed drying
- Solvent evaporative drying
- Torrefaction
- UBC
- Alkali-densification

For any given application, the propensity for spontaneous combustion may be a factor in the selection of an appropriate lignite drying technology, although the efficiency and costs of the process would usually be more important factors to consider.

However, the physical state of the dried product is an important factor for safe handling of upgraded lignite, which is an important consideration. Lignite dust is highly explosible, with explosibility increasing with decreasing moisture content and particle size, and with increasing volatile matter content (Woskoboenko 1988). The presence of lignite dust increases the risk of explosion and spontaneous combustion, and must be explicitly taken into account in any lignite processing operation.

In Victoria, the SECV gained experience in safe handling of bulk lignite dust, during trials of dust-fired railway locomotives in 1949-50. During these trials, using precipitator dust (6% moisture) from the Yallourn briquetting works, it was learned that the dust could be safely stored in sealed hoppers up to 28 tonnes

²⁵ See the following references: Chaffee et al. 2014; Choi et al. 2014; Fei et al. 2009; Jones & Raj 1989; Liao et al. 2016; Liu et al. 2016; Parsa et al. 2017; Ünal et al. 1992; Yuan et al. 2016.



capacity for at least four weeks (and probably indefinitely) at a temperature not exceeding 55°C (Herman 1952, p. 526).

Similarly, as mentioned in Section 5.5.2.1 above, Great River Energy transports 600,000 tpa of beneficiated lignite over 240km, from its Coal Creek Station drying plant to Spiritwood Station, in enclosed rail cars.

However, transport of lignite dust is not regarded as suitable as an option for transport by ship, where loading into open holds would create an unacceptable explosion risk. For transport by ship, the lignite must first be briquetted. Briquetting collapses the pore structure and removes a portion of the surface functional groups, thereby reducing the reactivity, and minimises the amount of dust produced during handling.

The strength of lignite briquettes is affected by the particle size distribution, which is in turn affected by the drying conditions. In general, finer particles produce stronger briquettes, but a mixture of smaller and larger particles is needed so that the interstices are filled and contact between particles is maximised. Industrially, the crushed lignite is screened to remove sizes greater than 4mm and over 50% of the feed is finer than 1mm (Ellison & Stanmore 1981). Thus, it is likely, although unproven, that high impact drying processes producing a very fine powder with narrow size distribution would be undesirable in association with briquetting processes.

The SECV developed protocols for safe transport of lignite briquettes by ship in sealed holds. The key requirements were that the briquettes should be at least seven days old, to allow the initial high rate of oxidation to occur safely in land stockpiles, and that the ship's hold should remain sealed throughout the voyage. The procedures developed by the SECV for safe shipping of briquettes were based on sound scientific principles and were successfully applied for 25 years. The principle of using sealed holds and "weathered" cargo could also be applied to other reactive coal cargos (Cunningham et al. 1992).

The key conclusion from this is that, for any given application, both the method of drying and the final form of the dried lignite are important considerations. If the product is intended to be used nearby to the drying plant, and massive stockpiles are not required, then a powdered product could be managed with appropriate safety precautions to avoid spontaneous combustion. In this case, the costs (both capex and opex) and reliability of the drying technology are the main considerations.

If large quantities of dry lignite have to be stockpiled, or the product is intended for export by ship, then briquetting is essential to minimise the risk of spontaneous combustion. In this case, the ability of the drying process to reliably and cost-effectively supply the briquetting plant, with an appropriate particle size distribution, would be major considerations.



7. Synthesis and evaluation

From the lignite drying technologies described in Section 5, it is evident that a diverse range of options exist, at varying degrees of technical maturity. This makes it difficult to assess the relative merits of each process. In order to provide an accessible basis for comparison, Table 7 below provides a summary of the key characteristics of each technology.

7.1. TRL LEVEL

Perhaps one of the most important characteristics to consider is the technology readiness level (TRL) of each process, as an indication of its technical maturity (defined in the Appendix). This is because the TRL will give an indication of the risk level, both in terms of technology and cost in selecting a drying process. Assessment of the TRL for any technology is not straightforward, and is highly subjective. For example, a TRL of 6 denotes a technology that has been fully proven at pilot scale, under realistic operating conditions, using a representative feedstock material. Ideally, a TRL of 6 would apply to a process in which all of the control and safety systems have been thoroughly tested under realistic operating conditions, and all the necessary scale-up parameters have been validated. In practice, this degree of validation is difficult to achieve, leaving room for differences in interpretation.

This leads to difficulties in comparing lignite drying technologies from around the world, since a process that has been established at TRL 6 for drying Chinese lignite from 45% to 30% moisture, say, cannot be said to be validated sufficiently for drying Victorian lignite from 65% to 15% moisture.

For the purposes of this report, all the available technologies have been assigned a subjective TRL ranking on the basis of drying Victorian lignite, since this represents the highest moisture content feedstock that may be expected. The TRL assigned is based on the knowledge and experience of BCIA and informed by relevant science based papers.

On this TRL ranking basis, the technologies can be assigned to four tiers of technology readiness, i.e.:

- ▶ Tier 1 (TRL > 6): RWE, Torftech Group, GTL Energy
- Tier 2 (TRL 6): ECT, Exergen, IER
- Tier 3 (TRL 5): Drycol Australia, Great River Energy, Kumera, NSENGI
- Tier 4 (TRL < 5): Ahrko, Cartwheel, KIER, Torreco

Currently, RWE's WTA fluidized bed drying process is the only technology that is at commercial scale under conditions representative of Victorian lignite. However, GTL Energy's combined pressing and drying system has been proven at demonstration scale with a similar lignite from New Zealand, and Torftech Group has sufficient pilot scale experience with Victorian lignite to design a large-scale TORBED drying system (generally at TRL 9) with confidence.



The second tier of technology comprises those with established experience at pilot scale with Victorian lignite. Of these, ECT is currently designing a large-scale facility in India for its Coldry process, while Exergen and IER have yet to find a market for their hydrothermal dewatering processes.

The third tier represents processes that are well established in other areas, and could reasonably be adapted to Victorian lignite through a program of pilot trials. A full-scale module of Drycol Australia's microwave drying process is currently processing Powder River Basin coal (28% moisture) for a commercial customer, and Great River Energy's DryFining process is successfully processing lignite (38% moisture) at Coal Creek Station. NSENGI's fluidized bed dryer is at TRL 9 for coking coal, and its modified version with added steam tubes has dried Victorian lignite from 60% to 30% moisture. Kumera Corporation has numerous applications of its tubular steam dryer for mineral concentrate drying (TRL 9), and has established the feasibility of drying lignite in its own pilot plant.

The fourth tier represents drying technologies that are focussed on a commercial outcome, but have not yet been sufficiently proven at pilot scale. These are interesting, but present a higher technical and commercial risk.

		Energy Intensity			Area		
Company	Drying Technology	TRL	Product basis, GJ/t product	Evaporative basis, GJ/t H ₂ O removed	GHG Intensity, t CO2-e/t product	for 1 Mt/yr, ha	Suitability for briquetting
Ahrko Systems	Swirling Pipe	4	n.d.	n.d.	n.d.	n.d.	No
Cartwheel Resources	Intense Gas Vortex	4	n.d.	n.d.	n.d.	n.d.	No
Drycol Australia	Microwave	5	2.23	1.98	0	1.71	Likely
ECT	Coldry	6	-	-	0	2.4	Yes
Exergen	CHTD ²⁶	6	0.13	0.2	0.04	n.d.	-
Great River Energy	DryFining	5	-	-	0	0.03	Possibly
GTL Energy	Roll press & tubular steam drying	6-7	2.43	2.06	0.16	2.7	Yes
IER	Cat-HTR ²⁷	6	n.d.	n.d.	0.16	15	No
KIER	COMB	4-5	4.00	3.14	0.42	3.6	Possibly
Kumera	Steam dryer	5	2.30	2.04	0.13	< 1	Likely
NSENGI	Fluidized bed	5	-	-	0	0.15	Possibly
RWE	WTA	8-9	0.75	0.63	0	0.26	Yes
Torftech	TORBED	6-7	3.87	3.11	0.37	0.43	No
Torreco	Torrefaction	4-5	n.d.	n.d.	n.d.	n.d.	No

Table 7: Comparison of lignite drying process performance

Dewaters to a moisture content of ~50%
 Produces both a synthetic crude oil and upgraded coal



7.2. SAFETY AND HANDLING

Another important characteristic to consider is the physical state of the product from the drying process, since this will dictate how the product can be safely handled and transported. A powdered product would be prone to spontaneous combustion or dust explosion, and can only be transported short distances in sealed containers. Finely powdered lignite cannot be briquetted for safe storage and transport without the use of binders, which are likely to be prohibitively expensive. Note that lignites have a wide variety of characteristics and the suitability for binderless briquettes is reliant on suitable characteristics as it is to the drying process.

In terms of producing a dried product suitable for binderless briquetting, the technologies may be ranked as follows:

- Tier 1: RWE, GTL Energy, ECT, (Drycol Australia), (Kumera), (Davenport Dryer)
- ▶ Tier 2: Great River Energy, NSENGI, KIER
- Tier 3: Ahrko, Cartwheel, IER, Torftech, Torreco

The first tier processes are those that are known to be suitable for producing binderless briquettes from Victorian brown coal, and are those that are therefore the most suitable for producing an export-grade product. This category also includes Drycol Australia and Kumera, since these processes are regarded as likely to produce dried lignite suitable for briquetting, although they have not been tested in this application. Davenport Dryer is also included because its steam tube dryer was used by GTL Energy to produce briquettes from North Dakota and New Zealand lignite.

The second tier processes are thought to be likely to produce briquette-grade product, but this would need to be validated through a program of pilot trials. There is a concern about the potential for significant dust production in each of these processes. The suitability of these processes for briquette production may be dependent on finding an alternative use of the dust, e.g. heat generation.

The third tier of processes are definitely unsuitable for briquette production. The Ahrko, Cartwheel and Torftech processes would each produce a fine lignite powder, potentially suitable as gasifier feedstock but not for briquetting. The IER and Torreco processes would produce a char-type product that could not be briquetted without a binder.

The Exergen process is not included in this ranking because it only dewaters Victorian lignite to 50% moisture, and requires further processing to the dried state. The quality of the resulting product will depend on the drying process employed.

7.3. ENERGY EFFICIENCY

Each of the technology providers was asked to provide mass and energy balance data, to allow estimation of the energy efficiency of the drying processes and the greenhouse gas intensity of each. Unfortunately, the



data obtained does not provide a straightforward basis for comparison. As shown in Table 7, there is wide scatter in the data and numerous gaps.

The gaps occur for two reasons. Firstly, some of the companies did not provide any relevant mass/energy balance data, i.e. Ahrko, Cartwheel, IER and Torreco. Secondly, some of them (ECT, Great River Energy and NSENGI) assumed that a source of industrial waste heat would be freely available to provide the energy for drying, so drying efficiency was not thought to be a relevant issue.

For those that did provide relevant data, three tiers of energy efficiency were apparent. The most efficient process was RWE's WTA fluidized bed dryer, which uses superheated steam with vapor recompression for energy recovery.

Next, with lower but similar energy efficiencies, were:

- Drycol Australia's microwave drying process
- GTL Energy's pressing and tubular steam drying process
- Kumera's tubular steam drying process with separate heat recovery dryer

It is interesting that the energy requirements for these technologies are so similar, despite the very different processes involved.

The least efficient drying processes were KIER's COMB dryer and Torftech's TORBED reactor. Both of these processes are types of flash drying and are hence very sensitive to the lignite particle size. In each case, the drying performance is limited by the drying rate of the larger particles, while particles under 1mm diameter dry very rapidly.

While Exergen's CHTD process appears to be the most energy efficient, this is only because it only dewaters to 50% moisture. As such, this is not a fair comparison.

7.4. GREENHOUSE GAS INTENSITY

The data available on greenhouse gas intensity for each process is even more varied than that for energy efficiency. In general, it would be expected that the most efficient processes would create the least CO_2 emissions. This is reflected in the observation that the CO_2 emissions for the KIER and Torftech processes are similar and significantly higher than those for the GTL Energy and Kumera processes.

On the other hand, some of the processes claim to have zero CO_2 emissions, which is achieved by attributing such emissions back to the sources of electricity (Drycol Australia and others), steam (RWE) and waste heat (ECT, NSENGI). The merits of this interpretation are arguable, and would not be supported by a life cycle analysis of each process.



7.5. PLANT FOOTPRINT

Table 7 includes a preliminary estimate of the area required for each drying technology to produce 1.0 million tpa of dried lignite. There is a wide scatter in the estimates provided by vendors, making interpretation rather problematic. However, some insight may be gained by considering the various approaches to scale-up of each technology.

In principle, the most compact drying configuration should be achieved using a single cylindrical drying chamber, as this provides the greatest volumetric capacity for a given surface area. This is exemplified by RWE's WTA fluidised bed, which comprises a single cylindrical drying chamber. For a 1.0 million tpa plant, RWE indicated that the space required would be 35m x 75m, i.e. 0.26 ha, which includes also the necessary access and lay-down space for service and repair work.

If the target plant capacity is achieved by using a greater number of smaller drying chambers, it may be expected that the plant footprint would increase in proportion. The overall space requirement would then depend on both the relative efficiency of each drying technology and the number of 'standard' modules needed to achieve the target throughput. For example:

- Torftech Group's TORBED CFB reactor would require 8 modules (each 18m x 30m x 23m high), i.e. 0.43ha, to produce 1.0 million tpa.
- Drycol Australia would require 19 of its 3MWh microwave platforms, each 45m by 20m, for a total of 1.71ha.
- ECT would require 6 of its 170,000 tpa Coldry modules, for a combined area of ~200m x 120m total, or 2 4ha
- ▶ GTL Energy would require 90m x 300m, or 2.7ha, for an unknown number of lines of its roll press and tubular steam drying process.
- KIER would require 95 of its 100 tonne/day COMB drying modules, for a combined area of 3.6ha. This is clearly impractical, but a more realistic estimate awaits the validation of the COMB process design at demonstration scale.

From Table 7 it can be seen that Great River Energy and NSENGI each provided very low footprint estimates for their technologies (0.03ha and 0.15ha, respectively), but these are not regarded as credible. Both processes rely on the use of waste heat, which can be of widely varying quality, and neither process has yet been validated for drying Victorian lignite to 15% moisture. As such, the estimates that were provided are regarded as speculative.

IER provided an estimated footprint of 15ha for its Cat-HTR process, with no explanation to justify this unusually large area. It is possible that, like KIER, the inflated area is based on multiplication of an early pilot scale design. As such, it does not seem credible.



An alternative approach to achieving a compact plant design is to stack multiple dryers over multiple levels in a drying facility. This was approach was suggested by Kumera, with the required 1.0 million tpa throughput being achieved using two processing lines, each comprising two Kumera steam dryers stacked vertically. In this way, the required footprint was estimated to be less than 1 ha.

This analysis suggests that the drying processes requiring only a small number of modules in parallel will occupy the smallest amount of space. This tends to be correlated with the experience of the vendor at commercial or demonstration scale. It may be expected that the footprint estimates for other drying processes will be reduced following a program of pilot scale work with Victorian lignite to improve confidence in scale-up.

7.6. COST CONSIDERATIONS

In general, vendors were unwilling to provide cost estimates for this report, for a variety of reasons. For one, the installed cost will be site-specific and, since few of the vendors currently have reference plants in Australia, separate engineering studies would be required to develop indicative cost estimates for drying Victorian lignite. In some cases, a program of pilot-scale work would be required to generate the engineering data needed before design of a commercial processing plant could be considered.

The plant footprint required for the drying process may be regarded as one of the factors influencing the overall cost. In general, the least expensive processes are likely to be those that require the least amount of space, since this reflects factors such as the experience of the vendor at commercial or demonstration scale, the cost and complexity of installing multiple drying modules in parallel, and the need to provide services (e.g. steam, electricity, waste heat) to each module.

Another variable that may need to be considered is the potential to recover the latent heat of vaporisation of the water removed during drying. While this can result in lower operating costs over the life of the equipment, it comes at the expense of a higher initial capital investment. Selection of the most appropriate option would need to be considered as part of the overall investment strategy for the project.

Other factors that will influence the process costs include the availability and quality of waste heat, and the cost of access to electricity and/or steam. The upstream costs associated with lignite handling may also be quite significant, especially if there is to be a number of drying modules in parallel. Downstream, systems will be needed for dust collection, handling and disposal, which may require a program of pilot-scale work to properly design.

Given the range of variables involved, it is not currently possible to speculate on the relative cost-effectiveness of the lignite drying technologies available. As a next step, it would be preferable to fund a short-list of vendors to provide an indicative quote for a drying plant in a specific location, where the availability of waste



heat, steam, etc. is clearly defined. A program of pilot-scale work may be required to generate the data needed for cost estimation.

8. Conclusions

This report provides a comparison of contemporary drying technologies that could be considered for projects seeking to utilize dried or briquetted lignite. The technology chosen would need to reflect the project's outputs and anticipated utilisation requirements. It is primarily based on information from relevant technology vendors supported by scientific papers where available, with a focus on drying of Victorian lignite, as a worst-case scenario. Not all contacted vendors responded, and it appears that some are no longer in business. Where this was unable to be verified, the best available contact details have been provided.

It is evident that there is still a wide variety of lignite drying technologies potentially able to be utilised in any given project. One of the main drivers for innovation in lignite drying technologies has been the quest for energy-efficient means to remove the high level of moisture present in lignite. This has led to the development of a range of evaporative and non-evaporative approaches, as well as innovative combinations of both, each with its advantages and disadvantages. However, only a small number have been adequately proven with Victorian brown coal, while others would require a program of pilot-scale trials to develop the data needed to scale up with confidence. As noted the reference coal is Victorian lignite and the relative efficiency performance of each technology has been assessed against this coal. It is possible that some technologies will perform better or worse against different coals. It should also be noted that high efficiency might not mean low cost when capital and operating costs are taken into account. In addition, the kinetics of each process is different, some technologies have a rapid drying rate others are slower but provide a product mix that is more versatile.

Despite this limitation, it is evident that there is still a wide variety of lignite drying technologies available. One of the main drivers for innovation in lignite drying technologies has been the quest for energy-efficient means to remove the high level of moisture present in lignite. This has led to the development of a range of evaporative and non-evaporative approaches, as well as innovative combinations of both, each with its advantages and disadvantages. However, only a small number have been adequately proven with Victorian brown coal, while others would require a program of pilot-scale trials to develop the data needed to scale up with confidence.

The most energy efficient process was found to be RWE's WTA fluidized bed dryer, using superheated steam with vapor recompression for energy recovery. Next, with similar energy efficiencies despite their different approaches, were Drycol Australia's microwave drying process, GTL Energy's pressing and tubular steam drying process, and Kumera's tubular steam drying process with separate heat recovery dryer. The least



efficient process were KIER's COMB and Torftech's TORBED flash drying systems, which are limited by the presence of lignite particles larger than 1mm diameter.

The drying technologies could also be differentiated between those that produce a fine, dusty powder, suitable for use as a gasifier feedstock, and those that produce a heterogeneous product suitable for binderless briquetting. In terms of making a dried product suitable for binderless briquetting and thus long-distance transport, the most suitable technologies were RWE's WTA fluidized bed dryer (coarse grained), the ZEMAG dryer, GTL Energy's pressing and tubular steam drying process (which uses Davenport steam tube dryers), and ECT's Coldry process. Other drying technologies that may also be suited to this application include those from Drycol Australia, Kumera, Great River Energy, NSENGI and KIER, but this would need to be validated through a program of pilot trials.

Other processes are regarded as definitely unsuitable for briquette production. The Ahrko, Cartwheel and Torftech processes would each produce a fine lignite powder, potentially suitable as gasifier feedstock but not for briquetting. The IER and Torreco processes would produce a char-type product that could not be briquetted without a binder.

Each drying process will affect the reactivity, or propensity for spontaneous combustion in a different way, although there has been no systematic study done to quantify the relative differences. For any given application, the reactivity may be a factor in the selection of an appropriate lignite drying technology, although the efficiency and costs of the process would likely be given higher priority.

There is no quantitative data currently available to allow a ranking of the relative cost-effectiveness of the various lignite drying technologies. In each case, the capital and operating costs will depend on site-specific factors, such as the availability and quality of waste heat, and the cost of access to electricity and/or steam. In general, the least expensive processes are likely to be those that require the least amount of space, since this reflects factors such as the experience of the vendor at commercial or demonstration scale, the cost and complexity of installing multiple drying modules in parallel, and the need to provide services (e.g. steam, electricity, waste heat) to each module. The costs associated with lignite handling will depend on the number of drying modules installed in parallel. Downstream, systems will be needed for dust collection, handling and disposal. Available options for utilisation of recovered latent heat will also affect costs.

As a next step, it would be preferable to fund a short-list of vendors to provide an indicative quote for a drying plant in a specific location. A program of pilot-scale work may be required to generate the necessary data.

It is clear from this report that there is no single drying technology that is available off the shelf and useful in all lignite applications. There are good options available for drying Victorian lignite, but most still involve a degree of technical risk with concurrent commercial risk. Proponents of new projects that require lignite drying are advised to engage with selected technology providers to derisk the drying process through appropriate pilot scale work.



9. Appendix: Technology Readiness Levels

The technology readiness level (TRL) index was developed by NASA during the 1970s and has since become a globally accepted benchmarking tool for tracking the progress and development of technologies, from blue sky research to actual system demonstration over the full range of expected conditions (Australian Renewable Energy Agency 2014).

The nine different TRLs are defined by CSIRO (Cavanagh et al. 2015) as:

- **TRL 1**: Scientific research begins translation to applied research and development. This is the lowest level of technology readiness. Examples might include basic paper studies of a technology's properties.
- **TRL 2**: Creation and invention begins. Basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytical studies.
- **TRL 3**: Active research and development is initiated. This includes analytical studies and laboratory studies to validate predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
- **TRL 4**: Basic technological components are integrated. Fundamental technological components are integrated to establish a system that works well work together.
- **TRL 5**: Reliability of the technology improves significantly. The technological components are integrated with reasonable reliability so it can be tested in a simulated environment. Examples include 'high-fidelity' laboratory integration of the technologies' components.
- **TRL 6**: Model and/or prototype system is tested in relevant or simulated application environment. Model or prototype, which is well beyond that of TRL 5, is tested in a relevant environment. This is a major step-up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment with a publication or technical report documenting the outcomes.
- **TRL 7**: Prototype near or at planned operational system. This represents a major step from TRL 6, in that it requires demonstration of an 'actual' system in an operational 'field' environment.
- **TRL 8**: Technology is proven to work. Technology completed and qualified through commission, testing and demonstration with minor technical issues.
- **TRL 9**: Actual application of technology is in its final form e.g. mature technology. Technology has proven itself through numerous successful operations and can be purchased commercially 'off-the-shelf'.



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