Federation University

Alternate Uses for Yallourn and Loy Yang Lignites

Assessment and Comparison of the Quality of Yallourn and Loy Yang Lignites in Relation to their Suitability for Alternate Uses

Confidential report prepared by the Carbon Technology Research Group for Environmental Clean Technologies Ltd

4th February 2022

ENVIRONMENTAL CLEAN TECHNOLOGIES LIMITED

Foreword

Environmental Clean Technologies ("ECT") is pleased to have supported Federation University in commissioning this report on the "**Alternate uses of Yallourn and Loy Yang Lignites.**"

Our company has been pursuing zero and low emissions use of lignite for over 15 years. However, over that time, available reports on the various lignite seams and their applicability to future applications have become dated and unreliable. This initiative intends to assemble all available, relevant data into one report, updated for the acceleration of technology solutions increasingly available to lignite as a feedstock. We see this report as a useful industry resource providing a ready reference for technology companies, research organisations and Governments alike when assessing the long-term value of Victoria's world-class lignite resources.

Through its headline "**Net Zero Emission Hydrogen Refinery"** project, ECT is pursuing a whole of resource approach that targets a carbon-negative footprint with zero waste discharge. The report most notably identifies "**four promising candidates for commercial production from Yallourn lignite: metallurgical reductants, hydrogen, humic substances and fertilisers**" (p33) and aligns well with both ECT's headline project and its suite of technologies:

COLDry	HydroMOR	COHGen
Zero-emission lignite drying	Primary iron production. Lignite-based, hydrogen-driven.	Next generation, low emission lignite-to-hydrogen technology
Ref: pp1-3, 8,10,12-15, 25 & 27	Ref: pp2,13 & 26	Ref: pp2, 26 & 30

Additionally, "**Advanced carbons such as carbon fibre, graphene, graphene oxide and quantum dots grow could also be commercially valuable products if these markets gro**w." (p33)

ECT has been reimagining the future use of lignite through the development of a suite of technologies and complementary processes transforming the resource via the highest environmental standards of mining and processing - ultimately delivering low-cost Viridian+* hydrogen, soil carbon and critical minerals in advanced carbon products, like graphite.

Realising this vision will accelerate Victoria's support of the burgeoning renewable, clean fuel and soil health economy. Zero Emission Fuel, Renewables and Food – the three most critical components of a sustainable future.

The stakes are high, and the region's wealth, jobs, and environment depend on preserving these lignite seams for future use. If done right, we could see the next Sir John Monash moment about to unfold in Victoria.

I sincerely hope that this report helps to inspire and inform the reader of the vast potential we have in our Victorian lignite reserves and that the application of modern technologies can deliver the best of both worlds – economic prosperity and environmental sustainability.

Thank you,

Glenn Fozard

Managing Director
Environmental Clean Technologies Limited

Federation University

Table of Contents

Executive Summary

This report commissioned by ECT identifies metallurgical reductants, hydrogen, humic substances and fertilizers as promising candidates for manufacturing in Victoria from Yallourn mine lignite. Depending on market conditions and research progress, carbon fibre, graphene, graphene oxide and quantum dots could become commercially attractive products in the medium-term.

Yallourn lignite has been used commercially in a number of industries including agglomeration, carbonisation, gasification, steel recarburisation etc. These commercial precedents highlight the relative ease of access to Yallourn mine lignite as well as its favourable properties. The ability to selectively reject hard, high-density, cracked material (typical of dark lithotypes and gelified macerals) has been important for some applications. Victorian lignite properties are highly variable and selective mining and/or lignite processing would offer improved process stability as well as product quality and consistency in many applications.

Technical investigation into at-line sensor and lignite sorting or selective mining technologies are recommended. Selective processing of Yallourn mine lignites could significantly reduce commercial risks related to woody lignites and dark lithotypes. Woody material in the rejected lignite could be sold for potting mixes or converted to activated carbons. There could be an opportunity to convert lignin-rich dark lithotypes to advanced carbon products like carbon fibre.

1 Background

This review into the benefits of Yallourn lignite compared to other Victorian lignites was commissioned by ECT. The identification of commercially attractive alternative uses is based on an overview of Yallourn, Loy Yang, Bacchus Marsh and Morwell lignite properties. Although lignite is no longer available from the Morwell mine, extensive research and commercial experience with this lignite are relevant to the review.

The review of lignite properties makes use of extensive historical datasets which are complemented by valuable data on the recent and future properties of Yallourn and Loy Yang mine lignites. Where relevant, recent research directions and findings are briefly discussed. This report excludes mining and mine rehabilitation considerations. The commercial prospects evaluation is based on a 1996 report (Verheyen, 1996). Tentative commercial prospects scores assigned to new lignite uses are based on similar products in the 1996 report or published data.

The key properties of Yallourn lignite generally relate to the low rank (i.e., high moisture content) and dark lithotype content (i.e., high gelified and woody lignite maceral content that tends to be hard and dense or fibrous). Dark lithotype and woody lignite macerals have been successfully rejected from Yallourn run-of-mine lignites prior to agglomeration and carbonisation for many decades. Yallourn lignite lithotypes are also generally well stratified, suggesting that contemporary at-line sensor technologies could be valuable for assisting selective mining or separating mined lignite for further processing. Options for at-line identification of desirable lignite properties include image processing based on colour, reflectance and fluorescence. Further technical investigation and research is recommended into adapting existing sensor and sorting technologies to Yallourn and other Victorian lignite.

The most promising technologies identified in this report are similar to those recommended by similar recent reviews(GHD, 2019; McManus, 2019; DJPR, 2021). These technologies include metallurgical reductants, hydrogen, humic substances and fertilizers. These products all have well-established local or international commercial precedents. Most products would benefit from rejecting hard, dense dark lithotypes and fibrous woody lignite but some products like activated carbons and phenols could be produced from rejected woody lignite (associated with high porosity carbons) or dark lithotypes (typically rich in phenolics). Opportunities to utilise CO_2 to extract or up-grade chemicals are also identified.

1.1 ECT Background

Environmental Clean Technologies Limited (ECT) own and are developing a portfolio of lignite upgrading and non-fuel lignite technologies which upgrade low-rank and waste feedstocks, refining them into higher value products with a low or net zero emissions footprint. The patented Coldry process has been demonstrated at pilot scale and a 25 000 tpa commercial demonstration plant is expected to be completed in 2022 (ECT, 2021). Coldry uses mechanical work to produce a densified lignite product (ECT, n.d.). The

drying process is more energy-efficient than conventional thermal drying and produces pellets which can be transported (ECT, n.d.). The use of low grade waste heat, is central to its efficiency allowing for no direct combustion of the feedstock and preserving the original chemical form of all constituents inherent in the feedstock whilst removing the water.

The Coldry product is central to the other iron processing (HydroMOR), hydrogen production (COHgen, catalytic organic hydrogen generation) and liquid fuels (CDP-WTE, catalytic depolymerisation waste-to-energy) patented technologies that ECT is developing (ECT, n.d.). Beneficial lignite properties for these processes are identified where relevant.

2 Current Victorian Brown Lignite Mining and Use

The vast quantities of potentially economically feasible lignite (33 billion tonne) in Victoria are mostly located in the Gippsland Basin and the Otway Basin (DELWP, 2020). The Loy Yang and Yallourn lignite mines are active in the Gippsland Basin (DELWP, 2020) and the Maddingley No 2 mine is active in the Otway Basin at Bacchus Marsh. The Gippsland Basin lignite is primary used for thermal electricity generation with smaller quantities used to manufacture briquettes and agricultural products. The Maddingley No 2 mine site is used as a landfill and the lignite is used in fertilisers (Calleja Group, n.d.). The ECT commercial demonstration facility is located in Bacchus Marsh.

2.1 Gippsland Basin

Victorian lignite from the Gippsland basin is generally low in ash, sulfur, heavy metals and nitrogen (DELWP, 2020). Despite the high moisture content (48-70% w/w), (DELWP, 2020), lignite mining near Yallourn at the Great Morwell Mine commenced in 1887 and the Great Morwell Coal Mining Company produced briquettes from 1892 to 1898 or 1899 (DJPR, 2021; Vines, 2008). Electricity generation from Victorian lignite in Gippsland was established by the State Electricity Commission of Victoria (SECV) in the 1920s (Vines, 2008; DJPR, 2021) and lignite-fired power stations continue to supply the majority of Victoria's electricity (DJPR, 2020).

Producing briquettes from Victorian lignites has been fraught with technical difficulties (Vines, 2008) – highlighting the unique Victorian lignite properties and the wide variation in properties across the various basins and seams. Briquetting was necessary to produce a transportable hard dry lump form of lignite. Appropriate attention to research and development facilitated commercial briquetting of lignites from Yallourn (Vines, 2008; DJPR, 2020) and later Loy Yang mines. Briquettes are currently produced from Loy Yang run-of-mine lignite and wood waste by IronWood at Morwell.

Reliable briquette production enabled other products including char and town gas to be produced from Victorian lignite in Gippsland. Raw and briquetted lignite was used to produce synthetic natural gas in Victoria from 1956, although the Morwell Gasification Plant closed in 1969 due to competition from natural gas ((Vines, 2008, p21).

In recent years, the Morwell lignite mine and Hazelwood power station have closed. The Loy Yang and Yallourn power stations and mines are scheduled to close in the coming decades. Agricultural products, particularly humic acids, continue to be produced and exported from Gippsland basin lignites (Omnia Nutriology, 2021).

2.1.1 Yallourn open cut mine

The current Yallourn open cut mine developed from the Great Morwell Mine and the lignite was used extensively for power generation and briquetting. Early attempts at briquetting were frustrated by technical difficulties arising from a poor understanding of the wide variation in lignite properties within seams. In particular, variable moisture content, maintenance issues caused by high sand areas (Higgins, Kiss, & Allardice, n.d.; Vines, 2008). Many of these difficulties were overcome by avoiding areas rich in silica, sand, woody lignite, dark lithotypes or moisture and around three million tonnes per year of Yallourn lignite was transported to the Morwell Briquette Works between 1960 and 2003 (Higgins, Kiss, & Allardice, n.d.; Vines, 2008). Unlike the adjacent Morwell open cut mine lignites, low moisture, low silica, woody maceral-free and light lithotype Yallourn lignites reliably produced strong, abrasion- and weathering resistant briquettes suitable for carbonisation and industrial boilers were successfully (Higgins, Kiss, & Allardice, n.d.; Vines, 2008).

Figure 1. Yallourn open cut mine east field (V Verheyen, n.d.)

2.1.2 Loy Yang open cut mine

The current Loy Yang open cut mine lignite production commenced in 1983 for commissioning the Loy Yang power station (Vines, 2008). Managing lignite quality and avoiding pockets of high sodium, overburden contamination, historical sediment contamination (typically associated with lignites naturally exposed to the elements or severely weathered), high ash, interseam intrusions and moisture content variability has been a challenge throughout the life of the Loy Yang mine. Nevertheless, lignite from the Loy Yang mine has been successfully used for thermal power production, converted to dry pulverised lignite, briquettes and agricultural products.

2.2 Maddingley Seam Lignite Mines

Bacchus Marsh lignite seams were identified in the 1890's and mining commenced at the Maddingley Brown Coal Mine Number One in 1944 (Vines, 2008). Four years later, the Maddingley Brown Coal Mine Number Two (Maddingley No 2) was established. Lignite from these mines was used primarily by Australian Paper Manufacturers but by 1992, Australian Paper Manufactures had replaced lignite-plant with natural gas burners (Vines, 2008). The Maddingley No 2 mine was purchased by the Calleja Group in 1992 and is currently used primarily as a landfill site (Calleja Group, n.d.; Vines, 2008). Some lignite is refined for used in agricultural products (Vines, 2008) and is located close to the ECT Coldry commercial scale demonstration plant under construction (ECT, 2021).

2.3 Recent and Future Gippsland Basin Mine Lignite Properties

Monthly or yearly composition and property data is available to assist with future planning in the two operating Gippsland basin open cut mines. The data in Table 1 shows that most Yallourn lignite parameter averages are expected to decrease moderately in the future. The average moisture and carbon contents are expected to increase by 1% and 0.5% while no sufficient change is expected in the sulfur concentration.

Figure 3 and Table 1 confidence intervals (CI) show that despite the relatively modest changes in average lignite properties, any process would need to accommodate relatively large day-to-day variations. For example, the average ash yield is expected to decrease from 2.3% (2008-2025) to 2.1% (2026-2032) but monthly average ash yields can be expected to range between 1.8% and 2.7%. Much larger variations can be expected on a daily and hourly basis. Selective lignite processing using at-line sensors and lignite sorting technologies could assist in preventing any process or product quality issues caused by lignite with extreme properties or composition.

Table 1. Recent and future lignite properties. Courtesy of Salva Consulting, 2021.

Parameter	Unit	Yallourn open cut mine					Loy Yang open cut mine
		2008-2025		Δ	2026-2032		2030-2048
		x̄	CI		x̄	CI	x̄
Ash	%, db	2.3	1.8-2.7	▼	2.1	1.8-2.4	1.84
Moisture	%	65.0	64.3-65.7	▲	66.0	64.7-67.3	60.8
Net wet specific energy	MJ/kg	6.9	6.8-7.1	▼	6.8	6.5-7.0	8.36
Carbon	%, db	65.0	64.2-65.7	▲	65.5	64.7-66.2	NR
Hydrogen	%, db	4.6	4.5-4.6	▼	4.5	4.5-4.6	NR
Nitrogen	%, db	0.59	0.57-0.61	▼	0.58	0.57-0.59	NR
Sulfur	%, db	0.29	0.24-0.34	○	0.29	0.26-0.32	0.37
Chlorine	%, db	0.10	0.072-0.12	▼	0.086	0.072-0.1	0.16
Aluminium	%, db	0.16	0.027-0.29	▼	0.13	0.015-0.24	0.35*
Calcium	%, db	0.12	0.1-0.14	▼	0.11	0.1-0.12	0.04
Iron	%, db	0.59	0.42-0.76	▼	0.49	0.43-0.56	0.18
Magnesium	%, db	0.21	0.16-0.26	▼	0.19	0.16-0.21	0.10
Sodium	%, db	0.082	0.067-0.097	▼	0.072	0.059-0.085	0.13
K_2O	%, db	0.011	0.007-0.014	▼	0.010	0.009-0.011	NR
TiO_2	%, db	0.016	0.007-0.026	▼	0.013	0.007-0.018	NR
Silica	%, db	NR	NR	NR	NR	NR	0.47
Fouling	Index	4.9	2.8-7	▼	3.5	2.9-4.1	NR

x̄, average; CI, 95% confidence interval (x̄ ± 2 standard deviation), Δ statistically significant ($p<0.05$, student's t-test) increase (▲) or decrease (▼). ○, no statistically significant change. NR, not reported; db, dry basis. Yallourn lignite properties based on weighted averages of monthly data. Loy Yang data based on yearly average predictions.* aluminium oxide.

Figure 2. Loy Yang open cut mine (V Verheyen, n.d.).

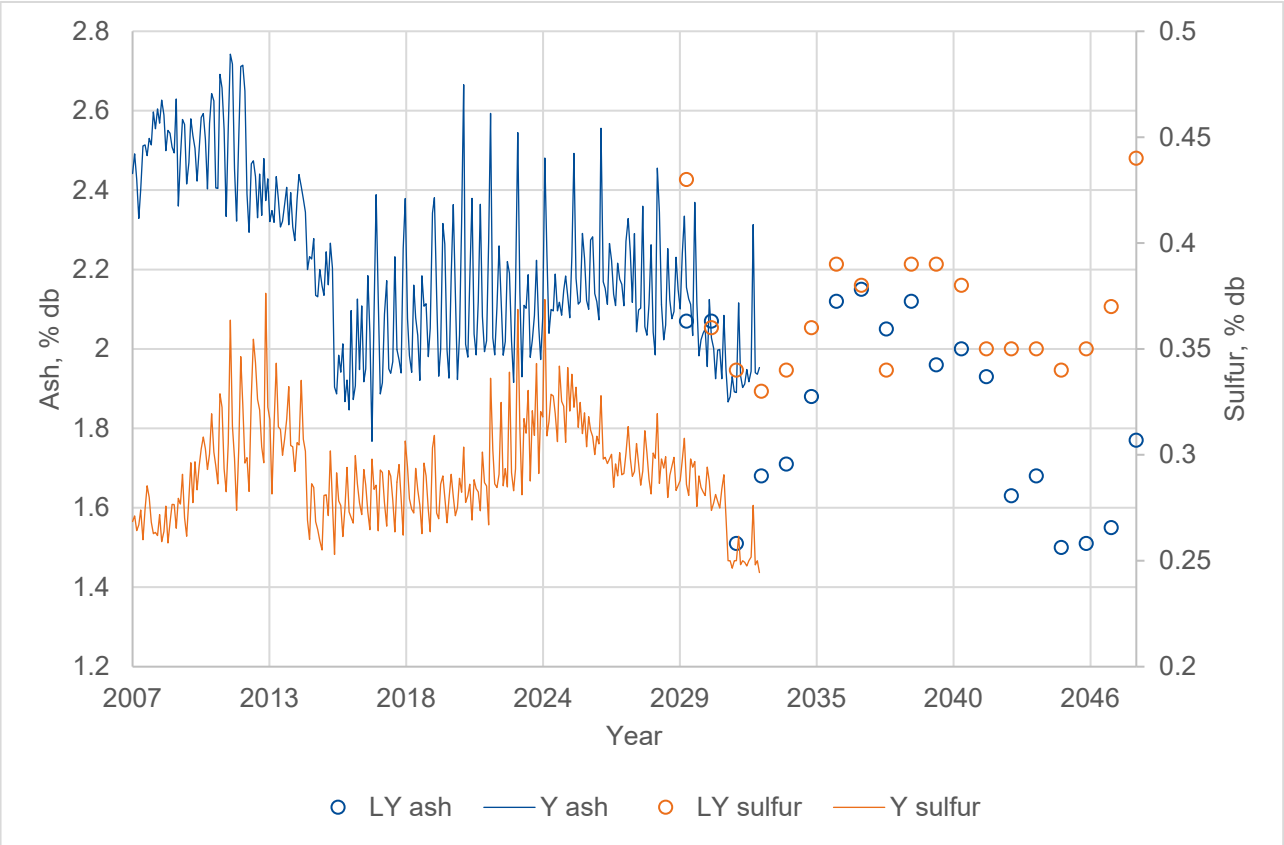

Figure 3. Ash yield and sulfur content of recent and future lignite from the Yallourn (Y) and Loy Yang (LY) lignite mines. Yallourn data are monthly averages and Loy Yang data are yearly averages.

2.4 Current and Potential Commercial Uses

Thermal power generation is the most well-known use of Victorian lignites but a range of other uses have been commercially successful since the 1890s (Vines, 2008). Briquettes produced at Yallourn and Morwell were valued for industrial and domestic heat production (CCV, 1989; Vines, 2008). Briquettes also facilitated the production of town gas and char. A well-established agricultural products business (Omnia Specialities) has also developed from the extraction and sale of lignite humic acids.

Potential future uses for Victorian lignite have been documented by extensive research and development programs established with the SECV (CCV, 1989; Vines, 2008). Some of the earliest reports recommended focuses on briquettes, carbons, chars and agricultural products (CCV, 1989). Similar themes continue in recent reviews and research (Kinaev & Bongers, 2016; ACI, 2019; McManus, 2019).

Natural gas has out-completed lignite-derived briquettes in both Australian domestic and industrial heat markets (Vines, 2008; CCV, 1989). However, there is a potential for these markets to shift from natural gas towards hydrogen in future decades. If this occurs, hydrogen production from Victorian lignite with CO_2 sequestration could become commercially viable in the short- to medium term (McManus, 2019). The cost of the lignite and CCS being key economic drivers in any business case. Research continues in the properties of densified Victorian lignite (Parsa, Tsukasaki, Perkins, & Chaffee, 2017).

Other gasification products including gaseous or liquid fuels, ammonia, urea and other chemicals continue to be promising candidates for commercial Victorian lignite operations (GHD, 2019; McManus, 2019). A recent commercial feasibility assessment indicated that H_2 and urea could be competitive with minimal government support (Kinaev & Bongers, 2016). Gasification technologies favour lignites with low ash yield, low-melting point ash, high fixed carbon content and low moisture. Local Victorian lignite gasification research topics include biomass co-firing (Shahabuddin & Bhattacharya, 2021) and carbon fuel cells (Rady, Giddey, Kulkarni, Badwal, & Bhattacharya, 2016).

High value carbon products including carbon fibres, fullerenes, carbon nanotubes, activated carbon monoliths, graphene and graphene oxides have been identified recently as potential markets for Victorian lignite (GHD, 2019; McManus, 2019). A key issue is quantifying any inherent advantages of producing these carbons from Victorian lignite over natural gas and bituminous coal feedstocks. Metallurgical carbons including blast furnace coke (McManus, 2019), PCI and direct reduction also continue to be potential Victorian lignite markets (CCV, 1989). These applications benefit from the low ash yield Victorian lignite and active research areas include hydrogen storage (Alfadlil, et al., 2019) and blast-furnace coke (Mamun Mollah, et al., 2016).

The low ash content of many Victorian lignites is beneficial for metallurgical applications, including direct reduced iron (DRI) identified as a potential use in 1989 (CCV, 1989). Direct reduction metallurgical technologies have the benefit of being viable at smaller scales than blast furnaces (CCV, 1989). This benefit could become considerable for processing diffuse ores such as magnesium, lithium and other rare-earth elements. The large volume of research demonstrating the ability of Victorian lignite-derived carbons to selectively adsorb high-value metals is another potential commercial application (CCV, 1989). Many of these applications benefit from Victorian lignite with relatively high cation exchange capacity and/or cations present as co-ordination complexes rather than discrete minerals.

Agriculture, soil productivity and soil carbon are also valuable target markets for Victorian lignite products. The bio stimulatory properties of Victorian lignite allow a point of difference against established inorganic fertilisers. Existing humic acid and fertiliser industries are located in both Gippsland and Bacchus Marsh (Calleja Group, n.d.; ACI, 2019; Omnia Nutriology, 2021) Recently, microbial conversion and incorporation of Victorian lignite into biorefinery concepts have been considered (GHD, 2019).

Many potential uses for Victorian lignite involve logistics to distant customers and would rely on efficient drying, densification and charring. Other uses rely on common processes such as gasification. As far as possible, potential uses of Victorian lignite are grouped by technology to minimise repetition.

2.5 Considerations for Current and Future Access

The ease and cost of access to sufficient lignite reserves is a key consideration for commercial Victorian lignite industry developments. The Victorian government has a clear preference for any new Victorian lignite project to use existing mines (DJPR, 2021). This has the benefit of reducing capital costs associated with mine infrastructure and services but may limit the quantities of lignite available until existing power station closures. Following power station closures, the scale of existing infrastructure may not be suitable or financially sustainable for winning small lignite quantities. The development of new mines will be problematic in terms of gaining required permits and social license. The need for upfront planning for rehabilitation and obligatory bonds are also impediments in the development of new mines.

3 Suitability of Yallourn Lignite for Commercial Production

Table 2 provides a high-level summary of the advantages and disadvantages of Victorian lignite for potential commercial uses. By necessity, the lignite properties listed in Table 2 relate to common, well-established commercial processes. A wide range of technologies are possible for many products and each technology benefits from specific lignite properties. This section briefly comments on the status of relevant technologies and preferred lignite properties. Section 4 provides further details on individual lignite properties and implications for commercial processes. Additional details are available in the references and extensive bibliography.

Drying, grinding and agglomeration are common to many manufacturing processes. Yallourn lignite has been the preferred feedstock for agglomeration and carbonisation even though the high moisture, gelified maceral, plant tissue maceral (including woody lignite) and dark lithotype content are technically disadvantages for these processes. Historically, dark lithotypes have been selectively rejected from Yallourn lignites destined for agglomeration.

Selective lignite processing using contemporary sensing and lignite sorting technologies could offer improved lignite and product quality control. Potential Victorian lignite products that could benefit from selective processing are indicated in Table 2. Most products would benefit from rejecting dark lithotypes and woody lignite but some products like activated carbons and phenols could be produced from rejected woody lignite or dark lithotypes. Woody lignites could also be useful in potting mixes.

3.1 Options for At-Line Identification of Desirable Lignite Properties

Early reports discussed benefits of sorting lignites by lithotype between mining and further processing to take advantage of the properties of individual lithotypes (Higgins, Kiss, & Allardice, n.d.). Process analytical techniques including sensor and data processing technologies have improved significantly in recent decades. This technology could reduce process risk associated with problematic lithotypes as well as providing benefits in product consistency, yield and quality. Opportunities exist to produce useful products from rejected lignite.

Lignite properties with important implications for chemical reactivity, grindability and product quality are associated with lithotype (Higgins, Kiss, & Allardice, n.d.). In general, lighter lithotypes are associated with higher hydrogenation yields and desirable briquetting behaviour while darker lithotypes are associated with the presence of woody material and poor ignition properties (Higgins, Kiss, & Allardice, n.d.; Durie, 1991).

Colour, specific gravity, needle hardness and porosity of air-dried lignites are associated with lithotype (Higgins, Kiss, & Allardice, n.d.). Shrinkage of raw lignite to air- or oven-dry is also associated with lithotype and particularly sensitive to woody content (Higgins, Kiss, & Allardice, n.d.). Although these tests are relatively simple, testing would be required to develop a suitable air-drying process, analyser requirements, maintenance needs and suitable correlations.

Figure 3. Lithotype banding in the Loy Yang open cut mine (V Verheyen, n.d.).

Liptinite is identified by fluorescence under blue light and associated with high chemical reactivity, resin and wax content (Higgins, Kiss, & Allardice, n.d.). Liptinite is also associated with light lithotypes (Higgins, Kiss, & Allardice, n.d.) suggesting that fluorescence intensity could also be used to identify lighter lithotypes.

Ash yield, mineral and inorganic content are generally independent of lithotype, although high ash yield and mineral content are often associated with interseam material. A range of sensors including optical, near-infra-red and x-ray could assist in segregating interseam and mineral-rich material. In theory, ignition index (time taken for a defined size lignite particle to ignite under controlled conditions), ash yield and ash fusion analysers could also be used at-line. While the technology to implement these high temperature tests could be challenging in a lignite mining and handling environment, many of these properties are sensitive to important minerals and cations including silica, calcium, aluminium and iron.

Contemporary sensing technologies can be incorporated into material handling systems in a variety of ways. The most promising options for sensing lithotypes and macerals in Victorian lignite require drying or other thermal treatments and would be best implemented at-line. This approach incorporates subsampling, sampling handling and preparation as well as measurement. Subsampling could be guided by an on-line (at the lignite-face or over a conveyer). The lignite mining and transport technology (bulldozers, dredgers, excavators, trucks and conveyers) in use also have important implications for preferred for at-line sensing and lignite sorting technologies. Further technical assessment to identify the most promising and practicable sensing and sorting technologies is recommended.

Table 2. High-level summary of potential commercial uses of Victorian lignites and commonly preferred lignite properties

Application	Evaluation score	Selective processing beneficial	Commonly preferred properties	Yallourn	Loy Yang	Bacchus Marsh	Comment
Common lignite processes							
Drying	NA		Low moisture	✔	✔ ✔	✔ ✔ ✔	The energy penalty associated with evaporative drying processes is related to moisture content. Moisture content may be less important for non-evaporative processes including Coldry.
Grinding	NA	✔ ✔	Low ash yield	✔ ✔	✔ ✔	✔	Reject woody lignite macerals Ash minerals associated with abrasion
			Low plant tissue macerals	✔	✔ ✔ ✔	✔ ✔	
Agglomeration and briquetting	61	✔ ✔	Low ash	✔ ✔	✔ ✔	✔	Dark lithotypes are generally enriched in gelified material and problematic for briquetting. Historical German-based criteria required <15% gelified material. High pH expected to benefit densified or solar dried lignites.
			Low dark lithotype content	✔	✔ ✔	✔ ✔ ✔	
			Low gelified (hard, dense) maceral content	✔	✔ ✔	✔ ✔	
			High pH	✔	✔ ✔	✔ ✔ ✔	
			Low plant tissue macerals	✔	✔ ✔ ✔	✔ ✔	
Processes and products							
Carbons		✔ ✔	Low gelified maceral content	✔	✔ ✔	✔ ✔	Dark lithotypes can be problematic for traditional agglomeration and carbonisation processes.
			Low ash	✔ ✔	✔ ✔	✔	
			Low iron	✔ ✔	✔ ✔ ✔	✔	
Active carbons	39-55		High micro and meso porosity	✔	✔ ✔ ✔	✔ ✔	All Victorian lignite surface areas well below the desired 600 m^2/g High cation content is only a moderate advantage because it would require water washing prior to sale for water treatment
			High surface area	✔ ✔ ✔	✔ ✔	✔	
			High cation content	✔	✔ ✔	✔ ✔ ✔	
			High plant tissue content	✔ ✔ ✔	✔	✔ ✔	
Premium carbons	39		Low ash	✔ ✔	✔ ✔	✔	Preferred lignite properties depend on manufacture approach and product (eg, high-hardness or ion exchange capability).
			High humic acid content	✔	✔ ✔	✔ ✔ ✔	
			High fixed carbon	✔ ✔	✔ ✔	✔	
			High oxygen content	✔	✔ ✔	✔ ✔	
Char and Coke							
Metallurgical reductant	63	✔ ✔	High calcium	✔	✔	✔ ✔	Dark lithotypes can be problematic for agglomeration and carbonisation required for metallurgical reductants.
			Low silica	✔ ✔	✔ ✔	✔	
			Very low S for recarburising steel	✔ ✔ ✔	✔ ✔	✔	
			Very low Ti for recarburising steel	✔ ✔	✔ ✔	✔ ✔ ✔	
Active carbon precursor	54	✔ ✔	Low gelified maceral content	✔	✔ ✔	✔ ✔	Reject dark lithotypes to avoid gelified macerals Woody lignite can be beneficial for active carbons.
			Low ash	✔ ✔	✔ ✔	✔	
			Low iron	✔ ✔	✔ ✔ ✔	✔	
High purity carbons	37		Very low sulfur	✔ ✔ ✔	✔ ✔	✔	Other properties including porosity, ash yield and tar yield etc depend on production process.
			Very low iron	✔ ✔	✔ ✔ ✔	✔	
Anode carbon	NA		Low sulfur	✔ ✔ ✔	✔ ✔	✔	Typically produced from aromatic tar rather than carbonised agglomerates.
			Low ash	✔ ✔	✔ ✔	✔	
			Low minerals and inorganics	✔ ✔	✔ ✔	✔	
			High tar yield	✔	✔ ✔	✔	
Carbon fibre	43		Low sulfur	✔ ✔ ✔	✔ ✔	✔	
			Low ash	✔ ✔	✔ ✔	✔	
			Low volatile matter	✔	✔ ✔ ✔	✔ ✔	
Graphene and graphene oxide	37	✔ ✔	High humic acid yield	✔	✔ ✔	✔ ✔ ✔	Select pale lithotypes.
Upgraded fuels							
Smokeless fuels	57	✔ ✔	Low dark lithotype content	✔	✔ ✔	✔ ✔ ✔	Dark lithotypes can be problematic for carbonisation of agglomerates to produce smokeless fuels. Lithotype and woody lignite content may be less important if char is agglomerated after carbonisation.
			High fixed carbon content	✔ ✔	✔ ✔	✔	
			Low moisture	✔	✔ ✔	✔ ✔ ✔	
			Low woody lignite (milling)	✔	✔ ✔ ✔	✔ ✔	
			Low sulfur	✔ ✔ ✔	✔ ✔	✔	
Powdered dry lignite	47	✔ ✔	Low moisture	✔	✔ ✔	✔ ✔ ✔	Low moisture, low woody lignite and low ash preferred for milling and drying.
			Low ash	✔ ✔	✔ ✔	✔	
			Low plant tissue macerals and woody lignite	✔	✔ ✔ ✔	✔ ✔	
			Low dark lithotype content	✔	✔ ✔	✔ ✔ ✔	
			Low gelified maceral content	✔	✔ ✔	✔ ✔	
			High pH	✔	✔ ✔	✔ ✔ ✔	
			Low woody macerals	✔	✔ ✔ ✔	✔ ✔	
Lignite-water slurry (e.g., DICE)	57		Low ash yield	✔ ✔	✔ ✔	✔	Low ash yield is crucial
			Low native moisture	✔	✔ ✔	✔ ✔ ✔	

Application	Evaluation score	Selective processing beneficial	Commonly preferred properties	Yallourn	Loy Yang	Bacchus Marsh	Comment
			High carbon content	✔ ✔	✔ ✔ ✔	✔	
Gasification	51-60		Low ash fusion temperatures (reducing)	✔	✔	✔ ✔	Under reducing conditions, Yallourn, Loy Yang and Bacchus Marsh ash deformation starts above 1320°C. Ca catalysis reduces gasification temperatures. High ash fusion temperatures preferred for non-slagging gasifier designs. Low ash fusion temperatures preferred for slagging designs.
			High ash fusion temperatures (reducing)	✔ ✔	✔ ✔	✔	
			High calcium	✔	✔	✔ ✔	
			High potassium	✔	✔	✔ ✔	
			High sodium	✔ ✔	✔	✔ ✔	
			Low ash yield	✔ ✔	✔ ✔	✔	
			Low moisture	✔	✔	✔ ✔	
Hydrogenation and Liquefaction	41-58	✔	Low ash yield	✔ ✔	✔ ✔	✔	Selecting for light lithotypes could be beneficial but lignite location has a stronger effect on yield. 1.3% Ca in Bacchus Marsh lignites could be a concern for liquid product fouling and filtration. Ca, Mg and Fe catalyse hydrogenation Sulfur can be beneficial for maintaining catalyst activity
			Low minerals and inorganics	✔ ✔	✔ ✔	✔	
			Low calcium	✔ ✔	✔ ✔	✔	
			High magnesium	✔	✔ ✔	✔ ✔ ✔	
			High iron	✔ ✔	✔	✔ ✔ ✔	
			High hydrogen content	✔ ✔	✔ ✔ ✔	✔	
			High H/C atomic ratio	✔ ✔	✔	✔ ✔ ✔	
			High volatile matter	✔ ✔ ✔	✔ ✔	✔	
			High batch autoclave conversion	✔ ✔ ✔	✔ ✔	✔	
			High tetralin extraction test	✔ ✔	✔	✔ ✔ ✔	
			High sulfur	✔	✔ ✔	✔ ✔ ✔	
			High light lithotype content	✔	✔ ✔	✔ ✔ ✔	
			High liptinite (ground mass including pollen, spores, resin and cuticle)	✔	✔ ✔	✔ ✔ ✔	
			Low densinite (gelified ground mass)	✔ ✔	✔ ✔ ✔	✔	
			Low porigelinite	✔ ✔ ✔	✔ ✔	✔	
			Low gelified (dense and hard) maceral content	✔	✔ ✔	✔ ✔	
Agriculture	15-67	✔ ✔	High light lithotype content	✔	✔ ✔	✔ ✔ ✔	Preferred properties are dependent product type.
			High total humic acid content	✔	✔ ✔	✔ ✔ ✔	
			High calcium	✔	✔	✔ ✔	
			High magnesium	✔	✔ ✔	✔ ✔ ✔	
			Low sodium	✔	✔ ✔	✔	
			High total organic acid content	✔ ✔	✔	✔ ✔	
			High pH	✔	✔ ✔	✔ ✔ ✔	
			High porosity	✔	✔ ✔ ✔	✔ ✔	
			High humic acid content	✔	✔ ✔	✔ ✔ ✔	
Extraction							
Humic acids	60-65	✔ ✔	High light lithotype content	✔	✔ ✔	✔ ✔ ✔	Light lithotypes preferred
			High total humic acid content	✔	✔ ✔	✔ ✔ ✔	
Woody lignite and lignin	NA	✔ ✔	High plant tissue macerals	✔ ✔ ✔	✔	✔ ✔	Dark lithotypes preferred
			High dark lithotype content	✔ ✔ ✔	✔ ✔	✔	
Fine chemicals							
Resins, wax esters	51-53	✔ ✔	Light lithotypes - rich in resins and waxes	✔	✔ ✔	✔ ✔ ✔	Select pale lithotypes and possibly fluorescent liptinite macerals.
			High cutinite (leaf cuticle derived macerals)	✔ ✔ ✔	✔	✔ ✔	
			High resinite (plant resin derived macerals)	✔	✔ ✔	✔ ✔ ✔	
Phenols	42	✔ ✔	Dark lithotypes	✔ ✔ ✔	✔ ✔	✔	Select dark lithotypes
Magnesium	49		High magnesium concentration	✔	✔ ✔	✔ ✔ ✔	
			Availability of ash	✔ ✔	✔ ✔	×	
Aromatic carboxylic acids	48	✔ ✔	Dark lithotypes	✔ ✔ ✔	✔ ✔	✔	Select dark lithotypes
Bulk chemical products							
Ion exchanger	56		High oxygen content	✔	✔ ✔	✔ ✔	
			High total acid content	✔ ✔	✔	✔ ✔	
			High porosity	✔	✔ ✔ ✔	✔ ✔	
			High surface area	✔ ✔ ✔	✔ ✔	✔	

✔ indicates the lignite has the desired property; NA, not assessed. Section 3.2 provides additional detail for each application, section 4 provides information about the commonly preferred properties and the full scoring matrix is provided in Appendix A (Table A1).

3.2 Technology and Commercial Prospects Evaluation

The technology and commercial prospects evaluation column in Table 2 is based on the criteria and method described in B and additional details are provided in the appendix (Table 10). The majority of the technical feasibility of production, commercialisation and applicability to Victorian lignite scores remain unchanged. The Yallourn lignites preferred column has been updated to reflect the dark lithotype and ash constituents of Yallourn lignites. Where possible, commercial prospects evaluation from the 1996 report (Verheyen, 1996) have been reproduced. Tentative commercial prospects assessments have been assigned to new technologies and products.

Products with technology evaluation scores 35 (Table 10) or above included chars, carbons, resins, wax esters, solid fuels and agricultural products. The only products with combined scores of 60 and above include metallurgical reductants, hydrogen, humic substances and fertilizers. These products all have well-established local or international commercial precedents.

Other recent reports considering non-fuel uses of Victorian lignite also recommend conversion to high value carbons, products from gasification and agricultural applications(GHD, 2019; McManus, 2019; DJPR, 2021). The absence of local commercial experience resulted in lower scores (9-19, Table 10) for advanced carbons (including carbon fibre, graphene, graphene oxide and quantum dots), premium carbons and high purity carbons. Potential growth in markets for advanced carbons could make these products commercially attractive if on-going research is successful.

CO_2 is a by-product of some lignite processing technologies and a number of opportunities to utilise CO_2 have been identified. CO_2 is a well-established solvent in the food industry and offers a number of benefits compared to traditional solvent extraction including avoiding toxicity and disposal issues associated with traditional solvents and reducing the reliance on energy-intensive thermal evaporation for product recovery. Uses for CO_2 include carbon activation reagent, gasification reagent and carrier gas, extraction of waxes and other low-polarity products as well as refining low-polarity by-products like tars.

3.2.1 Carbons

The low ash content and high porosity of Victorian lignite are advantageous for producing powdered chars and active carbons (Verheyen, 1996). However, particulate carbons are typically softer than commercial competitor carbons and require agglomeration or chemical digestion to increase hardness (Verheyen, 1996). Carbon properties (density, particle size, abrasion resistance and ability to regenerate) are generally more important than yield (indicated by fixed carbon).

Gelified macerals and dark lithotypes can be detrimental to carbonising briquettes (Higgins, Kiss, & Allardice, n.d.). However, these materials have been readily separated from run-of-mine Yallourn lignites prior to agglomeration and carbonisation (Vines, 2008; Verheyen, 1996). The slightly higher iron content of Yallourn mine lignites could be a disadvantage for some applications and the higher pH Bacchus Marsh lignites is suited to densified carbon production using shear-based agglomeration processes like Coldry (Tomita & Ohtsuka, 2004).

3.2.1.1 Active carbon

Competitive active carbons have high surface areas (>600 m^2/g), tailored pore-size distributions and potential for surface modification (Verheyen, 1996). Chars can be activated by either gases like steam and CO_2 (Verheyen, 1996) or chemicals including phosphoric acid and potassium hydroxide. Use of flue gas or CO_2 for activation, creates a possible use for CO_2-rich flue or process gases. The tendency of Victorian lignite to form highly porous chars (Verheyen, 1996) can be beneficial for active carbon production. A wide range of surface modifications have been demonstrated at laboratory scale with applications in metal refining industries including gold (Cullen, Siviour, Pearson, & MacDonald, 1972); Cullen, Siviour, & Pearson, 1974; CCV, 1989)

3.2.1.1.1 WATER TREATMENT

Active carbons are used widely for the removal of small organic molecules, colour, taste and odour (Verheyen, 1996). The low ash and trace metal content of Victorian lignite are beneficial for reducing the potential for toxic or undesirable metal leaching (Verheyen, 1996). Most applications will require some lignite pre-treatment (e.g., briquetting, extrusion) to achieve commercially competitive shapes (e.g., pellets or spheres) hardness and abrasion resistance (Verheyen, 1996).

Steam activation of Victorian lignite briquette fines or grus into active carbons for water treatment has been demonstrated at pilot scale (Verheyen, 1996).

3.2.1.1.2 VAPOUR AND GAS TREATMENT

The scoring conducted in 1996 (Verheyen, 1996) assumed that active carbons would be widely used to capture vehicle refuelling emissions. Catalytic removal of SO_x and NO_x from industrial flue gases by Victorian lignite derived active carbons had been investigated at laboratory scale in 1996 (Verheyen, 1996) and similar technology was in use in Germany (Verheyen, 1996).

Active carbons for vapour and gas treatment require finer pores (microporosity), which is not suited to natural Victorian lignite properties (Verheyen, 1996) Commercial competitiveness would also rely on improving the hardness and abrasion resistance of Victorian lignite-derived carbons (Verheyen, 1996).

Figure 4: Lumps of pale lithotype coal (top left), gelified dark lithotype coal (top right) and identifiable plant tissue (bottom) from Gippsland basin mines. Two-dollar coin included for size reference (V Verheyen, n.d.).

3.2.1.1.3 LOW VALUE SINGLE USE

Low value, single use powdered activated carbons were identified as a potential market for fines from a high-value carbon production process in 1996 (Verheyen, 1996) The wide availability of low-cost single use activated carbons from overseas (Verheyen, 1996) suggests this is unlikely to be a commercially viable core product for Australian-based manufacture.

3.2.1.1.4 PREMIUM CARBONS

Premium prices can be achieved for activated carbons with particular selectivity, attrition resistance or storage capacity (Verheyen, 1996). Key applications identified in 1996 include gold recovery (e.g., carbon in pulp) and military personnel protection from chemical weapons.

Hard carbon products have been produced at laboratory scale following KOH (alkali) digestion and the high fixed carbon and oxygen content of Victorian lignite are beneficial for this process (Verheyen, 1996). In

1996, research in this area was at the early stages (Verheyen, 1996) and the technology was commercial unproven.

3.2.1.1.5 MOLECULAR SIEVE

In 1996, producing molecular sieves from Victorian lignite was in the early development stage and relied on new manufacturing technologies. No assessment has been included in the current or past evaluation matrix.

3.2.1.1.6 HONEYCOMB MONOLITHS

Honeycomb monoliths have been produced from Victorian lignite successfully at the laboratory scale (Alfadlil, et al., 2019; ACI, 2019; McManus, 2019). This technology offers significantly lower pressure drops compared to conventional packed beds and Monash University are seeking commercial opportunities (Moreno-Castilla & Pérez-Cadenas, 2010; ACI2019; McManus, 2019). Conductive versions of honeycomb monoliths have also been produced at laboratory scale and these have potential applications in electrical swing adsorption for gas purification including CO_2 capture) (ACI, 2019; McManus, 2019). Hydrogen storage is another potential application for Victorian lignite-derived honeycomb monoliths (Alfadlil, et al., 2019). This technology is not included in the evaluation matrix because further research and development into scaling up their manufacture and reducing their cost is required.

Figure 5. Woody coal lumps from Gippsland basin mines (V Verheyen, n.d.).

3.2.1.2 Char

3.2.1.2.1 METALLURGICAL REDUCTANT (INCLUDE COLDRY +FEO, RETORT)

Victorian lignite chars are not suitable replacements for hard lump coke manufactured from coking coal, in part because they do not soften on heating (Verheyen, 1996; McManus, 2019). The high oxygen content in Victorian lignite does not enable a liquid mesophase production during heating which is required to produce low porosity dense coke. However, Monash University holds a provisional patent for a synthetic blast furnace coke prepared from lignite using tars and temperature and pressure. 50 mm briquettes that are suitable for industry standard evaluation tests have been produced at the laboratory scale (McManus, 2019). However, given the costs involved and competition from high quality as mined coking coals this route is unlikely to be

commercial. Alternative uses for Victorian lignite chars in blast furnaces include pulverised coal injection (PCI) and coking coal extenders (Verheyen, 1996).

Direct ore reduction (e.g., direct iron reduction or DRI) technologies are also at various stages of development including historical plans for a commercial DRI plant by Smorgons (now BlueScope) in the Latrobe Valley (CCV, 1989). Briquetted Yallourn lignites have been sold for recarburising steel (Verheyen, 1996), providing a commercial precedent for direct ore reduction. The ECT patented HydroMOR process (the successor to the Matmor process) incorporates direct ore reduction with the Coldry lignite densification technology (ACI, 2019).

Concentrations of impurities such as boron, phosphorus, sulfur, iron, vanadium and titanium are crucial for chars used in metal and metalloid reduction (Verheyen, 1996). Calcium promotes the carbothermic reduction reactions employed in blast furnaces and these reactions are moderated by silica.

3.2.1.2.2 ACTIVE CARBON PRECURSOR

Optimum chars for activation are produced with relatively low temperatures and short residence times (Verheyen, 1996). Despite the former Auschar process employing high temperatures and long residence times, these chars were successfully used to manufacture active carbons (Verheyen, 1996,) providing a commercial precedent. Potential benefits of combining charring and activation processes in a single thermal treatment were identified in 1996 (Verheyen, 1996). However, Victorian lignite derived char products would need to compete with chars created from wastes including wood waste and scrap tires (Verheyen, 1996).

3.2.1.2.3 CARBON CAPACITOR

Carbon capacitors were a relatively new application in 1996 (Verheyen, 1996). Recent interest in graphite and graphene are discussed under Advanced carbon products. No assessment is provided in the current or past evaluation matrix.

3.2.1.2.4 HIGH PURITY CARBONS AND SILICA REDUCTANT

Silicon material reduction to electronic grade silicon requires high purity carbons with ash yields below 0.2%. In 1996, further developments were required to bring Victorian lignite ash yields below 0.8% (Verheyen, 1996). Float/sink, oxidation and acid digestion were recommended for reducing ash yield (Verheyen, 1996). However, any Victorian lignite-derived high purity carbon would need to compete commercially with high purity carbons from naturally low ash content materials such as natural gas and wood waste (Verheyen, 1996).

3.2.1.2.5 FILTER AID

Filter aids were a potential application for off-specification chars (Verheyen, 1996). No special char properties other than particle size (>212 µm) are required, indicating that piloting would not be required (Verheyen, 1996).

3.2.1.3 Advanced carbon products

3.2.1.3.1 ANODE CARBON

Carbon anodes for aluminium smelting are generally manufactured from refinery cokes (Verheyen, 1996) but have been manufactured from similar Rhenish and Texas lignites (ACI, 2019). Carbon anodes must meet stringent density, electrical conductivity and purity (particularly sulfur and minerals) requirements (Verheyen, 1996). In 1996, the complexity of processes required to manufacture satisfactory anode carbons from Victorian lignite indicated that it would be difficult to compete commercially with petroleum refinery cokes (Verheyen, 1996) however, recent reports suggest a cost analysis is justified (ACI, 2019). No assessment is provided in the current or past evaluation matrix.

3.2.1.3.2 GRAPHITE

The natural mineral graphite is not mined in Australia and is subject to natural purity variations (ACI, 2019). High purity synthetic graphite is manufactured from natural gas. Victorian lignite derived synthesis gas could provide an alternative carbon source however, research into this application is required. Low quality graphitic materials can be produced by high temperature annealing of Victorian lignite-derived chars and graphite beads with graphene layers have been observed in gasifier chars (Tomita & Ohtsuka, 2004), However, these products would need to compete commercial with mined graphite (Verheyen, 1996). No assessment is provided in the current or past evaluation matrix.

3.2.1.3.3 CARBON FIBRE

Since 1996, the applications and demand for carbon fibre have grown significantly. The poor quality carbon fibres prepared from lignite-derived tars (Verheyen, 1996) have been improved on and successful production of carbon fibre from Victorian lignite blends has been reported at laboratory scale (Li et al., 2017; ACI, 2019). Further research and development is required but the carbon fibre market could grow significantly in coming years.

Victorian lignites offered no advantages to carbon fibre production in 1996. However, lignin-derived carbon fibre research has progressed significantly (Qu et al., 2021). Victorian lignites share many properties with lignin and creating a suitable low ash, low sulfur, low volatile matter precursor with these properties is worth investigating (ACI, 2019).

3.2.1.3.4 GRAPHENE

Graphene and its precursor, graphene oxide, have potential applications in a wide range of high-demand electronics including batteries, supercapacitors, electricity transmission, solar cells, next-generation lithium-ion batters, flexible touchscreens, photodetectors and ultrafast lasers (ACI, 2019). Humic acids, including those derived from Victorian lignite, have been identified as a potential source of graphene and graphene oxide (ACI, 2019; Huang et al., 2016). Any Victorian lignite-derived product will need to compete commercially with graphene and graphene oxide derived from graphite (ACI, 2019). However, the need to process, extract and purify humic acids from Victorian lignite may not be a barrier to graphene production because existing processing costs are high (ACI, 2019).

3.2.1.3.5 QUANTUM DOTS

Quantum dots (nm-scale semiconductors) have good chemical-inertness, biocompatibility and low toxicity with potential uses in electronics, sensors, drug delivery and surface modification (Ghaffarkhah, 2022). A patent has been awarded for extracting quantum dots from bituminous and anthracite coals, suggesting that Victorian lignites could also be a source of quantum dots (ACI, 2019).

3.2.1.4 Carbon black

Opportunities to produce carbon black from waste tars was identified in 1996 (Verheyen, 1996). Carbon blacks used in plastics, rubber and printing toners are typically supplied by oils and natural gas (Verheyen, 1996). No assessment is provided in the current or past evaluation matrix.

3.2.2 Upgraded fuels

3.2.2.1 Solid fuels

3.2.2.1.1 SMOKELESS FUEL

Chars with low volatile matter are suitable for use as smokeless fuels. AusChar produced smokeless fuels from Victorian lignite briquettes (Verheyen, 1996) in Gippsland, providing a commercial precedent. Opportunities to improve the ignition properties were identified in 1996 (Verheyen, 1996). Smokeless fuel production involves agglomeration and charring so similar lignite properties are preferred (Verheyen, 1996). There is an opportunity to agglomerate smokeless fuels made from lignite with sawdusts made from premium BBQ smoker woods (e.g. mesquite, hickory) to extend their efficacy and reduce cost and environmental damage.

3.2.2.1.2 POWDERED DRY LIGNITE

Powdered dry lignite has been produced from Loy Yang lignite in the Latrobe Valley at the Lurgi plant (Verheyen, 1996). No potential market was identified in 1996 and no new markets have been identified for this report. However, powdered dry lignite could be produced as part of a gasifier or other process. Milling and drying are required to produce dry lignite so low moisture and ash are preferred (Verheyen, 1996). Dark lithotypes and woody lignite can be problematic (Verheyen, 1996).

3.2.2.1.3 AGGLOMERATED LIGNITE INCLUDING BRIQUETTES

A range of processes have been demonstrated at laboratory, pilot or commercial scale for agglomerating Victorian lignite into regular shaped, dust-free agglomerates. Binderless briquettes require surface chemistry and moisture associated with low rank materials. They have been produced successfully from both Yallourn and Loy Yang lignite, although the energy cost of the traditional briquetting process is a significant disadvantage (CCV, 1989; Verheyen, 1996). Disc and drum pelletisation technologies have been

investigated at lab and pilot scale as alternative low energy technologies suited to producing spherical lignite pellets.

Concepts for producing spherical pellets and solar drying have been investigated at laboratory scale (CCV, 1989; Verheyen, 1996). A patent for densification by high-shear kneading and extrusion is now known as Coldry and owned by ECT. The Coldry process has been proven at pilot scale and a commercial demonstration plant is under construction (ECT, 2021).

Although the commercial market for briquettes and agglomerated Victorian lignite has been outcompeted by natural gas, these products are required for a range of Victorian lignite products including chars, metallurgical reductants, and active carbons (ACI, 2019). The briquetting or agglomeration process provides opportunities to incorporate metal ores for direct ore reduction or alkali metals to facilitate carbon activation (CCV, 1989; Verheyen, 1996).

In general, the softness of Victorian lignite is a disadvantage for forming ultra-hard briquettes and chars using binders (ACI, 2019). Both Yallourn and Loy Yang lignites have been briquetted successfully, although dark lithotypes from Yallourn lignites were avoided by selective mining. Low ash yield, particularly calcium and magnesium, are also beneficial for forming briquettes that do not deteriorate when exposed to significant fluctuations in ambient humidity (CCV, 1989). Low woody content is important for facilitating milling (Higgins, Kiss, & Allardice, n.d.).

3.2.2.2 Liquid fuels

3.2.2.2.1 TRANSPORT FUEL

Production of liquid transport fuels for internal combustion engines from Victorian lignite has been researched extensively and demonstrated at pilot scale by the BCLV (Brown Coal Liquefaction Victoria) project (Verheyen, 1996). However, fossil-fuel internal combustion engines for transport are being replaced with battery-electric and hydrogen fuel-cell motors. Biomass derived fuels are commonly blended with petroleum and are socially preferred for transport fuels.

The higher reactivity and low ash content of Victorian lignite are advantages over bituminous coals for hydrogenation to transport fuels (Higgins, Kiss, & Allardice, n.d.; Verheyen, 1996). Victorian lignite generally have high hydrogenation yields without the need for catalysts (Higgins, Kiss, & Allardice, n.d.). Transport fuels can also be produced by hydrogenation of syn gas (discussed in later sections) (Higgins, Kiss, & Allardice, n.d.).

3.2.2.2.2 FUEL OIL

Tar-derived fuel oils are generally by-products from char production (Verheyen, 1996). Auschar produced a tar and surfactant-based fuel oil substitute from Victorian lignite as a by-product from char production (Verheyen, 1996), providing a commercial precedent. Tar-derived products can also be used on-site for heat recovery (Verheyen, 1996).

Tar yields from Victorian lignite tend to be lower than equivalent German coals and are generally not considered commercially viable in traditional processes (Higgins, Kiss, & Allardice, n.d.). Higher tar yields can be achieved with flash pyrolysis and inorganic-carboxylate complexes could be indicative of potential yield (Higgins, Kiss, & Allardice, n.d.). The stability of these lignite tar derived products is an issue as the chemistry involved is not at thermodynamic equilibrium (as in fossil oils). Further chemical treatment to remove acids and stabilise free radicals is required

3.2.2.2.3 WATER/OIL MIXTURES

There has been renewed interest in coal-water or lignite-water slurries as an alternative to diesel fuel for large stationary reciprocating engines (DICE, direct injection coal engine) since 1996 (Jeffrey, 2014; Aurecon Australasia Pty Ltd, 2020). Research has been driven by the need for fast start-up dispatchable synchronous electricity generation to stabilise the electricity grid as the supply of asynchronous renewable electricity increases (Aurecon Australasia Pty Ltd, 2020).

The key challenge for DICE remains the ash yield and resulting limitations on run time between maintenance (Verheyen, 1996; Jeffrey, 2014). So far, DICE operation for 100 h between maintenance cycles have been demonstrated (Jeffrey, 2014). A review for ANLEC R&D indicated that DICE could be competitive for remote area diesel power generators (500 h between maintenance cycle times required) and natural gas-combined cycle gas turbines (1000-2000 h run time required, both remote and grid-input) (Jeffrey, 2014). DICE offers

lower cost fuel compared to traditional diesels, higher thermal efficiencies and lower capital costs than existing lignite-fired power stations, potential for stabilising intermittent generation, and potential for heat-integration with CCS (Jeffrey, 2014).

The use of lignite-oil mixtures in reciprocating engines would also be limited by the impact of ash yield on intervals between maintenance cycles. Benefits including increased hydrogen content and enriching the residue in metals during liquefaction of lignite-oil mixtures were identified in 1996 (Verheyen, 1996).

The low ash content of Victorian lignite is a significant advantage for DICE. Interestingly, recent references specify a 0.2% ash yield limit for DICE fuels (Jeffrey, 2014), which is significantly higher than the <0.05% ash yield limit specified in the 1996 report (Verheyen, 1996).

3.2.2.3 Gaseous fuels and other gasification products

Gasification is generally considered as a cleaner route to lignite-based products over more traditional thermal technologies. The reactivity of Victorian lignite enables fluidised-bed gasification to occur at lower temperatures than higher rank coals (Verheyen, 1996). The lower ash yield of Victorian lignite is also a benefit over many alternative coals (Verheyen, 1996) and the ion-exchanged metal cations are efficient catalysts under some gasification conditions (Tomita & Ohtsuka, 2004). The naturally low nitrogen and sulfur content is also beneficial for reducing cost of syngas clean-up (Tomita & Ohtsuka, 2004). A commercial precedent for producing syn-gas by fluidized bed gasification of Victorian lignite lump char exists (Verheyen, 1996). Fluidized bed and entrained flow Victorian lignite gasification have also been demonstrated at pilot scale including IDGC (integrated-drying combined cycle gasification) and hydrogen production (Verheyen, 1996; Tomita & Ohtsuka, 2004; Hydrogen Energy Australia, 2020).

Drying or other dewatering processes are required as part of gasification systems to accommodate the high water content of Victorian lignite (Tomita & Ohtsuka, 2004). However, reusing this water for producing hydrogen using the water-gas shift reaction could avoid social and environmental costs associated with industrial uses of surface water in Australia.

Unlike some bituminous coals, low rank coals and lignites are well suited to fluidized bed gasifiers. These gasifiers typically require particles between 5-6 mm. High ash fusion temperatures (to avoid undesired agglomeration) and catalytic cations (to promote gasification at relatively low temperatures) are also beneficial for fluidized bed gasification. Macerals that readily soften at high temperatures like eu-ulminite (highly gelified, recognisable plant tissue) can be problematic for fluidised bed gasification (Tomita & Ohtsuka, 2004). Phlobaphinite (plant tissue) attrinite (ungelified groundmass) and sclerotinite (dense, brittle groundmass) macerals are less susceptible to softening and are preferred (Tomita & Ohtsuka, 2004). The fluidised bed gasification of Victorian lignite was demonstrated in the IDGCC (integrated drying gasification combined cycle) pilot plant (Tomita & Ohtsuka, 2004).

Entrained flow gasifiers require fine particles (<75μm) and operate at high temperatures (Tomita & Ohtsuka, 2004). Slag formation and viscosity are crucial for stable entrained flow gasification (Durie, 1991; Tomita & Ohtsuka, 2004). Entrained flow gasification of Victorian lignite has been demonstrated at pilot scale in Victoria recently (Hydrogen Energy Australia, 2020).

Lump or agglomerated coal (typically 5-80 mm) are preferred for moving bed gasifier systems (Tomita & Ohtsuka, 2004). These gasifiers tend to have longer residence times, resulting in higher hydrocarbon and tar yield compared to fluidized bed and entrained flow gasifiers (Tomita & Ohtsuka, 2004). A commercial precent exists for gasification of Yallourn lump char at the Gas and Fuel Corporation (Verheyen, 1996).

The high sodium and low ash yield of Yallourn lignites are beneficial for gasification. The high ash fusion temperature could be beneficial for non-slagging gasifier designs (Tomita & Ohtsuka, 2004). The high water content is likely to result in a disadvantageous energy penalty associated with drying, although the water could be reused within the syn-gas refining process. The lower moisture content and ash fusion temperatures typical of Bacchus Marsh lignites could be beneficial, particularly for slagging gasifiers. However, additional syn-gas clean-up and ash handling considerations would be required for Bacchus Marsh lignites compared to Yallourn and Loy Yang. The yield, quality and properties of gasification products are largely determined by the gasification technology.

3.2.2.3.1 SYNTHETIC NATURAL GAS (TOWN GAS)

Synthetic natural gas was produced commercially from Victorian lignite lump char at the Gas and Fuel Corporation (Verheyen, 1996) using the Lurgi process in the 1960's. The yield and types of gasification by-

products depend on the gasification technology (1) fixed or moving bed, (2) fluidized bed, and (3) entrained flow. The need to monetise significant water, phenols, tars and ammonia by-products are likely to be additional barriers to production of synthetic natural gas. Interest in the production of syngas for electricity generation has moved towards interest in products including hydrogen, liquid fuels, urea and ammonia (Verheyen, 1996; McManus, 2019).

3.2.2.3.2 SYNTHESIS GAS FUELS AND PRODUCTS

An economic assessment of potential Victorian lignite-derived synthesis gas products in Victoria identified hydrogen and urea as the most economically feasible (V). The estimated levelized cost of hydrogen production was sensitive to carbon pricing, making hydrogen production a relatively high commercial risk (Kinaev & Bongers, 2016). However, Japanese commercial organisations are currently operating a Victorian lignite-to-hydrogen pilot plant in the Latrobe Valley (Hydrogen Energy Australia, 2020).

Synthetic petroleum products including jet fuel are unlikely to be commercially feasible until crude oil is above $130 for the life of the project (McManus, 2019). Methanol and ammonia are likely to require government significant subsidies (McManus, 2019), although demand for ammonia could grow significantly if it becomes a common fuel or hydrogen carrier (Hasan MH, et al, 2021). Dimethylether production requires further research (McManus, 2019) but could be competitive in countries that rely on imported natural gas (Kinaev & Bongers, 2016).

3.2.3 Pyrolysis by-products

3.2.3.1.1 PHENOLS

The opportunity to extract saleable phenols from a crude tar by-product from a carbonisation production process was identified in 1996 (Verheyen, 1996). Extracting phenols from the crude tar would reduce the oxygen content and improve the prospect of the tar being saleable as a fuel oil (Verheyen, 1996). Refining crude tars could be a potential use for supercritical CO_2 (Magomedov et al., 2019).

3.2.4 Agriculture

Use of ROM Victorian lignite and Victorian lignite-derived products in agricultural applications is well established (Verheyen, 1996; Omnia Nutriology, 2021). In many cases, the challenge is to add sufficient value to the lignite to cover transport and packaging costs (Verheyen, 1996). There is renewed interest in biological lignite solubilisation and transformation around the world with a range of possible products (Ghani et al., 2015). This research could have important implications for biotransformation of lignites in soils and is worth further investigation.

3.2.4.1 Run-of-mine lignite

There are some commercial precedents for refined lignite soil amendments (Calleja Group, n.d.; Heng, 1995; McManus, 2016). Mixed results from glasshouse and field research indicate that the impact of lignite on soil organic carbon, soil health and productivity depends on many factors including the native soil properties (McManus, 2016). The effects of Victorian lignite on soil are generally accepted to include improved water holding capacity, improved phosphorus and nitrogen fertiliser efficiencies and pH moderation (McManus, 2016) (Heng, 1995). Particular benefits have been shown in pot-trials for sodic soils (McManus, 2016). Other uses include additives for potting mixtures, organic fertiliser bases (eg, pelletised chicken manure) and rehabilitation of overburden (Heng, 1995). A key barrier to the use of moisture-rich Victorian lignite as a soil amendments is transport costs from mines to soils that would benefit from Victorian lignite (McManus, 2016).

High calcium, high magnesium and low sodium contents would be beneficial for agricultural use. High cation exchange capacity is indicated by high total organic acid content. In general, Bacchus Marsh lignite properties are more beneficial for agriculture than Gippsland basin lignites. However, both Yallourn and Loy Yang lignites are rich in cation exchange capacity and exchangeable ions.

3.2.4.2 Chars

Biochars are used widely in potting mixes and there is an established commercial biochar industry in Australia. Although there is no known precedent for blending Victorian lignite-derived chars with soil, the high porosity and ion-exchanger properties of Victorian lignite chars could be beneficial for soils. Further research is warranted on the effects of Victorian lignite-derived chars on soil structure and productivity.

3.2.4.3 Ash

Benefits of the high alkalinity (pH 8-9) as well as high calcium and magnesium content of waste ash has been demonstrated in field trials for overburden rehabilitation (Heng, 1995). The availability of ash stockpiles from Yallourn and Loy Yang lignites is advantageous for this application.

3.2.4.4 Humic substances

Humic substances, particularly humic acids, are well established in agriculture (Verheyen, 1996) and have found uses as drilling mud additives, binding mineral ores or black lignite fines, wood stain and paper colourant (Verheyen, 1996). Insoluble residues from humate extraction are typically classified as woody lignite. The small-scale commercial extraction facility described in 1996 has grown significantly in the intervening years (Verheyen, 1996; Omnia Nutriology, 2021). The high purity, solubility, density and low porosity of humic acid extracts could make them suitable for advanced carbon feedstocks discussed previously.

The high humic acid and light lithotype content in Bacchus Marsh lignites are beneficial for this application. However, humic acid is readily produced at commercial scale from Loy Yang lignites. Selective processing of light lithotypes could also improve humic acid yields from all three lignite sources. The presence of an existing, well-established humic acid production facility in the Latrobe Valley (Omnia Nutriology, 2021) could be a significant barrier to production of commercial humic acids.

3.2.4.4.1 HUMIC ACIDS – PLANT CROPS

Humic acids are a potential source of soil organic carbon (SOC) and the significant cation exchange capacity is believed to retain and moderate the release of fertilisers and trace elements (McManus, 2016). Commercial humic acid products for agriculture are well established internationally (Calleja Group, n.d.; McManus, 2016; Omnia Nutriology, 2021). Establishing and improving beneficial bioactive properties of humic acids is an active research area (Canellas et al., 2015).

3.2.4.4.2 HUMIC ACIDS – SEED COATING

The high cation exchange capacity and limited water-solubility of humic acids could be beneficial for seed coating applications (Omnia Nutriology, 2021). No assessment is provided in the current or past evaluation matrix.

3.2.4.4.3 HUMIC ACIDS – ANIMAL FEED ADDITIVE

The cation exchange and water holding capacity of humic acids are also beneficial as animal feed additives (McManus, 2016). There is significant interest in feed additives for methane-suppression, although the role of humic acids in this area is poorly defined. Humic acid-based animal feed additives are available commercially (McManus, 2016; ACI, 2019).

3.2.4.4.4 FULVIC ACIDS

Unlike humic acids, fulvic acids are water-soluble at all pH. This is beneficial for hydroponics and other applications where water-solubility is crucial. Fulvic acids are established commercial products and readily available from Asian markets. Research is required to develop novel fulvic acids and demonstrate agricultural efficacy.

The fulvic acid yield of Victorian lignite is generally low due to extraction by groundwater on geological time-scales. Humic acid oxidation is effective at generating fulvic acids (McManus, 2016).

3.2.5 Bulk chemicals

3.2.5.1 Extraction

3.2.5.1.1 HUMIC ACIDS

Earlier sections have outline potential high-value end products for humic acids including advanced carbons and agriculture. The presence of an existing, well-established humic acid production facility in the Latrobe Valley (Omnia Nutriology, 2021) could be a significant barrier to production of commercial humic acids.

3.2.5.1.2 TARS AND PITCHES

Tars and pitches are by-products of char production, pyrolysis and liquefaction (Verheyen, 1996). The physical properties of tars and pitches are highly dependent on feedstock and production process (Verheyen, 1996). The toxicity of many tars and pitches is beneficial for uses such as timber preservatives,

caulking compounds and road pavement bitumen, although these markets are traditionally supplied by oil refining and coking industry by-products (Verheyen, 1996). There could be an opportunity to upgrade tars or pitches using supercritical CO_2 (Magomedov et al. 2019).

3.2.5.1.3 WOODY LIGNITE/LIGNIN

Wood and wood waste was identified as a formidable competitor to Victorian lignite-derived woody lignite and lignin in 1996 (Verheyen, 1996). If these woody lignite and lignin-rich dark lithotypes are selectively rejected from process feedstocks, an alternate use could be worth further investigation. These lignite macerals are beneficial for manufacturing active carbons and could be useful in potting mixes (Verheyen, 1996). No assessment is provided in the current or past evaluation matrix.

3.2.5.1.4 SUPERCRITICAL FLUID EXTRACTION

If CO_2 utilisation becomes attractive in the Latrobe Valley, supercritical CO_2 extraction of low polarity Victorian lignite fractions could warrant further investigation. Waxes or resin extraction and tar or pitch upgrading (Magomedov, R.,et al, 2019) are the most likely applications to be technically feasible. This prospective process is not well enough developed to justify inclusion in the evaluation matrix.

3.2.6 Fine chemicals

Single-molecule or mixtures for structurally similar molecules can be considered fine chemicals. Despite the range of chemicals present in Victorian lignite, commercial fine chemical production from Victorian lignite has not been conducted in Victoria.

3.2.6.1 Solvent extraction

CO_2 by-products from combustion, gasification and industrial processes could potentially be utilised to extract fine chemicals from Victorian lignite. This would have numerous benefits including providing a beneficial use for CO_2, avoiding toxicity and disposal issues associated with traditional solvents and reduce the reliance on energy-intensive thermal evaporation for product recovery. Humic acids are extracted from Victorian lignite commercially and are discussed in section 3.2.3.4.

3.2.6.1.1 RESINS

Monocyclic isoprenoid-derived resin acid polymers are used widely in paints, polymeric coatings and gums (Verheyen, 1996). Pale and light coloured resins have more commercial value than more coloured resins (Verheyen, 1996). The Kaurex Peat Extraction Project described in 1996 (Verheyen, 1996) has been revisited and the RESWAX venture has operated a pilot plant including floatation technology (ResWax, 2021). RESWAX plans to commence commercial production in 2023 (ResWax, 2021).

Although occasional large resin deposits are found in Victorian lignite, most resin material is present in small particles dispersed through light lithotypes. Selective mining of thin, pale lithotype bands could potentially yield resin concentrations above the 20% limit for commercial viability (Verheyen, 1996).

3.2.6.1.2 WAX ESTERS

Wax esters (covalently bonded long chain fatty acids and alcohols) are used widely in protective coating on leather, greases and water proofing (Verheyen, 1996). Commercial wax values are determined by colour and melting point (Verheyen, 1996). In general, waxes extracted from Victorian lignite require bleaching to meet colour specifications (B). Montan wax is traditionally extracted from German lignites containing 10-18% wax (Verheyen, 1996). Victorian lignite wax yield is often near 1% (Verheyen, 1996). Yallourn lignites are rich in cutinite (leaf cuticle-derived macerals), indicating that they could be better sources of wax esters than either Loy Yang or Bacchus Marsh lignites.

3.2.6.1.3 PARAFFIN WAX

Long chain hydrocarbons with more than 20 carbons are readily obtained from existing petroleum products (Verheyen, 1996). Unlike resins and wax esters, selective mining is unlikely to increase the paraffin wax yield above the typical 1% from Victorian lignite (Verheyen, 1996). No assessment is provided in the current or past evaluation matrix.

3.2.6.1.4 PHENOLS

Phenols with short-chain (up to three carbons) substituents in Victorian lignite are derived from lignin. These compounds are not readily extracted from Victorian lignite without pyrolysis or other thermal treatment (Verheyen, 1996). An opportunity to wash tars with alkali to recover lignin-like phenols was identified in 1996.

Lignin-derived phenols are used in commercial dyes, preservatives and polymers (Verheyen, 1996) and alternate uses are being explored locally (Roy et al., 2021). Phenols are typically rich in dark lithotypes and this could be a potential use for these lignite fractions as part of a selective lignite processing system.

3.2.6.1.5 MAGNESIUM

Although the magnesium content of Victorian lignite is relatively low, magnesium is enriched in the plentiful ash from lignite-fired power stations. Latrobe Magnesium are constructing at 3000 tpa demonstration plant for producing magnesium, supplementary cementitious material, amorphous silica, char and iron oxide from the Yallourn fly ash stockpile (Latrobe Magnesium Ltd, 2021). The availability of Yallourn and Loy Yang ash stockpiles are beneficial for this application.

3.2.6.1.6 INORGANIC TRACE ELEMENTS

Lignites are known to contain many trace elements. A recent survey of Gippsland basin lignite ash rare earth elements failed to identify any significant element concentrations above background levels. Magnesium (discussed above), potassium and titanium could potentially be extracted from ashes (Verheyen, 1996). The availability of large ash stockpiles of Yallourn and Loy Yang lignites are beneficial for this application. No assessment is provided in the current or past evaluation matrix.

3.2.6.2 Oxidation

Oxidation can be used to increase yields of oxygen-rich chemicals including humic and fulvic acids. Commercial humic and fulvic acids are predominately sold into the agricultural industry and discussed further in section 3.2.3.4.

3.2.6.2.1 BENZENE POLYCARBOXYLIC ACIDS

The value of benzene polycarboxylic acids for polymerisation is dependent on the position of carboxylic groups on the benzene rings (Verheyen, 1996). The low rank of Victorian lignite means benzene polycarboxylic acids can be produced with relatively mild oxidation conditions in the laboratory (Verheyen, 1996). Beneze polycarboxylic acid yields are typically highest from dark lithotypes and this could be a potential use for these lignite fractions as part of a selective lignite processing system.

3.2.6.2.2 ALIPHATIC ACIDS

Short (up to four carbon atoms) and long (up to 36 carbon atoms) aliphatic acids are by-products from the production of benzene polycarboxylic acids (Verheyen, 1996). The value of these products was uncertain in 1996 but recent interest in biodegradable polymers manufactured from short-chain acids could be explored. In general, Victorian lignite offer higher aliphatic acids yields than higher rank coals (Verheyen, 1996). No assessment is provided in the current or past evaluation matrix.

3.2.7 Manufactured Ion-exchanger

The high oxygen content and porosity of wet Victorian lignite are beneficial for ion-exchange applications. High removal efficiencies of copper, lead mercury, uranium and cobalt have been demonstrated at laboratory scale (Verheyen, 1996). An option to concentrate heavy-metals in vitrified, non-leachable glassy pellets by combusting heavy-metal loaded lignite in a fluid-bed cyclonic agglomerating system was identified in 1996 (Verheyen, 1996). Transport and disposal costs associated with single-use Victorian lignite for this application are unlikely to compete effectively against well established, regeneratable ion-exchange resins (Verheyen, 1996).

4 Comparison of Victorian Lignite Properties and Implications for Potential Future Uses

Differences in lignite rank (geochemical maturity based on its carbon-oxygen ratio) within the Gippsland basin is generally small but the Loy Yang mine lignites are a higher rank than Yallourn (Higgins, Kiss, & Allardice, n.d.). Rank effects are seen in the moisture, porosity and chemical reactivity of lignite. In general, lithotype (colour and texture) and petrology (maceral composition where macerals are microscopically distinguishable component groups) have stronger relationships to lignite properties than rank (Higgins, Kiss, & Allardice, n.d.).

Where available, values from multiple references are supplied to illustrate variability in Victorian lignite properties across basins, seams, areas and mines. Morwell lignite properties are included in this section even though the open cut mine is no longer operating because these lignites have been used and researched extensively. Further discussion of current and future lignite properties in the Yallourn and Loy Yang mines is provided in section 2.3, alongside a discussion of day-to-day lignite variability.

Selective mining was considered necessary for many non-fuel applications in 1996 (Verheyen, 1996). Since then, sensor, measurement and computing technology has progressed significantly and further investigation into options for selective mining or lignite sorting after mining is warranted. Lignite components are differentiated by form, texture, structure, colour, reflection and hardness. Colour, reflectance, hardness and fluorescence (associated with liptinite) could be readily measured and used to guide mining or post-mining separation. Liptinite as an example is a lipid rich maceral and is mainly comprised of solvent soluble hydrocarbon material. Some success separating liptinite-rich fractions by float-sink and centrifugation has been shown at laboratory scale recently (Yan, Qi, Marshall, Jackson, & Chaffee, 2019). Other options have been discussed in section 3.1.

4.1 Lithotype and Maceral Classes

Light, medium-light and medium-dark lithotypes account for >80% of lignite from the Yallourn, Morwell and Bacchus Marsh lignite seams (Table 3). Yallourn seam lignites have been the preferred lignite for briquetting and carbonisation even though they tend to be rich in dark (72% dark and medium-dark) lithotypes which can be difficult to briquette (Higgins,Kiss, & Allardice, n.d.; Durie, 1991), In practice, dark lithotypes and gelified (dense, hard macerals) materials have been readily rejected from Yallourn run-of-mine lignites prior to processing (Higgins, Kiss, & Allardice, n.d.; Vines, 2008). The Bacchus Marsh field lignite is at the opposite extreme with just 18% dark lithotypes. The Morwell seams, including Loy Yang, also tend to contain more light lithotypes (59-79%) than Yallourn lignites.

The lighter lithotypes in the Bacchus Marsh field may indicate the lignite is richer in fatty acids, triterpeniods and humic acids (Durie, 1991, pp. 278-322). These properties, particularly humic acids, may be beneficial for agricultural applications.

The darker lithotypes in Yallourn seams are associated with higher aromatic carbon and lignin-related phenols and methoxy groups (Durie, 1991, pp. 278-322) as well as fibrous and gelified wood fragments (often >1mm) and thin layers of fusinised wood (Higgins, Kiss, & Allardice, n.d.). These structures can be problematic for grinding, sieving and other physical processing.

Like many other Victorian lignite properties, lithotype distribution can vary widely (more so vertically than horizontally) within seams (Higgins, Kiss, & Allardice, n.d.). Yallourn mine lignites contain a wider variety of lithotypes than lignites from the Morwell mine (Higgins, Kiss, & Allardice, n.d.). Compared to Morwell mine lignites, lithotype bands tend to be more distinct in the Yallourn lignite (Higgins, Kiss, & Allardice, n.d.). Darker lithotypes are more frequent in the middle and upper-levels of the Yallourn mine but these darker lithotypes are more common in the lower levels of the Morwell mine (Higgins, Kiss, & Allardice, n.d.)

As implied by the lithotype descriptions, the colour index of air-dried lignite correlates strongly with lithotype (Higgins, Kiss, & Allardice, n.d.). This implies that optical at-line colour sensors combined with an at-line drying process could be useful for sorting lignites prior to combustion, briquetting and other processes where particular lithotypes are preferable.

Groundmass macerals (smallest material visible under the optical microscope) make up 55-73% of the Yallourn, Morwell and Bacchus Marsh lignite volume. The amount of plant tissue is relatively similar (19-24%) in the Yallourn, Morwell and Bacchus Marsh seams. The Bacchus Marsh and Loy Yang field have a similar concentration of gelified material, which tends to be hard and friable. The Yallourn lignite contains approximately double the amount of gelified material compared to the Bacchus Marsh and Loy Yang fields. This is consistent with the enrichment of gelified material in darker lithotypes, which are characteristic of Yallourn lignites.

Gelified material is well known to be detrimental to forming briquettes with good weathering characteristics and low gelification is also associated with improved high temperature (≈800°C, semi-continuous vertical retort) char strength and abrasion resistance (Higgins, Kiss, & Allardice, n.d.). Although Yallourn lignites have been the preferred Gippsland Basin lignite for briquetting, the dark lithotypes were avoided because

they were not suitable for briquetting and particularly briquette carbonisation (Higgins, Kiss, & Allardice, n.d.; Vines, 2008). However, low-gelification is not a guarantee of successful briquetting with serious issues (including processing issues and briquette disintegration when exposed to humitidy and other weather fluctuations) experienced during numerous briquetting trials with the less gelified Morwell lignite (Higgins, Kiss, & Allardice, n.d.). The poor weathering of Morwell lignite briquettes resulted from the high cation content.

Table 3. Summary of lithotype and maceral classes

Area, field or mine	Units	Yallourn-Maryvale area	Yallourn mine	Morwell mine	Loy Yang field	Loy Yang mine	Bacchus Marsh field
Lithotype		**A,B**	**A**	**A**	**A**	**A, B**	**C**
Dark:Light	Ratio	72:18		21:79	40:60	42:59	18:82
Dark	%, v	17.9		1.6	6.2	12.1	nd
Medium dark	%, v	54.3		19.4	33.3	29.4	17.7
Medium light	%, v	21.2		43.2	37.1	41.1	57.1
Light	%, v	5.7		31.8	20.9	15.4	24.2
Pale	%, v	1.0		4.0	2.5	2.1	1.0
Microscopy - maceral classes							
Groundmass (Class I)	%, v	66	58.1	66.2	73.4		70
Plant Tissue (Class II)	%, v	19.5	23.6	19.3	18.5		21.7
Gelified Material (Class III)	%, v	14.4	18.2	14	8.1		8.1

v, volume. A, (Higgins, Kiss, & Allardice, n.d.); B, (Durie, 1991); C, (Higgins, Kiss, George, King, & Stacy, 1981).

4.2 Proximate and Ultimate Analyses

The moisture contents of Yallourn, Morwell, Loy Yang and Bacchus Marsh lignites range from 51.7-65.5% (ar) and there is considerable variation between moisture contents reported for the same location (Table 4). Yallourn lignites in Table 4 consistently had the highest moisture content (63.5-65.5%). Recent Yallourn mine lignite moisture contents have been around 65% and will increase to around 66% in the near future (Table 2). The high moisture content of Yallourn lignites is a disadvantage for any technology requiring evaporative drying or combustion. Bacchus Marsh lignites may be slightly dryer than Loy Yang lignites.

Bacchus Marsh lignite ash yields (>5%, db) and minerals-and-inorganics (3.5%, db) are considerably higher than Yallourn lignites (1-2.1% ash yield and 0.8-1.5% minerals-and-inorganics). The ash content of Yallourn mine lignites are expected to remain at the top end of this range through to 2032 (Table 2). Loy Yang and Morwell mine lignites have similar ash yield values in Table 4, although Loy Yang mineral-and-inorganic content is considerably lower than Morwell lignite. The implications of ash yield and mineral-and-inorganic content on combustion, slag viscosity and catalysis are dependent on the mineral and inorganic properties. These are discussed in more detail in the next section.

Bacchus Marsh lignites contain the lowest total carbon contents (64.4-65.3%) in Table 4, with carbon contents increasing from Yallourn (65.9-66.7%) to Morwell seams (68.3-69.2% for Morwell and Loy Yang mines and fields). Recent Yallourn mine lignite carbon content is below the historical range (65%, db) and no significant change is expected through to 2032 (Table 2). Fixed carbon and gross dry specific energy (GDSE) follow a similar trend, although the Loy Yang lignite GDSE tends to be lower than the Morwell lignite GDSE.

Bacchus Marsh lignites have considerably lower fixed carbon and volatile matter content compared to Yallourn lignites. Loy Yang lignites contain similar fixed carbon to Yallourn but volatile matter is generally

lower than Yallourn lignites and similar to Bacchus Marsh. Fixed carbon is a good indicator of high temperature (>800oc) char yield (Higgins, Kiss, & Allardice, n.d.).

Hydrogen content is similar across all lignites reported in Table 4, although the Morwell and Loy Yang lignites tend to have higher hydrogen content than Yallourn or Bacchus Marsh lignites. Again, the hydrogen content of recent Yallourn mine lignites is below the historical range and expected to decrease slightly through to 2032 (Table 2).

The H/C ratios for Bacchus Marsh lignites are slightly higher than Yallourn or Loy Yang lignites, indicating the Bacchus Marsh lignites may contain more saturated organic structure like waxes and fatty acids. This is consistent with the dominance of light lithotypes (typically rich in waxes, resins and fatty acids) in Bacchus March lignites. H/C ratios of recent Yallourn mine lignites are at the lower end of the historical range (0.846) but expected to decrease significantly to 0.810 to 2032 (Table 2).

High hydrogen content, H/C atomic ratio and volatile matter in Victorian lignite correlate strongly with hydrogenation reactivity (Durie, 1991) (Higgins, Kiss, & Allardice, n.d.) and tar yield (Higgins, Kiss, & Allardice, n.d.). However, it is unclear if the high H/C ratio and lower volatile matter Bacchus Marsh lignites would result in high or low hydrogenation conversion. The implications of H/C ratios and functional groups are discussed further in later sections. The whole of field and mine data for H/C in Table 4 confirms that on the whole supply basis the lignites have only slight but important differences. These would be amplified during mining given only select areas would be dug at any one time. Any lignite-to-X process needs to take into account the likely range of as mined lignite properties that will be encountered on an ad hoc basis.

Yallourn lignites typically have higher oxygen than either Loy Yang or Bacchus Marsh lignites. This is consistent with the relatively low Yallourn lignite rank. The higher oxygen content is mostly present as organic acids and phenols, resulting in relatively high cation exchange capacity and total acid content, which are discussed further in section 4.4.

Nitrogen content is similar across all lignites reported in Table 4. Yallourn and Loy Yang lignites had similar nitrogen contents although the nitrogen content of recent Yallourn mine lignites is more similar to Bacchus Marsh content (Table 2). Early estimates indicated that 20-30% of the nitrogen in Victorian lignite is converted to NOx during combustion in the Yallourn and Hazelwood power stations (Higgins, Kiss, & Allardice, n.d.). The low temperature combustion resulting from the high moisture content and large volume of recycled flue gas results in relatively low conversion of atmospheric nitrogen to NOx in these power stations (Higgins, Kiss, & Allardice, n.d.). This indicates that the higher nitrogen contents of Bacchus Marsh and contemporary Yallourn lignites may lead to higher NOx emissions from low-temperature oxidation compared to Loy Yang lignites.

All sulfur contents reported in Table 4 are low by world standards (Higgins, Kiss, & Allardice, n.d.) and is predominantly organic sulfur (with some pyrite and marcasite) in Gippsland basin lignites (Durie, 1991, 1-44). The relatively high sulfur content and estimated SOx emissions from Bacchus Marsh lignites may require additional attention to emissions clean-up in combustion applications but could be beneficial for maintaining catalysts in hydrogenation of gasification applications (Higgins, Kiss, & Allardice, n.d.). The lowest sulfur content is consistently reported in historical and current Yallourn mine lignites, which is a significant benefit for any oxidation processes. Loy Yang lignites have a slightly higher sulfur content than Yallourn lignites, but Loy Yang lignite sulfur content remains well below the 1.5-2.7% in Bacchus Marsh lignites.

Table 4. Proximate and ultimate analyses

Area, field or mine	Units	Yallourn-Maryvale area	Yallourn mine			Morwell mine			Loy Yang mine		Loy Yang field	Maddingley No 2 mine	Bacchus Marsh field
		A	B	A	2025-38#	B	B	A	B	2030-48#	A	B	C
Moisture	%, ar	64.7	65.5	63.6	66.0	62.5	61.0	58.6	60.1	60.8	62.2	59.5	60.5
Ash	%, db	2.1	1.7	1	2.1	1.5	1.7	3.1	3.3	1.8	1	5.2	7.4
Minerals and inorganics	%, db	1.5		0.8		1.8		1.8			0.8		3.5
Volatile matter	%, db	51.3	51.1	50.6		51.3	50.5	47.1	48.2		50.9	47.5	49.8
Fixed carbon	%, db	46.6		48.4				49.8			48.4		42.8
Carbon	%, db	65.9	66.7	65.9	65.5	68.3	69.2	67.9	67.8		68.9	64.4	65.3
Hydrogen	%, db	4.7	4.7	4.7	4.5	4.8	4.9	4.7	4.8		4.9	4.4	4.8
Oxygen	%, dmif	27.5		28.1				25.0			24.8		25.2
Nitrogen	%, db	0.5		0.52				0.6			0.51		0.57
H/C	atomic ratio	0.849	0.879	0.849		0.848		0.832	0.851		0.846		*0.882**
Sulfur	%, db	0.25	0.3	0.22	0.29	0.4	0.4	0.44	0.4	0.37	0.31	2.7	1.54
Sulfur emitted as SOx^	%, db	0.1		0.12				0.11			0.18		0.55
Calorific value													
Gross dry	MJ/kg	25.4	25.9	25.74		27	27.6	26.41	26.5		26.6	25.77	25.62
Net wet	MJ/kg	7.09		7.44	6.8			9.06		8.36	8.25	8.41	8.34

*Calculated from H and C concentrations in N; ^estimated from the total S minus the mass of S absorbed by Ca and Na (S emitted as SOx = S – 0.8 Ca – 0.7 Na); #Averages of monthly (Yallourn) and yearly (Loy Yang) predictions provided by Salva Consulting. A, (Higgins, Kiss, & Allardice, n.d.); B, (Durie, 1991); C, (Higgins, Kiss, George, King, & Stacy, 1981). db, dry basis; dmif, dry minerals and inorganics free basis.

4.3 Ash Composition

Although lignites contain minerals and inorganics rather than ash, ash yield and composition are useful parameters for predicting combustion, slag viscosity, ignition, fouling and milling characteristics. Ash yield, composition, properties and indices are summarised in Table 5. The composition and catalytic implications of minerals and inorganics present in as-mined lignite are discussed in the next section.

The ash composition summary in Table 5 highlights the variation in ash composition within mines, seams and formations. Silica is a hard and relatively inert mineral and the low silica concentration in the Bacchus Marsh field lignite is beneficial for milling and grinding (Higgins, Kiss, & Allardice, n.d.). The Loy Yang mine is notorious for pockets of high silica content (Vines, 2008) but the 16-27% silica in Yallourn ash should also be considered when milling / shearing is required as in the Coldry process .

Iron minerals and inorganics are known to promote both spontaneous combustion and ignition in combustion processes (Higgins, Kiss, & Allardice, n.d.; Durie, 1991, p 372). Aluminium and magnesium are known to suppress both these processes and the impact of these elements are incorporated into the ignition index. The Bacchus Marsh lignites have the lowest ignition indices in Table 5, suggesting that they may ignite readily but also be susceptible to spontaneous combustion. This problematic behaviour is already familiar to ETC operations at their Maddingly site. The low ignition index of Bacchus Marsh lignite is consistent with the dominance of pale lithotypes but inconsistent with the moderate iron, aluminium and magnesium concentrations in Table 5.

Within the Gippsland basin, Morwell lignites have been established as the most readily ignitable. Yallourn and Loy Yang mine lignites are considered to have similar ignition characteristics, although high aluminium and dark lithotype lignites found in the Yallourn mine are known to be difficult to ignite. However, high ignition indices of Yallourn and Loy Yang lignites are associated with lower risk of spontaneous combustion during storage and handling. This is particularly beneficial for non-combustion applications.

Bacchus Marsh and Morwell lignites have the highest fouling indices in Table 5 and serious fire-side fouling issues were experienced when Morwell mine lignites were first used in industrial combustion (Durie, 1991, 579-650). These lignites also have the lowest initial deformation temperatures below 1300oC under oxidising conditions. Unlike Morwell lignites, the Bacchus Marsh lignite have a more moderate PACE index (a revised version of the earlier fouling index). Early reports on fire-side fouling take care to note that fouling indices were developed from multiple-linear regression of data from the Gippsland basin and the correlations do not necessary apply equally across different seams. For this reason, the high fouling index of the Bacchus Marsh lignite should not preclude these lignites from consideration in combustion systems. Yallourn and Loy Yang lignites both have initial deformation temperatures above 1300oC, significantly lower PACE and fouling indices as well as extensive history of successful combustion. The decrease in the fouling index in Table 2 suggests fouling is unlikely to be a serious issue for future Yallourn mine lignite combustion.

Importantly, significant changes in Victorian lignite ash properties have been observed well below the ash fusion temperatures and up to half the ash mass can be volatilised during each test (Higgins, Kiss, & Allardice, n.d.). Metals that are typically present in Victorian lignite as cations (e.g., sodium, magnesium and iron) are more strongly associated with fouling than discrete minerals (Durie, 1991, 579-650). The sulfite and sulfate salts of these cations are regularly found in fire-side deposits alongside aluminosilcates and silica minerals formed by oxidation or reduction of discrete minerals in the lignite (Durie, 1991, 579-650).

The preferred mineral and inorganic content of Victorian lignite is dependent on the gasifier design (Tomita & Ohtsuka, 2004). Low viscosity slags (indicated by ash fusion temperatures under reducing conditions) are preferred or required by entrained flow gasifiers and other slagging gasifiers (Tomita & Ohtsuka, 2004). Other gasifier designs including moving bed and fluidized bed avoid liquid slag formation and benefit from higher ash fusion temperatures (Tomita & Ohtsuka, 2004). Yallourn, Loy Yang and Bacchus Marsh ash deformation commences above 1320°C under reducing conditions (Higgins, Kiss, & Allardice, n.d.). The slightly lower ash fusion temperatures for Bacchus March lignite suggests this lignite might be preferred in a slagging gasifier.

Early work showed that Victorian lignite ashes to do not conform adequately to traditional ash melting point indices (particularly the acid-base mineral ratios) (Higgins, Kiss, & Allardice, n.d., p 87). The unique Victorian lignite ash fusion behaviour has been attributed to the presence of sodium and calcium sulfates in Victorian lignite ashes, which have significantly different behaviour to the quartz and clay minerals that dominate

traditional black coal ashes (Higgins, Kiss, & Allardice, n.d.). Table 5 shows the very low clay, pyrite and quartz content of Victorian lignite in both the Gippsland Basin and Bacchus Marsh lignites.

This same early study (Higgins, Kiss, & Allardice, n.d.) established that alumina yield is a significant factor in ash fusion behaviour under both oxidising and reducing conditions. High calcium concentrations tend to decrease ash fusion temperatures under oxidising conditions, while magnesium and silica have more complex effects on ash fusion behaviour under reducing conditions. Morwell lignites have the lowest ash fusion temperatures under reducing conditions in Table 4, with flow commencing just above 1300°C. Bacchus Marsh reducing ash fusion temperatures are lower than both Loy Yang and Yallourn lignites. Loy Yang ash fusion temperatures are slightly lower than Yallourn ashes under reducing conditions.

4.4 Mineral and Inorganic Composition

Although ash composition is widely used to indicate lignite behaviour during combustion and other high temperature processing, ash precursors are present in Victorian lignite as discrete minerals and inorganics (Higgins, Kiss, & Allardice, n.d.; Durie, 1991, p342). Lignite valorisation processes which do not relay on combustion, require a thorough understanding of the potential impact of these guest materials. Table 6 shows the mineral and inorganic content of Victorian lignite ranges from 58% in the Morwell mine to 80% in the Yallourn mine and Loy Yang field. Discrete minerals include quartz, silica, clays, and pyrite or marcasite. Ions or inorganics are typically exchanged with organic functional groups (especially carboxylates) or water-soluble salts (including NaCl and presumably Fe2(OH) and Al(OH)2) (Higgins, Kiss, & Allardice, n.d.). Many of the inorganic ions have important implications for catalysis and adsorption.

Chlorine is mostly present as an anion rather than covalently bonded with the organic lignite structure in Victorian lignite (Higgins, Kiss, & Allardice, n.d.). Chlorides are associated with acid-gas corrosion in high temperature processes and can promote corrosion of stainless steels and other materials. Although chloride concentrations vary across the Gippsland Basin, Yallourn mine lignites contain similar concentrations of chloride compared to Bacchus Marsh lignites. The chloride concentration of Yallourn ROM lignite is expected to decrease slightly (Table 2), suggesting that chloride is unlikely to be a significant factor in lignite future utilisation.

Calcium has been associated with fouling and difficulty filtering liquid products in hydrogenation and liquefaction processes. The lowest calcium concentrations (up to 0.05 %, w/w db) are reported in the Yallourn mine and Loy Yang field. Although calcium concentrations are variable in the Yallourn-Maryvale area, concentrations are expected to decrease in future mining areas (Table 2). The calcium concentrations in the Bacchus Marsh field(1.3% w/w, db) are significantly higher than those of Morwell lignites (up to 0.82 %) which have been associated with CaCO3 precipitation and reactor blockages during liquefaction and hydrogenation (Durie, 1991, 579-650).

However, high concentrations of calcium are known to catalyse gasification reactions, enabling gasification to proceed at lower temperatures (Tomita & Ohtsuka, 2004). These properties could be beneficial for a variety of pyrolysis and gasification processes including ECT's COHgen (ECT, n.d.). Exchanging other ions such as nickel and potassium onto Victorian lignite can also be effective catalysts and gasification as low at 500°C in steam has been reported in the presence of nickel ions (Durie, 1991, p342). An additional benefit of gasification in the presence of nickel ions was the recovery of nickel metal from char and ash.

Ion-exchanged metal cations such as iron and tin also catalyse hydrogenation processes and efficiencies comparable to commercial cobalt-molybdate catalysts have been achieved. Ion-exchanged metal ions are more efficient than blending with solid catalysts, indicating that the higher total organic acid content of the Yallourn lignites is likely to be beneficial compared to Loy Yang and Bacchus Marsh lignites.

The high iron content of Morwell lignite has been associated with more efficient hydrogenation than Loy Yang lignites (Durie, 1991, p342). Bacchus Marsh lignites contain similar levels of non-pyritic iron to Loy Yang but the moderate non-pyritic iron concentration in Yallourn mine lignites could be beneficial for hydrogenation. Interestingly, the total iron content of the Yallourn mines are currently higher than those reported historically (Table 2). Small decreases in the total iron content are expected in future ROM, although the portion of iron present in pyritic and complexed forms is not known.

Mineral and inorganic content is also important for metallurgical applications including chars (Higgins, Kiss, & Allardice, n.d.). Direct ore reduction (e.g., direct iron reduction or DRI) technologies are also at various stages of development including plans for a commercial DRI plant by Smorgons (now BlueScope) in the Latrobe Valley (CCV, 1989) and ECT's HydroMOR process (ECT, n.d.).

Between 52 and 56% the oxygen in Victorian lignite is present as carboxylic and phenolic groups. The carboxylic and phenolic oxygen in Loy Yang and Bacchus Marsh lignites are similar while Yallourn mine lignites have higher total oxygen, carboxylic and phenolic oxygen. Yallourn lignites are slightly more acidic than Loy Yang lignites. Lower Victorian lignite pHs are associated with higher exchangeable magnesium and calcium content. Higher pH is also associated with stronger agglomerate properties from shear-based technologies like Coldry (Tomita & Ohtsuka, 2004).

Table 5. Ash composition, fusion temperatures and combustion related indices

Area, field or mine	Units	Yallourn-Maryvale area	Yallourn mine		Morwell mine	Loy Yang field	Loy Yang mine	Bacchus Marsh field
Ash composition		**A**	**A**	**B**	**A**	**A**	**B**	**B, C**
SiO2	% in ash	12	15.9	26.9	5.9	14.3	16.4	2.6
Al2O3	% in ash	4.1	5.1	8.6	1	15.3	3.4	4.5
Fe2O3	% in ash	29.5	21	20	10.4	6	9.3	5.3
TiO2	% in ash	0.18	0.24	0.5	0.06	0.21	0.3	0.02
CaO	% in ash	8.5	6.5	6	35.6	6	24.7	24.9
MgO	% in ash	17.8	21.1	14.3	16.2	12	14.2	17.4
Na2O	% in ash	6.9	8.4	6.5	4.3	16.2	4.9	4.1
K2O	% in ash	0.18	0.11	0.3	0.16	0.19	0.3	0.38
SO3	% in ash	20.8	20.2	17.1	25.8	29.3	26.6	40.9
S(E)	%, db	0.1	0.12		0.11	0.18		0.55
Ash	%, db	2.2	1.2		3.3	1.1		
Common minerals								
Clay	%	nd	nd		nd	nd		0.1
Quartz	%	nd	0.1		0.3	nd		0.1
Pyrite	%	nd	nd		0.1	nd		0.1
Ash fusion temperatures								
Oxidising – initial deformation	°C	1341	1365		1257	1336		1294
Oxidising – hemispherical	°C	1403	1420		1300	1417		1338
Oxidising – flow	°C	1427	1439		1317	1444		1376
Reducing -initial deformation	°C	1300	1349		1236	1337		1322
Reducing – hemispherical	°C	1362	1427		1284	1401		1354
Reducing – flow	°C	1392	1451		1303	1443		1372
Combustion related indices								
Ignition	Index	2.4	2.4		2	3.1		1.8
Fouling	Index	0.125	0.038		0.199	0.017		0.507
PACE	Index	1.99	2.03		3.81	2.68		2.79

[#]Averages of monthly (Yallourn) and yearly (Loy Yang) predictions provided by Salva Consulting. A, (Higgins, Kiss, & Allardice, n.d.); B, (Durie, 1991); C, (Higgins, Kiss, George, King, & Stacy, 1981). nd, not detected.

Table 6. Minerals, inorganics and acidic organic oxygen functional groups

Area, field or mine	Units	Yallourn-Maryvale area	Yallourn field	Yallourn mine		Morwell field	Morwell mine		Loy Yang field		Loy Yang mine	Bacchus marsh field	
Minerals and inorganics		**A,B**	**B***	**A**	**2025-2038#**	**B**	**A**	**B**	**A,B**	**B**	**2030-2048#**		**C**
Ash	%, db	2.1		1			3.1		1				7.4
Minerals and inorganics		1.5		0.8			1.8		0.8				
SiO_2	%, db	0.3		0.17			0.19	0.14	0.16		0.47		0.23
Al_2O_3	%, db	0.14		0.07			0.04		0.2		0.35		0.4
K_2O	%, db	0.011		0.01	0.01		0.01		0.002				0.034
TiO_2	%, db	0.011		0.004	0.013		0.002	<0.005	0.002				0.002
FeS_2	%, db	0.01		nd			0.03		<0.01				0.42
Fe (NP)	%, db	0.53		0.17			0.22		0.04				0.06
Fe (T)	%, db	0.53		0.17	0.49		0.23		0.04		0.18		0.26
S (T)	%, db	0.26		0.22	0.29		0.45	0.3	0.31		0.37		1.74
Ca	%, db	0.12	0.21	0.05	0.11	0.52	0.82		0.04	0.02	0.04		1.3
Mg	%, db	0.2	0.19	0.15	0.19	0.44	0.32		0.07	0.03	0.10		0.77
Na	%, db	0.09	0.05	0.07	0.07	0.19	0.1		0.14	0.01	0.13		0.22
Cl	%, db	0.11		0.09	0.09		0.05	0.07	0.18		0.16		0.13
NaCl	%, db		0.08			0.43				0.05			
(Fe complex)+	meq/g		0.70			0.42				0.05			
(Al complex)+	meq/g		0.32			nd				0.05			
Total cations	meq/g		0.31			0.7				0.07			
Organic functional groups		**A**	**B**	**A**		**B**	**A**		**B**	**A**		**B**	**C**
Hydrogen ion concentration	pH	4.05		3.75			5.25			3.98			6.39
Total acid	meq/g, db	6.61		6.63			6.14			5.55			5.52
Phenolic OH	meq/g, db	3.86	3.72	3.9		3.7	3.7		3.04	3.04		3.03	3.06
COOH	meq/g, db	2.27	2.21	2.35		1.9	1.54		2.39	2.41		1.12	1.15
COO-	meq/g, db	0.48	0.49, 0.3	0.39		0.59, 0.63	0.77		0.1, 0.11	0.1		1.3	1.3
COO- + COOH	meq/g, db	2.75		2.74			2.37			2.51			2.45
Exchangeable metals	meq/g, db	0.44		0.26			0.83			0.1			1.37
Phenolic O	%, db		5.95			5.92			4.86			4.85	
Carboxylic O	%, db		8.64			7.97			7.97			7.74	
Acidic O	%, db		14.9			14.1			13			13.1	
Total O	%, dmif	27.5	26.9	28.1		25.3	25		24.7	24.8		25.1	25.2
Acidic oxygen	%, dmif	15.2	55	15.1		56	13.9		53	13		52	13.2

* Mode and occurrence of inorganics for the Yallourn-Maryvale area are presented as averages of the three samples reported in Durie (1996, pp. 579-650); NP, non-pyritic; T, total. A, (Higgins, Kiss, & Allardice, n.d.); B, (Durie, 1991); C, (Higgins, Kiss, George, King, & Stacy, 1981).

Table 7. Porosity, density hardness and shrinkage of Victorian lignites.

Area, field or mine	Units	Yallourn-Maryvale area	Yallourn mine	Morwell mine	Loy Yang field	Bacchus Marsh field
Physico-chemical properties		**A**	**A**	**A**	**A**	**B**
Surface area	m^2/g	262	274	274	263	210
Hg density	g/cm^3	0.873	0.937	0.829	0.8	0.859
He density	g/cm^3	1.432	1.42	1.428	1.428	1.499
Porosity	%	39	34	41.9	43.9	42.7
Total pore volume	cm^3/g	0.459	0.379	0.512	0.531	0.501
Micropore volume	cm^3/g	0.07	0.073	0.073	0.07	0.056
Shrinkage	%	543	55.7	42.7	45.5	46.8
Raw lignite density	g/cm^3	1.119	1.12	1.142	1.129	1.151
Petrology - Physical tests						
Specific gravity, moist	g/cm^3	1.117	1.079	1.121	1.131	1.144
Needle hardness, moist	kg/mm^2	1.72	1.61	2.55	1.99	2.32
Specific gravity, dry	g/cm^3	0.815	0.822	0.801	0.738	0.855
Needle hardness, dry	kg/mm^2	7.7	9.2	11	4.9	8.9
Shrinkage, dry	%	53.5	54.9	44.4	45.3	50.5
Shrinkage, air dried	%	42.3	44.2	33.6	29.2	32.6
Colour	Index	85.9	88.8	100.6	111.9	117.9

A, (Higgins, Kiss, & Allardice, n.d.); B, (Higgins, Kiss, George, King, & Stacy, 1981).

4.5 Porosity, Density, Hardness and Shrinkage Properties

Moist needle hardness and specific gravity correlate with rank (Higgins, Kiss, & Allardice, n.d.) and the lowest rank lignite (Yallourn mine) has the lowest moist needle hardness and specific gravity in Table 7. Moist needle hardness and specific gravities are consistent with Loy Yang fields containing moderate rank lignites and Bacchus Marsh lignites being higher than either Yallourn or Loy Yang. Both techniques could be implemented as at-line sensor for sorting lignite by rank if it was beneficial for downstream technologies.

The specific gravity of air-dried lignite and shrinkage during oven- or air-drying correlate strongly with lithotype (Higgins, Kiss, & Allardice, n.d.), providing potential at-line monitoring techniques for sorting lignites based on lithotype. Air-dried lignite needle hardness is also sensitive to lithotype, although this test can be sensitive to shear applied during sampling (Higgins, Kiss, & Allardice, n.d.).

High porosity is beneficial for combustion and processes (including direct hydrogenation) limited by mass-transfer kinetics (Higgins, Kiss, & Allardice, n.d.). The Loy Yang field lignites have the highest porosity in Table 7 and Bacchus Marsh lignites porosity is slightly lower. Yallourn mine lignite porosity is significantly lower than that of Loy Yang and Bacchus Marsh.

4.6 Solubility and Aromaticity

Humic acid extracted from Victorian lignite is a well-established biostimulant-soil conditioner industry in the Latrobe Valley (McManus, 2016) and animal feed additive in Australia (McManus, 2016). Refined lignite from the Maddingley No.2 mine is also commercially available as a soil conditioner (Calleja Group, n.d.). Table 8 shows that Bacchus Marsh has a significant advantage over Yallourn and Loy Yang lignites in both total and free humic acid content. Loy Yang field lignites are richer in total and free humic acids than Yallourn lignites. Humic acids are associated with light lithotypes and these trends are consistent with the lithotype

distribution. The higher magnesium and calcium concentrations in Bacchus Marsh lignites could also be beneficial for agricultural applications.

All the lignites in Table 8 were significantly more soluble in acetone than toluene. The high toluene solubility of Yallourn mine lignites is consistent with the presence of lignin-related aromaticity in dark lithotypes. Bacchus Marsh lignites were significantly more soluble in acetone than the Gippsland basin lignite, which is consistent with the light lithotypes and liptinite content of Bacchus Marsh lignites. Toluene and acetone solubility data could be used to guide research and development of supercritical CO_2 extraction or refining technologies, which could become a beneficial, local use for CO_2.

4.7 Tar, Liquefaction and Hydrogenation Related Properties

Victorian lignite are readily converted to liquid fuels and products by direct hydrogenation and the batch autoclave and tetralin extraction yield results in Table 8 are generally higher than those of higher rank coals (Higgins, Kiss, & Allardice, n.d.). Nevertheless, Yallourn lignites in consistently outperformed the Loy Yang lignites in the batch autoclave and tetralin extraction tests in Table 8. Gippsland Basin lignites consistently report higher autoclave batch conversions than tetralin extraction results and the discrepancy has been attributed to hydrogenation catalysis by native minerals and inorganics (Higgins, Kiss, & Allardice, n.d.). The close agreement between autoclave batch conversion and tetralin extraction may indicate that Bacchus Marsh minerals and inorganics are unable to catalyse hydrogenation. This could have implications for other processes that rely on catalysis by native mineral and inorganics.

Fischer assay is a widely used standardised test for predicting product yields and the tar and oil parameter in Table 8 can be a good indicator of tar yield from Victorian lignite (Higgins, Kiss, & Allardice, n.d.). The highest tar and oil yield in Table 8 (13% for Loy Yang lignites) is at the lower limit for commercial tar production (Higgins, Kiss, & Allardice, n.d.). Tar yield is associated with light lithotypes and >15% liptinite is generally preferred. However, selectively processing light lithotypes is unlikely to be sufficient to achieve commercially viable tar yields from Victorian lignite unless flash pyrolysis is employed (Higgins, Kiss, & Allardice, n.d.). This suggests that pyrolysis of dark lithotype-rich Yallourn lignites would produce less tar by-products from pyrolysis processes than the liptinite-rich Bacchus Marsh lignites.

The char yields from the Fischer assay ranged from 61.2-63.6% for Gippsland Basin lignites and the lighter-lithotype Bacchus Marsh lignites produced slightly less char (58.7%). This is consistent with the lower Bacchus Marsh fixed carbon (Table 4) and indicates that higher pyrolysis or carbonisation char yields could be achieved from Yallourn or Loy Yang lignites.

The Bacchus Marsh and Yallourn-Maryvale area lignites produced slightly more (18-19.8%) than the Yallourn mine, Morwell and Loy Yang lignites. The Yallourn mine has moved further east into the Yallourn-Maryvale area since the 1980 historical data presented in Table 8, suggesting that lignites from the contemporary Yallourn mine and Bacchus Marsh fields could produce higher gas yields from pyrolysis processes like COHgen compared to Loy Yang. Yallourn and Loy Yang lignites produced superior gas yields from hydrogenation, suggesting that gas yields could be increased by incorporating hydrogenation. This could be particularly relevant if a hydrogen industry becomes established in the Latrobe Valley.

4.8 Maceral Classifications

Some macerals (lignite components visible under the optical microscope which are grouped together due to their equivalent optical properties e.g. colour, shape, texture, reflectance) such as liptinite (groundmass including plant-derived spores, pollen, cuticle and resin) have significant implication for lignite properties and utilisation. Small plant fragments (<10 µm) and amorphous ground mass (humodentrinite) is the most common maceral in all lignites in Table 9. The very low but sporadic inertinite content (dense materials that are often chemically inert) is consistent with the low ash yields and minerals-and-inorganic content of Victorian lignite (Higgins, Kiss, & Allardice, n.d.).

The high concentrations of densinite (tightly packed groundmass particles) and gelified (dense, hard material) dark lithotype lignites result in high true density, air-dried specific gravity, total pore volume and low porosity. These properties correlate with gelified material maceral classifications and could be useful for at-line monitoring to facilitate rejecting dark lithotype lignites.

Yallourn lignites contain the lowest concentrations of humodetrinite (groundmass containing small plant fragments) and lower ungelified ground mass (attrinite) than either Loy Yang or Bacchus Marsh lignites. Yallourn lignite also contain significantly more recognisable plant tissues (humotelinite) compared to Loy

Yang and Bacchus Marsh lignites. The presence of better-preserved plant material can be problematic for milling and drying lignite, indicating that Loy Yang and Bacchus March lignites could be preferred for milling, grinding, shearing and other physical processing.

Table 8. Solubility, liquefaction and hydrogenation related properties

Area, field or mine	Units	Yallourn-Maryvale area	Yallourn mine	Morwell mine	Loy Yang field	Bacchus Marsh field
Solubility		**A**	**A**	**A**	**A**	**B**
Total humic acids	%, db	63.3	56	58.8	63.1	81.4
Free Humic acids	%, db	45.7	41.6	33.9	46.9	58
Soxhlet extraction						
Toluene	%, db	2.4	4.9	3.9	1.4	2.1
Acetone	%, db	18.2	16.7	27.1	34.7	61.4
Batch autoclave hydrogenation						
Batch conversion	%, db	90	88	93	84	80
Oils	%, db	20	20	21	18	13
Distillation residue	%, db	39	36	45	35	46
Gas	%, db	25	25	18	22	17
Water soluble	%, db	6	8	10	8	5
Fisher assay						
Char	%, db	61.2	62.4	63.6	63.1	58.7
Tar and oil	%, db	10.4	11.3	10.1	13	11.6
Water soluble	%, db	10.5	10.4	10.9	9	9.9
Gas	%, db	18	15.9	15.5	15.1	19.8
Other						
Air drying H_2O loss	%, ar	58.6	nr	Nr	54.7	52.9
Tetralin extraction test	%, db	78.5	78.2	77.7	77.4	80.7
Volatile carbon	%	19.3	17.5	17.7	20.7	21.4
H/C	Atomic ratio	0.849	0.849	0.832	0.846	0.871

A, (Higgins, Kiss, & Allardice, n.d.); B, (Higgins, Kiss, George, King, & Stacy, 1981).

Both Bacchus Marsh and Loy Yang lignites contain significantly more liptinite macerals than Yallourn lignites. Finely fragmented liptinite ground mass (liptodentrinite) is the most common liptinite maceral in all lignites included in Table 9 and represents more than 6% of both Loy Yang and Bacchus Marsh lignites. Liptinite macerals typically have very high volatile matter content (more than 75%) and liptinite content correlates strongly with volatile matter. These macerals are also associated with high hydrogenation reactivity and concentrations correlate with hydrogen content and Fischer Assay yields. Despite the presence plant tissue in some liptinite macerals, all liptinite macerals have been included in the ground mass classification of Victorian lignite to simplify lignite utilisation assessments (Higgins, Kiss, & Allardice, n.d.). Liptinite macerals fluoresce under blue light and this could be another tool for at-line classification and separation of Victorian lignite (Durie, 1991, pp. 45-102).

Table 9. Micropetrography and maceral composition

Area, field or mine	Units	Maceral class	Brief description	Lithotype correlation	Yallourn-Maryvale area	Yallourn mine		Morwell mine	Loy Yang field		Bacchus Marsh field
Maceral analysis					**A**	**A**	**A**	**A**	**A**	**A**	**B**
Humodetrinite	**%**		**Ground mass containing small plant material fragments (<10 um) and amorphous matrix.**	**v**	**59.3**	**55.7**	**60.2**	**62.3**	**66**	**61.2**	**62.8**
Attrinite	%	Groundmass	Ungelified groundmass.	vv	56.4	52.4	58.9	60.6	64.7	41.5	59.3
Densinite	%	Gelified material	Gelified ground mass containing densely packed particles. Generally confined to dark or medium-dark lithotypes and >10% densinite indicates a high degree of gelification.	^	2.9	3.3	1.3	1.6	1.3	19.7	3.5
Humotelinite	**%**		**Recognisable decomposed, gelified and coalified plant tissue.**	**^^**	**22.4**	**26.2**	**21.5**	**18.9**	**16.5**	**17.7**	**17.8**
Textinite	%	Gelified material			1.4	2.3	1.1	1.8	0.4	1.7	0.5
Textoulminite	%	Plant tissue	Slight to moderate gelification	^^	14.4	14.4	14	11.8	12.6	6.3	13.9
Euulminite	%	Gelified material	Highly gelified	^	6.6	9.6	6.3	5.3	3.5	9.7	3.5
Humocollinite	**%**		**Amorphous humic gels, intensely gelified plant tissue and structureless cell excretions.**	**^**	**10.6**	**11.9**	**11.5**	**12.6**	**8.6**	**15.3**	**84**
Telogelinite	%	Gelified material		^	0.7	0.8	0.3	0.3	0.3	0.5	0
Detrogelinite	%	Gelified material			0.1	0.1	0.1	0	0	0.2	0
Eugelinite	%	Gelified material			0	0	0.1	0.1	0	0.1	0
Porigelinite	%	Plant tissue			1	1	2.1	1.4	2.4	1.9	3.3
Phlobaphinite	%	Plant tissue			4	5.9	3.9	4.3	3	4.3	4
Pseudophlobaphinitie	%	Plant tissue			4.7	4	5.1	6.4	2.8	8.2	1
Liptinite	**%**		**Fluoresce under blue light. Tend to be resistant to chemical alteration or decay and are often higher in volatile matter and hydrogen.**	**vv**	**6.6**	**5**	**5.6**	**4.5**	**8.3**	**3.8**	**10.2**
Sporinite	%	Groundmass	Spores and pollen	vv	1	1.2	1	1	0.7	0.9	1.1
Cutinite	%	Groundmass	Cuticle		0.3	0.4	0.1	0.1	0	0.3	0.1
Resinite	%	Groundmass	Resin		0.3	0.4	0.2	0.3	0.5	0.1	1
Suberinite	%	Groundmass			1.4	1.2	1.3	1	1	0.9	1.3
Liptodetrinite	%	Groundmass	Finely fragmented liptinite ground mass.	vv	3.6	1.7	3	2	6.1	1.6	6.8
Inertite	**%**				**1**	**1**	**1.1**	**1.4**	**0.6**	**1.2**	**0.6**
Sclerotinite	%	Groundmass	Dense, hard or brittle material with very high reflectance in incident light. Often chemically inert and may be the last macerals to carbonise.	^	0.7	0.7	0.8	1.1	0.4	0.8	0.5
Semifusinite	%	Gelified material	Generally limited to dark and medium dark lithotypes.	^	0.1	0.1	0	0.1	0	0	0.1
Fusinite	%	Gelified material	Similar to wood charcoal. Generally limited to dark and medium dark lithotypes.	^	0	0.1	0	0	0	0.1	0
Inertodetrinite	%	Gelified material			0.1	0.2	0.2	0.2	0.1	0.3	0

A, (Higgins, Kiss, & Allardice, n.d.); B, (Higgins, Kiss, George, King, & Stacy, 1981).

4.9 Beneficial Properties of Yallourn Lignites

The distinctive properties of Yallourn lignites include high moisture content, predominately dark lithotypes, significant plant tissue macerals (including woody macerals), high gelified maceral content, high volatile matter, high total organic acid content, low pH, high surface area and low porosity. Fortunately, highly gelified materials are have been readily separated for Yallourn run-of-mine lignites. As a result, Yallourn mine lignites have been the preferred agglomeration and carbonisation feedstock (Durie, 1991; Verheyen, 1996; Vines, 2008). Implementing contemporary sensing and sorting technologies could result in significant improvements in process stability as well as improved product quality and consistency.

Woody lignite is likely to be rejected from most primary production processes but is beneficial for manufacturing activated carbons and some agricultural applications (Verheyen, 1996). The high total organic acid content, low pH and high surface area would be advantageous for applications benefitting from ion exchange including agriculture and direct metallurgical reduction. Fortunately, the lithotype banding in the Yallourn mine is more distinct than other mines, which could facilitate selective mining using dozers or post-mining separation of lignite (Higgins, Kiss, & Allardice, n.d.).

The extensive experience with converting Yallourn lignites to products including briquettes, chars, steel recarburisation and smokeless fuels provide commercial precents for many potential products. The availability of future mine lignite properties is also beneficial.

5 Recommendations for End Uses of Yallourn Lignite

The lignite properties and commercial prospects evaluation identifies four promising candidates for commercial production from Yallourn lignite: metallurgical reductants, hydrogen, humic substances and fertilisers. Advanced carbons such as carbon fibre, graphene, graphene oxide and quantum dots grow could also be commercially valuable products if these markets grow. These products could benefit from further technical, commercial and economic investigation and targeted research.

The dark lithotypes, gelified macerals and woody lignite can be problematic for drying, milling, agglomeration and carbonisation have been readily separated from Yallourn run-of-mine lignites for many decades. The use of rapidly advancing at-line sensor and sorting technology could be significantly reduce the commercial risk in processing Yallourn lignites. Selective processing of Yallourn lignites is also likely improve consistency in saleable products by reducing variability in the feedstock. Further technical investigations into adapting existing technology to sensing and sorting Yallourn lignites are recommended.

If Yallourn lignites are selectively processed, rejected lignite is likely to be rich in dark lithotypes and woody lignite. Woody lignite is beneficial for activated carbons and some agricultural applications such as potting mixes. Dark lithotypes are typically rich in aromatic lignin-related structures that could be incorporated into local biorefinery concepts or possibly used as a carbon fibre feedstock.

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Appendix A

Technology and commercial prospects evaluation for each application are provided in Table A1. Section 3.2 in the main report provides additional information about each application or product while section 4 and Table X provide further information about the relevant lignite properties.

Table A1. Technology and commercial prospects evaluation matrix

	2021 scores				Evaluation of technology^								Commercial prospects evaluation#							
Application or product	Technology Evaluation	Commercial Evaluation	Overall	Overall score assigned in 1996@	Technical feasibility of production (concept=5, lab proof=10, pilot plant=5)		Commercialisation status (plant constructed=6, currently produced=4, special economics=-2)		Applicability to Victorian lignite (low rank lignite=1, lignite=2, high cation lignitess=2)		Yallourn lignites preferred (Dark lithotypes preferred=5, ash yield and constituents=5, other properties=5)		Production Set-up Costs (<$0.5 M=4, <$5 M=15, >$5 M=7)		Lignite Tonnage and Type (<1 kt per year=2, <100 kt per year=5, >100 kt per year=10)		Target Market Expanding/Decreasing (expanding=10, stable=5, decreasing=0)		Niche Market High Value Adding (niche exists=15, new market=10, established competitive market=5)	
					Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment
Carbons																				
Active carbon																				
Water treatment	36	19	55	53	18	5,9,4*	10	6,4,0*	4	1,1,2* Hardness is key barrier	4	0,2,2 High woody lignite and low ash beneficial	7	>$5M	4	<100 kT/y	5	Expanding	3	2,0,1 Niche exists in existing competitive market
Vapour/gas treatment	36	16	52	50	19	5,9,5*	10	6,4,0*	3	1,1,1*	4	0,2,2 High woody lignite and low ash beneficial	7	>$5M	3	>100 kT/y	3	Stable	3	Established competitive market
Low value single use	37	2	39	35	20	5,10,5*	8	6,4,-2*	5	1,2,2*	4	0,2,2 High woody lignite and low ash beneficial	0	Waste material	2	<100 kT/y	0	Decreasing	0	Established competitive market
Premium carbons	16	23	39	37	15	5,10,0 Additional laboratory proof has been obtained since 1996.	-2	0,0,-2*	3	1,1,1*	0	0,0,0 Light lithotypes preferred	5	>$5M	2	<100 kT/y	8	Expanding	8	5,0,3 Niche exists in existing competitive market
Char																				
Chemical feedstock	35	17	52	48	20	5,10,5*	8	6,4,-2*	3	1,2,0*	4	0,2,2 High woody lignite and low ash beneficial	7	>$5M	10	>100 kT/y	0		0	Established competitive market
Active carbon precursor	36	18	54	55	20	5,10,5*	8	6,4,-2*	4	1,2,1*	4	0,2,2 High woody lignite and low ash beneficial	7	>$5M	7	>100 kT/y	3	Stable	1	Established competitive market
Metallurgical reductant	37	26	63	58	19	5,9,5*	8	6,4,-2*	3	1,2,0*	7	0,5,2 Woody lignite and low ash beneficial	7	>$5M	7	>100 kT/y	7	Expanding	5	Established competitive market
High purity	17	20	37	37	10	4,6,0*	0	0,0,0*	5	1,2,2*	2	0,0,2 Low sulfur and iron beneficial	7	<$5M	2	<1 kT/y	6	Expanding	5	New market
Filter aid	35	6	41	41	20	5,10,5*	10	6,4,0* Possible use for off-spec char	5	1,2,2*	0	0,0,0 No specific lignite properties required	0	Use of off-spec lignite	2	<1 kT/y	2	Stable	2	Established competitive market
Advanced carbons																				
Carbon fibre	19	24	43	very low	10	5,5,0 Relevant laboratory-scale research in progress	0	0,0,0 No commercial precedent	2	0,2,0 High volatile matter disadvantageous	7	0,2,5 Low ash and sulfur beneficial	7	>$5M	2	<1 kT/y	7	Expanding	8	5,0,3 Niche exists in existing competitive market
Graphene and graphene oxide	13	24	37	new	6	5,1,0 Successful preliminary laboratory trials	0	0,0,0 No commercial precedent	2	1,1,0	5	0,5,0 High humic acid content and light lithotypes are preferred	7	>$5M	2	<1 kT/y	7	Expanding	8	5,0,3 Niche exists in existing competitive market

Application or product	2021 scores			Overall score assigned in 1996@	Evaluation of technology^								Commercial prospects evaluation#							
	Technology Evaluation	Commercial Evaluation	Overall		Technical feasibility of production (concept=5, lab proof=10, pilot plant=5)		Commercialisation status (plant constructed=6, currently produced=4, special economics=-2)		Applicability to Victorian lignite (low rank lignite=1, lignite=2, high cation lignitess=2)		Yallourn lignites preferred (Dark lithotypes preferred=5, ash yield and constituents=5, other properties=5)		Production Set-up Costs (<$0.5 M=4, <$5 M=15, >$5 M=7)		Lignite Tonnage and Type (<1 kt per year=2, <100 kt per year=5, >100 kt per year=10)		Target Market Expanding/Decreasing (expanding=10, stable=5, decreasing=0)		Niche Market High Value Adding (niche exists=15, new market=10, established competitive market=5)	
					Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment
Quantum dots	9	21	30	new	3	3,0,0 Concept only. Further research required.	0	0,0,0 No commercial precedent	1	0,1,0	5	0,5,0 High humic acid content and light lithotypes are preferred	7	>$5M	2	<1 kT/y	7	Expanding	5	New market
Upgraded fuels																				
Solid fuels																				
Smokeless fuel	35	22	57	64	20	5,10,5*	8	6,2,0*	5	1,2,2*	2	0,2,0 Light lithotypes, high fixed carbon, low moisture and low woody lignite preferred	12	<$5M	5	<100 kT/y	5	Expanding	0	Established competitive market
Powdered dry lignite	35	12	47	47	20	5,10,5*	10	6,4,0* Two commercial plants have operated in Latrobe Valley	5	1,2,2*	0	0,0,0 Dark lithotypes and woody lignite problematic for grinding. Low moisture content preferred for drying.	7	>$5M	5	<100 kT/y	0	Decreasing	0	Established competitive market
Agglomerated and briquetted lignite	37	23	60	61	20	5,10,5*	10	6,4,0 Score somewhat dependent on technology	5	1,2,2*	2	0,2,0 Dark lithotypes, woody lignite and high moisture content problematic for milling and drying.	7	>$5M	10	>100 kT/y	0	Decreasing	6	New market
Liquid fuel																				
Fuel oil	33	25	58	58	20	5,10,5*	8	6,4,-2* Historically sold as by-product of char production	5	1,2,2*	0	0,0,0* Most likely a by-product of char production or other pyrolysis process	7	>$5M	10	>100 kT/y	5	Stable	3	Established competitive market
Water/oil mixtures	24	33	57	63	19	5,9,5*	0	0,0,0*	3	1,1,1*	2	0,2,0 Low moisture, low ash required	7	>$5M	10	>100 kT/y	10	Expanding	6	New market
Gaseous fuels and gasification products																				
Synthesis gas for electricity	35	21	56	65	19	5,9,5*	8	6,2,0*	5	1,2,2*	3	0,3,0 Low moisture, low ash, high Ca preferred	7	>$5M	7	>100 kT/y	4	Stable	3	Established competitive market
Substitute natural gas	32	23	55	57	20	5,10,5*	4	6,0,-2*	5	1,2,2*	3	0,3,0 Low moisture, low ash, high Ca preferred	7	>$5M	10	>100 kT/y	6	Expanding		
Gasification - syn gas - products																				
Hydrogen	26	34	60	New	20	5,10,5 Current pilot plant in Victoria	-2	0,0,-2 Local and export infrastructure required	5	1,2,2*	3	0,3,0 Low moisture, low ash, high Ca preferred	*7*	*$12 billion for 320 000 kg/h.*	*10*	*60, 000 tonnes per day*	*7*	*Expanding*	*10*	*New market*
DME	26	31	57	New	20	5,10,5 Victorian lignite gasification demonstrated at pilot scale. Commercial DME	-2	0,0,-2 Local and export infrastructure required	5	1,2,2 High catalytic cation content beneficial	3	0,3,0 Low moisture, low ash, high Ca preferred	*7*	*$12 billion for 320 000 kg/h.*	*10*	*60, 000 tonnes per day*	*4*	*Stable*	*10*	*New market*

Application or product	2021 scores: Technology Evaluation	2021 scores: Commercial Evaluation	2021 scores: Overall	Overall score assigned in 1996@	Evaluation of technology^: Technical feasibility of production (concept=5, lab proof=10, pilot plant=5) Score	Comment	Commercialisation status (plant constructed=6, currently produced=4, special economics=-2) Score	Comment	Applicability to Victorian lignite (low rank lignite=1, lignite=2, high cation lignitess=2) Score	Comment	Yallourn lignites preferred (Dark lithotypes preferred=5, ash yield and constituents=5, other properties=5) Score	Comment	Commercial prospects evaluation#: Production Set-up Costs (<$0.5 M=4, <$5 M=15, >$5 M=7) Score	Comment	Lignite Tonnage and Type (<1 kt per year=2, <100 kt per year=5, >100 kt per year=10) Score	Comment	Target Market Expanding/Decreasing (expanding=10, stable=5, decreasing=0) Score	Comment	Niche Market High Value Adding (niche exists=15, new market=10, established competitive market=5) Score	Comment
						production from syngas overseas.														
Methanol	26	26	52	New	20	5,10,5 Victorian lignite gasification demonstrated at pilot scale. Commercial methanol production from syngas overseas.	-2	0,0,-2 Local and export infrastructure required	5	1,2,2 High catalytic cation content beneficial	3	0,3,0 Low moisture, low ash, high Ca preferred	7	*$13.1 billion for 500 tonnes/h.*	10	*60, 000 tonnes per day*	6	*Expanding*	3	*Established competitive market*
Urea	26	25	51	New	20	5,10,5 Victorian lignite gasification demonstrated at pilot scale. Commercial urea production from syngas overseas.	-2	0,0,-2 Local and export infrastructure required	5	1,2,2 High catalytic cation content beneficial	3	0,3,0 Low moisture, low ash, high Ca preferred	7	*$13.65 billion for 830 tonnes/h.*	10	*60, 000 tonnes per day*	5	*Stable*	3	*Established competitive market*
Ammonia	26	27	53	New	20	5,10,5 Victorian lignite gasification demonstrated at pilot scale. Commercial ammonia production from syngas overseas.	-2	0,0,-2 Local and export infrastructure required	5	1,2,2 High catalytic cation content beneficial	3	0,3,0 Low moisture, low ash, high Ca preferred	7	*$13.65 billion for 470 tonnes/h.*	10	*60, 000 tonnes per day*	7	*Expanding*	3	*Established competitive market*
Agricultural products																				
Soil conditioner, potting mixes and soil fertility boosters																				
Run-of-mine lignite	20	13	33	45-48	15	5,5,5 Mixed laboratory and field results	0	0,0,0 No current commercial operation	5	1,2,2*	0	0,0,0 Light lithotypes preferred. No ash property requirements.	4	*<0.5M*	3	*<100 kT/y*	0	*Decreasing*	6	*New market*
Chars	22	23	45	45-48	15	5,5,5 Mixed laboratory and field results	0	0,0,0 No current commercial operation	3	1,2,0* Based on char chemical feedstock score	4	0,2,2 High woody lignite and low ash beneficial	7	*>$5M*	3	*<100 kT/y*	5	*Expanding*	8	*New market*
Ash	20	13	33	45-48	15	5,5,5 Mixed laboratory and field results	0	0,0,0 No current commercial operation	5	1,2,2*	0	0,0,0 No ash property or lithotype requirements.	4	*<0.5M*	3	*<100 kT/y*	0	*Decreasing*	6	*New market*
Fertilizer																				
Organic fertiliser base	37	30	67	70	20	5,10,5*	10	6,4,0*	5	1,2,2*	2	0,0,2 Light lithotypes, high Ca, Mg, total acid content and pH preferred	12	*<$5M*	3	*<100 kT/y*	5	*Expanding*	10	*Niche exists*
Inorganic fertiliser additive	37	30	67	65	20	5,10,5*	10	6,4,0*	5	1,2,2*	2	0,0,2 Light lithotypes, high Ca, Mg, total acid content and pH preferred	12	*<$5M*	3	*<100 kT/y*	5	*Expanding*	10	*Niche exists*
Humic substances																				
Humic acids - plant crops	35	25	60	New	20	5,10,5*	10	6,4,0 Commercial precedents in Australia	5	1,2,2*	0	0,0,0 Light lithotypes preferred. No ash property requirements.	12	*<$5M*	3	*<100 kT/y*	5	*Expanding*	5	*Established competitive market*

Application or product	2021 scores: Technology Evaluation	2021 scores: Commercial Evaluation	2021 scores: Overall	Overall score assigned in 1996@	Evaluation of technology^: Technical feasibility of production (concept=5, lab proof=10, pilot plant=5) Score	Technical feasibility Comment	Commercialisation status (plant constructed=6, currently produced=4, special economics=-2) Score	Commercialisation Comment	Applicability to Victorian lignite (low rank lignite=1, lignite=2, high cation lignitess=2) Score	Applicability Comment	Yallourn lignites preferred (Dark lithotypes preferred=5, ash yield and constituents=5, other properties=5) Score	Yallourn Comment	Commercial prospects evaluation#: Production Set-up Costs (<$0.5 M=4, <$5 M=15, >$5 M=7) Score	Production Set-up Costs Comment	Lignite Tonnage and Type (<1 kt per year=2, <100 kt per year=5, >100 kt per year=10) Score	Lignite Tonnage and Type Comment	Target Market Expanding/Decreasing (expanding=10, stable=5, decreasing=0) Score	Target Market Comment	Niche Market High Value Adding (niche exists=15, new market=10, established competitive market=5) Score	Niche Market Comment
Humic acid - animal feed additive	35	30	65	New	20	5,10,5*	10	6,4,0 Commercial precedents in Australia	5	1,2,2*	0	0,0,0 Light lithotypes preferred. No ash property requirements.	*12*	*<$5M*	*3*	*<100 kT/y*	*5*	*Expanding*	*10*	*Niche exists*
Ammonia controlled release	35	25	60	New	20	5,10,5*	10	6,4,0 Commercial precedents in Australia	5	1,2,2*	0	0,0,0 Light lithotypes preferred. No ash property requirements.	*7*	*>$5M*	*3*	*<100 kT/y*	*5*	*Expanding*	*10*	*Niche exists*
Fulvic acid	35	28	63	New	20	5,10,5*	10	6,4,0 Commercial precedents in Australia	5	1,2,2*	0	0,0,0 Light lithotypes preferred. No ash property requirements.	*15*	*<$5M*	*3*	*<100 kT/y*	*5*	*Expanding*	*5*	*Established competitive market*
Bulk chemicals																				
Extraction																				
Humic acids	35	30	65	66	20	5,10,5*	10	6,4,0*	5	1,2,2*	0	0,0,0 Light lithotypes preferred. No ash property requirements.	12	<$5M	3	<100 kT/y	5	Expanding	10	Niche exists
Tars and pitches	28	13	41	41	15	5,10,0*	10	6,4,0*	3	1,2,0*	0	0,0,0* Most likely a by-product of char production or other pyrolysis process	8	<$5M	2	<1 kT/y	0	Decreasing	3	Established competitive market
Manufactured products																				
Ion-exchanger	27	29	56	69	20	5,10,5*	0	0,0,0*	5	1,2,2*	2	0,0,2 High surface area and total acid content beneficial. No preference for ash or lithotypes.	4	<$0.5M	5	<100 kT/y	8	Expanding	12	Niche exists
Fine chemicals																				
Solvent extraction																				
Resins	37	16	53	58	20	5,10,5*	10	6,4,0*	5	1,2,2*	2	0,0,2 Light lithotypes and high resinite macerals preferred.	4	<$0.5M	2	<1 kT/y	5	Stable	5	New market
Wax esters	35	16	51	58	20	5,10,5*	10	6,4,0*	5	1,2,2*	0	0,0,0 Light lithotypes and high cutinite macerals preferred.	4	<$0.5M	2	<1 kT/y	5	Stable	5	New market
Phenols	28	14	42	37	15	5,10,0*	3	3,0,0* Possible by-product from gasification	5	1,2,2*	5	5,0,0 Dark lithotypes preferred	2	<$0.5M	2	<1 kT/y	3	Stable	7	New market
Magnesium	26	23	49	new	16	5,10,1* Demonstration plant in Latrobe Valley planned	0	0,0,0	5	1,2,2 High Mg content beneficial	5	0,0,5 Yallourn ash readily available but lignite not rich in Mg	7	>$5M	2	<1 kT/y	6	Expanding	8	5,0,3 Niche exists in existing competitive market
Oxidation																				
Aromatic polycarboxylic acids	24	24	48	43	14	5,9,0*	0	0,0,0*	5	1,2,2*	5	5,0,0 Dark lithotypes preferred	4	<$0.5M	2	<1 kT/y	10	Expanding	8	New market

Application or product	2021 scores			Overall score assigned in 1996[@]	Evaluation of technology^								Commercial prospects evaluation[#]							
	Technology Evaluation	Commercial Evaluation	Overall		Technical feasibility of production (concept=5, lab proof=10, pilot plant=5)		Commercialisation status (plant constructed=6, currently produced=4, special economics=-2)		Applicability to Victorian lignite (low rank lignite=1, lignite=2, high cation lignitess=2)		Yallourn lignites preferred (Dark lithotypes preferred=5, ash yield and constituents=5, other properties=5)		Production Set-up Costs (<$0.5 M=4, <$5 M=15, >$5 M=7)		Lignite Tonnage and Type (<1 kt per year=2, <100 kt per year=5, >100 kt per year=10)		Target Market Expanding/Decreasing (expanding=10, stable=5, decreasing=0)		Niche Market High Value Adding (niche exists=15, new market=10, established competitive market=5)	
					Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment	Score	Comment
Pyrolysis																				
Phenols	21	23	44	46	18	5,10,3*	0	0,0,0*	3	1,2,0*	0	0,0,0* Most likely a by-product of char production or other pyrolysis process	9	<$5M	5	<100 kT/y	4	Stable	5	New market

[@]Verheyen (1996)

^Technology evaluation scores are the sums of the three sub-scores listed in the comments column. Sub scores are presented in the same order as the column heading. For example, 5,9,4 under Technical feasibility of production indicates the concept score is 5, lab proof scores 9 and pilot plant scores 4.

*Technology evaluation score has not changed since 1996.[#] Normal type scores and notes are transcribed from 1996. *Italic type scores and comments are estimates from 2021. Agriculture commercial prospects scores are based on humic acid extraction scores from 1996 and the authors local experience. Gasification synthesis gas product commercial prospects scores after Kinaev & Bongers (2016).*