PHASE 2 REPORT

PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY

BIOCHAR INVESTIGATION

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SYNOPSIS

This report investigates biochar and biomass supply options, considers pyrolysis equipment suitable for mass production of biochar and provides commentary on pilot testing and plant trials of biochar/coal mixtures injected into No. 5 Blast Furnace at the Port Kembla Steelworks.

This Project received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program.

The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

EXECUTIVE SUMMARY

Actively addressing climate change and investing in carbon reduction technologies are explicitly highlighted in BlueScope's Climate Strategy.

From 2006-2014, BlueScope, OneSteel and CSIRO undertook a major R&D program to develop innovative, practical technologies involving the substitution of fossil-based fuels, such as coal, with renewable biomass materials. The program included bench-scale testing of a novel large-scale pyrolysis process and preliminary studies of biomass supply in Australia, as well as theoretical and pilot scale combustion studies showing the superior performance of biochar relative to coal for blast furnace injection.

Picking up on this previous work, BlueScope has been investigating the use of biochar in Port Kembla Steelwork's (PKSW) blast furnace Pulverised Coal Injection (PCI) process as a coal replacement for some of the 400,000 tonnes of PCI coal injected per annum.

This report focuses on the potential supply of biochar and biomass, equipment options to produce biochar from biomass, pilot testing of biochar/coal at the UOW's Bulk Materials Engineering Australia (BMEA) test facility and plant trials of injecting a biochar/coal mix into PKSW's No. 5 Blast Furnace.

Supply of Biochar and Biomass, and Pyrolysis Technology

Use of biochar in steelmaking processes has the potential to reduce net CO_2 emissions whilst still using current equipment. A review of biochar production in Australia was undertaken which found the following:

- Biochar supply to PKSW from existing commercial suppliers within Australia appears unlikely given there is insufficient capacity in local production.
- While biochar import could still be an option, it appears to be logistically difficult, expensive and potentially risky from a sustainability perspective.
- Current biochar supplies in Australia are expensive, both from a cost and transport perspective.
- Hence, if biochar usage were to proceed at PKSW, BlueScope may have to invest in larger scale biochar production

To fund potential large-scale biochar production, considerable supplies of suitable biomass would need to be found. A review of Australian biomass sources found the following:

- A number of biomass supply options appear possible, either from forestry or waste sources.
- Forestry wastes and timber reclaimed from landfill streams appeared to be the most sustainable, however the current lack of investment in utilizing forestry wastes and heavy metals contamination of waste timber make them challenging to use.
- In the short term, utilising woodchips from sources unsuitable for paper production may be the best option, with bush fire damaged timber wood chips being an opportunity. These have the added benefit of potentially being transported by sea, lowering transport costs.
- In the longer term, sourcing of biomass from invasive weeds or dedicated biomass plantations should be considered.

Given the inherently high moisture and low carbon levels in raw biomass, pyrolysis is required to ensure that the resultant biochar material is suitable for steelmaking applications. A review of current pyrolysis technologies in combination with a determination of the requirements for scale biochar production found the following:

- Pyrolysis technology is a wide and varied field, with several different options potentially available.
- However, given the requirements for larger scale biochar production, multiple hearth furnace or rotary kiln technologies are options that BlueScope may need to investigate and developer further if large scale biochar usage were to proceed at PKSW.
- Collection and valorisation of pyrolysis by-products needs further investigation as a potential revenue stream utilising a larger proportion of the biomass feedstock. However, given there is no market demand for either upgraded products or raw bio-oil, in the short term all by-products would likely be utilised for onsite energy production.

Pilot Testing of Coal/Biochar Blends

To support the plant demonstration of a pulverised blend of biochar-coal for injection at PKSW No. 5 Blast Furnace (BF), test work was conducted by BMEA to characterise the flow properties and pneumatic conveying characteristics of various biochar/coal blend ratios. In addition, segregation testing of the worst-case blend of biochar-coal was carried out.

The work found the following:

- In terms of flow characteristics and handleability there was little difference between the performance of biochar-coal blends containing up to 30% biochar and 100% coal
- Similarly, with pneumatic conveying there was little difference between the conveying behaviour of biochar-coal blends when compared to coal alone
- As such, indications are that the operational variations of the injection line at PKSW when conveying blends up to 30% biochar should be minor and that only small changes to operational parameters such nitrogen flow rates may be needed to convey the biochar-coal blends.

Plant Trials of Coal/Biochar Blends

From November 2021 until February 2023, biochar, purchased with funding from ARENA, was delivered and stored at PKSW. This was followed in February and March 2023 with biochar trials at the PCI Plant. These industrial-scale trials consisted of 10 events in a staged series, encompassing biochar additions to coal ranging from 5 to 30% on a dry basis for time periods from 1 to 24 hours. The work found the following:

- Bulk biochar can be successfully handled and stored in a similar fashion to most bulk materials used at PKSW, albeit that it requires more water to reduce dust emissions to an acceptable level.
- Biochar and biochar-coal blends up to a maximum of 30% can be proportioned, elevated, and stored with the existing equipment at the PCI Plant, without experiencing problems with material flow, excessive spillage or segregation.
- Grinding and drying of biochar/coal blends up to a maximum of 30% biochar can be undertaken successfully and safely with current equipment at the PCI Plant, with only minimal changes made to the process to achieve standard moisture and sizing aims.
- Pneumatic handling of the biochar/coal blends, up to a maximum of approximately 20% can be successfully conveyed and proportioned to the 28 tuyere lines at up to 50t/hr without experiencing unstable flow, blockages, or segregation.
- Biochar/coal blends of up to approximately 20% biochar can be successfully used to replace pulverised coal in blast furnace operations for at least short periods of time, without detriment to the stability, productivity of the process or indeed the quality of the hot metal.

Given the positive results of these trials, it is recommended to source larger quantities of biochar to fund several trials of biochar addition to PCI coal for a minimum of 72 hours at levels of up to 30% biochar in coal. These trials would enable optimisation of process parameters and plant performance.

Contents

List of acronyms and abbreviations

ARENA	Australian Renewable Energy Agency
AIE	Alkaline iron electrolysis
BF	Blast furnace
BMEA	Bulk Materials Engineering Australia
BOF	Basic oxygen furnace
C	Carbon
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CCUS	Carbon capture and usage or storage
CO_2	Carbon dioxide
DCA	Direct carbon avoidance
DR	Direct reduction
dmt	Dry metric tonne
DRI	Direct reduced iron
EAF	Electric arc furnace
GHG	Greenhouse gas
H_2	Hydrogen
H2-DR	Hydrogen-based direct reduction
HBI	Hot briquetted iron
HCI	Hot compacted iron
HPSR	Hydrogen plasma smelting reduction
LCA	Life Cycle Analysis
MOE	Molten oxide electrolysis
NG-DR	Natural gas direct reduction
N_2	Nitrogen
O_2	Oxygen
OPEX	Operational expenditure
PKSW	Port Kembla Steel Works
R&D	Research and development
SAF	Submerged Arc Furnace
SCU	Smart carbon usage
SWOT	Strengths, Weaknesses, Opportunities and Threats
t	Tonne
TGR-BF	Top gas recycling – blast furnace
TRL	Technology readiness level
UoW	University of Wollongong
wmt	Wet metric tonne
Y	Years

1 Introduction

The use of charcoal or biochar has been investigated via numerous studies in recent times and all these have shown that biochar derived from sustainable biomass sources can be used in iron and steelmaking to replace some fossil coal-based carbon sources. The Paris Agreement [1], states that biomass from sustainable sources is deemed to emit no CO_2 as any CO_2 that is generated will be taken up by re-growth of the biomass. This treatment of biomass emissions in turn could result in a reduction in net CO_2 emissions from steelmaking, whilst still using current well understood and optimised processing technologies such as the blast furnace [2][3]. However, as with any raw material feedstock, the key is consistent supply of material of a suitable quality and cost. This chapter focuses on biochar supply and then proceeds to examine biomass properties and its supply routes, along with appropriate processing technology to produce biochar at sufficient scale and cost, with the potential production of pyrolysis bio-oils also discussed.

1.1 BlueScope's Stated Aim for Biochar

BlueScope recognises that climate change is an existential threat to the world and that CO_2 emissions reduction is key to reducing the effects of climate change [4]. As such, BlueScope has set a target of a 12% reduction in CO_2 emissions relative to FY2018 from all its steelmaking sites including the Port Kembla Steelworks (PKSW) by 2030. As an integrated steelworks, relying heavily on fossil coal as a reductant and fuel source, this is a big challenge for PKSW. Several strategies have been proposed to meet this, one of which involves the use of biochar derived from sustainable biomass. While biochar has the potential for wider application throughout the ironmaking chain, the difficulties in establishing a biochar supply chain means that in the short term it is unlikely that the full 12% reduction in CO_2 emissions could be realized via biochar usage alone. As such, replacing 30% of pulverized coal used for blast furnace injection is being considered as a more realistic option in this time frame, with the option to increase biochar use this in the medium to longer term, should it prove to be viable.

It should be noted that while this amount of biochar would be used in conjunction with blast furnace-based ironmaking in the short-to-medium term, future ironmaking processes, most likely based on renewably sourced hydrogen direct reduction, will still require some level of carbon addition. This carbon would be required to either assist with the final reduction and melting of directly reduced iron or to act as the primary alloying element in steel. As such, biochar usage in steelmaking may continue beyond the application of the current blast furnace technology and should be viewed as a longer-term investment in future steel production.

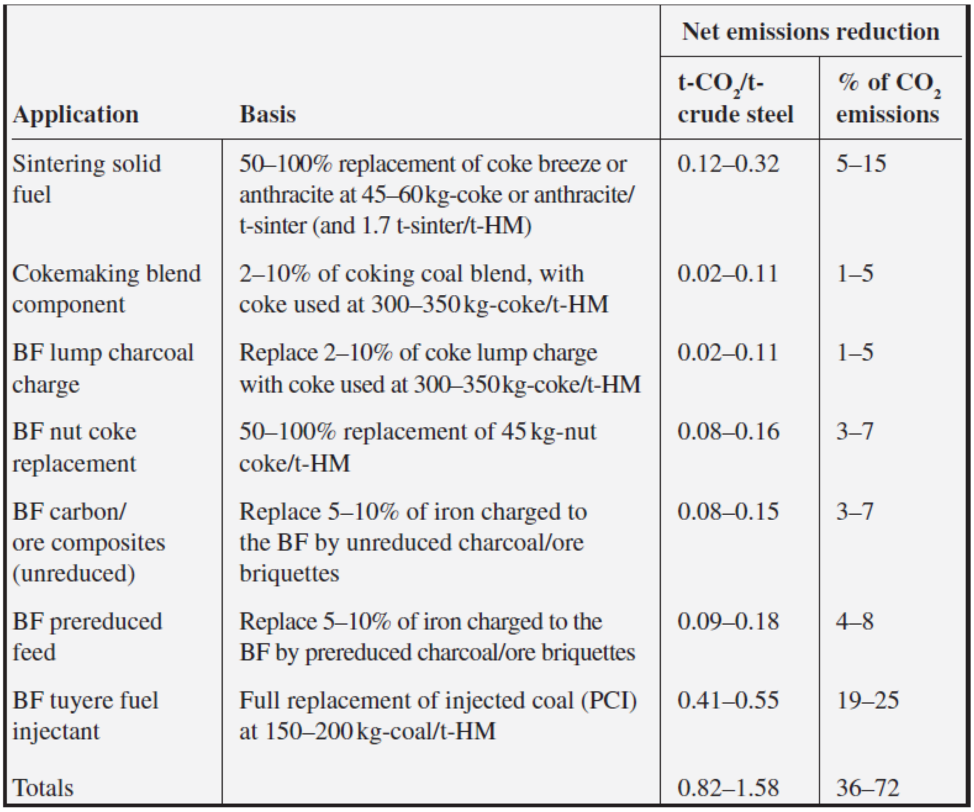
1.2 Biochar Properties

Like coal, biochar that is to be used for ironmaking requires a relatively tight specification in terms of ash, ash chemistry, heavy metal concentrations and to a lesser extent volatile matter content. Ash is important as higher proportions reduce the amount of solid carbon in the biochar and increases fuel consumption and potentially requires additional fluxes to be melted in the blast furnace. Some ash components such as phosphorus-, sulphur-, alkali- and zinc-based oxides are problematic in iron and steelmaking processes and therefore must be minimized. Similarly, heavy metals (e.g. lead, mercury and arsenic) may be problematic for integrated steelworks due to the potential impact on environmental discharges and in extreme cases to employee health. Finally, volatile matter content might be minimized, to maximize the solid carbon reaching the blast furnace. However, given volatile matter content is dictated by pyrolysis temperature, which in turn dictates the biochar yield [5][6], there is still some question about the ideal level, from a cost and blast furnace operations perspective. This question cannot be addressed until longer duration, large-scale trials with biochars of different volatile matter content are conducted at a blast furnace. Indeed, there are significant moves to test at full scale the use of torrefied wood or bio-coal (timber subject to pyrolysis below 320^{o}C) as a coal substitute in blast furnace applications [7][8].

1.3 Australian Steel Industry CO_2 Breakthrough Program

Previous work by the Australian Steel Industry CO_2 Breakthrough Program [9] identified that an integrated steelworks could potentially use biochar to replace several carbonaceous feedstocks used in ironmaking (see Table 1). Unfortunately, a number of applications are unproven or are not necessarily applicable to PKSW. A more conservative assessment is shown in Table 2, where biochar potentially replaces around 740,000t p.a. of fossil coal-derived carbon. More recent work has focussed on the more modest goal of using biochar to assist in achieving a 12% reduction in CO_2 emissions from ironmaking at the PKSW, which might be met in part via the replacement of 30% of the coal injected into the blast furnace with biochar. At the time the CO_2 Breakthrough Program was completed in 2014, virtually no production capability of suitable biochar existed in Australia, barring an operation in Western Australia which was intrinsically linked to silicon production and not available for general sale.

Table 1 – Potential applications of biochar in iron and steelmaking operations [2]



		Net emissions reduction	
Application	Basis	t-CO_2/t-crude steel	% of CO_2 emissions
Sintering solid fuel	50–100% replacement of coke breeze or anthracite at 45–60 kg-coke or anthracite/t-sinter (and 1.7 t-sinter/t-HM)	0.12–0.32	5–15
Cokemaking blend component	2–10% of coking coal blend, with coke used at 300–350 kg-coke/t-HM	0.02–0.11	1–5
BF lump charcoal charge	Replace 2–10% of coke lump charge with coke used at 300–350 kg-coke/t-HM	0.02–0.11	1–5
BF nut coke replacement	50–100% replacement of 45 kg-nut coke/t-HM	0.08–0.16	3–7
BF carbon/ore composites (unreduced)	Replace 5–10% of iron charged to the BF by unreduced charcoal/ore briquettes	0.08–0.15	3–7
BF prereduced feed	Replace 5–10% of iron charged to the BF by prereduced charcoal/ore briquettes	0.09–0.18	4–8
BF tuyere fuel injectant	Full replacement of injected coal (PCI) at 150–200 kg-coal/t-HM	0.41–0.55	19–25
Totals		0.82–1.58	36–72

Table 2 – Potential realistic applications of biomass derived biochar in ironmaking and steelmaking operations at PKSW (adapted from [2])

Application	Basis	Biochar consumption (t p.a.)
Blast furnace pulverised coal replacement	Up to 100% replacement at 150kg/t-HM and 7900t-HM/day	426,205
Sintering solid fuel	Up to 30% replacement of solid fuel (displaces Anthracite)	68,710
Coking coal replacement	Up to 3% replacement without impact on coke properties	67,648
Steelmaking re-carburizer	Full replacement of calcined anthracite or petroleum coke	1000
	Total	**563,563**

2 Current State of Biochar Supply in Australia

As part of the ARENA funded project, sourcing of biochar for full scale industrial trials was undertaken which by necessity included an investigation of the current biochar supply market in 2021-2022. Potential larger scale biochar suppliers were sought pre-dominantly through searches of available electronic resources, but also through BlueScope supplier networks, links from academic papers and industry groups such as the Australian and New Zealand Biochar Industry Group among others.

Since 2014, biochar production in Australia has increased, with reported production capacity of around 10,000-20,000t p.a. [10] (excluding that used for silicon production in Western Australia). However much of this production appears to be small scale and is predominantly sold for horticultural or agricultural applications. Biochar production from these producers appeared to be only in the hundreds of tonnes per annum which was often sold in 5 – 20kg bags – a situation which is far from the ideal for steelmaking purposes. Barring a small number of these producers, none were prepared to commit to large scale orders for biochar to support an industrial trial of 1000t, let alone consider upscaling production to potentially meet the demand required for longer term use of biochar at PKSW. Table 3 lists potential suppliers investigated with some associated detail.

To further complicate the situation, biochar from these producers was derived from several different feedstocks via a few different production processes, resulting in biochars with quite varied properties. For example, one supplier began using pyrolysis in early 2022 with a bio-solids feedstock. This installation was set to produce some 2,000tpa of biochar from 34,000t/a of bio-solids, however on further investigation the biochar was found to be very high in ash, volatile matter and trace elements such as zinc, making it unsuitable for use at PKSW. Similarly, another production facility used waste timber from landfill streams which resulted in biochar with higher levels of lead (most likely from treated timber), again making it unsuitable for ironmaking applications. Table 4 shows selected properties of several supplied biochars in comparison to an ideal BlueScope specification. As can be seen, many biochars were unsuitable for ironmaking purposes.

Table 3 – Potential Australian suppliers of biochar

Potential Biochar Supplier	Product	Approximate Biochar Production Capability as at June 2022 (t p.a.)	Comment
Supplier 1 – WA	Biochar undersize – from timber	~3000	Suitable
Supplier 2 – QLD	Biochar – from timber or nut shells	~2000	Potentially suitable
Supplier 3 - QLD	Biochar – from timber	~1500	Suitable
Supplier 4 - WA	Biochar from gasification tech	Currently 0 – 8000tpa proposed	No sample
Supplier 5 - WA	Biochar – from various biomass sources	Currently 0 – scale up proposed	Potentially suitable
Supplier 6 - NSW	Bio-carbon from gasification	<1000	No sample
Supplier 7 - VIC	Biochar – from timber	<2000	No sample
Supplier 8- WA	Biochar – from various biomass sources	0 –~6000 in concept proposal	No sample – may be suitable but will be very fine
Supplier 9 - WA	Biochar - from waste timber	~1500	No sample
Supplier 10 - QLD	Biochar - from biosolids	~2000	Not suitable chemistry
Supplier 11 - NSW	Biochar from forestry timber	0 – proposed <1000	Suitable
Supplier 12 – SA	Biochar from waste timber	<2000	Not suitable - chemistry
Supplier 13 – SA	Biochar from waste timber	<1500	No sample
Supplier 14 - NSW	Biochar - waste from biodiesel process	0 – ~<2000 in concept proposed	No sample – but potentially high ash
Supplier 15 - TAS	Biochar from forestry waste	0 –~ 100,000 in concept proposed	No sample
Supplier 16 - VIC	Biochar from various biomass sources	<2000	No sample
Supplier 17 - NSW	Biochar from timber	< 1500	No sample
Supplier 18 - VIC	Biochar from timber	<500	No sample
Supplier 19 - VIC	Biochar from timber	<500	No sample
Supplier 20 - NSW	Biochar from timber and agricultural wastes	concept proposal only	No sample
Supplier 21 - NSW	Biochar from invasive native species	concept proposal only	No sample

Table 4 – A comparison of biochar properties from several different suppliers with an ideal BlueScope specification (*NB data is anonymous as samples and specifications were supplied on a confidential basis)*

Parameter	Unit	Ideal BSL Specification	Producer 1	Producer 2	Producer 3	Producer 4	Producer 5	Producer 6	Producer 6
Biochar Ash	Mass %db	<10	3.5	16.5	4.3	1.3	52.8	7.1	16
Volatile Matter	Mass %db	<20	4.5	23	~10	~17.3	-	19.3	8.1
Sulphur	Mass %db	<0.6	0.01	0.018	0.05	<0.01	-	0.05	0.22
Moisture	Mass %	<12	10	11	50.4	53.6	-	46.3	63.5
Lead	mg/kg	<10	1.9	1.4	90.3	< 1	37	4.2	260
Arsenic	mg/kg	<10	0.56	<0.5	14.9	< 2	1.5	< 0.5	2.1
Zinc	mg/kg	<50	11	24	144	6.7	1789	40	760

Aside from horticultural applications, other investigations into biochar supply also found that a key focus of the industry was on the use of biochar for carbon sequestration and therefore by extension, its use as a means of generating revenue through the purchase of carbon credits – particularly through the more lucrative European carbon trading schemes. As such, there appeared to be little focus on biochar production as a bulk commodity within Australia, despite the potentially large market that could be available in steelmaking and the seemingly ready availability of biomass in Australia.

Overall, current Australian biochar production and the capability of the biochar industry to further invest appears to be limited; therefore, this may not be an ideal sustainable source for significant volumes of biochar to PKSW, at least in the short to medium term. Note at the time of investigation and writing, there were a considerable number of projects in the concept phase which could potentially supply higher quantities of biochar, but even with these proposed new projects, the scale tended to be smaller than which would be required to supply PKSW.

2.1 Biochar Import

Several countries produce charcoal or biochar, primarily as a cooking fuel; however, in the case of Brazil, biochar is produced as a carbon source for steelmaking. Given the lack of supply in Australia, several potential sources linked to Brazilian charcoal production amongst other foreign sources were examined. Table 5 lists the potential suppliers from foreign sources that were investigated. Unfortunately, none of them appeared to be particularly prospective, there being either limitations on the amount that was available, a high cost, logistical complications or issues with certifying the sustainability of the biochar product in line with BlueScope's strict procurement requirements [11]. As noted above, for biochar to be used as a means of CO_2 emissions reduction, the biomass used needs to be from sustainable sources. Numerous issues, particularly with the production of plantation timber in Brazil, meant that this source of biochar was particularly problematic from a sustainability perspective, as were other options from parts of Asia. Given these difficulties, while importing biochar may be an option, it does not appear a particularly viable one for BlueScope.

Table 5– Potential importers of biochar investigated

Potential Biochar Supplier	Product	Approximate Biochar Production Capability as at June 2022 (tpa)	Comment
Importer 1	Biochar from international sources	Import as required	Most likely Brazilian Supply
Importer 2	Torrefied wood	Import as required	Agent for Perpetual Next Biocoal
Importer 3	Biochar production South Africa – from invasive acacia	<2000	Small scale – logistically difficult
Importer 4	Biochar import from Brazil	Import as required	Brazilian supply - problematic
Importer 5	Charcoal from Brazil	Import as required	Brazilian supply - problematic

2.2 Biochar Costs – Purchase Price and Transport

At approximately 400kg/m^3, biochar has an inherently low density in comparison to coal and many other ironmaking feedstocks. Due to its structure, biochar also appears to be able to absorb considerable amounts of moisture with minimal effect on the handleability. During sourcing of biochar for the ARENA funded trial, moistures of 30% were seen in delivered product, while moisture levels approaching 40% were seen in stored product after water was added for handling purposes.

The lower density means that transport efficiency is much reduced as the volumetric limits of a transport vehicle are exceeded well before the weight limits. Furthermore, as biochar is not presently considered a commodity, moisture levels are not necessarily accounted for in its pricing, nor is biochar sold with standardized moisture levels. Both the density and moisture factors contribute additional cost based on dry tonnage of carbon delivered. This is symptomatic of an immature supply chain.

In addition to cost factors noted above, many of the biochar producers were very much focussed on biochar being a means of carbon sequestration, which in turn could potentially come with a carbon credit. As such, many producers would apply a “carbon credit premium” to their pricing, in the expectation that biochar would be used for that purpose, often under European carbon credit schemes such as Puro.earth. This in turn considerably inflated the price, depending on what the carbon credit price was at the time (often upwards of $120/t[1]). Depending on the source and whether a carbon credit premium was applied, quoted biochar prices ranged from ~$180/t FOB up to approximately $1000/t FOB, though most sources were quoted at greater than $500/t. The much lower figure reflects a specific situation where the biochar was a plant by-product that was simply not utilised.

In combination with the higher transport costs and moisture implications, biochar cost per dry tonne of material delivered to the PKSW is uncompetitive, at the time of writing, with coal suitable for blast furnace injection. Even with the imposition of a carbon price, the ability to purchase biochar at a competitive price from the Australian market appears to be difficult, even if it were available. Note that in recent times coal prices have risen significantly, so the price differential is less evident; however, it is difficult to envisage biochar purchased from current producers being an economically viable option in the short term.

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[1] Prices quoted in Australia dollars

Overall, given the current and even expected medium-term state of the Australian biochar industry, there appears to be little prospect of sufficient or economically viable biochar supply being available for PKSW from external producers. As such, should large scale usage of biochar proceed at PKSW, to ensure continuous supply of quality biochar for the purposes of coal replacement, BlueScope may have to invest in the production of biochar, either at PKSW or in a nearby region. In either case, BlueScope would need to look at purchasing significant supplies of biomass as a feedstock for biochar production.

3 Biomass Supply

Biomass is defined as renewable organic material that comes from plants or animals and covers a wide variety of materials from algae, agricultural wastes such as animal manure and crop residues, biogenic wastes from paper and fibre production, timber derived materials and even biogenic materials contained in municipal solid waste. As may be expected, the wide range of biomass materials comes with a significant variation in chemical composition, in particular carbon content, moisture, ash and proportion of trace elements such as heavy metals. In general, biomass has a relatively low carbon content and higher moisture, making it unsuitable for direct use in steelmaking applications. Drying and thermal decomposition of these materials in the absence of oxygen (i.e. pyrolysis) is required to produce carbon rich solid products (biochars) that are more suitable [2][8]. Given this, biomass materials that are in continuous supply, (i.e. not related to seasonal harvest) high in carbon, and low in moisture and ash, are preferred on a cost and quality basis as they will yield the largest amount of suitable biochar per unit of input mass [5][12][13]. It is for these reasons that timber derived biomass is preferred as a feedstock for biochar production for steelmaking purposes. This feedstock will be the focus of this report.

3.1 Previous work

Considerable work was done under the Australian CO_2 Breakthrough Program to evaluate potential sources of biomass [14]. The project comprehensively identified significant quantities of waste biomass available from the forestry and agricultural industries in 2008. ABARES[2] reports since then show that the harvest of forestry products has increased considerably since 2008 (see Figure 1 [15]) though there has been a decrease in recent years due to fires, extreme weather conditions and flooding. However, despite this, ABARES reports that some 27.1 million cubic metres of timber were harvested in 2020 – 2021, consisting of predominantly timber from softwood and native plantations [16]. The 2008 work estimated that of the available biomass in hardwood forestry, around 55% of the material was left in the forest, while for softwood forestry, 25% remained. As such, while there was limited information, ABARES estimated that for 2011-2015 there was around 7.2Mt of harvest residues potentially available on Australia's eastern seaboard (NSW, VIC, QLD, and TAS), predominantly from hardwood and softwood plantations [17]. However, according to ABARES, part of these residues can be utilised for chip production, so only approximately 5.5Mt of this might be available ABARES also estimated sawmill residues to be approximately 4Mt in 2011-2015. Modelling results indicated that the availability of these types of residues would most likely continue at this level until 2050. More recent work focussing specifically on the forestry areas on the north coast of NSW estimated that forestry residues could be 1Mt from that region alone [18]. It should be noted that sawmill residues are generally used at the sawmill or sold to downstream processors, which may mean that they are commercially unavailable, at least in the short term. As such, as with the 2008 work, there appears to be a significant amount of forestry residues potentially available; however, whether these can be harvested and transported economically needs to be determined.

Further work was also conducted during the Australian CO_2 Breakthrough Program on assessing other sources of biomass, namely municipal waste, waste timber and special purpose plantings. The latter two were identified as viable, with particular focus on special purpose plantings [19].

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[2] Australian Bureau of Agricultural and Resources Economics and Sciences

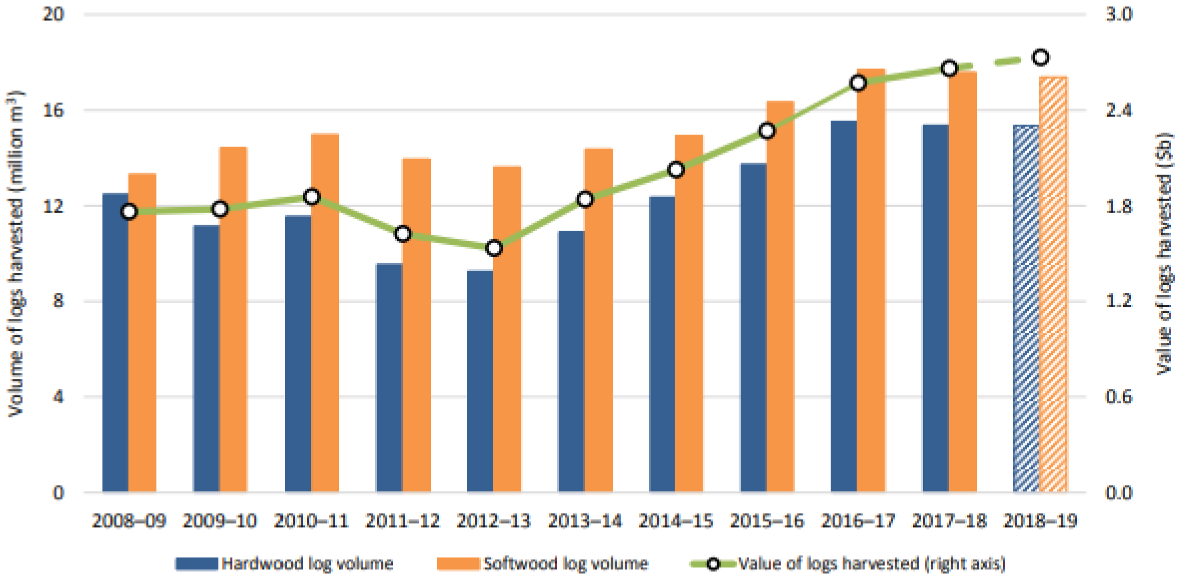

Figure 1 – Trends in hardwood and softwood log volumes Australia-wide since 2008 – 2019 [15]

3.2 Forestry Biomass

To check on the availability of residues or biomass in general, BlueScope conducted a survey of potential biomass suppliers. This consisted of a formal Request for Information (RFI) from parties who expressed an interest in being involved. The survey sought responses on the availability and type of biomass, biomass quality parameters and ideally an indicative price for the material. A list of parties contacted is shown in Table 6.

Table 6 - Forestry related organizations involved in the BlueScope Biomass RFI

Supplier	Area
Midway Ltd	Forestry, Sawmilling or Wood Chip Exports
Pentarch Forest Products	Forestry, Sawmilling or Wood Chip Exports
Altus Renewables	Forestry, Sawmilling or Wood Chip Exports
Proviro Group	Forestry, Sawmilling or Wood Chip Exports
Plantation Energy Australia	Forestry, Sawmilling or Wood Chip Exports
Green Triangle Forest Products	Forestry, Sawmilling or Wood Chip Exports
NSW Forestry Corporation - Hardwoods	Forestry, Sawmilling or Wood Chip Exports
VicForests	Forestry, Sawmilling or Wood Chip Exports
OneFortyOne - plantations and sawmilling	Forestry, Sawmilling or Wood Chip Exports
PF Olsen	Forestry, Sawmilling or Wood Chip Exports
SFM Forest Products	Forestry, Sawmilling or Wood Chip Exports
Sustainable Timber Tasmania	Forestry, Sawmilling or Wood Chip Exports
Timberlink	Forestry, Sawmilling or Wood Chip Exports
Boral Timber (Nowra and Narooma)	Forestry, Sawmilling or Wood Chip Exports
Forico	Forestry, Sawmilling or Wood Chip Exports
New Forests Timber Products	Forestry, Sawmilling or Wood Chip Exports
Softwood Plantation Exports (SPE)	Forestry, Sawmilling or Wood Chip Exports
QB Mathie - Pty Ltd	Forestry Transport - interest in biomass production of bushfire damaged timber

Unfortunately, the number of responses to the RFI was limited, though indications were from the BlueScope Commodities Team that this was not an unusual occurrence. However, several key parties did respond with relevant information. Table 7 shows a summary of some of the information from the RFI process, which was current at the time of the investigation.

Table 7 – Responses from forestry related organizations to BlueScope's Biomass Supply RFI

Supplier	Product	Location	Source	Approximate Available (gmt/yr*)	Indicative Price ($/gmt*)
Biomass Supplier 1	Hardwood/softwood residues - Biomass blend	Tasmania	Plantations	315,000	$99
Biomass Supplier 2	Hardwood chips - non target species+forest residues	Southern NSW	Managed Forestry	250,000	Not supplied
Biomass Supplier 1	Sawdust	North coast NSW	Managed Forestry	28,000	Not supplied
Biomass Supplier 3	Hardwood/softwood residues	Victoria	Managed Forestry/plantations	100,000	$50
Biomass Supplier 4	Hardwood chips - managed forestry	Southern NSW	Managed Forestry	390,070	Not supplied
Biomass Supplier 5	Hardwood chips	Tasmania	Plantations	1,500,000	$ 110
Biomass Supplier 6	Wood chip and whole log	North coast NSW	Managed Forestry	325,000	Not supplied
Biomass Supplier 7	Hardwood chips	Green Triangle (VIC/SA)	Plantations	400,000	Not supplied
Biomass Supplier 8	Hardwood chips	Various - Tiwi Islands, SE QLD and Northern NSW	Plantations	500,000	$102
Biomass Supplier 9	Hardwood/softwood residues - Biomass blend	Various - VIC/SA/TAS	Managed Forestry	Not supplied	Not supplied
Biomass Supplier 10	Hardwood forestry and sawmill residues	South Coast NSW	Managed Forestry	100,000	Not supplied
Biomass Supplier 11	Briquettes - compressed wood fibre	Southern NSW	Managed Forestry	14,000	$250
Biomass Supplier 12	Pulp logs	NSW generally	Managed Forestry	50,000	$80

**gmt = green metric tonnes*

These responses show that the focus was primarily on the production of premium woodchips. Only three respondents provided information on forestry residues, with many producers indicating that there was not yet sufficient demand for residues from Australian forestry to justify investment in infrastructure and equipment to process these residues. Even where forestry residues were indicated as the main product, the price and availability were similar to that of higher-grade woodchips, as several producers indicated that while the residue product might be lower grade, the processing costs and transport costs might be quite high. Despite this, indications were that significant residues were available, in the order of 500,000 – 800,000gmt per year, which would be sufficient to produce approximately 130,000t p.a. of biochar for BlueScope, assuming 40% moisture and a 30% biochar yield. Aside from this, the RFI process identified significant material was available in the form of premium hardwood and softwood chips. This is not unexpected given Australian exports of wood chips are quite large e.g. for the year ending September 2020, Australia exported 5.723Mbdmt[3] of woodchips [20]. While this material may come at a premium cost, it still represents a form of biomass that could be utilised if the economics of biochar usage were favourable.

Issues identified in the 2008 work [14] still exist today, these being concerns about what the removal of residues may do for forest fertility and more importantly the lack of processing and handling equipment for the residues. In Australian forestry, equipment and practices focus on the removal of saw and pulp logs and as such there is little provision for the handling or processing of residues, which range from sticks, leaves and bark to residual stumps. While forestry companies recognise that the residual material has potential value, in general there appears to be little incentive at present to begin extraction of this resource.

However, while recovery of forestry residues remains difficult for premium woodchips, indications are that there are timber species which are less desirable for papermaking, but nonetheless, could be chipped for the purposes of biochar production. Given that infrastructure is already established for the production, handling and transport of these materials (particularly seaborne transport), use of wood chips as a feedstock for biochar production at PKSW is perhaps one of the better initial options.

Note also that the extensive bush fire damage of timber resources during 2019-2020 could present an opportunity in the short term. Here, timber resources that are no longer suitable for their normal applications (either sawn timber or chips for paper production) could potentially be available as a cheaper source of biomass to produce biochar. Several mentions were made of this in discussions with biomass suppliers, with reference to both softwood and hardwood resources. The case of Kangaroo Island’s timber resources is a particular example [21] as is the use of wood chips made from fire damaged timber at Boral’s Berrima Cement Works [22]. Unfortunately, fire damaged timber may only be available for a short period of time, as plantation managers remove this material quickly, often by clear felling and burning. As such, it is unclear whether BlueScope’s biochar concept could take advantage of this opportunity. Indications are that fire damaged resources are already being removed and burnt to make way for conventional agriculture or new plantations.

An alternative to wood chips is wood pellets. These are produced using wood residues that may be difficult to handle or come from timber sources that are not able to be used for other applications (i.e. effectively the same material as would be targeted as a feedstock for biochar). Wood pellets have the benefit of being drier and denser than wood chips (reducing transport costs); however, they must be protected from weather.

Globally demand for wood pellets as a carbon neutral source of fuel for heating and power generation is increasing, particularly in South-East Asia, with the market expected to grow in coming years with the increasing focus on biomass being a sustainable fuel (see Figure 2, [23]). While the wood pellet industry is small in Australia currently, the increased demand appears to be stimulating development [24] and as such, this could form an additional source of timber-based biomass. Even with current developments, production remains relatively low and much of the supply seems to be tied up in longer term contracts, which could make it difficult to access. Furthermore, wood pellet production specifically for the export market could reduce the availability of timber residues for use in the Australian biochar production.

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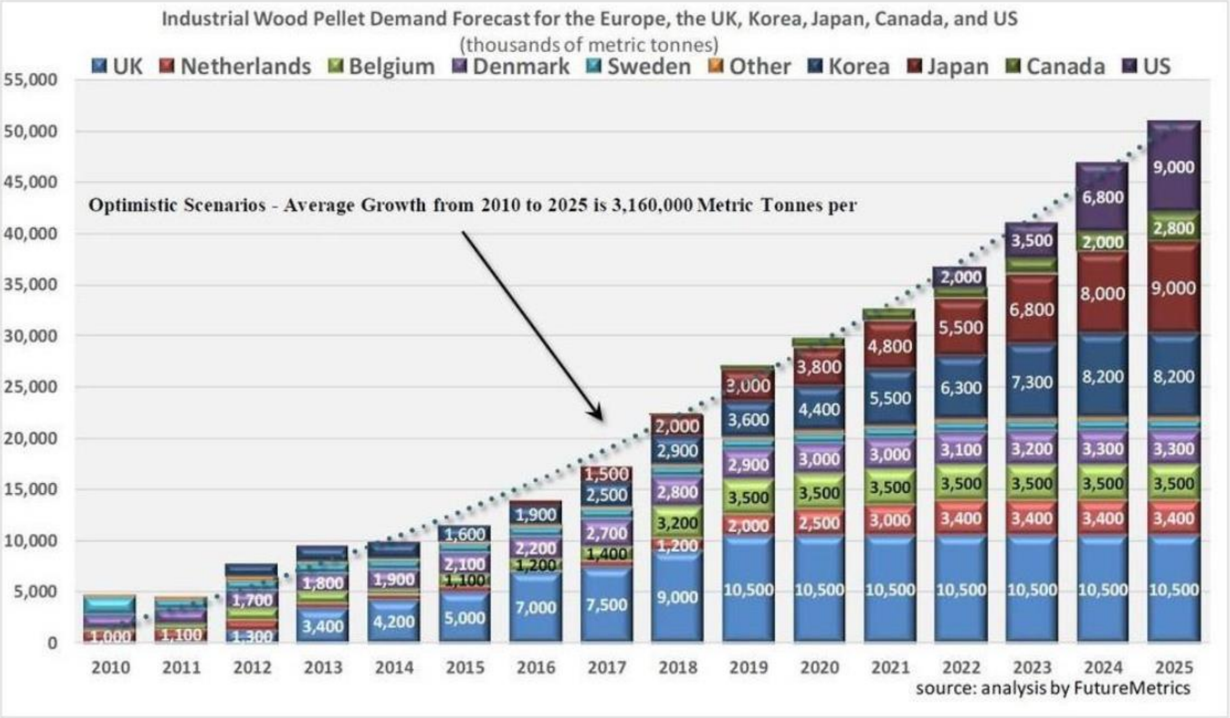
[3] bdmt = bone dry metric tonnes



source: analysis by FutureMetrics

Figure 2 – Projected growth of wood pellet demand in 2020 [22]

3.3 Waste Timber Biomass from Landfill Streams

Waste timber biomass was also identified as a potential source in previous work, with estimates that there was up to 500,000t p.a. of waste wood material in NSW from several sources that was going to landfill [19]. This consisted of clean and contaminated timber, along with particle board, MDF and plywood, all of which was generated from the manufacturing, construction, and demolition industries. Given this material was aggregated, sorted and potentially dryer than forestry biomass, this was regarded as an attractive source of biomass. However, given the source of the timber could be unknown, it comes with some risks with respect to contamination and potentially sustainability concerns.

Sources of waste timber were re-investigated again in the most recent study and indications are that there is still significant generation of timber waste in Australia, perhaps up to 2.3Mt in 2018-19. Recycling of this waste timber via use in composting or particle board seems widespread, as is its use in process engineered fuels for either local consumption or export. Despite this, it is estimated that there is still some 354kt. of timber sent to landfill in NSW [25] in 2018-19, from commercial, industrial, construction and demolition sources. As part of the RFI process noted previously, waste producers from around NSW's Illawarra region and surrounding areas were also included (see Table 8, with Table 9 detailing the responses received). Unfortunately, barring one seemingly very positive response, there appeared to be less timber available than was suggested above.

Table 8 – Waste related organizations contacted as part of BlueScope's biomass RFI

Supplier	Area
Veolia	Waste
SUEZ	Waste
ResourceCo	Waste
Benedict Resource Recovery	Waste
Banks Meadow Recycling	Waste
Sydney Recycling Park	Waste
Cleanaway	Waste
thinkstep anz	Consultancy with expertise in the wood waste industry

Table 9 – Responses from waste related organizations to BlueScope's biomass RFI

Supplier	Product	Location	Source	Approximate Available (dmt/yr)	Indicative Price ($/gmt)
Waste Biomass Supplier 1	Combined woody green waste (20%), C & I* woody waste (40%), timber offcuts (40%)	Sydney basin	Waste collection	550,000	$1.00
Waste Biomass Supplier 2	C & I Woody Biomass	Sydney basin	Waste collection	Not supplied	Not Supplied
Waste Biomass Supplier 3	C & I Woody Biomass	Sydney basin	Waste collection	8,000	Not Supplied

*C&I = commercial and industrial

Further investigation via other contacts indicated that while considerable timber was in waste streams, there was increasing demand for clean timber to produce process engineered fuels or for waste to energy projects. In addition, while all attempts were made to sort timber, contamination with copper chrome arsenate (CCA) treated timber was a significant possibility. Both aspects were confirmed through a BlueScope commissioned study by the Illawarra Shoalhaven Joint Organization (ISJO) [26], a group that champions the interests of several local council areas and works on collaborative projects to further local development aims. In the absence of specific data on waste flows across the Illawarra and Sydney region, this study used previous surveys, published data and consultations with representatives from various industries to better evaluate the availability of waste timber biomass.

The study found that there were significant flows of timber reaching waste handling and landfill sites, sufficient for BlueScope's demand of 300,000t p.a.; however, most of this material was already utilised in alternative markets. As such, the actual availability of this material is determined by the commercial terms. Given much of the timber appears to be going into export markets, it is hoped that the scale of BlueScope's more local demand could be influential in securing material.

The quality of this biomass source remains in question. As part of the ISJO study, five samples of waste timber biomass, from different sources were obtained from several different companies. These were analysed to provide data on the composition, ash, moisture, and heavy metals concentrations (see Table 10). Four of the five materials were found to be potentially useful as a feedstock for biochar production, however the concentrations of heavy metals, particularly lead, arsenic and zinc were relatively high, most likely from difficulties in removing CCA treated timber and painted products. Note that these concentrations were not high if the biomass was to be used in soils or compost; however, limited research indicates that elements such as lead and zinc most likely remain in the biochar post pyrolysis [27]. Furthermore, due to the removal of volatiles, the concentrations of these elements could be 3-4 times higher in the biochar than the original biomass. Higher concentrations of lead and zinc in biochar inputs to ironmaking processes are problematic as the heavy metals have the potential to concentrate in recycled waste streams with those concentrations potentially “cycling up” to hazardous levels. Similarly, arsenic could be a problem, but dependent on pyrolysis temperature could also be found in pyrolysis gas streams, presenting further problems for airborne emissions or indeed concentrations in pyrolysis by-products. As such, higher concentrations of these metals in inputs are to be avoided as much as possible, though further work should be undertaken to better determine the partitioning of these elements at different pyrolysis temperatures. However, use of these waste timber materials to supplement a biomass feedstock with much lower trace metals concentrations (such as forestry biomass) could be undertaken safely, as input levels could fall to normal levels under these circumstances.

Table 10 – Analysis results from waste timber biomass samples supplied by ISJO

Parameter	Unit	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 4	Comment
Moisture	% wet	20.3	52.74	23.99	11.49	10.76	Supplier 2 very wet
Inherent Moisture	% ad	6.3	5.7	6.4	4.1	5.8	
Ash	% ad	1.4	12.1	1.5	1.4	2.9	Supplier 2 - very high ash
Volatile Matter	% ad	74.5	69.2	76.4	78.7	75.8	
Fixed Carbon	% ad	17.8	13	15.7	15.8	15.5	
Total Sulphur	% ad	0.04	0.05	0.05	0.03	0.05	
Fluorine	mg/kg	< 20	< 20	< 20	< 20	< 20	
Arsenic	mg/kg	33.5	117	3.1	< 0.2	0.6	High levels in Supplier 1 and 2 material - indicating CCA contamination
Chromium	mg/kg	39	167	10	13.2	22.9	High levels in Supplier 1 and 2 material - indicating CCA contamination
Copper	mg/kg	23.8	92.8	3.9	< 2	3	High levels in Supplier 1 and 2 material - indicating CCA contamination
Zinc	mg/kg	38	104	26	47	1220	High zinc levels – Supplier 4
Lead	mg/kg	32.31	36.73	4.35	21.9	13.7	High levels comparative to coal barring the Supplier 3 sample

Overall, waste timber biomass from landfill streams remains a possibility as a means of supplementing other biomass streams for biochar production; however, complications with the current commercial situation regarding this material and then contamination with trace metals and ash materials means it is an input stream that will require further assessment and effort to firstly secure and then use in general operation.

3.4 Short Rotation Biomass Cropping

The biomass sources listed above, other than the direct purchase of premium wood chips, in general rely on waste streams. These are attractive in terms of price and current availability but do have several drawbacks. As noted in 2008 [19], the reliability of supply from waste streams is not necessarily guaranteed given that producers will always try to minimise the production of this material to reduce costs. Furthermore, depending on circumstance, the sustainability of these biomass resources could be called into question, given the potential effect on soils and ecosystems of wider scale removal from the forest and the undocumented history of waste timber. As has been mentioned previously, the quality of waste streams cannot be guaranteed and lastly, as the bioenergy industry is expected to expand in the longer term to meet the challenge of climate change, the pricing of “quality” timber biomass waste will inevitably be subject to competition, making it less attractive as a feedstock for biochar to replace relatively low-cost coal.

To overcome a number of these factors and to guarantee the supply of appropriate quality biomass in the medium to longer term for steelmaking, another alternative is to establish dedicated plantations of fast-growing biomass to harvest in a short rotation. This methodology has a long and successful history in Brazil, where large plantations of eucalyptus variants [28][29] continue to provide the feedstock for charcoal production for use in the Brazilian steel industry.

The use of short rotation woody biomass plantations for energy production has long been discussed [30] and has been undertaken to a degree in WA with mallee plantations [31] (though not necessarily successfully [32]). Woody biomass plantations have also become a focus for Australian studies in recent times [33]. The use of such short rotation crops would have several benefits in steelmaking, with potentially more control over quality and quantity of the biomass, as well as optimization of species selections, harvesting times and harvesting methods for this form of agriculture.

Nonetheless, there are some issues with this form of biomass supply. While Australia with its low average population density and ready availability of land is well suited to the production of biomass, rainfall, the effects of climate change and potential bush fires are a concern. Issues regarding land use must also be dealt with as energy crops have the potential to displace food and fibre production and as with all plantations, concerns around the use of monocultures and loss of biodiversity must be addressed [34]. Development of machines and efficient harvesting systems will also be required to ensure that biomass costs remain low, given Australia’s higher labour costs compared to Brazil. Finally, the establishment time – even with faster growing species planted now it will take 3-7 years before biomass from a dedicated plantation will be available.

Hence, in the short term, this material is probably not a viable source of biomass for supply of biochar to PKSW; however, given that biochar will still be required in the medium to long term for steelmaking purposes, establishing access to plantations of faster growing timber species should be considered present-day, given the lag time between establishment and production.

3.5 Other Biomass Sources

The biomass sources noted above are the most accessible and therefore have the most potential to supply biomass at sufficient scale for a PKSW biochar supply. However, these sources are subject to competition and quality issues, while forestry biomass may also come with sustainability questions from sections of the community. Such issues would not necessarily be relevant if a biomass source consisted of plants that were invasive and were required to be removed to prevent significant ecological damage. A number of these sources have been identified and could be a source of cost- and environmentally effective timber-based biomass.

The first of these is invasive native scrub (INS), which is a significant problem in central and western NSW that has arisen due to changes in land use over time. Here grazing practices and changes to fire regimes have resulted in large areas of thickened shrubs and trees that out compete ground cover for resources, leading to increased soil erosion, significantly reduced access for stock and therefore reduced land productivity [35]. INS areas continue to develop in response to climatic conditions and are generally controlled with manual clearing or larger scale burning. Given this material will be cleared and its removal will result in an environmental benefit, if it could be economically aggregated and transported it could be a significant source of biomass. The report by ISJO [26] noted that there was an estimated 24 million tonnes of INS within a 75km radius of Cobar, with significantly more within the rest of the Cobar region. However, the resource is relatively dispersed, and harvesting would most likely be labour intensive, thereby adding to the cost.

Similar to INS is the problem of the Prickly Acacia, a noxious plant species native to India and South Africa that has spread across many parts of Queensland and can now found in New South Wales, the Northern Territory and

South Australia [23]. In 2003, Prickly Acacia was estimated to cover up to 7 million acres. Like INS, it out competes other species, leading to increased soil erosion, reduced biodiversity, and stock access. Prickly Acacia is now a restricted invasive species and is increasingly a plant of concern. Surveys have been conducted which indicate that the amount of Prickly Acacia could be in the order of 100Mt, a significant amount of biomass. Indeed, so significant is it as a resource that it is increasingly being viewed as a potential feedstock for wood pellet production, most likely as a fuel source for electricity generation. As with INS, if this material could be economically aggregated and transported, it could be a significant source of sustainable biomass for many years, though, like INS the labour-intensive nature of the harvesting and difficulties in transporting the resource will have cost implications.

Overall, while attempts have been made to begin aggregation of INS in Cobar [36] and begin harvesting and processing of Prickly Acacia [37], none of these projects has yet achieved a reliable degree of development to be a useful supply of biomass in the short term. However, the sustainable and potentially, economic nature of these biomass resources, as well as the potential environmental benefit that could be derived from their harvest, pyrolysis and use as a coal substitute, means that they are a biomass resource that should be closely monitored and utilised for steel production, should they become commercially available.

3.6 Biomass Costs and Transport

As with biochar, the lower inherent density of biomass means transport is somewhat problematic and this is even more so with biomass, given the inherently high moisture content (up to 40%). Unless the initial cost of the biomass is particularly low, transport for long distances overland will most likely be too expensive for the resulting biochar to be competitive with coal. As noted previously, based on the prices quoted during the RFI process [$50 - $100/gmt FOB], the cost of even low-quality wood chips sourced from currently under-utilised forestry wastes is still similar to higher quality wood chips. Hence, at this time, overland transport appears to be limited to resources within a relatively short radius of a biochar production facility. Previous work in the CO_2 Breakthrough Program suggested that distances of no more than 100km were necessary for a project to be viable [38]. Waste timber from land fill streams, should the issue of contamination be sufficiently resolved, is perhaps a more viable alternative for overland transport. However, even then, the dispersed nature of the resource NSW-wide means that the focus should be on aggregators in the immediate Illawarra and Shoalhaven areas and extending up into the Sydney basin. Furthermore, the cost of waste timber from landfill streams is relatively expensive, quoted at $100/t [26].

As noted previously, considerable infrastructure exists for the transport of large quantities of biomass by sea, with major seaports for wood chip being in southern NSW, Victoria, and Tasmania. Given PKSW has a large deep-water port and infrastructure that could unload large shipments of biomass, this transport route could present the best option to guarantee biomass supply at minimal transport cost. This could make the development of a biochar production plant at PKSW commercially attractive. Some issues do exist in that PKSW's facilities are heavily utilised, so further shipments of an additional material could be problematic. Furthermore, storage options for additional materials are somewhat limited on the PKSW site, so receiving large quantities of biomass could also be an issue from a materials handling and storage perspective. Further investigation on assessing seaborne or other options for biomass supply is continuing.

Overall, in terms of biomass supply, there are several different options which could be viable under appropriate circumstances; however, there are a few impediments to supply from several sources. In summary:

- Forestry waste - lack of collection and processing infrastructure, concerns about impacts on nutrient levels in forests, as well as questions over the sustainability of this resource and competition,
- Waste timber – contamination issues, along with competition for these resources from the waste to energy sector,
- Short rotation woody biomass cropping – low level of current development and lag time for supply, and
- Alternative biomass supplies such as INS and Prickly Acacia – collection, processing, and transport infrastructure yet to be established.

Hence, in the short to medium term, the only viable source of biomass appears to be wood chips: ideally from less desirable species and perhaps fire damaged forests, most likely delivered to a biochar processing facility by sea, which in turn suggests that PKSW may be an ideal location for initial investment in biochar production.

4 Pyrolysis Technology

Based on literature surveys, pyrolysis equipment for the purposes of liberating energy from biomass has a long and varied history [39][40][41] (see Figure 3). Beginning with simple pit charcoal production that existed from ancient times, particularly to produce charcoal for ironmaking, pyrolysis technology began to further develop in the 18th century. Here the collection of liquid condensable products became a focus as well as the production of solid charcoal or biochar material. This development continued into the 19th century with the establishment of the wood distillation industry, often thought to be the precursor to the modern petrochemicals industry. The rise of the petrochemical industry and the increasing use of coal for ironmaking purposes ultimately caused the decline of the wood distillation industry until the oil crisis of the 1970's forced the world to re-consider biomass derived products as a substitute for fossil petroleum. Since then, development of biomass pyrolysis has to a degree focussed on the liberation of liquid fuels from biomass via fast pyrolysis and other biomass derived liquid (bio-oil) production techniques [42]. In recent years however, there has been increasing investigation into the use of biochar for carbon sequestration and soil improvement, and therefore technologies to support this concept [43]. The focus on biomass usage for CO_2 emissions reduction has also led to the development of lower temperature pyrolysis or torrefaction technology to produce pelletized material for power generation and to a much lesser extent, ironmaking [44][8].

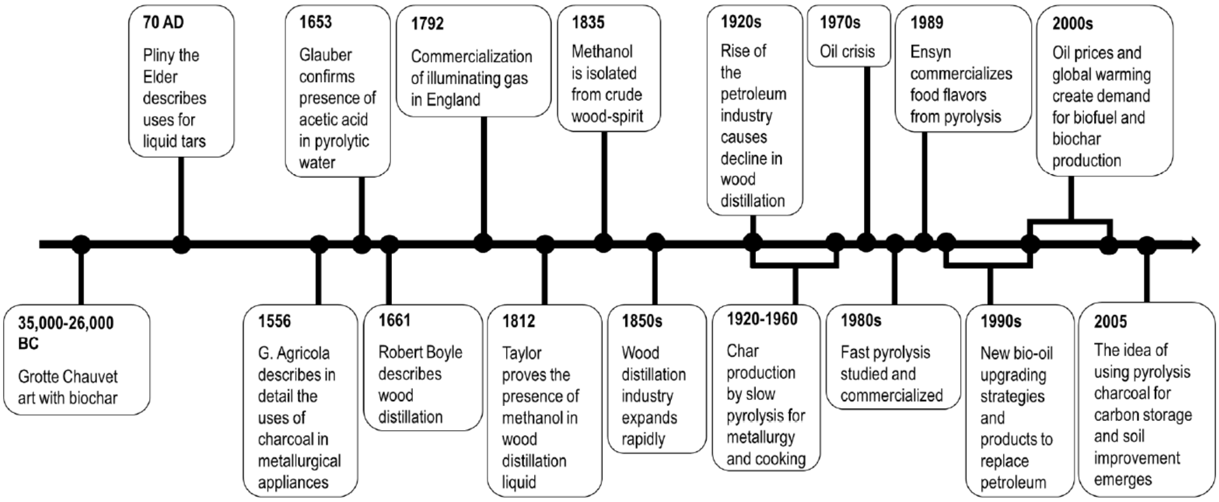


Figure 3 – Timeline for pyrolysis technology developments [39]

A survey of available pyrolysis equipment was conducted through readily available literature and commercial information. Table 11 shows a summary of the results which again demonstrates that there are a considerable number of technologies currently available for biomass pyrolysis, both of Australian and overseas origin, with some more successful than others. With this list of available technologies in focus, BlueScope's specific set of requirements for biochar production means that not all of the technologies will be suitable.

As such, prior to any technology selection, it is important that a defined set of selection criteria is established. In summary, it is as follows:

- Production capacity – given the scale of the biochar requirement (130,000t p.a.) and the relatively small scale of the available real estate at PKSW or potentially elsewhere close to port facilities, a single pyrolysis unit will need to be capable of producing at least 20,000t p.a. of biochar and ideally more. Depending on biochar yield (generally less than 50%), this single unit will need to process around 40,000t p.a. of biomass, which most likely means the process will have to be a continuous rather than a batch or semi-continuous one
- Process heating – the chosen pyrolysis process must be autogenous, in that all the heat for the pyrolysis and drying of the biomass must be provided by the biomass itself. This is required to ensure that the biochar production process is still deemed to be CO_2 emissions free. The use of supplementary fuels (most likely derived from fossil carbon sources) will not be an option as this will reduce the effectiveness of biochar as a means of emissions reduction. Supplementary fuels will also add considerable cost to the process.
- By-products i.e. non-biochar outputs of pyrolysis – these will need to be captured, either to provide fuel for pyrolysis, or further processed to produce electricity or additional products (most likely liquid) that could be sold as a means of generating a revenue stream that offsets the cost of the biochar.
- Biomass feedstock – the economics of biochar use will be dictated by the cost of the biomass feedstock and as such, the chosen pyrolysis technology will need to be able to handle a chipped product, which is generally more readily available, cheaper, and easier to transport than cordwood. The pyrolysis technology should also be able to handle biomass from different sources and tolerate a reasonable variation in biomass properties, particularly with respect to moisture and contamination such as nails, plastic, and paint.
- Process control – for an initial facility for production of biochar for PKSW, the chosen pyrolysis process needs to be able to control pyrolysis temperature and ideally be able to operate within a temperature of 250ºC up to 600ºC. In general, pyrolysis temperature controls the degree of pyrolysis and therefore the final properties, particularly the volatile matter and carbon content of the final biochar product [6]. While previous work identified that a higher carbon, low volatile matter biochar is the preferred injectant for a blast furnace, indications were that biochars with higher volatile matter and lower carbon could still be adequate coal substitutes [6][8]. Given that the yield of higher volatile matter biochar is higher per tonne of biomass, then this option will tend to decrease the biomass required and therefore will be more economically viable, assuming that blast furnace performance is not negatively affected. At what level biochar volatile matter would start to effect blast furnace performance is yet to be determined and as such flexibility with respect to pyrolysis temperatures could be very valuable for an initial facility. This flexibility would allow tuning of the biochar properties to find an optimum balance between biomass costs and blast furnace performance. How valuable this flexibility is and what cost the flexibility will add to a project, will need to be critically evaluated.
- Biochar yield – current ironmaking processes require solid carbon and given also the limited market for pyrolysis derived liquid hydrocarbons (see later). the chosen pyrolysis technology needs to ensure the yield of biochar per tonne of biomass input is as high as possible, whilst still producing a suitable product and maintaining the autogenous nature of the pyrolysis process. As such, technologies employing slow pyrolysis would only be suitable.
- Technology Readiness Level (TRL) - the chosen pyrolysis technology should be sufficiently developed to be commercially available, perhaps to a TRL of 8 or 9, ideally with at least one site where the technology is currently in use, with a proven record of availability and productivity.

Table 11 -Survey of available pyrolysis technologies

Technology Name	**Supplier – Country of Origin**	**Technology Type**	**Estimated Biochar Capacity (where figures available – t p.a.)**
Carboval	Paul Wurth – Brazil/Belgium	Continuous Lambiotte-style shaft reactor	8000
Charmaker Pro	Earth Systems – Australia	Batch Missouri kiln	1095
CBC	Crucible Group – Australia	Continuous longitudinal screw type reactor	4000
CSIRO Reactor	CSIRO/Pyrochar – Australia	Continuous shaft reactor	Not supplied
Energy Farmers Australia	Energy Farmers Australia	Continuous shaft reactor	8760
ECHO2	Rainbowbeeeater - Australia	Continuous longitudinal screw type reactor seemingly	Not supplied
Renewed Carbon	Renewed Carbon – Australia	Continuous longitudinal screw type reactor - multiple units in parallel	Not supplied
Pyreg- P500	Pyreg GMBH - Germany	Continuous longitudinal screw type reactor seemingly	230
Chaotech Slow Pyrolysis	Chaotech Slow Pyrolysis – Australia	Screw type reactor	350
Carbonex	Carbonex – France	Batch kilns	20000
Dual CCT18	Pyrocal – Australia	Continuous rotary hearth gasifier	3400
SIFIC/CISR Retort	Balt Carbon – Latvia	Continuous Lambiotte based shaft reactor	6000
Anergy	Anergy – Australia	Continuous indirect heated rotary kiln	365
Torr-Coal	Torrcoal/Perpetual Next – Netherlands	Continuous indirect heated rotary kiln - to be used for torrefaction only, but could go to higher temperatures	43800 - torrefied
Abri-Tech	Abri-Tech – Canada	Continuous longitudinal screw type reactor - however with a steel shot heat carrier and integral chain flail dryer - biooil production	N/A
CML Process	Innov-Energie - France	Batch type kiln	2500
Hershoff Multiple Hearth Furnace	bspthermal – USA	Hershoff Multiple Hearth Furnace	20000
Hershoff Multiple Hearth Furnace	Hankin Environmental Systems – USA	Multiple hearth furnace	40000
NESA solution (MHF) - John Cockerill	John Cockerill – Belgium	Multiple hearth furnace	17520
Wood-Roll Process	Cortus Pty Ltd – Sweden	Combined dryer, rotary kiln and gasifier with steam reforming in the gasifier	N/A
Niutech	Niutech China	Appears to be a rotary kiln arrangement - predominantly for tyre recycling	10000
Zebio-C-1800 Continuous Carbonizer	ZE Energy – Japan	Screw fed rotary kiln, with integral dryer	7884
Continuous Carbonizer	Yamato Sanko – Japan	Rotary kiln - externally heated - similar to the Zebio.	Not supplied
MECC - Biodiesel production	Global EcoFuel Solutions (GEFS) – Spain	Mechanical Catalytic conversion - externally heated, quite complex in some respects - biodiesel	N/A
Reenergi - Grinding Pyrolysis	Renergi Pty Ltd – Australia	Rotary kiln arrangement with heated steel balls - lab scale only	Not supplied
Microwave Pyrolysis	Advanced Environmental Technologies Ltd	Microwave assisted pyrolysis	Not supplied

Table 11 - continued

Technology Name	Supplier – Country of Origin	Technology Type	Estimated Biochar Capacity (where figures available – t p. a.)
Eco-Reps TRU (thermal recovery unit)	Eco-Reps Pty Ltd	Continuous longitudinal paddle or screw reactor - followed by thermal oxidizer for gases.	3000
RTP Technology	Honeywell UOP – USA	Hot sand based gasification reactor - bio-oil production	N/A
Choren Process	CHOREN Industrietechnik GmbH - Germany	Paddle pyrolysis reactor with extensive gas treatment train - focus on syngas production	N/A
	Thyssenkrup GMBH – Germany	Multiple hearth furnace based system - though appears confined to torrefaction - not full pyrolysis	30000 - torrefied
Spirajoule	Biogreen - France	Continuous screwfeed reactor - using pyrolsis gases/electrical heating of screw	2500
CarbonFX	AIREX – Canada	Integrated torrefaction unit - indirect screw dryer, coupled to a cyclonic torrefier. Uses torr-gas and NG as a heat source.	Not supplied
SynCraft - CW1800X2-1000	Syncraft – Austria	Seemingly a floating bed gasifier - aimed at syngas production, but does generate char, supposedly for sequestration	1000
Green Carbon	Polytechnick Biomass Energy - Austria	Small scale retort-based process - heating using pyrolysis gases and a biomass combustion unit	Not supplied
Biomass Gasifier	ID Gasifiers – Australia	Small scale gasification process - Australian based.	Not supplied
Hershoff Multiple Hearth Furnace	IFCO – USA	Standard multiple hearth furnace - with pyrolysis capability	20000
Perpetual Next - HTT	Perpetual Next - Netherlands	High temperature torrefaction reactor. Originally developed in Britain - larger scale plant based in Estonia.	20000 - torrefied
ACTOF	Smart Terra Care LLC - USA	Integrated drying and thermal treatment reaction. Appears to be rotary kiln based.	20000
Patriot	Patriot Hydrogen – Australia	Small scale rotary kiln based pyrolysis and syngas production focus on hydrogen	N/A
ARTiChar	ARTi – USA	Small scale screw pyroysis unit - heated via after burner	700
CPMTP	Stephen Joseph – Australia	Appears to be a rotary kiln type with a linked biomass dryer and associated combustion plant.	5000
CoalTec	CoalTec – USA	Fixed bed gasifier - though does appear to produce biochar	Not supplied
HTP Process	CharTechnologies - Canada	Indirect rotary kiln type	Not supplied
CAC-H2 Gasifier	CAC-H2 – Singapore	Gasification system - focussed on hydrogen and ammonia production	Not supplied

4.1 Pyrolysis Technology Selection

Pyrolysis of biomass is fundamentally a simple process, in that biomass is heated in the absence of oxygen, with the temperature involved and the speed of the reaction determining the relative yields of solid, liquid and gaseous products. In general, higher temperatures, faster reaction speeds and higher gas throughputs favour the generation of liquid and gaseous materials over solid biochar, hence the references to fast and slow pyrolysis. As such, how pyrolysis is undertaken, what feedstock is used, at what scale and what the final requirements are for the solid product or other non-condensible products has resulted in a very wide array of technologies. Though many technologies appear to have been developed, due to the lack of competitiveness of biomass derived products with fossil coal and oil, seemingly few of these technologies have been implemented at a commercial scale.

Using similar guidelines to those above, previous work in the Australian CO_2 Breakthrough Program in 2008 [40] comprehensively surveyed an array of commercially available, larger scale technologies to produce biochar. The survey found that of the available technologies at the time, either a Lambiotte retort style reactor or a multiple hearth furnace (MHF) would be most suitable for BlueScope's application. However, the Lambiotte retort can only operate on larger timbers, not wood chips. Based on the current guidelines, the MHF would likely have been selected in 2008. Since then, further development of pyrolysis technology has occurred, specifically for biochar production. A review of more recent developments indicates that augur and rotary kiln type reactors appear to be the focus. Figure 4 provides a very useful overview of pyrolysis technologies, indicating that for BlueScope's application, along with the MHF, augur or rotary kiln reactors could be viable.

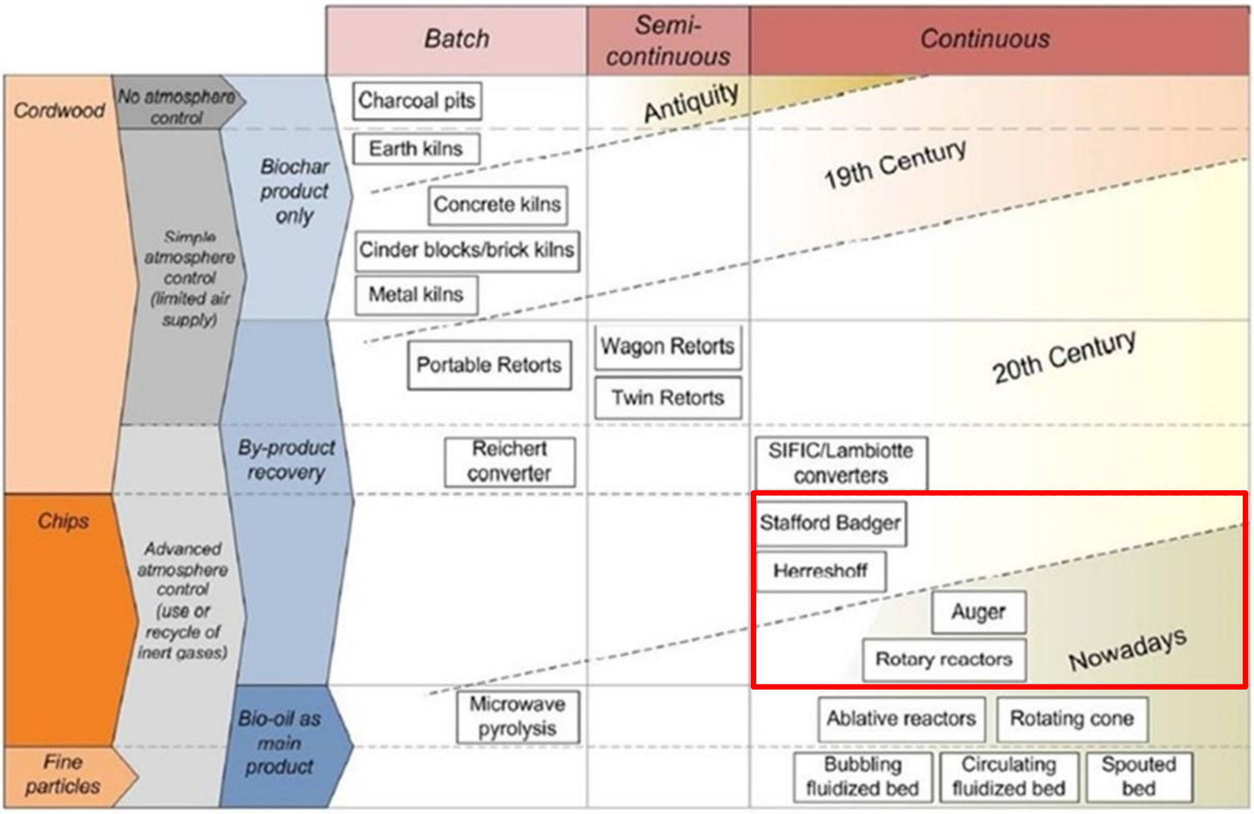


Figure 4 – Graphical representation of developments of application pyrolysis technologies [39], with those applicable to BlueScope's application highlighted

4.1.1 Multiple Hearth Furnace (MHF)

The MHF or Herreschoff kiln is a cylindrical refractory-lined vessel which can be up to 8m in diameter. The vessel contains a number of self-supporting horizontal refractory hearths, which are swept by a series of steel, air cooled rotating “rabble” arms. Biomass is charged to the topmost hearth and the rabble arms lift and turn the material and move it either inwards or outwards on each hearth where it drops through holes to the hearth below. During normal operation hot gases rise through the hearths from bottom to top, thereby drying and pyrolyzing the descending biomass and potentially facilitating the conversion of some of the pyrolysis gases into solid carbon, increasing biochar yield. Heat is provided to the system predominantly via the combustion of pyrolysis gases that occurs due to the controlled injection of air at strategic elevations. The use of pyrolysis gases makes the unit fully autogenous once the pyrolysis temperature is over a threshold of approximately 300ºC. The injection of air along with the feed rate of biomass is used as a means of controlling the pyrolysis process and to a degree, the pyrolysis temperature and therefore the yield of biochar per tonne of biomass. Due to the large amount of volatiles evolved, the exhaust gases exiting the top of the furnace generally have a high proportion of tars and residual hydrocarbons which must be treated. Surplus volatiles are generally combusted to produce process heat or steam, though the liquid by-products could be condensed from the exhaust gases. Unfortunately, indications are that because the exhaust gases are diluted by the presence of combustion products and additional nitrogen (from air), condensation of liquid by-products is much more problematic [45]. Figure 5 give a schematic view of an MHF.

MHFs can reportedly produce up to at least 20,000t p.a. of biochar per unit depending particularly on the moisture of the feedstock [40], but indications are for units of larger diameter and with more hearths, higher production is possible. Note that unlike other technologies, the MHF can act as a drying and pyrolysis unit. This reduces the efficiency and productivity of the overall unit, but it may be a useful option in an application where limited real estate is available for installation.

MHFs have the benefit of being able to be run on a variety of feeds and could potentially tolerate some levels of contamination such as paint or plastic in the feedstock. Equipment suppliers do indicate that there are relatively low limits for this contaminated material, particularly for ash bearing materials. MHFs have some other drawbacks. Firstly, due to the action of the rabble arms, the biochar produced tends to be quite fine; however, given BlueScope’s application, this is unlikely to be a problem. Secondly, due to the use of a refractory lining, the capital cost for a unit will be relatively high.

Overall, MHFs are a robust operational unit that has been used for many years for charcoal production, particularly in the USA where they are used to produce charcoal for the barbeque market. In addition to charcoal production, MHFs have been used extensively for other applications such as calcination, roasting of non-ferrous ores, incineration, and regeneration of activated charcoal in water treatment. BlueScope has experience with MHF technology at its New Zealand Steel operation, where it runs 4 MHFs as an integral part of their ironmaking process chain. There was also a small unit at PKSW for regeneration of activated carbon at the Coke Oven’s Gas Processing plant, although this is no longer in use.

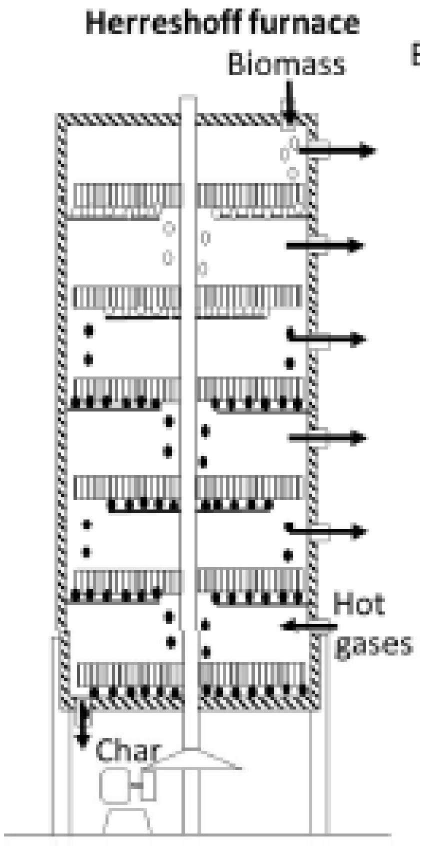


Figure 5 – Schematic of a Herreschoff or Multiple Hearth Furnace [39]

4.1.2 Augur, Screw or Paddle Reactors

While there are many designs, these types of reactors generally consist of an externally heated horizontal tube containing a central axle, fitted either with paddles or a feed screw which agitates and propels the biomass through the reactor, thereby increasing the speed of biomass drying and the extent of the pyrolysis reaction. Heat carriers like sand or steel balls also appear to be used in different designs of these type of reactors. The augur or paddles themselves can also be heated to assist with pyrolysis. Due to the external heating of the process and sealing at either end, more concentrated pyrolysis gases remain within the reactor for longer periods, potentially facilitating further conversion of pyrolysis gases (particularly the condensable fraction) into solid biochar, perhaps to a greater extent than the MHF. The pyrolysis chamber also tends to remain oxygen-free unlike the MHF which could improve biochar yield, though indications are that different designs use controlled air injection, for additional heating and possibly, syngas generation. Pyrolysis vapours are exhausted out of the top of the reactor, while biochar is discharged from the bottom. The pyrolysis vapours are usually combusted to provide heat for the process, though as with other pyrolysis processes there are usually excessive volatiles which in turn are generally burnt for power generation. However, several of the designs also look at condensation of the pyrolysis vapour stream to recover products such as pyroligneous acid, wood vinegar or pyrolysis bio-oil [46].

This design of pyrolysis equipment is quite popular as there are a few commercial units available with a focus on small scale waste to energy projects, often mobile, that utilise municipal or agricultural waste. For more efficient operation, the biomass should be dried prior to pyrolysis. Figure 6 shows a schematic of a commercial screw pyrolysis unit [47].

The use of moving parts/bearings/screws in a hot environment, temperature control problems and the difficulties in scaling up this type of design appear to have, to date, limited the applications of these reactors to small and mid-scale applications i.e. much less than 20,000t p.a. for a single unit. Note also that there are variations on the design of the augur pyrolysis unit - rather than using a screw to propel the biomass through the reactor, a vibrating conveyor system is used. This system appears to be limited to lower torrefaction type temperatures, but reportedly can produce 20,000t p.a. of carbonized wood chip material [48].

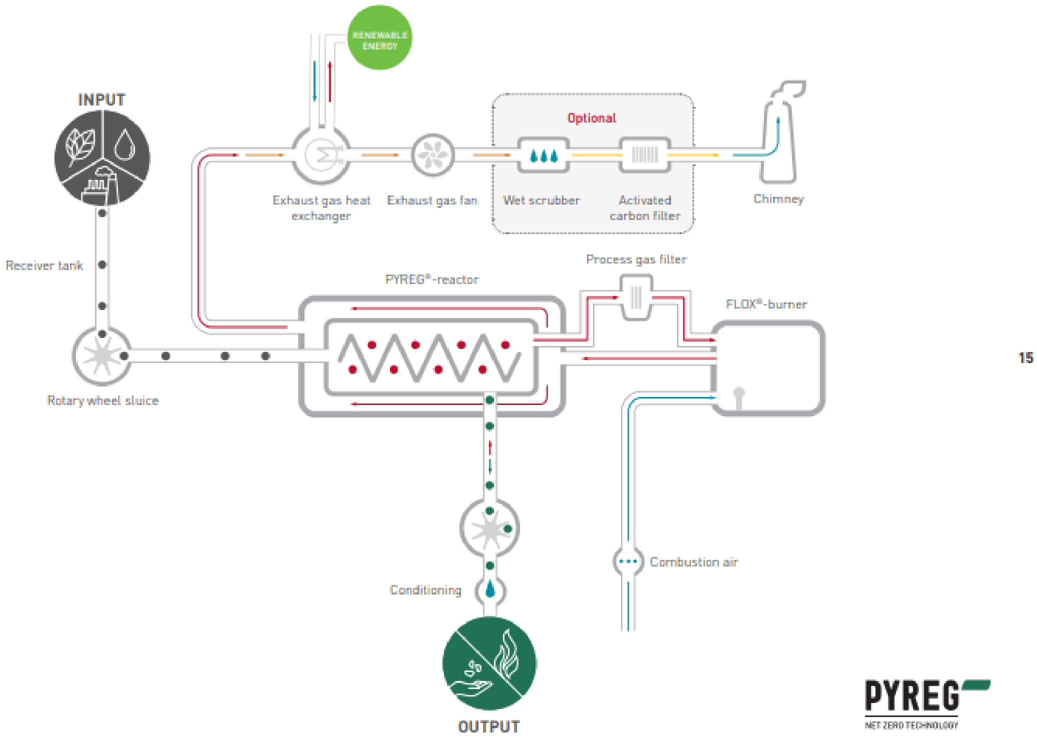


Figure 6 – Schematic of a commercially available screw pyrolysis unit [47]

4.1.3 Rotary or Drum Reactors

Like auger reactors, rotary reactors are essentially a near horizontal tube containing “lifters” (analogous to paddles). Biomass is charged into one end of the tube and the rotary reactors themselves rotate. This, combined with internal “lifters”, results in efficient drying and pyrolysis, with the pyrolysis gases and biochar being discharged from the other end of the drum (see Figure 7). Rotary reactors can be heated via the combustion of volatiles in the reactor (like the MHF), but more recent designs use indirect heating of the shell to provide the heat for pyrolysis, with volatiles generated during the pyrolysis process combusted for heating and drying of the biomass (usually in a separate dryer). Similar to the augur reactor, the sealed nature of the reactor and the more concentrated stream of pyrolysis gases could result in additional biochar production at the expense of liquid byproducts. In general, there appears to be excess energy in the pyrolysis gases, so it is often recovered with a boiler or other forms of heat recovery. The excess volatiles could be condensed to form bio-oil or similar related by-products, but there is little evidence in the literature that this is occurring for rotary reactor technology [42][43].

Most applications of pyrolysis using rotary reactors appear to be limited to small to mid-scale waste-to-energy applications using a variety of carbonaceous waste products (tyres, municipal waste, bagasse or even sewage sludge); however, indications are there is nothing in the design that limits scaling up to larger sizes, barring perhaps sealing of the unit to prevent oxygen ingress.

Rotary reactors, like MHFs appear to be able to run on a variety of feeds and be flexible with respect to pyrolysis temperatures. Unlike augur reactors, scale up seems to be possible with units up to 20000t p.a., though currently there are limited applications of larger scale rotary pyrolysis units reported. The most prominent of these, and of particular interest to BlueScope, is the Torero project which will utilise the Torrcoal rotary kiln pyrolysis technology [49] to produce a torrefied wood material for direct use in steelmaking [7].

Overall, rotary reactors are a robust technology with the basic technology having been developed and used for many years in the cement and calcination industries, albeit with direct rather than indirect heating. However, since they are a horizontal unit, space limitations become more critical for this technology.

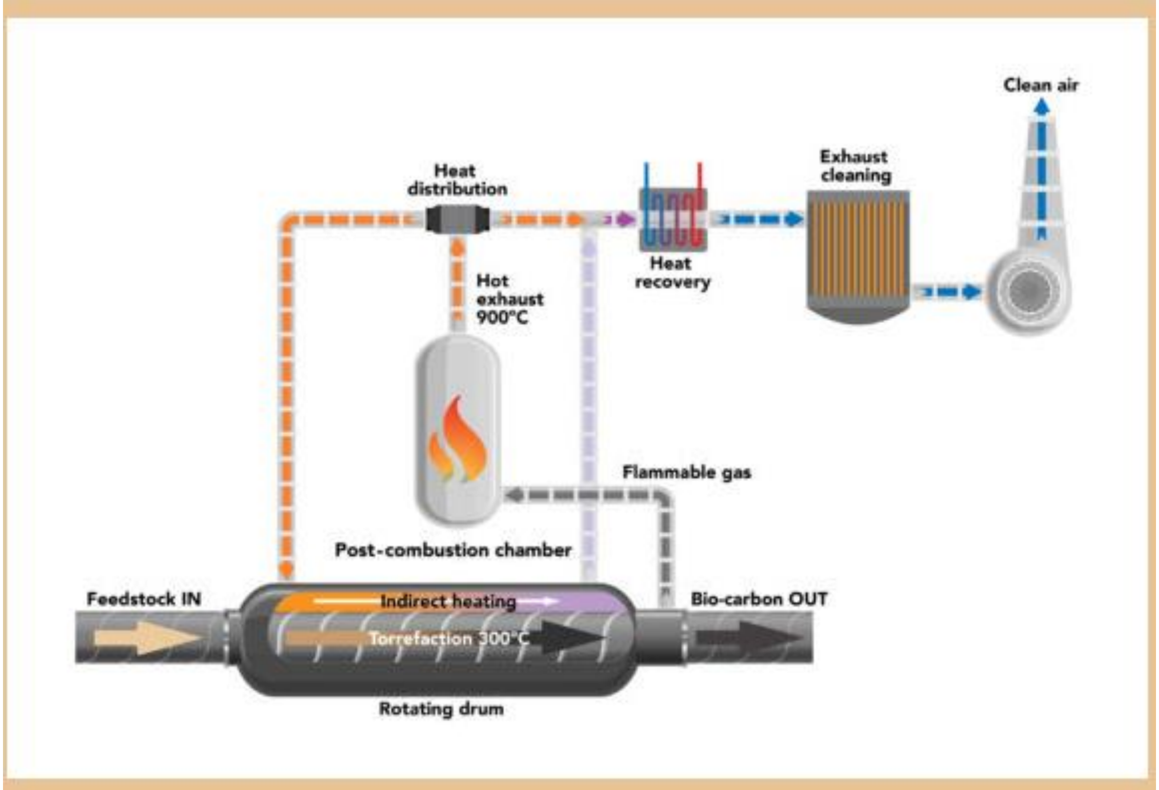


Figure 7 – Schematic of the rotary kiln TorrCoal pyrolysis process [49]

4.1.4 Badger Stafford Process

The Badger Stafford process is an autogenous retort-based process that was used with great success by the Ford Motor Company at their Iron Mountain plant in Michigan [45]. Figure 8 shows a schematic of the process that used scrap wood that was chipped down to an appropriate size, up to 200x50x20mm. The sawdust and shavings were screened out and treated in separate rotary furnaces to minimize the impact on retort permeability. The resultant sized material was then dried to 0.5% moisture and heated to 150^{o}C in rotary dryers before being elevated to 12.2 x 3.05m refractory-lined retorts, entering the controlled atmosphere of these vessels via a barrel valve. The pre-heated timber descended through the retort under gravity and due to the nature of the material, would heat up autogenously once it reached the critical temperature range of 280-350^{o}C. Gaseous by-products would leave via the top, while charcoal was discharged from the bottom, with both exits controlled by barrel valves, thereby preventing oxygen ingress. The counter-current nature of the retorts meant that ascending gases would pre-heat the descending feed, therefore making the process quite efficient and without the necessity to introduce oxygen to promote heating. The latter resulted in a more concentrated by-product stream and as the internal temperatures in the retorts was regulated to 515^{o}C, charcoal yield was also quite high at ~272kg of charcoal per dry tonne of wood.

Given the simple and autogenous nature of the process, the flexibility with respect to input sizing, the lack of moving parts and a concentrated by-products stream, this process would appear to be one that is suited to the production of biochar for use in steelmaking. This is despite the drawbacks with thermal efficiency and tar buildup and perhaps lack of flexibility with respect to pyrolysis temperature. The suitability of the process was noted by CSIRO in the Australian CO_2 Breakthrough Program, who developed a 100kg/hr pilot scale plant modelled on the Badger Stafford process [50]. Unfortunately, it has yet to be scaled up to a commercial scale. Whilst there are developments in this direction [51], it is still not at a level suited to BlueScope's initial application. Nevertheless, given its benefits, particularly around concentration of waste gas streams and potential linkages with future demands for bioenergy, it is an option that should be carefully considered for future upgrades to a pyrolysis plant.

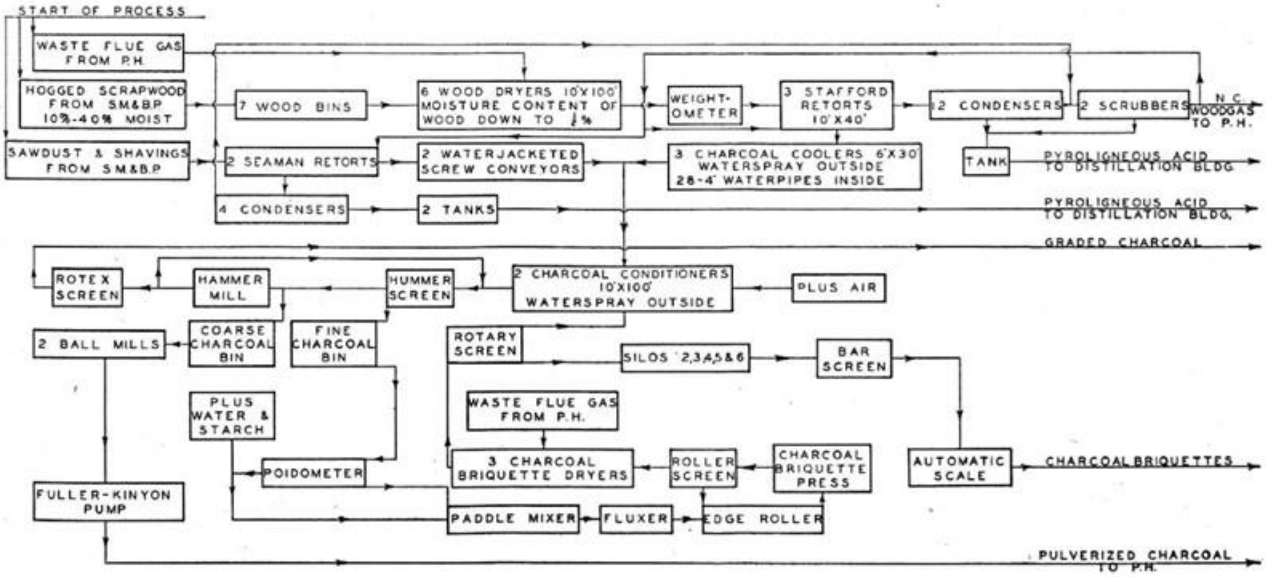


Figure 8 – Badger Stafford Flow Chart [45]

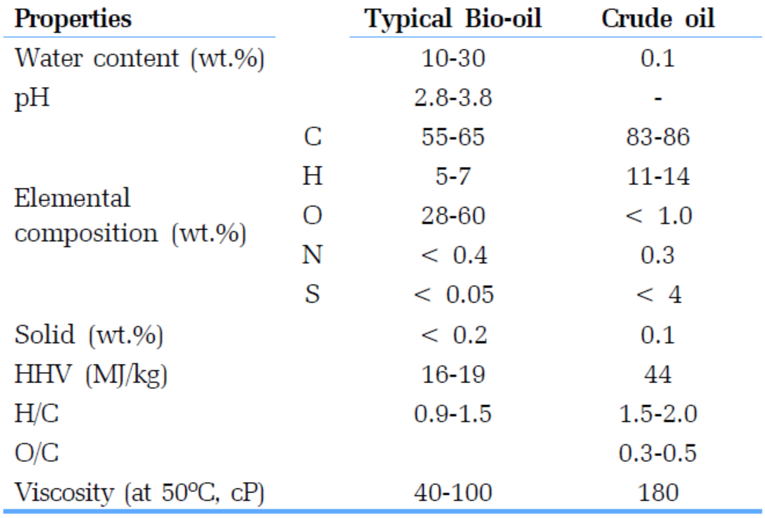
In summary, given the benefits and risks for the different methods and designs of pyrolysis technologies described above, only two of the technologies fulfill BlueScope's requirements to the most significant extent: the MHF and the rotary kiln technology, particularly, the Torrcoal process. As such, further work on the biochar concept should focus on these two technologies.

4.2 Pyrolysis By-products

As has been noted, the pyrolysis of biomass results in a relatively low mass yield of biochar (perhaps 20-40% on a dry timber basis), with majority of the biomass during pyrolysis partitioning to a gaseous by-product stream [5] [52]. For a BlueScope biochar production concept, this could equate to around 300,000t p.a. of by-products. Depending on pyrolysis conditions, the by-product stream consists of approximately 15-30% non-condensable gas with the remainder being condensable liquid, potentially containing high proportions of water. Both non-condensable and condensable streams contain proportions of carbon and hydrogen which therefore have a fuel value. Indications are that the non-condensable fraction of the by-products should be sufficient to provide fuel for drying and pyrolysis processes [38], leaving the condensable fraction to be used for alternative purposes. In most slow pyrolysis processes, all by-products are simply combusted to produce heat for the process, with excess energy used for steam/electricity generation, though in some limited applications some form of single stage condensation appears to be used [46][53].

However, the Australian CO_2 Breakthrough Program identified that the condensable by-products could play an integral role in the economics of a biochar project as they could potentially be sold [38]. While bio-oil composition appears to vary depending on pyrolysis technique and biomass feedstock, in general, bio-oil is a dark brown liquid containing high levels of moisture and often higher levels of entrained char particles [54]. Table 12 shows the properties of bio-oil in compared to crude oil. The high levels of oxygen and moisture combine to produce a liquid which has a low heating value, is corrosive and immiscible with petroleum derived fuels. Furthermore, it tends to separate and increase in viscosity during storage. The CO_2 Breakthrough Program suggested that the liquid bio-oil could be sold as a low-quality diesel substitute, but indications are that this would only be for specific, stationary applications [53] due to the lower heating value of the bio-oil. The favoured application for raw bio-oil appears to be for domestic heating in Europe [55]. In Sweden, it has also been used for process heating in producing iron ore pellets [56][57].

Table 12 – Properties for bio-oil and fossil crude oil [54]



Properties		Typical Bio-oil	Crude oil
Water content (wt.%)		10-30	0.1
pH		2.8-3.8	-
Elemental composition (wt.%)	C	55-65	83-86
	H	5-7	11-14
	O	28-60	< 1.0
	N	< 0.4	0.3
	S	< 0.05	< 4
Solid (wt.%)		< 0.2	0.1
HHV (MJ/kg)		16-19	44
H/C		0.9-1.5	1.5-2.0
O/C			0.3-0.5
Viscosity (at 50°C, cP)		40-100	180

To fully realize the value of the bio-oil, some form of upgrading would be required. This could be undertaken via several methods, starting with processing of the raw pyrolysis gases to remove char, followed by fractional condensation to provide different liquid streams with different properties [58]. Alternatively, various techniques like those for hydrocarbons such as catalytic cracking or hydrotreatment amongst others could be used to upgrade the bio-oil. However, these do not overcome the inherent lower hydrogen and high oxygen content of the bio-oil i.e. it would not be a direct diesel substitute [54][59]. Instead, bio-oil subjected to catalytic upgrading and hydrotreatment could be used as a jet fuel [60], which is becoming a primary focus for the bio-energy industry. Additional upgrading could also be useful for the generation of organic compounds which are currently produced from petroleum [54]. Bio-oil could also be gasified to produce a clean synthetic gas (syngas), most likely via steam reforming at elevated temperatures [61], which could potentially be injected into domestic gas lines. At an industrial scale, this application could have potential given the proximity of large gas mains to PKSW.

Finally, bio-oil or “pyroligneous acid” could be sold into horticultural applications where it reportedly improves plant growth and assists in preventing insect attack [46][62]. While there is considerable work underway here, the demand from horticulture is not expected to be high enough to consume the large quantities of bio-oil produced during production of biochar for PKSW.

Overall, despite considerable research and development on the use and upgrading of pyrolysis bio-oils, barring some smaller applications, they are yet to be used widely as a replacement for petroleum fuels, nor is there a ready market in the short to medium term. Hence, there is unlikely to be any direct revenue from the pyrolysis by-products from BlueScope’s proposed production of biochar, and investment in the short term on condensation and further treatment of bio-oils is most likely not viable. Pilot-scale testing of pneumatic conveying of pulverised biochar-coal mixtures under PKSW conditions

5 Pilot-scale testing of pneumatic conveying of pulverised biochar-coal mixtures under PKSW conditions

To support the plant demonstration of a pulverised blend of biochar-coal for injection at PKSW No. 5 Blast Furnace (BF), test work was conducted at the University of Wollongong (UOW) to characterise the flow properties and pneumatic conveying characteristics of various blend ratios. The aim of the investigation was to identify and if required, mitigate any potential issues to store, handle and pneumatically convey the pulverised biochar-coal blended product from the PKSW Pulverised Coal Injection (PCI) plant to the BF plant. The pilot-scale pneumatic conveying test work undertaken, addressed specific operational risks for PKSW when introducing biochar into the PCI plant such as blockages in the pneumatic line, segregation, reduction of throughput and major adjustments to the operating parameters for the pneumatic conveying system. The test work would also identify if changes would be required to operate the pneumatic conveying system reliably to steadily supply the biochar-coal product to the BF at the necessary mass flow rates.

The main test program carried out at UOW was separated into two areas of testing and investigation being:

a. Measurement of flow properties; and
b. Pilot-scale pneumatic conveying testing.

In addition, segregation testing of the worst-case blend of biochar-coal was carried out, involving fluidisation of the product for long periods to examine whether biochar and coal separated in a control volume.

5.1 Measurement of flow properties

Two biochar products from different suppliers were supplied to ALS Coal Technology, Queensland (ALS) where these products were blended, homogenised and milled. The biochar samples were blended by mass in a ratio of 60% from supplier A and 40% from supplier B. The sample was then milled in a Raymond type roll mill to 75-80% passing 90µm. PKSW provided ALS samples of pulverised coal (prepared at PKSW) that were used to create the blended products. The following blends were prepared and supplied to UOW where material testing was conducted at the as-received moisture content:

- 100% pulverised coal (Figure 9)
- 85% pulverised coal blended with 15% pulverised biochar (Figure 10)
- 70% pulverised coal blended with 30% pulverised biochar (Figure 11)
- 100% pulverised biochar (Figure 12)

The following characterisation and flow property tests were measured at ambient conditions:

- Bulk density
    - Compressibility (Bulk density vs. major consolidation stress)
    - Loose poured
    - Tapped
- Angle of repose
    - Poured
    - Drained
- Particle size distribution
- Instantaneous low pressure yield loci, flow function, effective angle of internal friction
- Wall friction measurements on:
    - Stainless steel 316L-2B (SS 316L-2B)
    - Black mild steel

Figure 9: As received sample of 100% coal

Figure 10: As received sample of 85% coal - 15% biochar

Figure 11: As received sample of 70% coal - 30% biochar

Figure 12: As received sample of 100% biochar

Full details and results of the flow property testing are provided in Appendix 1 (BMEA Report BME2206-1). A summary of the key results follows:

- The flowability index provides an indication of a bulk solids cohesive strength using its Flow Function where Table 13 provides a comparison of the flowability index for each blend tested. The blends were generally found to have good handling characteristics with low to moderate cohesive characteristics based on internal shear testing. Internal shear testing showed that the bulk strength of the 100% pulverised coal and 85% pulverised coal blended with 15% pulverised biochar sample were very similar. When the proportion of biochar was increased to 30%, the internal bulk strength of the product reduced indicating that the product may be easier to handle.
- The bulk density of the biochar is lower than coal resulting in the bulk density of the blended sample reducing with increasing proportions of biochar. The bulk density versus consolidation pressure for the various coal and biochar blends is shown in Figure 13 and the loose-poured bulk density measurements are provided in Table 14.
- The variation of the bulk density between 100% pulverised coal and 70% pulverised coal blended with 30% pulverised biochar was up to approximately 10% depending on the method used to measure bulk density (viz.

tapped, loose poured or consolidated). As a result, the volumetric capacity of storage and conveying equipment may be affected storing and handling lower bulk density products.

- Tapped bulk density measurements were conducted on the biochar-coal blends to examine if the tapped bulk density measurements could be used to estimate the portion of biochar and coal within a sample. The results provided in Figure 14 showed that distinctive tapped bulk density curves could be developed for each blend that could be utilised to examine segregation of the biochar-coal blends.
- Wall friction testing showed that the wall friction angles displayed very minor changes when pulverised biochar was added to the pulverised coal. The characteristics for the biochar blends to flow from bins and hoppers were assessed based on the flow property data to help investigate any changes of the critical arching dimensions or modes of flow from a mass-flow hopper. The results indicated that the flow patterns when discharging the pulverised blends of coal and biochar under deaerated conditions should be similar when storing and handling 100% pulverised coal.

Table 13: Flowability Index for the pulverised products

Blend	Major Consolidation Stress (kPa)	Flowability Index	Handleability
		Instantaneous	
100% Coal / 0% Biochar	10	0.304	Good flow characteristics
85% Coal / 15% Biochar	10	0.299	Good flow characteristics
70% Coal / 30% Biochar	10	0.238	Relatively free flowing

Table 14: Loose-poured bulk density test results of pulverised products

Blend	Loose-Poured Bulk Density (kg/m^3)	
	Range	Average
100% Coal / 0% Biochar	582 - 598	591
85% Coal / 15% Biochar	552 - 572	561
70% Coal / 30% Biochar	534 - 559	549
0% Coal / 100% Biochar	539 - 548	543

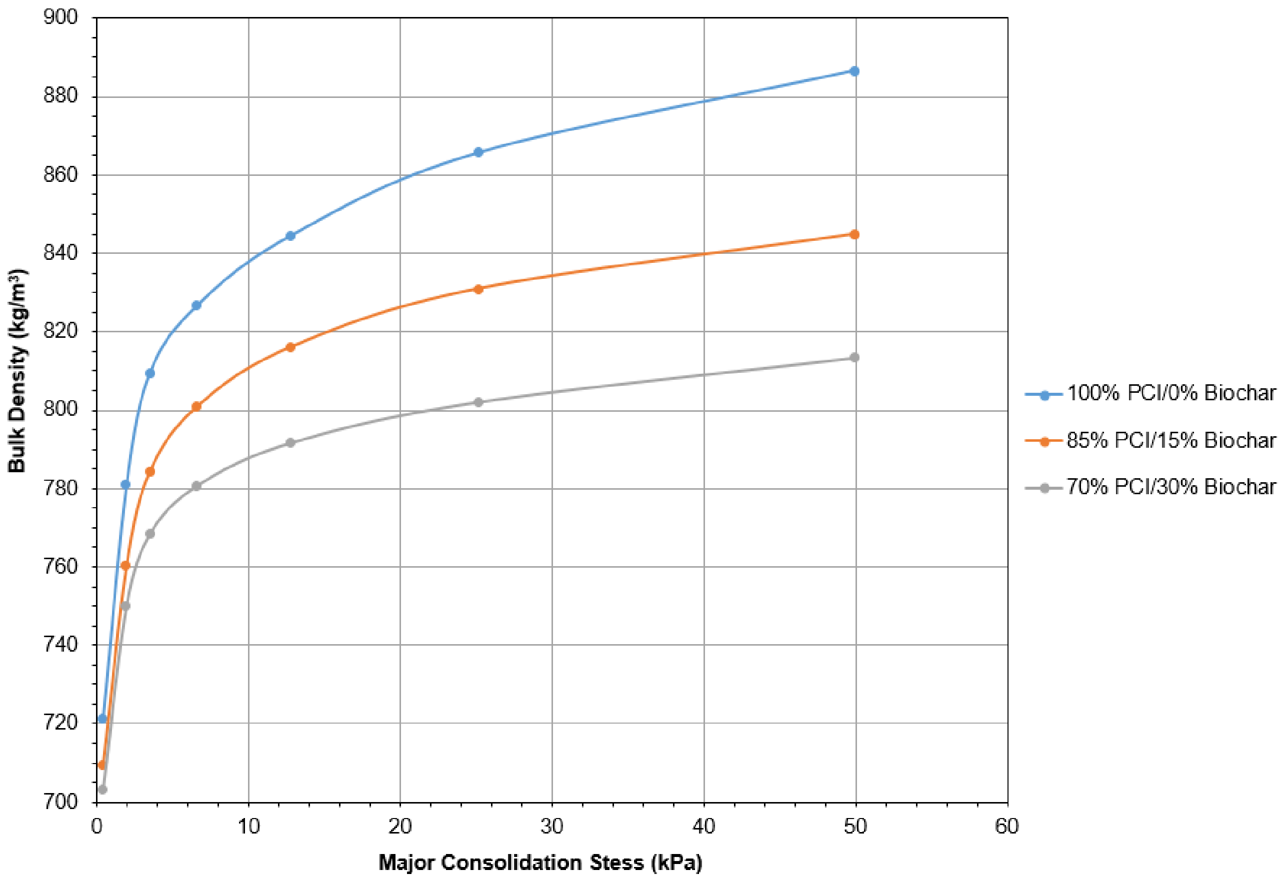


Figure 13: Bulk density variation for various coal and biochar blends

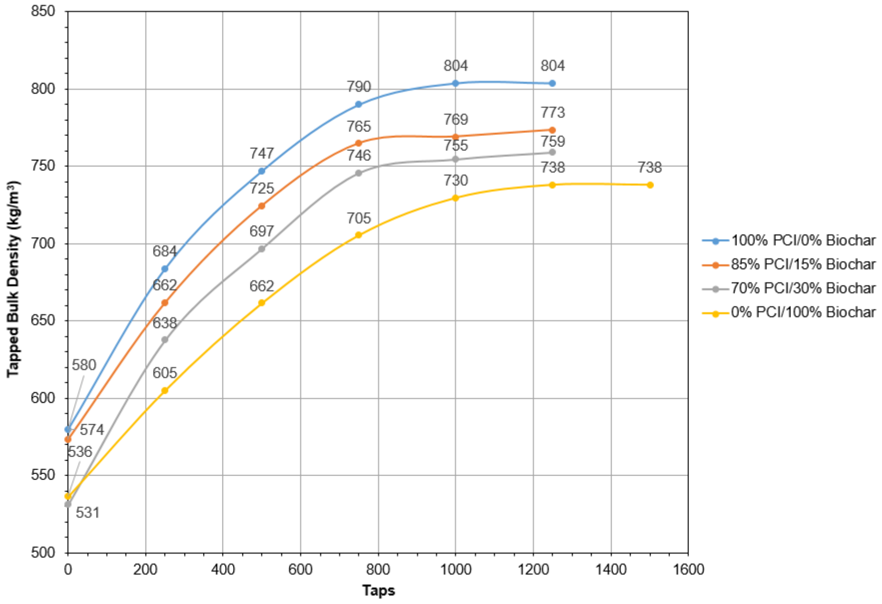


Figure 14: Tapped bulk density test results of pulverised products

5.2 Pilot-scale pneumatic conveying tests

UOW's pneumatic conveying test facility, consisting of two pipelines of different diameter and varying conveying length, was used to study the pneumatic conveying characteristics of bulk materials.

The pneumatic conveying system at PKSW operates at high pressure (greater than 1350 kPa-gauge) using large injection hoppers and nitrogen to transport the pulverised coal from the PCI plant to the BF. The pilot-scale test rig at UOW operates at lower pressure and uses air to convey material that results in some differences of the gas density and velocity of the gas through the pipeline. Due to the high pressure and gas density in the PKSW pipeline, the velocity of the gas and pulverised product is relatively low compared to the velocity of the material through UOW's test rig.

Although there are some differences between the operating pressure and pipeline length between the UOW pilot-scale test rig and the PKSW system, the pilot-scale test rig is fit-for-purpose to examine the differences in the conveying characteristics of the biochar-coal blends. The aim of the pilot-scale testing is to primarily examine the differences in the total pipeline pressure, solids flow rate and stability during conveying where a feasible quantitative assessment can be conducted on a low-pressure system with a shorter pipeline length. Operating a pneumatic conveying system at higher static pressures increases the momentum of gas flow that helps to transport powders and testing at lower static pressures tends to be more conservative to examine minimum transport conditions. Specifications of the UOW pilot-scale test rig include:

- 500-litre bottom-discharge blow tank feeder (700 kPa-gauge maximum safe working pressure) with 100 mm N.B. full-bore outlet valve, fluidising-discharge-air and conveying-air shown in Figure 15. The blow tank is mounted on load cells to monitor the mass of solids entering the pipeline.
- 2 m^3 receiving bin with pulse-jet insertable filter and cone-type outlet valve. The receiving bin is mounted on load cells to monitor the mass of solids discharging from the end of the conveying pipeline shown in Figure 16.
- Mild steel conveying pipeline, with 69 mm internal diameter (D) and length (L) of 136 m, vertical lift (L_v) of 5.8 m, and 7 x 0.5 m radius 90° bends (N_b) shown in Figure 17.

Details of all pilot-scale pneumatic conveying tests and results are provided in Appendix 2 (BMEA Report BME2206-2). The pneumatic conveying trials measured the pressure at various location in the pipeline (see Figure 17) over a range of air and solids flow rates to develop a pneumatic conveying characteristics (PCC) plot for each blend. The PCC plot shows the total pipeline air pressure drop (Δpt) at different air flow rates for various tonnage lines or solids flow rates. The PCCs are shown in Figure 18 through to Figure 20 for the various blends where these plots assist to evaluate the pneumatic conveying behaviour of each blend.

The pneumatic conveying trials showed the pulverised products conveyed well in dilute phase (high air flow) and also fluidised dense phase (low air flow and high solids loading). As the air flow was reduced further and the flow mode changed to dense-phase, minor fluctuations of the solids flow rate and/or some deposition of the products was observed along the pipeline with some tests.

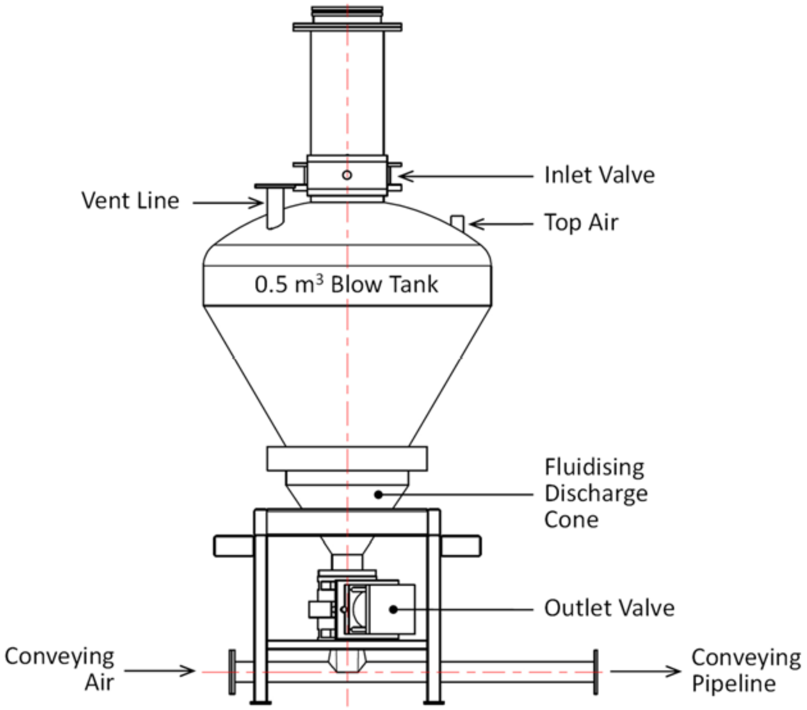


Figure 15: Schematic layout of $0.5m^3$ blow tank feeder

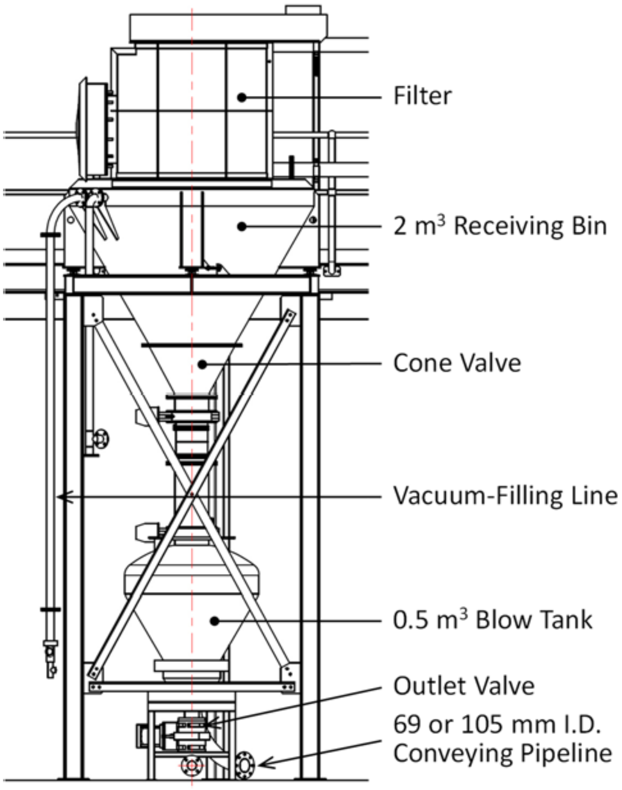


Figure 16: Test rig showing blow tank feeder and receiving bin with filter

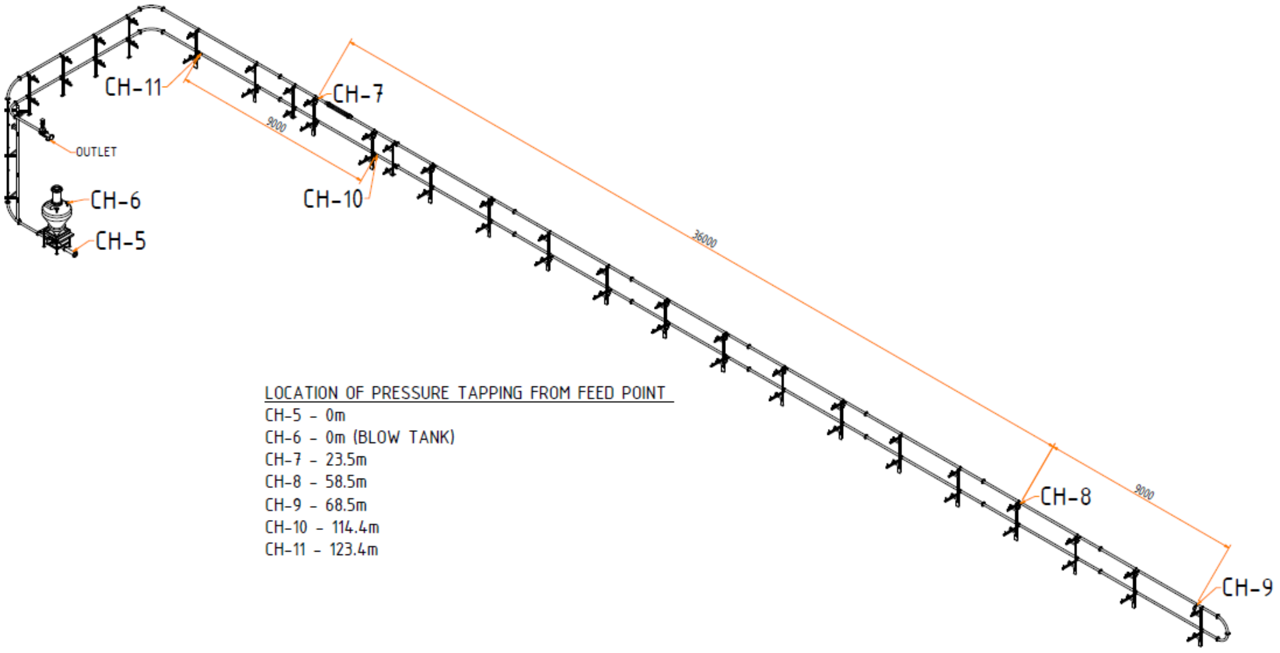


Figure 17: Test rig showing DN65 pipeline and pressure tapping locations

All the blends generally displayed good pneumatic conveying characteristics, based on the following findings:

- The experimental total pipeline air pressure drop (Δpt) tended to decrease when the proportion of biochar was increased from 0% to 15% and finally 30% by mass when comparing the results at the same conveying rate (m_s) shown in Table 15 and Table 16 or solids loading ratio (m^*) shown in Table 17. The reduction of the pipeline pressure drop with the biochar blended products compared to the 100% PCI is less than 13% indicating that the biochar blends are marginally better to convey.
- Material deposition in the pipeline occurred with all products during some tests when the selected operating conditions were near to the lower boundary conditions. It is likely that the initial blow tank pressures were set too high for some tests causing material to surge into the pipeline at the start of test. As a result, unsteady flow may have occurred during the tests that led to deposition in the pipeline at the end of the tests with inadequate air flow to clear the pipeline.
- All the products responded well to the flow rate of air through the blow tank to adjust the conveying rate which is encouraging if similar adjustments need to be on site.
- It was difficult to determine the lower boundary where pipeline blockages or unstable flow will occur. As a result, the minimum transport boundaries where flow conditions become unstable and result in violent pressure surges or pipe blockages were not able to be defined properly.
- The powders displayed very good pneumatic conveying characteristics with no tendency to block the conveying line.
- For similar blow tank air flow rates (via the fluidisation discharge cone) and conveying air flow rates, a minor reduction of the solids conveying rate was observed when biochar was blended with the PCI product.

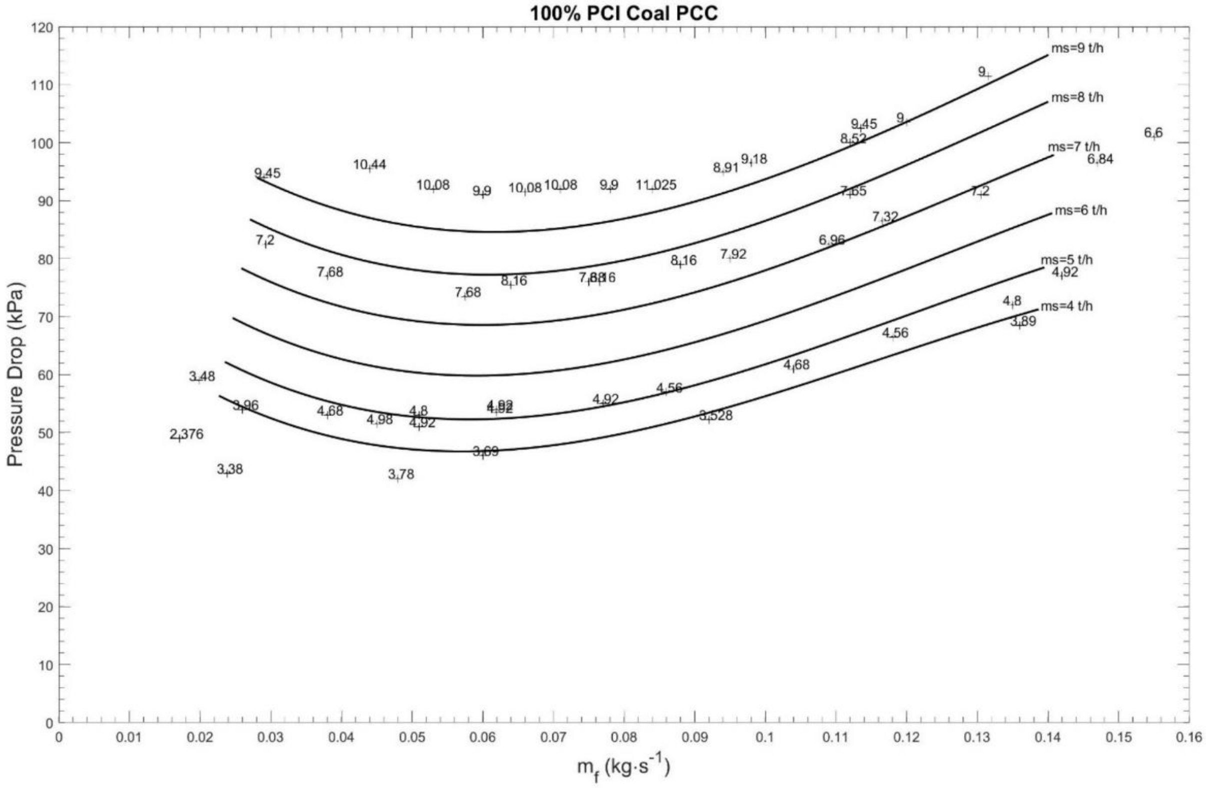


Figure 18: PCC for 100% Coal (D = 69 mm, L = 136 m, L_v = 5.8 m, N_b = 7)

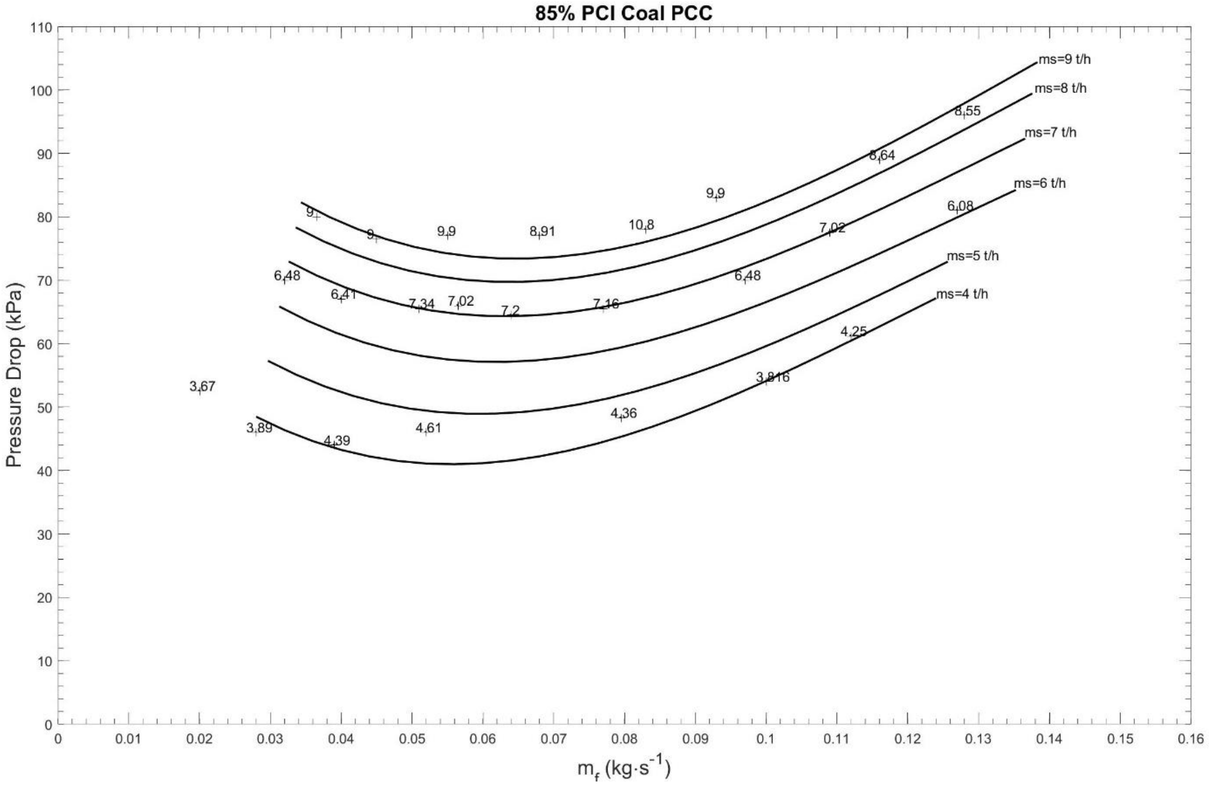


Figure 19: PCC for 85% Coal – 15% Biochar (D = 69 mm, L = 136 m, L_v = 5.8 m, N_b = 7)

Table 15: Comparison of total pressure line drop from UOW test rig at solids conveying of 5 tph (D = 69 mm, L = 136 m, L_v = 5.8 m, N_b = 7)

Air mass flow rate (kg/s)	0.04	0.08	0.12
Solids loading ratios (m*)	34.7	17.4	11.6
Blend	**Exp. □p_t (kPa)**		
100% Coal - 0% Biochar	55	55	70
85% Coal - 15% Biochar	52	52	70
70% Coal - 30% Biochar	48	50	66

Table 16: Comparison of total pressure line drop from UOW test rig at solids conveying of 8 tph (D = 69 mm, L = 136 m, L_v = 5.8 m, N_b = 7)

Air mass flow rate (kg/s)	0.04	0.08	0.12
Solids loading ratios (m*)	55.6	27.8	18.5
Blend	**Exp. Δp_t (kPa)**		
100% Coal - 0% Biochar	81	80	96
85% Coal - 15% Biochar	75	72	89
70% Coal - 30% Biochar	75	75	91

Table 17: Comparison of total pressure line drop from UOW test rig at solids loading ratio of 70 and 50 (D = 69 mm, L = 136 m, L_v = 5.8 m, N_b = 7)

Solids loading ratios (m*)	70	50
Blend	**Exp. Δp_t (kPa)**	
100% Coal - 0% Biochar	89	80
85% Coal - 15% Biochar	81	73
70% Coal - 30% Biochar	82	74

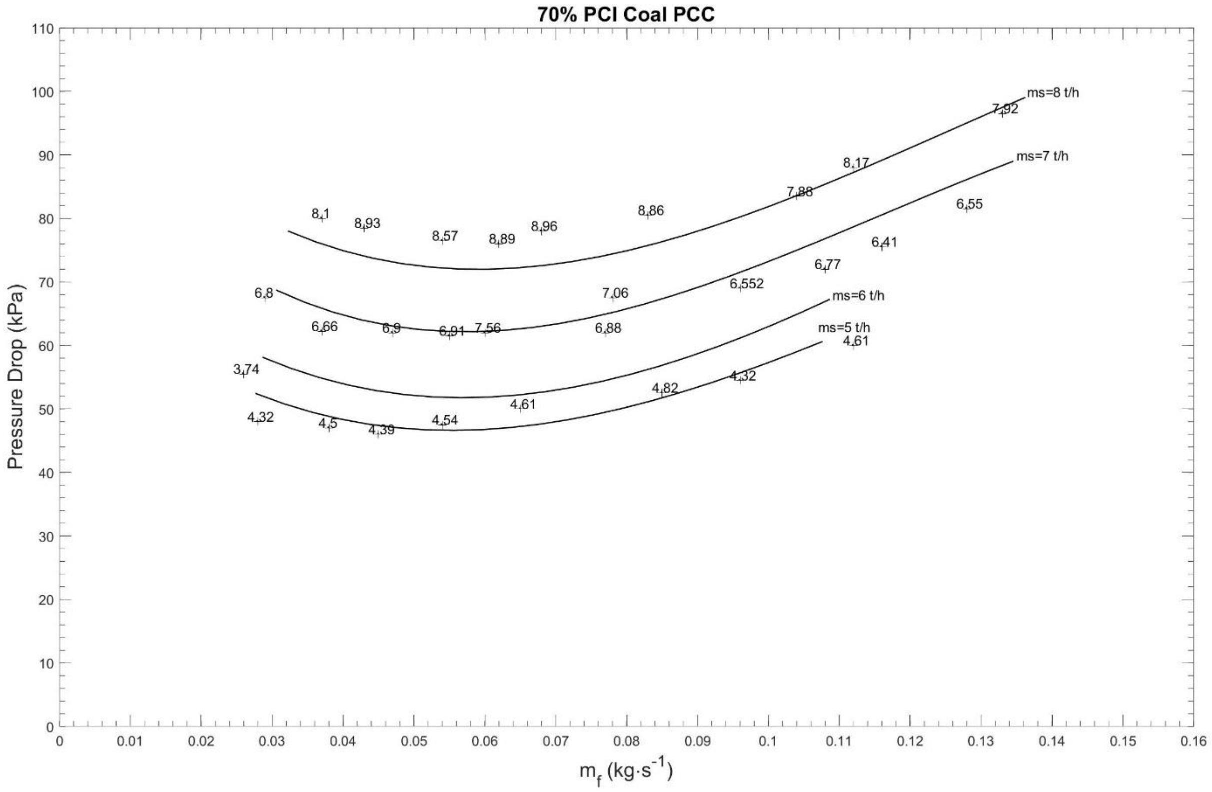


Figure 20: PCC for 70% Coal – 30% Biochar (D = 69 mm, L = 136 m, Lv = 5.8 m, Nb = 7)

5.3 Blend segregation tests

Additional segregation testing was conducted where the 70% coal - 30% biochar blend was fluidised for long periods to examine if the biochar and coal were segregating. The longest duration test was 15 minutes which is a similar cycle time of the injection hoppers at PKSW. The experimental setup to examine segregation under fluidisation is shown in Figure 21. The tapped bulk density data (see Figure 14) was used as a metric to identify segregation in a fluidised bed. The test results suggested fluidising the biochar-coal blends for long periods of time did not appear to cause segregation examining the results shown in Table 18. As a result, no additional testing was conducted on the other blends as the 70% coal - 30% biochar blend was believed to be the worst-case product for likelihood of segregation.

Figure 21: Setup of fluidisation test rig to examine segregation

Table 18: Comparison of tapped bulk density with 1250 taps of 70% coal / 30% biochar before and after fluidisation

Blend	Section of the Fluidised Bed	Tapped Bulk Density (kg/m³) – 1250 Taps	
		Range	Average
70% Coal / 30% Biochar – No Fluidisation	-	756 - 766	759
70% Coal / 30% Biochar – 90s Fluidisation	Upper Section	757 - 763	761
	Mid-Section	759 - 762	761
	Lower Section	758 - 763	761
70% Coal / 30% Biochar – 15min Fluidisation	Upper Section	754 - 760	757
	Mid-Section	744 - 757	751
	Lower Section	745 - 757	753

5.4 Summary of Pilot Testing

Although the operating pressures of the pilot-scale test rig and PKSW pneumatic conveying system differ, conveying powders at higher pressures can help to reduce the minimum conveying velocity required for reliable flow compared to “low-pressure” systems. Therefore, the PKSW injection system should be able to successfully convey the biochar-coal blends at gas velocities lower than those tested through pilot-scale test rig during the various test programs. This is due to the increased momentum of gas flow at higher static pressures.

Based on the findings from the pilot-scale trials conducted at UOW using a low-pressure pneumatic conveying rig, the operational variations of the injection line at PKSW when conveying 100% PCI of blends up to 30% biochar should be minor. The conveying rates when handling increasing biochar blends may fluctuate and reduce; however, the variations could be corrected by adjusting the proportion of nitrogen flow into the injection hoppers with respect to the pipeline supplementary gas flow.

The pilot-scale pneumatic conveying testing indicated that minor operational parameters of the PKSW pneumatic injection system such as the operating pressure and gas flow rates may need to be modified to convey the biochar-coal blends.

Overall, the prior testing of the biochar-coal blends increased the confidence of PKSW’s BF and PCI plant operators in adapting the operations of the injection system to feed the BF with pulverised biochar-coal blend, at the required pressure and mass flow rate under steady conveying conditions.

6 Biochar plant trials – No. 5 Blast Furnace

6.1 Introduction

Steelmaking generates approximately 6% of global CO_2 emissions. With an increasing focus on these and the implications for climate change, considerable work has gone into evaluating options for reduction of these CO_2 emissions in the last two decades. One such significant study was the Australian CO_2 Breakthrough Program [9] which was a joint research effort between the CSIRO, BlueScope and what was then OneSteel (now GFG Alliance) which ran between 2006 and 2014. This work focussed on the use of charcoal or biochar as a coal substitute, which if made from renewable biomass sources could be used to reduce net CO_2 emissions. Unfortunately, this project was wound up before having the opportunity to conduct large scale industrial trials of biochar.

The use of biochar as a coal substitute was once more brought into focus in late 2019 as a result of BlueScope management setting itself a target of 12% CO_2 emissions intensity reduction across its steelmaking facilities by 2030. Given the work in the CO_2 Breakthrough Program it was determined that the next logical step was to source biochar for full scale industrial trials, where the biochar would be used as a replacement for coal for pulverised coal injection to the ironmaking blast furnace. Work in 2020 initially focussed on finding a source of 1000t of biochar with only limited success, with most suppliers surveyed being unable to supply the quantity within a reasonable timeframe. Only one suitable supplier was found in Western Australia, however the delivered cost was significantly higher than the cost of coal used for pulverised coal injection. As such, in April 2022, BlueScope signed an agreement with the Australian Renewable Energy Agency (ARENA) which covered funding for a study entitled "Port Kembla Steelworks Renewables and Emissions Reduction Study". This body of work was to examine options for CO_2 emissions reduction specific to BlueScope's Port Kembla Steelworks (PKSW) with most of the funding to be used to purchase biochar for full scale industrial trials. This report outlines the sourcing, storage and full-scale trials of this biochar between June 2022 and April 2023.

6.2 Biochar Sourcing and Supply

Initial work in 2020 identified only one suitable supplier situated in Western Australia. This supplier used biochar in their process, producing large quantities of biochar from sustainably sourced jarrah timber. Due to the nature of this supplier's biochar requirements and regulatory limitations, the supply of lump biochar was not possible, however an undersized fraction that was not used in their process was available. This material was generally sold to farmers or the horticultural industry and as such was acceptably priced. As can be seen from Table 19, this biochar was relatively high quality, being low in ash, volatile matter, and trace elements. It was however quite fine and therefore difficult to handle, particularly at low moistures. At that time, a 500t stockpile was available, however by the time the ARENA agreement was signed in April 2022, this material had already been sold and a much smaller amount of around 250t was all that was left, along with any further biochar that might be available over time from continuing production.

As a result, to meet the ARENA requirement of a minimum of 600dmt, another supplier was sought. After considerable searching, which encompassed potential overseas supply, a small-scale biochar supplier from Charleville in Queensland was found. Renewable Carbon Resources Australia (RCRA) used a "pit" style charcoal making process to pyrolyse wood from previously felled gidgee trees from licensed land clearing. The biochar so produced was of lower quality than that from WA (see Table 20) being higher in ash and volatile matter, but it was of a larger particle size, acceptably priced and critically, some 350wmt were available over a 4-month period. This biochar was to be transported in 1t bulk bags.

Table 19 – Typical WA biochar properties - 2020

Property	**Unit**	**Value**
Ash	Mass % adb	2.4
Volatile Matter	Mass % adb	2.8
Moisture	Mass % arb	6
Ultimate Carbon	Mass % adb	87.6
Total Sulphur	Mass % adb	0.01
Ash Al_2O_3	Mass % db	13.2
Ash SiO_2	Mass % db	48.4
Ash CaO	Mass % db	14.6
Ash MgO	Mass % db	3.5
Ash P_2O_5	Mass % db	0.84
Arsenic	mg/kg	<0.5
Lead	mg/kg	3.5
Mercury	mg/kg	<0.2
Zinc	mg/kg	28
Size > 20mm	Mass % db	0
Size < 5mm	Mass % db	97.1

Table 20 – Typical properties of RCRA biochar - 2022

Property	**Unit**	**Value**
Ash	Mass % adb	10.1
Volatile Matter	Mass % adb	19.4
Moisture	Mass % arb	5.7
Ultimate Carbon	Mass % adb	69.6
Total Sulphur	Mass % adb	0.01
Ash Al_2O_3	Mass % db	4.7
Ash SiO_2	Mass % db	34.7
Ash CaO	Mass % db	53.1
Ash MgO	Mass % db	2.04
Ash P_2O_5	Mass % db	0.08
Arsenic	mg/kg	<0.5
Lead	mg/kg	2.5
Mercury	mg/kg	<0.2
Zinc	mg/kg	69
Size > 20mm	Mass % db	15.4
Size < 5mm	Mass % db	1

6.3 Biochar Transport and Storage

Transport proved to be a particularly costly item with respect to biochar purchasing, mostly due to the fact limited trade with Western Australia meant that there was no opportunity for backloads and trucks had to be sent to WA empty, effectively doubling the transport cost. As WA biochar became available, a truck would be sent over and return with around 35t of semi-dry biochar. This was despite the B-double being completely full, the result of the low density of biochar at around 400kg/m^3. This also contributed to the high transport cost as did variable moisture contents. RCRA logistics were somewhat less costly, given that even though the RCRA production site was deep in western Queensland, backloads through to at least Brisbane were possible.

Due to the small size of the WA biochar particularly, but also the limited supply of biochar and the long storage time required to amass sufficient biochar for trials (planned for late 2022), undercover storage was required. Two areas at BlueScope’s No.1 Works were secured for biochar storage. The first of these was to receive and to a lesser extent store WA biochar, while the second was to receive either dampened WA biochar (see below) or RCRA bagged biochar.

Deliveries of WA biochar started in November 2021, however early on it was found that due to the small particle size and in general very low moistures (<10%), the biochar was extraordinarily dusty, even when the material was hosed during tipping. As such, to eliminate issues with dust during transport within BlueScope, the biochar had to be thoroughly dampened on delivery. This was achieved by using a garden sprinkler on the biochar pile for around 24hrs post a new delivery (see Figure 1). Unfortunately, this resulted in biochar that was high in moisture, considerably higher than the normal coal feed for the PCI Plant. As such, this was problematic given it had the potential to overwhelm the drying capacity of the grinding and drying mill and therefore impact grinding rate.

WA biochar deliveries continued through all of 2022, usually at a rate of 1-2 B-double loads per month as material became available. As the primary dump off area became full, damp biochar was then trucked to secondary storage to be mixed with the RCRA biochar.

RCRA biochar deliveries were planned to begin in early 2022, however production delays meant that material only began to arrive in May 2022 and unfortunately wet weather and flooding in western Queensland through much of 2022 hampered production and delivery of this product. This was to the point where only 191t of the expected 350t were delivered in sufficient time. As B-double loads of material arrived, they were unloaded with a forklift, before the 1t bags were emptied manually (see Figure 23). Due to the relatively small available storage space, the RCRA biochar could not be kept as a separate material. Given plans at the time, the expected proportions of WA and RCRA biochar in the final biochar blend were expected to be 70% and 30% respectively, so once RCRA material was on the floor, it was then blended with dampened WA biochar in the appropriate ratio before being piled up (see Figure 24).

Figure 22 – WA biochar pile with sprinkler

Figure 23 – RCRA biochar delivered

Figure 24 – Unbagged RCRA and blended WA and RCRA pile

Note that due to the supply issues at RCRA and the sourcing of additional supplies of WA biochar, the final totals for each supplier was 796dmt from WA and 168dmt from RCRA, meaning the actual ratio was 82.6% WA and 17.4% RCRA. As such, when delivering biochar to the PCI coal stockyard for the trials, as well as the pre-blended biochar, additional WA biochar was also delivered. Both biochar supplies were then mixed as the material was loaded into the PCI Plant.

6.4 Biochar Analysis

As each shipment of biochar arrived, samples were taken and analysed, primarily to determine moisture, however ash, ash chemistry and volatile matter were also determined. For limited shipments, ultimate and trace element analyses were also conducted. Average selected results for the two biochars can be seen in Table 21.

Table 21 – Average and range of key results from WA and RCRA biochar shipments

Parameter	Unit	Average WA	Range WA	Average RCRA	Range RCRA
Moisture	Mass % arb	17.4	4.0 - 40.7	11.8	8.4 - 17.7
Ash	Mass % adb	3.5	1.6 - 5.4	14.9	10.1 - 19.5
Volatile Matter	Mass % adb	4.5	3.0 - 7.5	22.4	19.3 - 34.9
Total Sulphur	Mass % adb	0.01	0.0 - 0.07	0.02	0.0 - 0.05
Calorific Value	kcal/kg adb	7779.0	-	5947.0	-
Ultimate C	Mass % adb	86.7	82.8 - 91.5	65.6	63.1 - 69.6
Ultimate H	Mass % adb	1.50	1.44 – 1.55	2.20	2.04 - 2.29
Ash Al_2O_3	Mass %db	16.9	12.1 - 25.0	6.8	4.7 - 8.5
Ash SiO_2	Mass % db	50.0	28.3 - 61.3	46.0	34.7 - 57.3
Ash CaO	Mass %db	10.3	5.7 - 16.19	39.0	26.7 - 53.1
Ash MgO	Mass % db	2.6	1.6 - 4.4	1.7	1.4 - 2
Ash Fe_2O_3	Mass %db	12.0	6.4 - 18.1	2.5	1.9 - 3.2
Ash Na_2O	Mass % db	1.8	1.1 - 2.2	0.4	0.3 - 0.5
Ash K_2O	Mass %db	1.8	1.2 - 2.7	0.9	0.7 - 1.1
Ash P_2O_5	Mass %db	0.6	0.3 - 1.3	0.1	0.1 - 0.1

Moisture Results from Stockpiled Biochar:

Biochar moisture was a key concern for the biochar trials, given that drying of the biochar was required as part of processing and the moisture content was key in determining the dry concentration of biochar. Previous samples had shown that biochar could absorb considerable amounts of water, up to 40% without fluidizing. As such, a number of samples were taken throughout the storage period in an effort to determine moisture levels (see Table

22). Note that due to the difficulties in sampling in the middle of the piles, these results were only indicative, but were the best available. Based on the last of the sample results before the trial and a mass weighted average, a moisture of 27% was adopted as biochar moisture for process calculations.

Table 22 – Moisture results for biochar used in trials

Date of Sample	Material	Location	Moisture %
3/5/2022	WA Biochar – damp	Shed 2	35.4
8/11/2022	WA Biochar – damp	Shed 1	24.6
8/11/2022	WA Biochar – damp	Shed 1	27.5
8/11/2022	Blended Biochar	Shed 2	27.9
8/11/2022	Blended Biochar	Shed 2	29.6
6/2/2023	WA Biochar – damp	Shed 1	29.0
6/2/2023	WA Biochar – damp	Shed 1	30.3
6/2/2023	Blended Biochar	Shed 2	24.5

6.5 Background to the Trials

Pulverised coal injection is an important and beneficial part of blast furnace ironmaking. Pulverised coal injection of anywhere between 30t to 65t/hr allows lower quality non-coking coals to be used directly in the ironmaking process with limited pre-processing, thereby reducing the requirement to charge coke into the blast furnace, reducing costs and any environmental emissions that might result from the making of coke. Pulverised coal also has the added benefit of allowing more of the blast furnace volume to be dedicated to iron ore, thereby increasing the productivity of the blast furnace. Pulverised coal is also a valuable process control tool, given its injection at the tuyeres can rapidly influence blast furnace core temperature and therefore process stability.

6.6 PCI Plant Coal Handling Overview

BlueScope's pulverised coal plant was installed and commissioned in 2002 and has successfully supplied pulverised coal to both the now de-commissioned No. 6 Blast Furnace and the current No.5 Blast Furnace. Figure 25 shows the schematic of the PCI Plant. Here the process begins with a mixing plant, where up to three materials can be blended in appropriate ratios. This mixing plant is filled using a front-end loader to load coal from the PCI coal stockyard. Post the mixing plant, the blended materials are then transported via a bucket elevator to the top of the PCI Plant where they are deposited on the raw coal screen, with the undersize going to the Raw Coal Storage Bin (RCSB). Oversize material is sent down a separate chute to the oversize material bin.

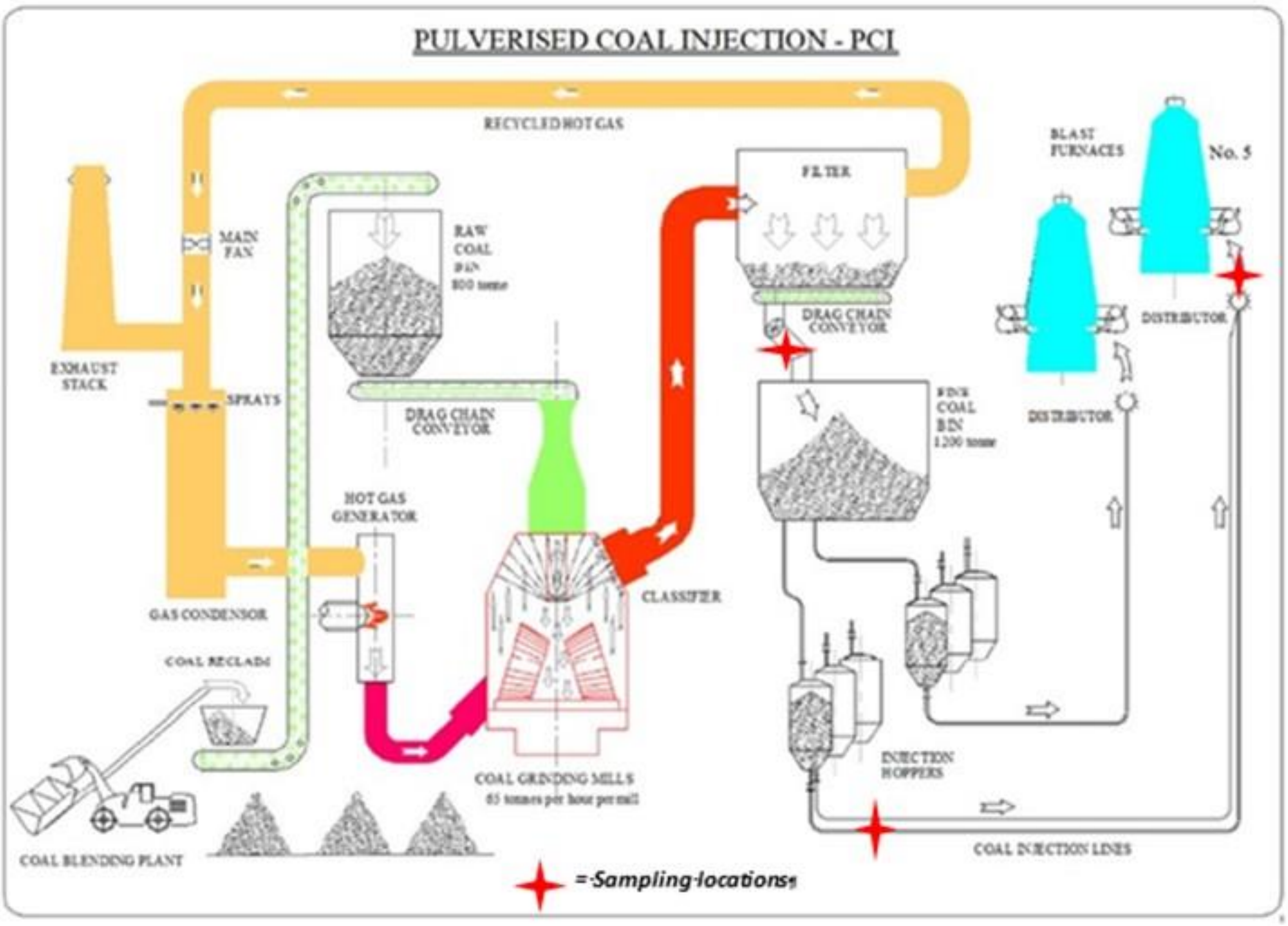


Figure 25 – Schematic of the PKSW PCI Plant showing sampling locations

6.6.1 Grinding and Drying System Overview

From the base of the RCSB, coal is transported into the top of the grinding and drying mill by a drag chain conveyor. The grinding and drying mill utilises three hydraulically held vertical rollers, a rotating table and air classifier, in combination with a stream of hot, low oxygen gases from the blast furnace gas-fired hot gas generator to crush, dry and classify material. Once material is of the appropriate size, it can be transported through the classifier in the gas stream, before it is filtered out using a baghouse. Periodic shaking of the bags allows the material to drop to the bottom of the baghouse where it is transported into the Pulverised Coal Storage Bin (PCSB) with a drag chain conveyor through a rotary valve. A sampling point for pulverised material is located here. Note that oversize material that can't be ground will be spun off the grinding table and are collected in the mill reject boxes These are emptied during periodic mill stoppages.

6.7 Injection System Overview

In the PCSB, pulverised material is kept in a low oxygen atmosphere and is transported using nitrogen into three injection hoppers. Once full, an injection hopper is pressurized with nitrogen before it is connected to the main conveying line to the blast furnace, where the pulverised material is pneumatically transported through a coarse filter (the scalping plate) and then on to the blast furnace with nitrogen. The three injection hoppers work in sequence to ensure that there is a continuous supply of pulverised material being transported. The main conveying line also has a sampling point for collection of material post the PCSB.

6.8 Blast Furnace Distributor Overview

Once in the main conveying line, the pulverised material and nitrogen travels approximately 900m to the blast furnace distributor, where the pulverised material is split into 28 separate lines for injection into the blast furnace tuyeres. The blast furnace itself is a large steel pressure vessel that is lined with water cooled protective “staves” and carbon refractory blocks. Iron ore in the form of lump ore, pellets and sintered fines is dumped in the top of the furnace in alternating layers with coke. In the lower part of the furnace, hot blast air, pure oxygen and pulverised coal are injected through water cooled tuyeres, which results in the combustion of the descending coke and the injected coal. This combustion provides heat and carbon for the reduction of iron ore in the upper areas of the furnace and carburization of the liquid iron in the lower part.

6.9 Trials - Risks

As may be expected given their respective sources, biochar and coal do have some significant differences in properties. Table 23 shows a comparison of key properties of both the biochar and coal blends expected to be used during the trial.

Table 23 – Comparison of key properties of coal and biochar

Property	Units	Typical Blended Biochar	Typical Coal Blend for PCI
Ash	Mass % adb	5.5	9 - 15
Volatile Matter	Mass % adb	7.6	10 - 25
Bulk Density	kg/m^3 dry	~400	~750
Moisture Content	% arb	27	8 - 12
Ultimate Carbon	%adb	83	79 - 82
Ultimate Hydrogen	%adb	1.5	3.5 – 5
*HGI**	-	65	70 - 80
Particle Morphology	-	Acicular – mimicking original timber structure	Roughly cubic

** Lower number if harder to grind*

As can be seen, while the two materials are broadly similar, there are key differences in bulk density, Hardgrove Grindability Index (HGI), moisture holding capacity and particle morphology. As such, a number of risks to the coal injection and blast furnace processes at PKSW as a result of the biochar usage were identified as follows:

- Lower bulk density and different materials handling characteristics of the biochar could limit the ability of the mixing plant and conveying system to proportion, elevate and process the biochar/coal blends at the aim grinding rate.
- Combination of the different structure, lower bulk density and possibly poorer grindability could result in overly coarse or overly fine pulverised material, which in turn could limit the ability of the baghouse to filter the material. Variations in size could also result in difficulties in conveying the material pneumatically.
- Higher moisture load coming from the trial biochar could result in a poorer drying outcome, which in turn could limit grinding/drying rate below the aim, or indeed below the minimum required rate for supply to the blast furnace.
- Given levels in injection hoppers are weight controlled, the lower bulk density of biochar/coal blends and therefore greater volume per unit mass could result in overfilling of these units.
- The lower bulk density and the different structure of the biochar could result in segregation of coal and biochar through various stages in the system, triggering vessel full limits and impeding grinding and/or injection.
- Lower bulk density and different structure of the biochar could also affect the stability of pneumatic conveying to the blast furnace along with the ability to deliver the aim injection rate.

- Differences in combustion behaviour and ash chemistry could result in issues at the blast furnace tuyeres and affect the blast furnace process stability.
- All of the above risks, either singly or in combination ultimately could result in the unexpected disruption to supply of fuel to the blast furnace, which given the capacity of the PCSB and the difficulties in emptying this vessel could persist for a number of days. This in turn could cause a sudden disruption to the stability of the blast furnace process, potentially followed by many days of reduced productivity. Note that previous work on biochar combustion [63], grinding of biochar/coal blends [64] and pneumatic conveying (refer chapter 5 and Appendices 1 and 2) had to a certain degree alleviated some of the concerns noted above.

6.10 Trials – Planning Rationale

Given the considerable risks to the operational stability and productivity of the PCI Plant/Blast Furnace and the fact that once the biochar was in the process chain, removal was almost impossible and mitigation of the potential negative affects very difficult, a very conservative trial plan was developed, see Table 24. This plan was a staged one with a review process between each step, to ensure that any issues arising from each trial were addressed before continuing. In this way it was hoped that any problems could be detected before they were sufficiently large to cause a significant disruption to the process. To further safeguard the blast furnace process, the pulverised coal injection rate was limited to a maximum of 40t/hr, with the blast furnace production limited to approximately 7750tpd of hot metal. Round the clock supervision and additional sampling of coal/biochar blends was also to be undertaken by technical personnel.

Table 24 - Overall biochar trial plan

Trial	Biochar Proportion (% dry)	Expected Duration (hrs)
Trial 1A	5	1
Trial 1B	5	2.5
Trial 1C	7	3.6
Trial 1D	8	6.3
Trial 2A	10	12
Trial 2B	10	24
Trial 3A	20	12
Trial 3B	20	24
Trial 4A	30	12
Trial 4B	30	24

6.11 Trials - Methodology

Prior to the trial the following was undertaken:

- PCI Plant equipment was upgraded to limit the effect of mechanical/process issues on the trial outcomes;
- Sufficient supplies of coal were made available so that a stable base coal blend could be maintained for the entire duration of the trials;
- Blast furnace production and injection rate were to be set at 7750tpd and 40t/hr respectively for the trial periods;
- Blast furnace control systems and calculations were modified to be able to account for the presence of biochar in the injected material;
- Modelling of mixing plant and injection operations was conducted to determine the required operational setpoints, given the expected implications of the lower biochar density.

Just prior to each trial step:

- Sufficient biochar to fund the entire planned trial stage was delivered to the PCI Coal Yard;

- In the shift immediately before the planned trial, a designated bin in the mixing plant was emptied and cleaned ready for receival of biochar or a biochar/coal blend;
- In the shift immediately before the planned trial, the Raw Coal Storage Bin (RCSB) was run down to as close as possible to the designated minimum of 300t. This was to allow a more rapid path for the biochar to present to the grinding mill and injection circuit;
- Similarly, in the shift immediately before the planned trial, the Pulverised Coal Storage Bin (PCSB) was run down as close as possible to a designated range of 950 – 1050t, again with the intention of ensuring that biochar progressed through the system during the sampling period.

During the trials themselves:

- For all trials – loading of biochar and biochar/coal blends and the operation of the mixing plant and elevation equipment were carefully supervised;
- For Trials 2A and later, mixing plant flowrates were to be reduced as appropriate to account of expected effects of the lower density biochar on mass flowrates (in a volumetrically constrained system);
- For all trials the grinding rate was generally set to a maximum of 60t/hr, except for periods where the process dictated that a slightly higher or lower rate was necessary;
- For all trials, close monitoring of key variables at the PCI Plant and Blast Furnace was undertaken;
- For Trials 2A and later, PCSB and injection hopper maximum and minimum fill levels were decreased to account for the expected increase in volume of the coal/biochar blends;
- For Trials 2A and later – frequent sampling of material at the exit of the grinding sequence and PCSB were conducted, with the former tested for size and moisture. Less frequent sampling was done at the pulverised coal distributor and injection lines, 4, 8, 11 & 25;
- For Trials 2A and later – blast furnace burdening was adjusted at an appropriate time to account for the differences in biochar and coal properties;
- To monitor for any negative effects on tuyere combustion, photography and videography surveys were conducted of tuyeres were conducted prior to the trials and for Trials 2A and later.

Post the trials:

- Samples of pulverised material were analysed using a new proprietary technique to estimate the proportion of biochar in the material. *(Note that this technique is quite labour-intensive and the results are only approximate to within +/-5% (absolute), so only selected samples have been tested to determine biochar content to date – further work is continuing)*.
- Further analysis work was conducted to determine the effect of biochar usage on both the PCI Plant and BF operation.

6.12 Trials - Results and Discussion

6.12.1 Trials 1A – 1D – Biochar

Due to the low proportions involved in the initial trials, biochar could not be directly weighed out by the mixing plant. To overcome this, appropriate quantities of the pre-blended and WA biochar were delivered to the coal stockyard. This was to be blended with the 2 standard coals to provide an approximate blend of 25% biochar, 75% coal on a dry basis. Note that these proportions were approximate due to the lack of exact moisture measurements of both biochar and coal. For trials 1A-1D, 50t of wet biochar were mixed with 150t of wet coal in the coal stockyard two days before trials were due to start. Both tonnages were weighed using the load cells on an appropriate front end loader. Unfortunately during that period, considerable rain fell, so both the biochar blended pile (see Figure 26) and the coal in the yard were quite wet.

6.12.2 Trial 1A – 5% Biochar Addition for 1 hour

Table 25 - Trial 1A key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Blend (wmt)	Blend Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 1A	13/2/23 05:40	5	1	11	11	2

Figure 26 – Biochar and blended coal – PCI Plant Coal Yard – 13/2/23

The trial began well, plant setup was as per plan, with the RCSB and PCSB being at the required levels. Blended biochar/coal was loaded into Bin 3 of the mixing plant using a loader with load cells. The aim wet tonnage of material was achieved, though as noted rain would have affected the actual tonnes of dry biochar. No issues were seen with the mixing plant with the biochar/coal blend flowing easily through Bin 3 after some initial vibration to encourage coal flow. No issues were also seen during elevation to the RCSB through the bucket elevator, with the total coal flowrate maintained at 295t/hr.

From there, monitoring of the process indicated that the small quantity of biochar did not present a problem. Wet material was detected reaching the grinding mill around 1 hour after elevation, but this was expected given that all of the material in the coal yard was wet. No issues were seen for operation of the grinding mill, the injection system or blast furnace during the day or the following night.

6.12.3 Trial 1B – 5% Biochar Addition for 2.5 hours

Table 26 - Trial 1B key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 1B	14/2/23 05:45	5	2.5	27.3	27.3	5

Trial 1B started with blast furnace consumption of pulverised coal lower than expected overnight and the RCSB level approximately 60t higher than expected, potentially delaying the arrival of the biochar into the grinding mill. The aim amount of blended coal/biochar was weighed into Bin 3 and elevated as per Trial 1A with no issues.

Monitoring of the process did not show any indication that biochar was problematic. A small number of adhoc samples at the exit of the grinding mill found there was almost no impact on sizing or moisture, though one moisture reading was very high. This high moisture reading was quickly followed by a lower value.

During this trial, grinding did have to stop prematurely at 08:30 due to maintenance requirements, which may have influenced the result. Despite this and the single higher moisture result no other process parameters seemed to be affected. The grinding and drying process continued unaffected throughout the remainder the day and following night, with smooth operation noted, and a grinding rate of 70t/hr was achieved. Note that this is unlikely to be due to biochar directly but, does indicate that higher grinding rates were able to be maintained with 5% biochar present.

6.12.4 Trial 1C – 7% Biochar Addition for 3.6 hours

Table 27 - Trial 1B key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 1C	15/2/23 05:30	7	3.6	56.2	56.2	10

The RCSB and PCSB were at the planned levels initially, and no significant issues were seen in elevating the coal/biochar blend, barring issues getting the biochar/coal blend flow started through Bin 3 as per Trial 1A.

Ensuing monitoring of the grinding and injection process did not show any indication of the presence of biochar. Some changes were apparent in the operation of the High-Performance Burner (HPB) in the hot gas generator, which might have indicated the presence of wet biochar, but as noted previously the standard coals were very wet as well.

Ad hoc samples taken showed no indication that the small quantity of biochar introduced into the system influenced either the grind or moisture outcomes. No further operational changes were noted for the remainder of the day and the following night.

6.12.5 Trial 1D – 8% Biochar Addition for 6.3 hours

Table 28 - Trial 1D key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 1D	16/2/23 08:00	8	6.3	113	145	20

The start of Trial 1D was delayed due to front-end loader availability. This however proved to be beneficial as lower blast furnace consumption of pulverised coal overnight had resulted in the RCSB level initially being 100t higher than expected, so the final RCSB level was close to aim at 320t.

The remaining biochar/coal blend material in the coal yard was loaded. As noted previously, additional rain did have an effect, in that the final tonnage was higher than expected by a reasonable margin, indicating that the biochar proportions for previous trials were lower than expected. Note that the additional tonnage might have included some additional coal from the floor and walls of the coal stockyard. As with the previous trials, no issues with the mixing plant or elevation were noted. Grinding proceeded at the aim of 60t/hr but was prematurely interrupted as the PCSB was filled earlier than expected. However, despite this disruption, no issues were detected with grinding throughout the day. The operation of the HPB was again slightly affected, in that additional fuel (Blast Furnace Gas or BFG) was required to ensure mill exit temperature targets were reached, indicating that wetter material was reaching the mill, but again this was not necessarily due to the biochar itself. Ad hoc samples taken again showed no detectable influence of biochar on the size distribution or moisture of the pulverised product. No issues with the performance of the injection system were notable during the remainder of the day or into the night. Similarly blast furnace performance appeared unaffected.

6.12.6 Trials 1A-1D Summary

Trials 1A through to 1D appeared to show that the use of biochar at lower proportions had no significant issues observed in the operation of the mixing plant, elevation sequence, grinding and drying mill or the injection sequence. Some changes were apparent in the operation of the High-Performance Burner which could have been consistent with wetter biochar reaching the grinding and drying mill, but these were only minor, with similar changes seen with normal coal during periods of wet weather. After reviewing these results, further trials were approved.

6.12.7 Trial 2A – 10% Biochar Addition for 12 hours

With the increase to the proportion and mass of biochar, the mixing plant could now accommodate biochar as a single material. As such, the day before each ensuing trial step, biochar deliveries from the undercover storage areas of both the blended biochar material and additional WA material were made to the coal yard, with the mass of biochar delivered measured via the BlueScope weighbridge. As such, while outdoor storage did result in wetter biochar at times due to rain, the proportion of biochar was not affected as was notable during Trials 1A-1D. Note that mixing of the pre-blended and WA biochar in the stockyard was somewhat adhoc, however there appeared to be sufficient blending of the two biochar sources such that there were no obvious signs of variation in the biochar feed through the mixing plant for any of the following trials.

Table 29 - Trial 2A key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 2A	21/2/23 08:40	10	12	66	63	46

Figure 27– Biochar PCI Plant Coal Yard – 21/2/23

Figure 28 – Biochar and blended coal through Bin 3's two parallel weighfeeders 21/2/23

Trial 2A started late due to issues with RCSB filling and lower than expected consumption of pulverised coal by the Blast Furnace. As a result, an additional 3hrs of grinding was required to bring the RCSB level down to the aim of 300t. Once this was done, this necessitated a reduction in the overall grinding rate to 50t/hr to ensure a longer period of operation prior to filling the PCSB to accommodate mandated stack testing.

On this occasion, all the biochar was elevated as a single material through Bin 3 (see Figures 27 and 28), as if it were a normal coal. The biochar material flowed easily through Bin 3 and the 12% biochar addition (10% on a dry basis) of the total 260t/hr was able to be easily maintained. Note that the aim total feedrate was reduced to accommodate the expected lower density of the biochar. No issues were notable with the elevation of the biochar coal mixture, with no additional spillage seen.

From there, monitoring of the grinding and drying indicated that the 10% biochar was processed with no problems (see Figures 29a – 29b). The biochar proportion in the material at the exit of the mill rose rapidly within 1-2 hours of this material being added to the system. This was somewhat quicker than the 6hrs that might be expected from geometry and plug flow assumptions; however, it is in line with operational experience, in that changes to coal inputs are often seen around 1 hour after they occur. This is thought to be due to the split nature of the RCSB which used to feed 2 grinding mills rather than the 1 that is currently operating. Feeding of only 1 mill can result in stagnant material and therefore unexpected flow patterns, which is consistent with these observations regarding biochar. At the time of writing this report, testing of additional Trial 2A samples is yet to be completed, with a preferential focus on later trials, so there is no indication of when the biochar proportion started to drop away.

The figures also show that mill operating conditions appear relatively consistent throughout the period of biochar addition, which matches with the observations made during the trial. Inspection of the mill table reject material boxes showed no sign of any biochar. Some small pieces of timber were found in the oversize material bin which were most likely from the biochar. These appeared to be the result of contamination of the biochar supplied from WA, where the biochar was stored in a yard also containing unprocessed timber. While the presence of timber contamination could potentially jam and damage equipment such as the bucket elevator or drag chain conveyors, the contamination wasn't something inherent to biochar itself and future supply arrangements should guarantee that contamination like this is minimized as much as possible. Given this and the fact that current coal supplies also come with contaminants like timber, the presence of timber in the biochar was considered not to be significant with respect to the trial results.

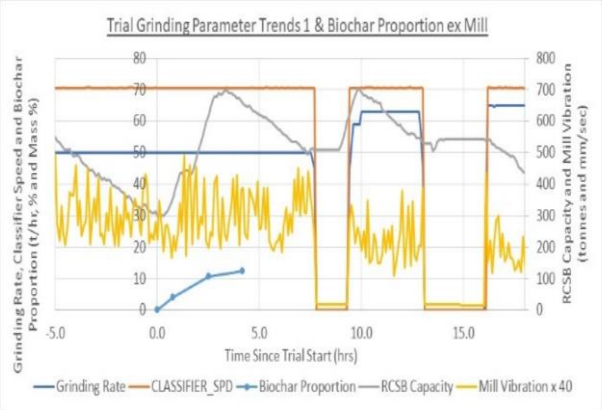


Figure 29a – Trial 2A - grinding parameters and biochar proportion

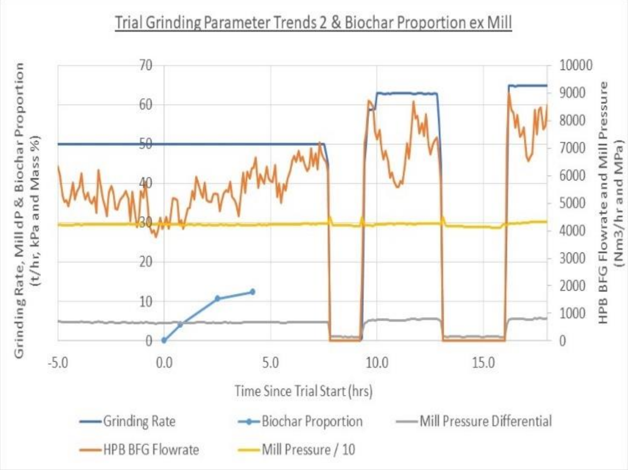


Figure 29b – Trial 2A – further grinding parameters and biochar proportion

With the proportion of biochar rising to the expected level of approximately 10% there appears to be no significant change to the proportion of -90µm material or the moisture in the pulverised product as can be seen in Figure 30. There is some slight texture in the trends for the +200µm proportion, but this does not appear significant over the full extent of the trend or indeed operational experience.

On the injection front, similar stable conditions prevailed throughout the trial period, with pulverised coal rate maintained at around the aim of 40t/hr, with in general a steady dilution (barring an initial rise) and in general normal variation in the coal flow distributor pressure (R value - see Figure 31a). The only notable change in injection performance was an increase in the coal flow concentration as measured by the pneumatic flowmeter (see Figure 31b). This was somewhat unexpected as the lower density of the biochar was expected to trigger a reduction in coal flow concentration, but indeed the opposite appears to be true.

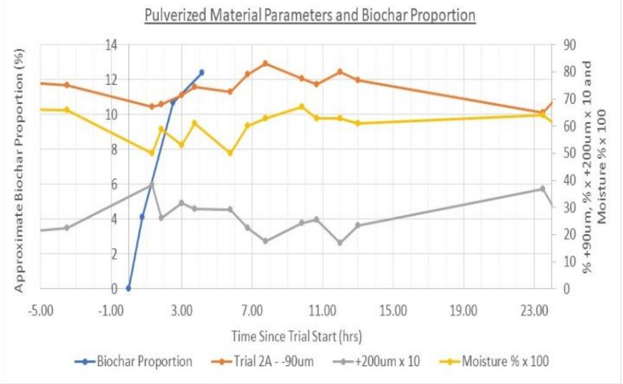


Figure 30 – Trial 2A - biochar proportion, mass% -90um, mass% +200um x 10 and mass% moisture x 100

Why this is the case is unclear, but indications are that the flowmeter is one based on capacitance measurements and as such is calibrated purely for coal. The presence of biochar is most likely influencing the result. However, despite this change, it made little impact on the injection operation and indeed indications are the higher measurement, at least initially would have resulted in more stable operation of the injection system due to coal flow concentration moving away from the lower end of the control limits. One other notable aspect of this trial was the rapid appearance of biochar in the injected material, followed by its continued presence, sometime after it was assumed to have been fully purged from the coal supply system. As with the RCSB, the PCSB is a common supply vessel which was used to supply 2 furnaces, the current operating No.5 Blast Furnace and the now mothballed No.6 Blast Furnace. As result of the single furnace operation, the PCSB only feeds from one side of the vessel, so like the RCSB it has stagnant material and unexpected flow patterns. The rapid appearance and continuing presence of biochar at lower concentrations is thought to be most likely due to this effect more than anything else, for example segregation of biochar within the PCSB.

Blast Furnace operation, as with that of the PCI Plant saw little change as a result of 10% biochar injection. Barring the slight burden changes that were made to account for the biochar injection, as can be seen from Figures 32a and 32b there was no impact on blast furnace K factor, differential pressure, and hot blast pressure, both measures of resistance to gas movement through the burden, all of which often respond to poorer combustion of injected coal. Similarly unaffected were the hot blast volume and the measured temperature of liquid iron or hot metal leaving the furnace, both of which are linked to production rate and respond to changes in fuel composition and combustion efficiency. Important quality parameters, the proportion of silicon and sulphur in hot metal were also stable, where they would normally respond to significant changes in the chemistry of the furnace inputs (such as biochar) and any instability in the furnace operation.

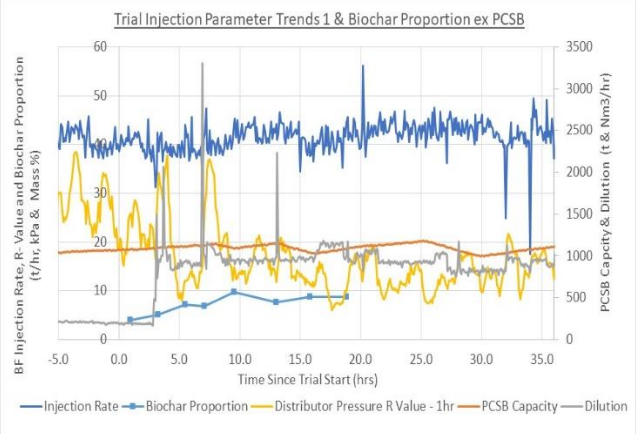


Figure 31a – Trial 2A – injection parameters and biochar proportion

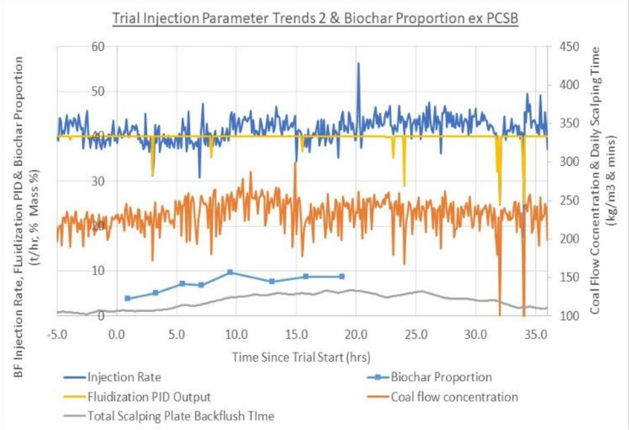


Figure 31b - Trial 2A – further injection parameters and biochar proportion

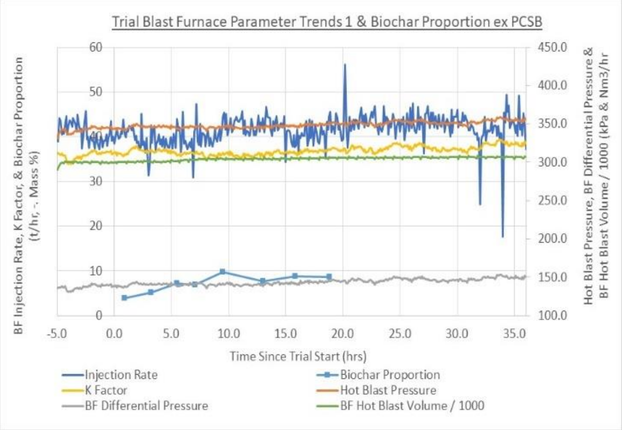


Figure 32a - Trial 2A – blast furnace parameters and biochar proportion

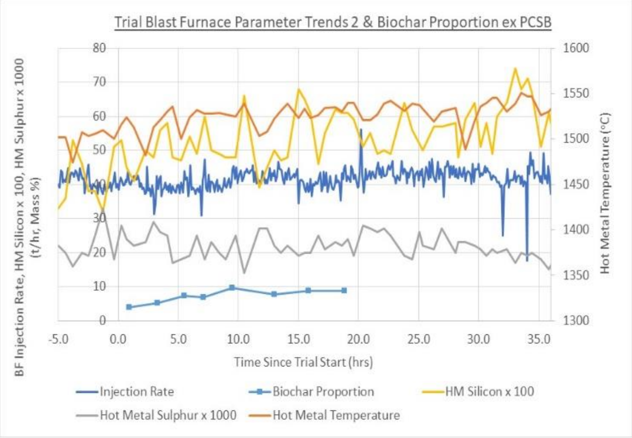


Figure 32b - Trial 2A – further blast furnace parameters and biochar proportion

6.12.8 Trial 2B – 10% Biochar Addition for 24 hours

Table 30 - Trial 2B key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 2B	23/2/23 05:20	10	24	132	110	80

Trial 2B started as per plan, with the RCSB and PCSB being close to the aim levels. Due to the amount of biochar to be used, the biochar addition was to be split into two parts, the first for the morning elevation of material to the RCSB, with the remaining biochar to be added during the normal afternoon elevation of material to the RCSB (see Figure 33). Note that due to transport issues, the amount of biochar delivered was roughly 20t short of the aim. This couldn't be remedied prior to the trial, so it was expected that the nominal trial duration would be curtailed by around 4 hours.

As with Trial 2A there was no issues with feeding of the biochar through the mixing plant, with again the biochar proportion of 12% in the total feed rate of 260t/hr easily maintained. No significant issues with spillage were noticeable on the elevation sequence, however it was noted that there was some biochar leaking out of the primary vibro-feeder (located just before the bucket elevator). The amount wasn't large, and indications were this may have been more related to weather conditions, with prevailing wind influencing the spillage in this location, even with normal coal. The oversize screen bin did contain some larger lumps of firewood sized timber (see Figure 34), again this is most likely minor contamination from the biochar supplier.

Figure 33– Biochar PCI Plant Coal Yard post first elevation 23/2/23

Figure 34 – Oversize screen scrap box – 23/2/23

Grinding and drying of the 10% biochar proceeded as per Trial 2A with no discernible issues (see Figures 35a and 35b). As can be seen, the biochar proportion rose quickly to the aim level as per Trial 2A, but then stayed elevated for approximately 18 hours. This could indicate that the flow through the RCSB is relatively predictable. Throughout this whole time the grinding and drying parameters remained quite steady. This was despite the grinding rate on this occasion being raised to 60t/hr. Note that due to PCSB levels and the higher-than-expected Blast Furnace consumption rate of 42 – 44t/hr compared to the aim of 40t/hr, grinding had to continue with only a 1hr break during the day compared to around a normal 2-4hr break. As a result, mill refractory temperatures reached quite high levels during nightshift, but not to the point that triggered a slow-down of the grinding rate. There was a slight indication too that that drying system was working somewhat harder, with the HPB BFG fuel gas flowrate increasing slightly, but this might have been due to the higher grinding rate in comparison to Trial 2A.

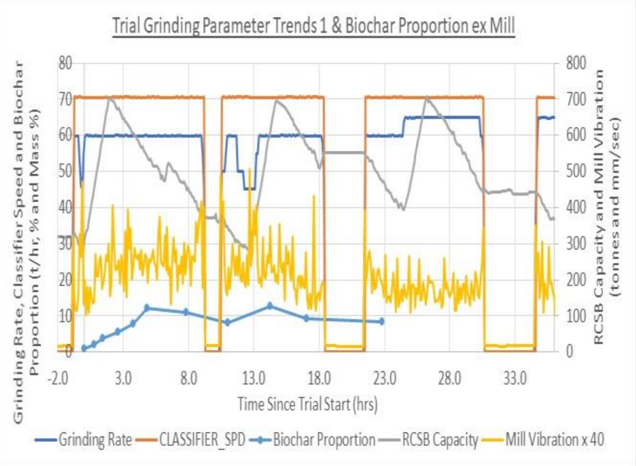


Figure 35a – Trial 2B - grinding parameters and biochar proportion

Figure 35b – Trial 2B – more grinding parameters and biochar proportion

While the issues with burner output, longer grinding time and higher refractory temperatures were a concern, the sizing and moisture of the pulverised material were relatively unaffected as can be seen from Figure 36. Throughout the trial, there was little noticeable change in the -90μm proportion, but there did appear to be slight increases in the +200μm proportion and moisture, which appeared coincident with the increase in biochar. While the relationship didn't appear to be strong, it was consistent with expectations regarding the expected impact of the wetter, less dense biochar on pulverised coal sizing and moisture. However, the magnitude of the changes was small and indeed were still in the range of normal process variation, so no action was required.

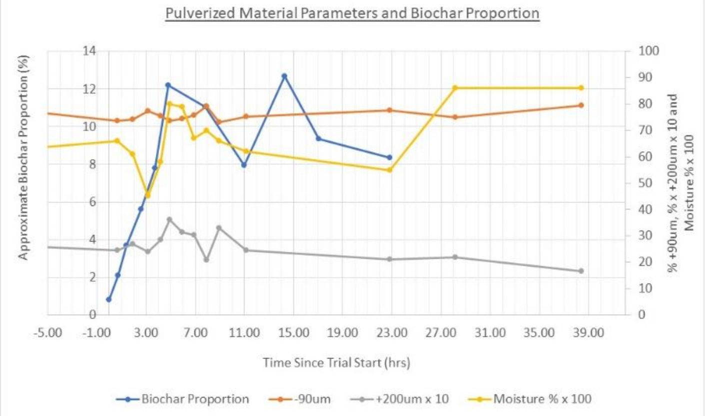


Figure 36 – Trial 2B - Biochar proportion, mass% -90um, mass% +200um x 10 and mass% moisture x 100

Pneumatic conveying of biochar at 10% of the pulverised coal blend also did not result in any significant impacts to the injection process barring changes made to injection hopper fill levels. As noted for Trial 2A, injection metrics in general remained steady for the duration of the trial period as can be seen in Figures 37a and 37b. This was despite the increase in the injection rate as noted above. Note there was a decrease in dilution at the 23hr mark, triggered by higher pressures in the distributor, but this does not appear to be linked to the presence of biochar. As with Trial 2A, coal flow concentration was seen to increase in conjunction with the peak in the biochar proportion of the injected material around the 9-hour mark in Figure 37b. While this was expected to be an instrumental issue with the flowmeter, to counter this and return the operation to a more normal state, fluidization nitrogen was increased by 5%. This was successful in bringing measured coal flow concentration back into the normal range without disrupting the injection process. Note that with this trial the proportion of biochar in the injected material did seem to follow a predictable trajectory, in that the aim value was reached after 10 hours, followed by a steady period of roughly 24 hours before the biochar proportion started to drop away. However, even after 40 hours, there still seemed to be biochar present in the injected material. The biochar while still present was at a much lower level and as such could be within the resolution of the detection technique. Given that the amount of biochar addition was lower than planned, the longevity of higher biochar proportion was somewhat unexpected, but again it seems to be consistent with the assumptions around flow dynamics through the PCSB.

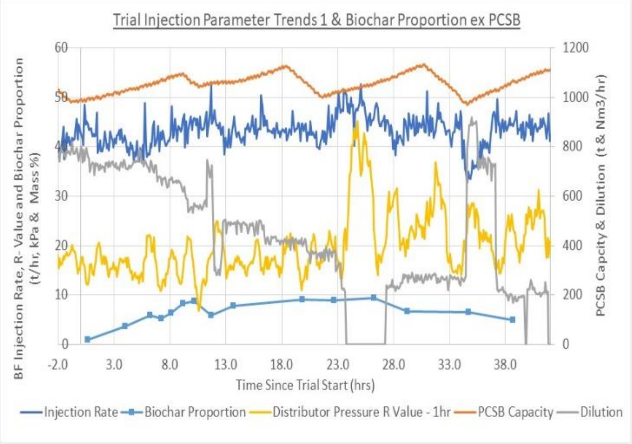


Figure 37a – Trial 2B– injection parameters and biochar proportion

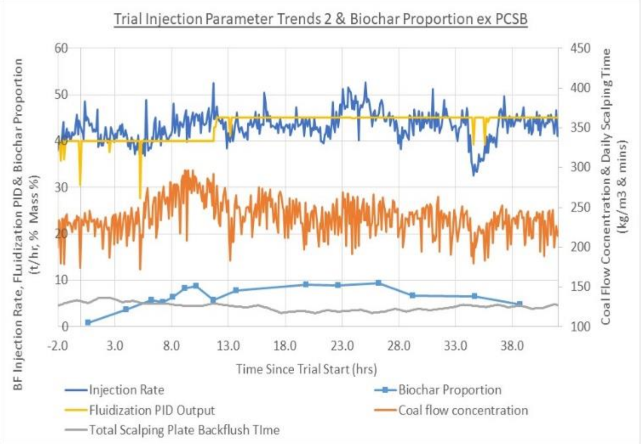


Figure 37b - Trial 2B – further injection parameters and biochar proportion

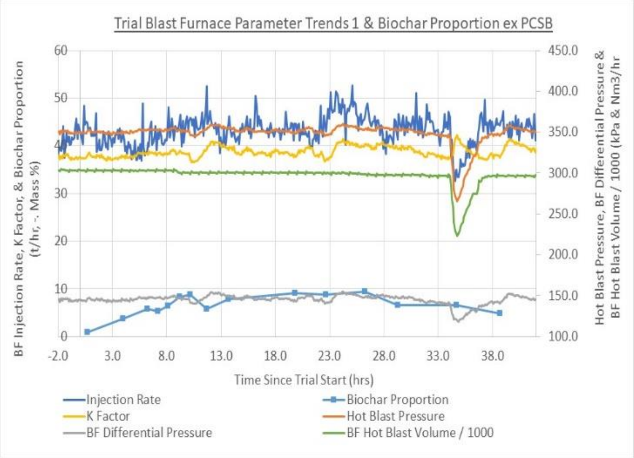


Figure 38a - Trial 2B – blast furnace parameters and biochar proportion

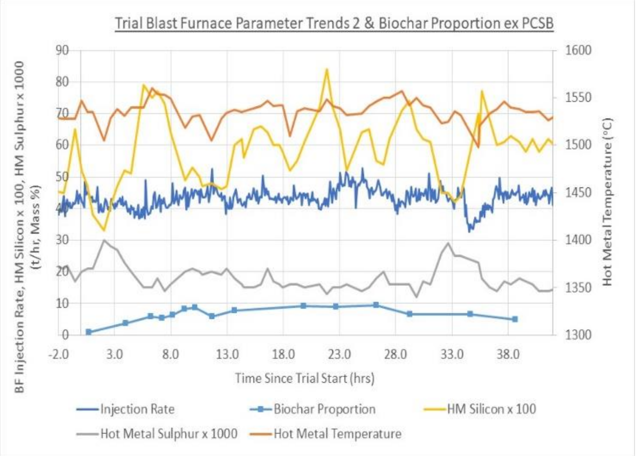


Figure 38b - Trial 2B – further blast furnace parameters and biochar proportion

As expected from Trial 2A – blast furnace performance was unaffected by the inclusion of biochar for the longer duration of 24 hours, with blast furnace metrics as can be seen in Figures 38a and 38b in general remaining steady despite the longer duration. Indeed, the Blast Furnace increased the injection and production rates, despite the biochar trial underway. Note there was a disturbance very late in the trial period, but this appeared to be the short-term impact of a casting delay and not biochar related.

6.12.9 Trials 2A – 2B Summary

As can be seen from the above, no issues of note were seen with the operation of the mixing plant or blast furnace. Grinding and drying only saw minimal impacts from the use of biochar, with perhaps a slight increase in moisture and +200µm material seen at the exit of the mill, while injection saw only an increase in the coal flow concentration as measured by the flowmeter. Despite this, none of these changes were significant enough to be a particular cause for concern. As such, on the basis of these trials, it would appear that 10% biochar addition appears to be quite achievable with the current equipment at the PCI Plant and Blast Furnace.

6.12.10 Trial 3A – 20% Biochar Addition for 12 hours

Table 31 - Trial 3A key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 3A	28/2/23 07:00	20	12	132	135	98

The start of the trial was hampered by mechanical issues with Bin 3. This was ultimately traced back to a weighfeeder encoder issue, thereby preventing the easy proportioning of the biochar into the coal blend. However, by adjusting the overall feedrate and the various proportions of coal and biochar, it was possible to continue the biochar trial using only 1 weighfeeder for biochar. As a result, initial proportions of biochar in coal would not have been at 20% and could potentially have been at 30% for a short period. Despite this poorer start, the majority of the biochar was processed through the mixing plant with the 20% biochar/coal blend being elevated to the RCSB with no issues.

Grinding and drying of the 20% biochar/coal blend, unlike previous trials was somewhat disrupted with the grinding rate reduced to 58t/hr to increase grinding time to accommodate mandated stack testing (a result of the initial delays in starting biochar elevation). Further disruption was then experienced as a result of maintenance work which crash stopped the grinding circuit for around 5 hours. Despite the unplanned stop, the mill restarted at 60t/hr without any problems, but the grinding rate did have to be increased to 65t/hr for a period to manage stocks. In general grinding wasn't seemingly affected by the disruptions to the process or indeed iby the presence of biochar in the coal blend. As can be seen from Figures 39a and 39b, biochar proportion again rose to a maximum level around 4 hours after the start of the trial and remained at the aim level for 12 – 15 hours, with the operation generally being steady and operating as per normal even at peak biochar levels..

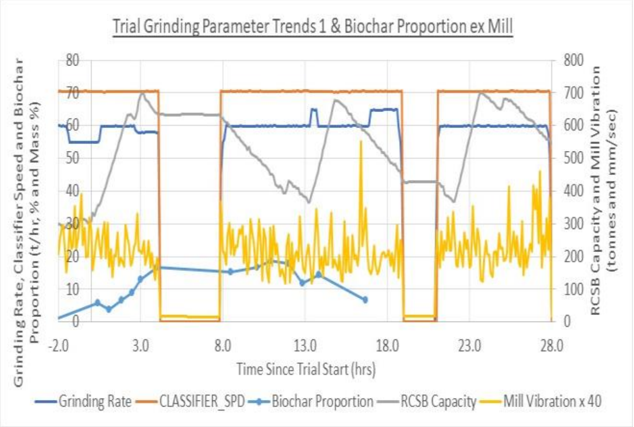


Figure 39a – Trial 3A - grinding parameters and biochar proportion

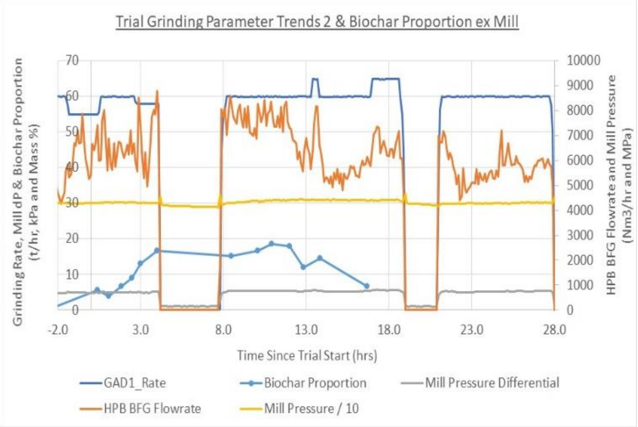


Figure 39b – Trial 3A – more grinding parameters and biochar proportion

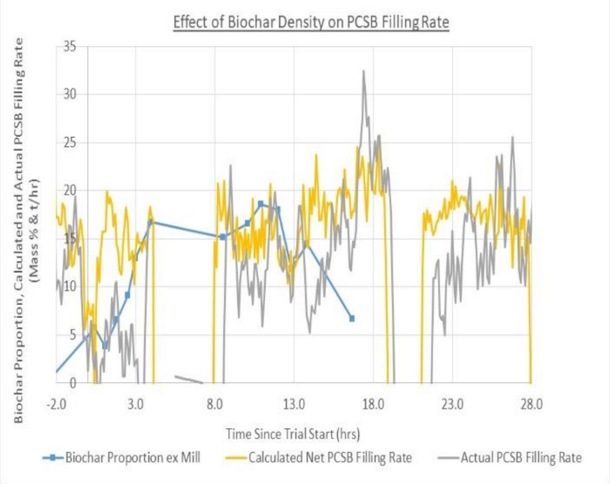


Figure 40 – Trial 3A – Biochar impact on grinding rate as shown by the difference between the calculated and actual filling rate of the PCSB

Only two things were of note with grinding and drying, the High-Performance Burner output and indications that biochar density was beginning to affect the grinding rate. As can be seen from Figure 39b, burner output was higher with an increase in the HPB BFG flow, but again this was consistent with expectations of wetter biochar material. With respect to biochar density affecting grinding rate, this could be seen in a comparison the grinding rate and the calculated net filling rate of the PCSB. The grinding/drying mill is fed by the action of a drag-chain conveyor, the dimensions of which then feed into the calculation of grinding rate, based on an assumed coal density. However, this assumed density is fixed so with a lowering of the blend bulk density due to the presence of biochar, the actual feedrate to the mill is reduced. This can be seen in Figure 40 which shows a plot of the net PCSB filling rate (i.e. grinding rate – injection rate) with the actual change in PCSB mass. While subject to measurement induced variation, prior and post the biochar trial, the calculated PCSB filling rate is generally matched by the change in the PCSB mass. However, during the trial itself, the PCSB mass change rate is generally the lower of the two variables, that is the actual grinding rate (i.e. the material reaching the PCSB) is less than the calculated one – an obvious impact of the lower density and higher moisture of the biochar. This could potentially become problematic at higher biochar proportions and at times where the aim injection rate is very high, however at current rates, this can simply be accounted for by increasing the grinding rate by a factor. Indeed, the grinding rate calculation should be something that could be relatively easily changed to account for the proportion of biochar in the blend.

While mill operation seemed to be unaffected by the addition of 20% biochar, given the results of Trials 2A and 2B, some effect was expected to be seen in the sizing and moisture results and this proved to be case as can be seen in Figure 41. As the biochar proportion rose, it can be seen to be affecting the proportion of 90µm and +200µm fractions during this trial with moisture also seen to increase at a similar time. However, the magnitude of the changes while significant were still insufficient to trigger any process changes.

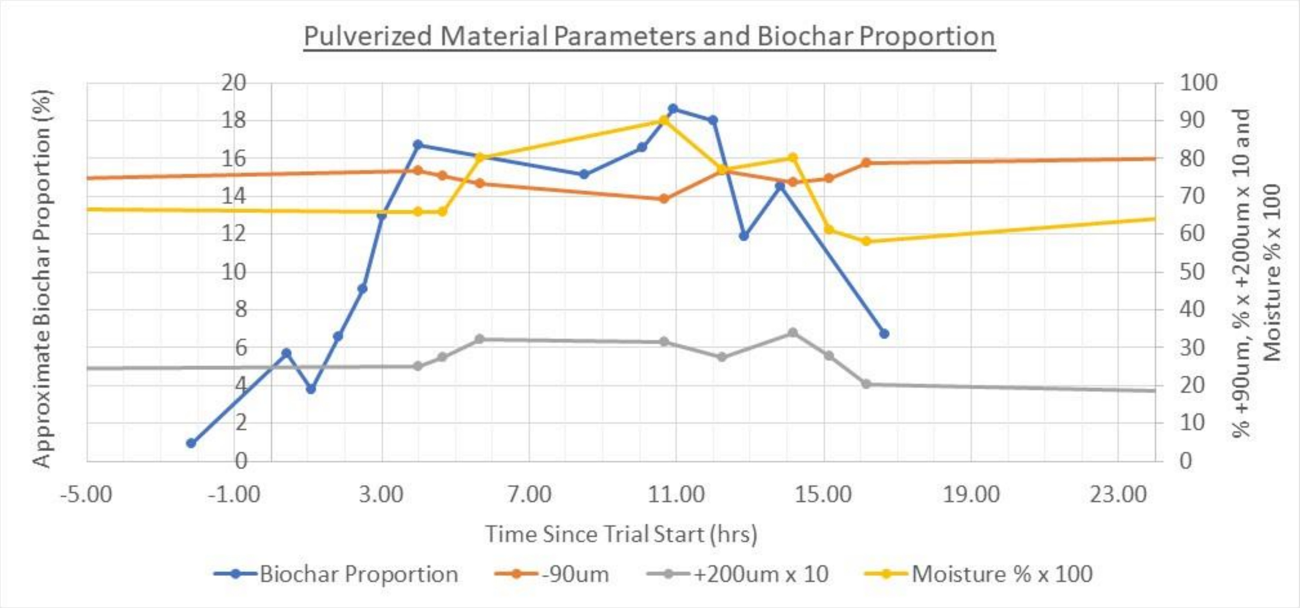


Figure 41 – Trial 3A - Biochar proportion, mass% -90um, mass% +200um x 10 and mass% moisture x 100

Despite the slightly coarser material and higher moisture, the injection process remained relatively unchanged from normal operations, barring the planned reductions made to aim injection hopper fill levels to account for the lower biochar density. Figures 42a and 42b show the steady nature of the injection operation, which appears to show little influence of the presence of biochar. Note that while the amount of scalping plate cleaning time was expected to increase with the coarser material, there was little evidence of this occurring. The biochar concentration in the conveying line was somewhat lower than expected, peaking at approximately 11.8% but in the main remaining around the 10% mark for up to 20 hours. This again would appear to be due to the flow dynamics within the PCSB, exacerbated by the smaller quantity of biochar used. As such, while ostensibly the injection process was unaffected by a 20% biochar/coal blend, in reality it would appear that the actual biochar proportion injected was less than this.

As with previous trials, the only notable effect was the increase in coal flow concentration, which again was easily controlled with a slight increase in fluidization nitrogen flow. Note that despite the aim injection rate being 40t/hr, rates of 45t/hr and 47t/hr were easily maintained during the trial.

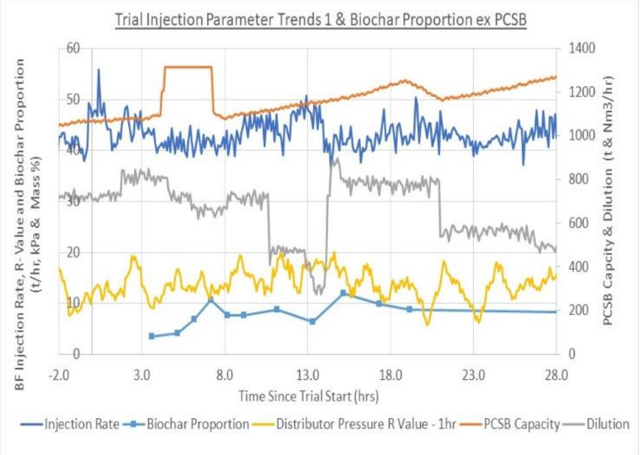


Figure 42a – Trial 3A– injection parameters and biochar proportion

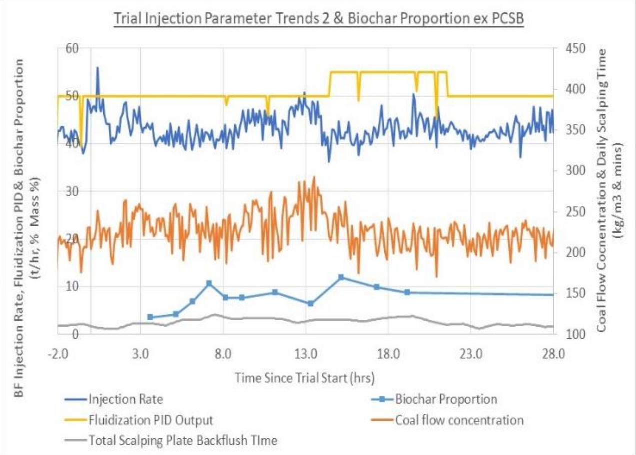


Figure 42b - Trial 3A – further injection parameters and biochar proportion

As with injection, the operation of the blast furnace was similarly unaffected, with no changes seen in the operation, barring slight burden adjustments necessary to account for changes in the biochar chemistry. Figure 43a and 43b show again that key process variables such as hot metal temperature, silicon and sulphur along with hot blast pressure remained relatively steady. Note that production rate actually increased during the biochar trial.

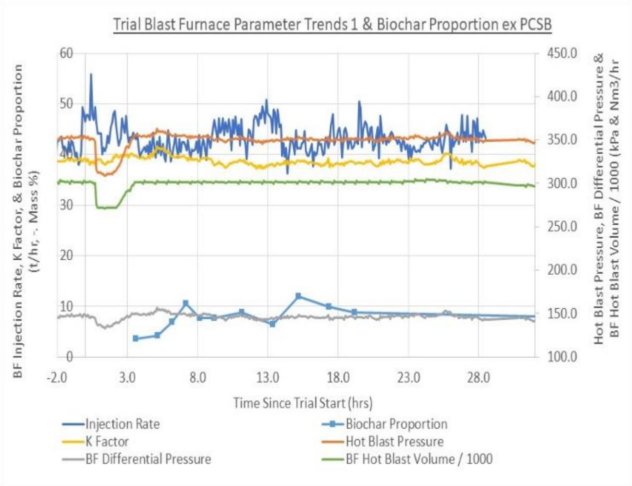


Figure 43a - Trial 3A – blast furnace parameters and biochar proportion

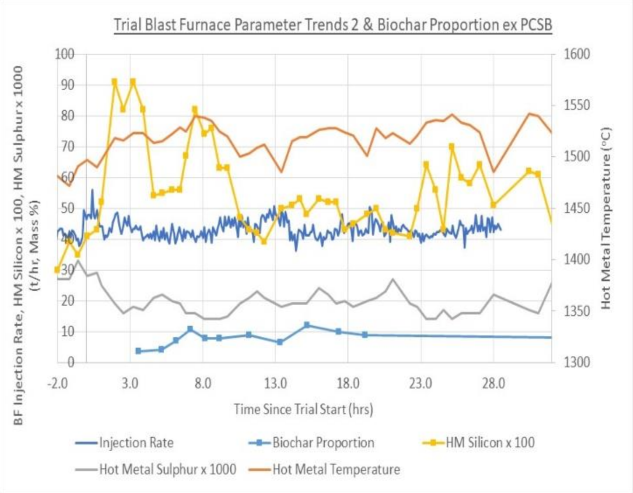


Figure 43b - Trial 3A – further blast furnace parameters and biochar proportion

6.12.11 Trial 3B – 20% Biochar Addition for 24 hours

Table 32 - Trial 3B key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 3B	21/3/23 05:30	20	24	303	306	223

As a result of a blast furnace stop in early March 2023, Trial 3B was delayed until the end of March to allow time for the blast furnace to stabilize operations after restart. During that period the injection rate aim was increased to 46t/hr. This necessitated an increase in the biochar requirement, which potentially increased the risks of the biochar trial. However, given the uneventful trials to that point, there was considerable confidence that there would be few problems.

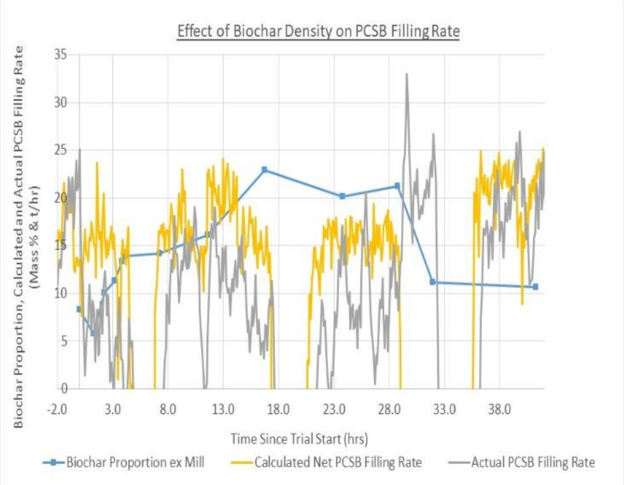


Figure 44 – Trial 3B – Biochar impact on grinding rate as shown by the difference between the calculated and actual filling rate of the PCSB

Figure 45 - Timber found blocking biochar flow in Bin 3 – 21/3/23

Trial 3B started on time, with PCSB being around its planned level, though the RCSB was at 320t compared to the plan of 300t. As with previous elevations, the flow of biochar through Bin 3 was unimpeded once it was established, despite the fact that the biochar appeared wetter than normal due to rain. With the increase to 20% of the blend, biochar was easily delivered at 24% of a total of 295t/hr though the speed of the two biochar weighfeeders was noticeably faster on this occasion and biochar levels appeared higher. Elevation proceeded without incident, though biochar spillage at the primary vibrofeeder was more noticeable for this trial. Note that not all of the biochar was able to be elevated at the normal morning and afternoon elevations, with that last material actually being elevated around 22hrs after the start of the trial. Why this occurred is still unclear, however given the mass in the RCSB is calculated based on a level detector, it could be that the lower density of the biochar was artificially influencing the monitored level in the RCSB. This coupled with the lower density also affecting the actual grinding rate, (which as with Trial 3A was apparent during this trial, see Figure 44) could have contributed to coal mass in the RCSB being perceived as higher than it was. This in turn could have limited the ability to fill the RCSB in a timely fashion. Much of this is supposition at this point, with further investigations continuing. However, at current rates of injection, it would appear not to be a significant problem, but for future operations with biochar, several measures currently used to control the operation of the grinding and drying plant will need to be re-evaluated in light of the lower density of biochar. Note that a large piece of wood was found blocking 1 leg of Bin 3, similar to those seen in the oversize material bin (see Figures 45 and 46). Again, this was contamination relating to supply and not something inherently from the biochar itself, so it was not a particular cause for concern with respect to the outcomes of the biochar trial.

From there grinding and drying of the biochar/coal blend proceeded without any significant impacts on most mill parameters of concern, with grinding in general at 60t/hr with a period at 65t/hr to manage coal stocks. Figures 47a and 47b highlight the fact that in general the grinding and drying process was stable, even as biochar proportion increased to the maximum of around 20%, however, there were noticeable changes to the HPB BFG flowrate for this trial, most likely due to the increase in moisture load from the rain.

Moisture input was already known to be high as a result of the wet biochar, however it would appear that additional moisture was causing a reduction in the mill output temperature which necessitated an increase in burner output. Indeed, burner output reached a maximum at around 15 hours and to ensure the drying process could be controlled, a reduction in the grinding rate back to 60t/hr was required.

Figure 46– Oversize material bin – 21/3/23

Also apparent is an increase in the classifier speed by 1% in response to sizing results that were overly coarse. This was new for this trial, in that while the size distribution of the ground material had shifted in previously trials, this was first time that the change was sufficient to result in a change to operating parameters. This is most likely due to the increasing biochar proportion but could also have been related to the moisture which could have changed the grinding characteristics of the blend. However, while the change to classifier speed was unusual, the magnitude was relatively small and this was sufficient to control the grind, so there was still considerable scope available in control options to make further changes should they be required. As such, while notable, the operational changes seen here do not have significant consequences for the operation.

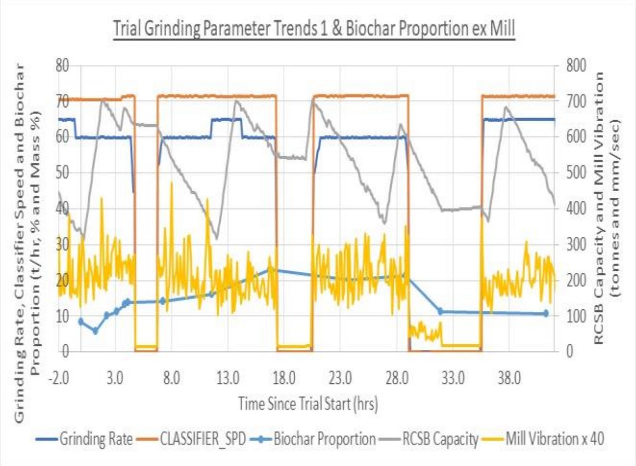


Figure 47a – Trial 3B– injection parameters and biochar proportion

Figure 47b - Trial 3B – further injection parameters and biochar proportion

Sampling results confirmed the observations above. As can be seen from Figure 48 the proportion of biochar increased rapidly until the 4-hour mark as per previous trials, but then appeared to plateau at around 15% for a number of hours before finally rising to the around the aim of 20% some 16 hours into the trial. Post this the biochar proportion remained high before dropping away, but even then, appeared to remain at 10% for some considerable time. Why this behaviour is different to Trial 2B is unclear, but perhaps the extended time to elevate the biochar, coupled with the lower density resulted in an extension of the period where biochar was present. Perhaps too at the higher biochar proportion, there is more tendency for mixing in the RCSB and therefore a longer time for biochar to leave the system. Figure 48 also shows the proportion of -90µm decreased and the +200µm proportion increased quite considerably compared to previous trials. The vertical line on the figures corresponds to the time when the classifier speed was changed which can be seen to return the sizings to a more normal range. Moisture too responded to the increase in biochar rising to higher levels, but again not to a level which caused concern. Interestingly moisture level did not seem to show any correspondence with the grinding rate change. As such the mill could still control moisture even with the higher moisture load and HPB output. Note that biochar proportion seems to be a little out of step with grinding and drying metrics, but this appears to be due to one sizing result at ~21 hours. Given the general trend in biochar proportion, this result could be an artefact of the measurement technique and may be overly high.

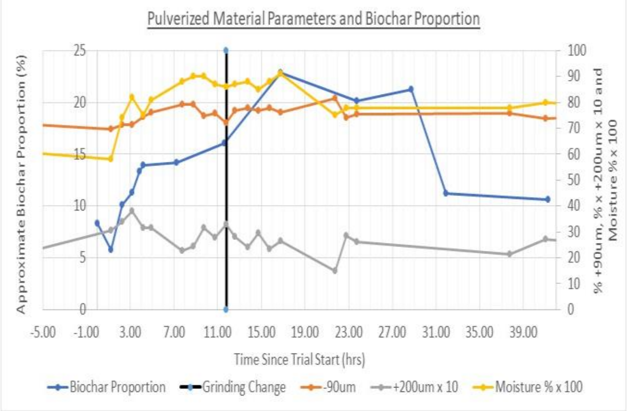


Figure 48 – Trial 3B - Biochar proportion, mass% -90um, mass% +200um x 10 and mass% moisture x 100

As with Trial 3A, coal blended with 20% biochar provided no problems for the injection system, with the required rate easily maintained with no significant disruptions to the process. As can be seen in Figures 49a and 49b scalping plate back flushing time remained as per normal operation, dilution remained within normal limits and R value was relatively steady during the trial period as biochar increased in the conveying line to a maximum. Coal flow concentration did increase as per expectations from previous trials, but an increase in fluidization nitrogen flow wasn't required on this occasion. It is interesting to note that the coal flow concentration broadly follows the change in biochar proportion in the samples from the conveying line but doesn't necessarily register that biochar continues to be present sometime after the concentration returns to normal. Why this is the case is unclear, but it is most likely that the biochar proportion was sufficiently low that the flowmeter couldn't register a change in the coal flow concentration. Again, with this trial, biochar concentrations measured in the conveying line were lower than what might have been expected, most likely due to dilution in the PCSB, however the peak value did at least reach 17.6%, which was closer to aim than Trial 3A. The difference could also be simply due to the amount of biochar in the PCSB during the longer trial and suggests that longer trials will be needed to fully evaluate the effect of biochar on the injection system.

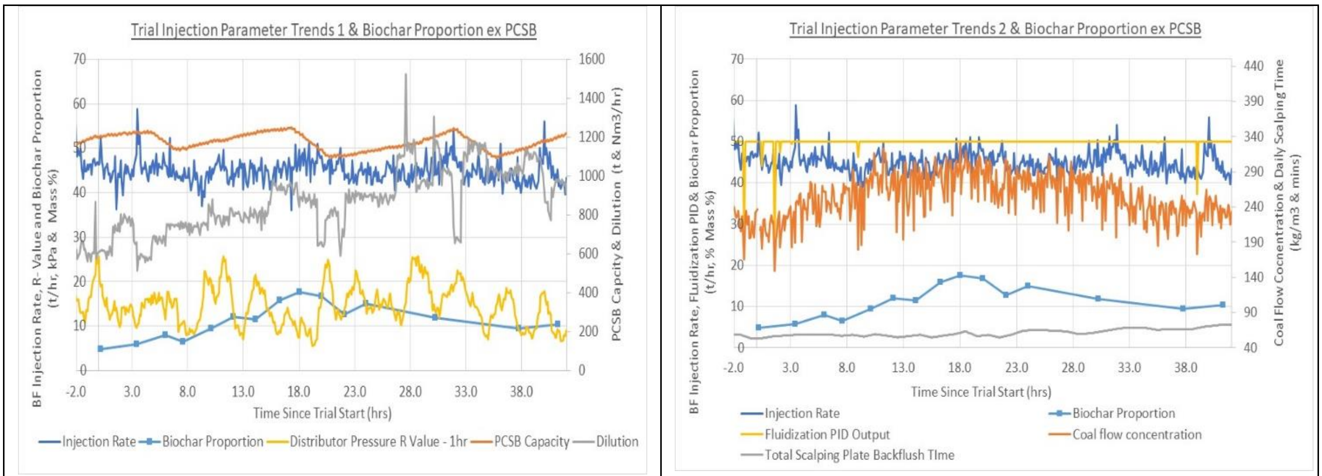


Figure 49a - Trial 3B– injection parameters and biochar proportion

Figure 49b - Trial 3B – injection parameters and biochar proportion

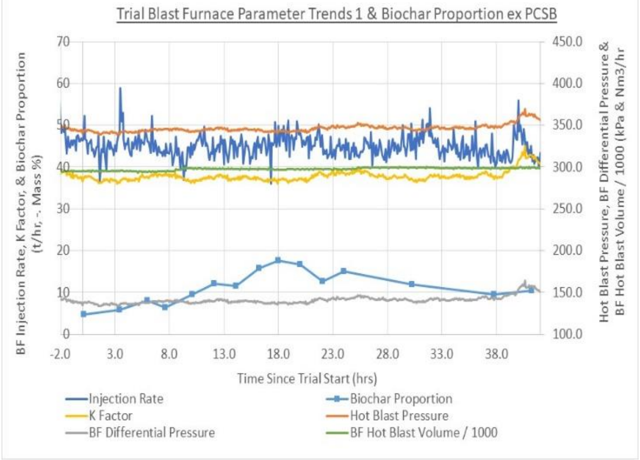


Figure 50a - Trial 3B– blast furnace parameters and biochar proportion

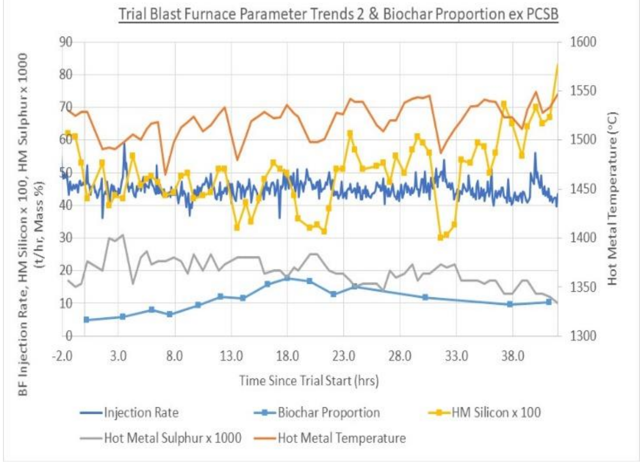


Figure 50b - Trial 3B – further blast furnace parameters and biochar proportion

As with injection performance, blast furnace operation appeared to be unaffected by the inclusion of 20% biochar in the injected coal blend with no operational difficulties experienced. As can be seen in Figures 50a and 50b, the now standard key metrics remained unchanged during the trial period, despite the injection rate being increased to an average of 46t/hr, with periods at close to 50t/hr. That being said, the biochar proportion was lower than the aim of 20% and certainly was only at a peak value for a short time, so whether it can be concluded that the blast furnace was not affected by the higher proportion of biochar is perhaps debatable. However, the aim biochar proportion in coal only occurred for perhaps 6 hours. This is a very short time from a blast furnace perspective, perhaps too short for any negative effects to become apparent.

6.12.12 Trials 3A-3B Summary

Overall, even though Trial 3B was undertaken a month after Trial 3A, with potential changes in equipment, blast furnace burden chemistries and hearth condition in that time the results of the 20% series of trials were very encouraging. The results show that the mixing, grinding and drying functionality of the PCI Plant can easily handle 20% biochar even at high moistures. Injection results were also encouraging, certainly enough to say that longer trials at this level of biochar are relatively low risk, but based on the measured biochar levels, longer duration trials would appear to be necessary to ensure that the aim biochar concentration is achieved for long enough periods to give more meaningful results than perhaps are shown here.

6.12.13 Trial 4A – 30% Biochar Addition for 12 hours

Table 33 - Trial 4A key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 4A	23/3/23 05:30	30	12	226	232	170

Loading of biochar started as planned and biochar once more continued to feed effectively once flow was established. Despite initial concerns regarding the volumetric capability of the weigh-feeders at this level of biochar addition, the mixing plant was still able to maintain a 34% addition rate at 260t/hr, at least initially. However, weigh-feeder speed was noticeably higher at this level, but there still appeared to be additional capability to increase biochar addition rate if need be. The increased proportion of the biochar was very evident on the main feed conveyor and indeed there was a larger pile of material building up at the first transfer point. This build-up got to the point where the maximum feed-rate had to be reduced to 250tph. Again, this appears to be the lower biochar density influencing the total volume of the blended coal and biochar, however it wasn't a big concern. Despite the increased proportion of biochar, spillage through the bucket elevator appeared to be minimal and barring the one disturbance noted above and another to remove some contamination from a spillage chute (not necessarily related to biochar), no further issues were seen with the elevation of biochar.

Grinding and drying started at 60t/hr initially, with the classifier set at 1% higher than normal (71%), to pre-emptively control the increase in the proportion of +200μm material seen on previous trials. However, despite the start at the normal grinding rate, as Figures 51a and 51b shows, as biochar began to present to the mill, HPB BFG flow increased considerably, to the point 10 hours into the trial, the grinding rate had to be decreased to 58t/hr to control moisture in the pulverised product. As moistures returned to more normal levels the grinding rate was returned to 60t/hr without any problems. The BFG flow requirement was a response to the higher proportion of biochar but also due to significant rain the night before, both of which contributed to a considerably higher moisture load than normal. However, it was expected at some point that moisture load would affect the process and the control actions taken were sufficient to control the issue. As with Trial 3B, the biochar density and higher moisture was apparent in the comparison of the calculated net PCSB filling rate and the actual rate of change of the PCSB mass (see Figure 52). Again, while notable it did not affect the process, other than the fact that grinding continued longer than expected as the actual grinding rate was lower than calculated figure. Figure 52 show that other than this and the moisture issue, the mill operation was stable with no other issues notable.

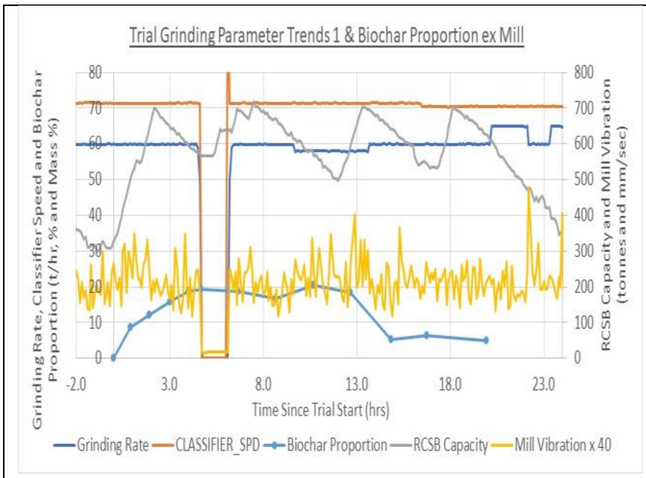


Figure 51a – Trial 4A– grinding parameters and biochar proportion

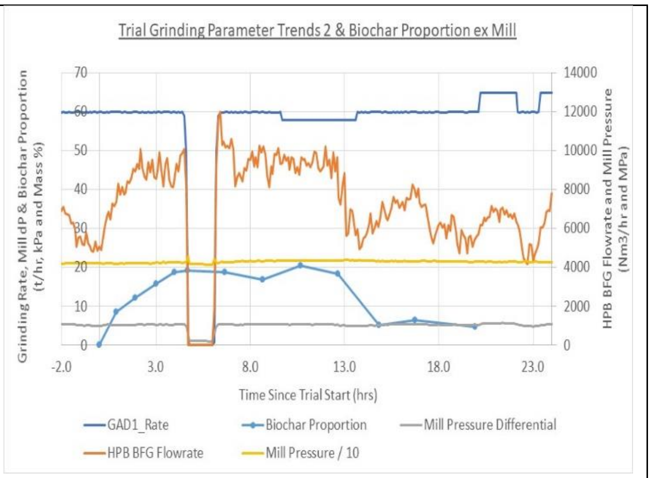


Figure 51b - Trial 4A – further grinding parameters and biochar proportion

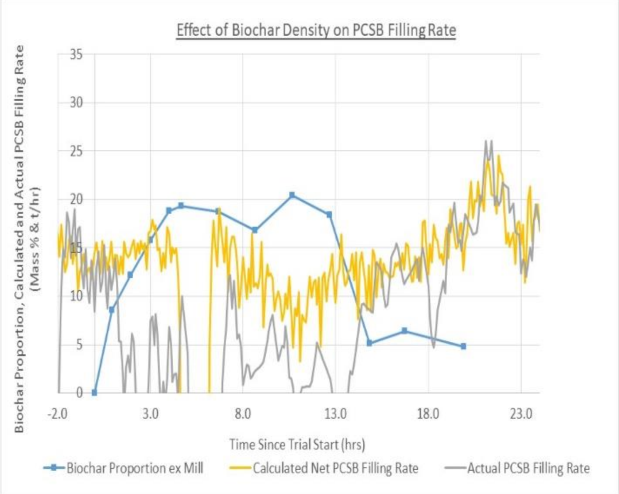


Figure 52 – Trial 4A – Biochar impact on grinding rate as shown by the difference between the calculated and actual filling rate of the PCSB

As with previous trials, biochar proportion at the mill exit increased rapidly in the first 4 hours of the trial before plateauing at approximately 20% where it remained for the duration of the trial before falling away. In general, this behaviour can be seen to be relatively normal, however unlike previous trials the aim biochar proportion of 30% was not reflected in the proportion measured at the exit of the mill. Why this is the case is unclear as all other measures, e.g. input mass, proportioning through the mixing plant and to a lesser degree the change in BFG flow requirement confirmed that 30% biochar entered the mill. The progress of the biochar through the mill also very much matched that of the previous trials, so the lower measured value does not appear to be the result of significant hold up of biochar in the RCSB which then presented as a lower biochar proportion over a longer time. As such, it suggests that something was affecting the measurement of the biochar proportion. Further investigation is continuing but given the measurement method relies on a calibration based on the properties of the base coals, indications are that a change to a new shipment of one type of coal could be responsible. Despite this, change in the biochar proportion (disregarding the magnitude) still corresponds to process changes and is still a useful indicator.

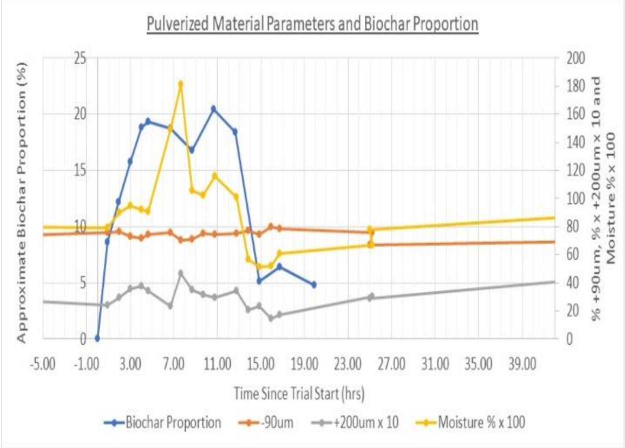


Figure 53 – Trial 4A - Biochar proportion, mass% -90um, mass% +200um x 10 and mass% moisture x 100

This is highlighted in Figure 53, where the increasing biochar proportion resulted in a decrease in the -90µm fraction and an increase in the +200µm fraction. The increase in +200µm fraction was perhaps slightly higher than previous trials, but only marginally. However, while the increase was notable it was not a particular cause for concern and certainly triggered no process changes. As mentioned previously, this wasn’t the case with the moisture in the pulverised material at the exit of the mill. As can be seen the moisture levels increased considerably in step with the proportion of biochar, rising to a maximum 1.81% for a single sample. Given the limit on moisture for pulverised material is 1.5%, this triggered the reduction in grinding rate.

This appears to have been successful in controlling the moisture, however the moisture did appear to be reducing in advance of the grinding rate change, which in conjunction with the rapid rise and then fall in moisture suggests that rather than being a direct consequence of wet biochar per se, a limited amount of wet material with a very high moisture passed through the process. This is known to occur during periods of wet weather where water pools in the coal stockyard and results in very localized areas of high moisture in the coal stockpiles. Be that as it may, the process was still sufficiently robust and responsive to deal with the higher moisture, which augurs well for future operation, should inherently wetter biochar be used in the future.

Biochar addition of 30% to the pulverised material blend again in general had little impact on injection parameters. Despite the higher proportion of +200µm, no additional blockages or issues with the scalping plate attributable to biochar were notable and dilution and R value remained within normal limits (see Figures 54a and 54b). Coal flow concentration again rose as expected and triggered an increase in the fluidization nitrogen flow, but again no further issues were reported with respect to injection. Note that as with the measured biochar proportion at the exit of the grinding mill, conveying line proportions were also lower than expected. While some dilution of the biochar proportion has been seen on previous trials, the degree seen here would seem to be out of step with that seen in previous trials, again suggesting that something was different with the measurement technique.

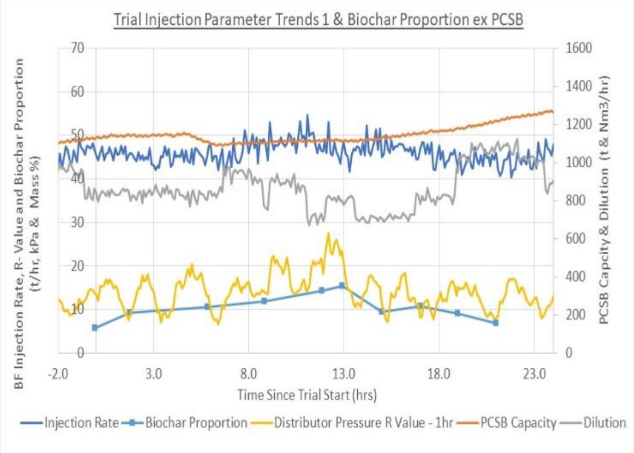


Figure 54a – Trial 4A– injection parameters and biochar proportion

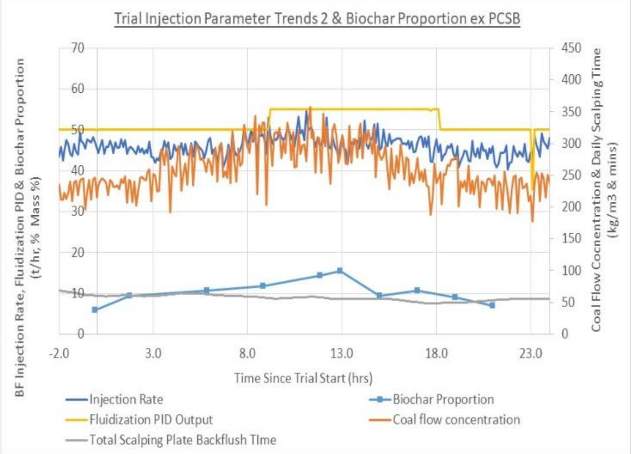


Figure 54b - Trial 4A – further injection parameters and biochar proportion

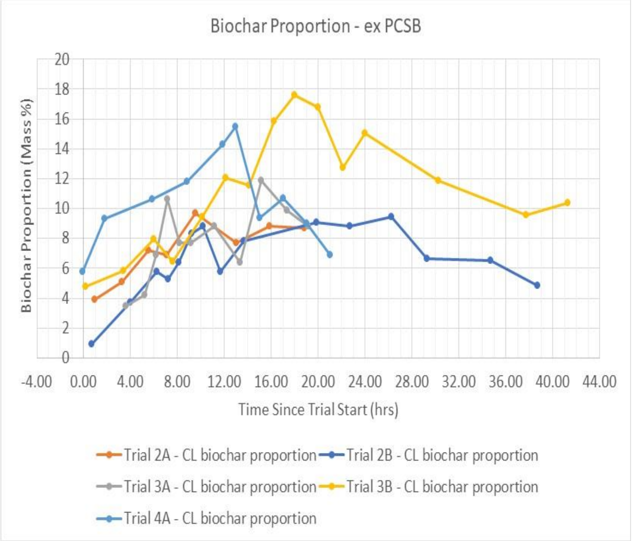


Figure 55 – Trials 2A to 4A – Conveying line biochar proportions

On the assumption that the biochar proportion was higher than the measured value, what was also notable about the trend in conveying line biochar concentration for this trial was the relatively high starting concentration as can be seen in Figure 55. This is somewhat unusual but was most likely related to the fact that unlike other trials a 24hour biochar trial (Trial 3B) had been completed only the day before. As such, given the extended time that biochar appears to stay in the PCSB, it is likely that biochar from Trial 3B was inflating the early results from this trial. This highlights again that trials for longer durations are most likely required to obtain a representative and uniform biochar concentration in the injected material and that for future stop/start trials such as this, additional time between trials will be required.

Continuing the trends of previous trials with respect to blast furnace operation, no significant changes were noted other than the minor changes to the blast furnace burden to account for the slightly different slag chemistry of the biochar. As with previous trials a steady injection rate was maintained at around 46t/hr and up to 50t/hr for short periods with no problems notable. Figure 56a and 56b shows steady and efficient operation, with no impact on process stability or hot metal temperature and chemistry.

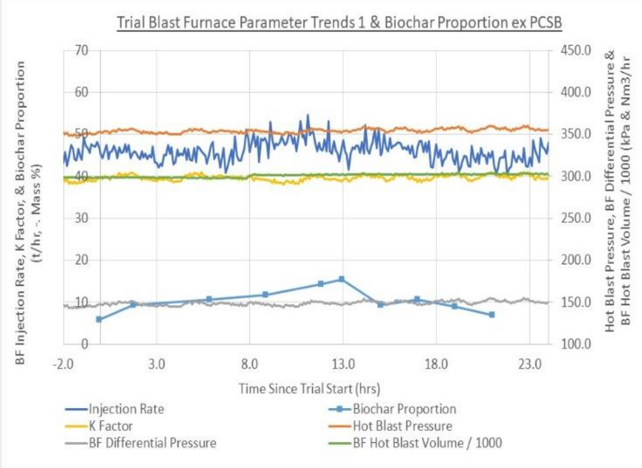


Figure 56a - Trial 4A– blast furnace parameters and biochar proportion

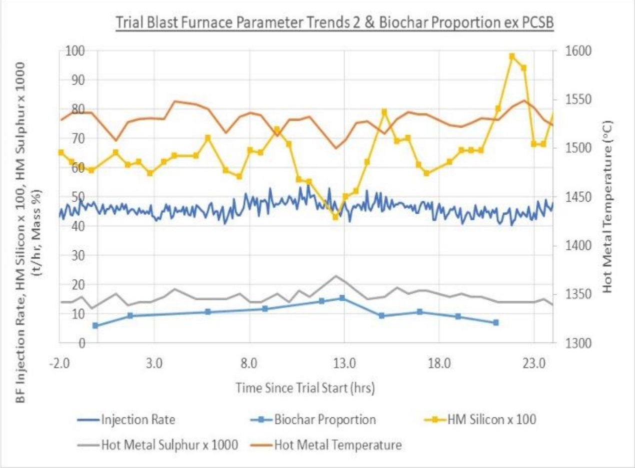


Figure 56b - Trial 4A– further blast furnace parameters and biochar proportion

6.12.14 Trial 4B – 30% Biochar Addition for 24 hours

Table 34 - Trial 4B key parameters

Trial	Date/Time Start	Biochar Proportion (% dry)	Aim Duration (hrs)	Aim Biochar (wmt)	Biochar Loaded (wmt)	Estimated Tonnes of Biochar (dmt)
Trial 4B	28/3/23 05:30	30	24	453	438	320

Trial 4B was the last of the trials in the series and as a result it was always planned that this trial would consume all the remaining biochar stock. Initial planning at an injection rate to the furnace of 40t/hr indicated that there would be sufficient biochar to fund the entire trial, however the increase to the injection rate midway through the trials to 46t/hr meant that remaining stocks weren't sufficiently high to enable a full 24-hour trial. However, the final shortfall of 11t wasn't as much as was feared, resulting in a shortening of the trial duration (on paper at least) by approximately 1 hour. Note also since all of the remaining material was consumed, this last batch of material was subject to some contamination, firstly by scrap steel and lastly by timber. Both appear to be a result of cleaning out the undercover storage sheds which picked up material stored previously and as such were not related to the biochar.

Trial 4B started as planned, with the RCSB a little higher than ideal at 330t, however given this was to be a 24hour trial, this was not expected to significantly prolong the trial beyond the planned sampling time. Note that while all trials had previously utilised Hopper 3, Hopper 2 was selected for this last trial to better assess the flexibility of the mixing plant and the potential for any spillage if biochar was in a different position on the main conveyor. As with Trial 4A, the elevation rate was set at 260t/hr and the 34% addition rate was easily maintained by Hopper 2 weigh-feeders, though they were operating noticeably faster than normal as was expected. Unlike Trial 4A however, no build up at the first transfer point was noticeable on this occasion, suggesting that the flow characteristics of the coal/biochar blend were different from 5 days before. Why this is the case is not clear, but given this material appeared to be dryer, then this is a likely explanation for the different characteristics. No spillage was apparent at the primary vibro-feeder on this occasion and elevation was problem free, with spillage from the bucket elevator as normal.

Similar performance of the biochar/coal blend was seen during the evening elevation to the RCSB and then again early the following morning where the last of the biochar was elevated. As noted above, steel scrap was found in some of the biochar in the coal stockyard, but all appeared to have been removed by the metal remover. Some timber was apparent and unfortunately a larger section of plywood blocked 1 leg of Hopper 2, leaving about 2t of residual biochar which was not able to be elevated until much later in the trial. Overall, however the biochar itself again did not appear to cause problems for the mixing plant or elevation sequence, even after an extended period of handling biochar at 30% of the total blend.

Grinding and drying was conducted at 60t/hr and a classifier setting of 1% higher than normal (71%) and proceeded without any problems for the entire trial period, an improvement on the previous trial (see Figures 57a and 57b). This was despite the steel and timber contamination. Note that for a short period the grinding rate was decreased to 45t/hr purely to manage levels in the RCSB and PCSB, so that the afternoon elevation could be conducted on time. The higher moisture in the biochar was again evident in the performance of the High-Performance Burner, however on this occasion the action required wasn't to the same extent, suggesting that the biochar was somewhat dryer as observed above. The relationship between the calculated net filling rate of the PCSB and the rate of change in the PCSB was again in evidence, a fact noted by the plant operators. Apart from these now expected changes, the grinding and drying operation proceeded smoothly with no problems.

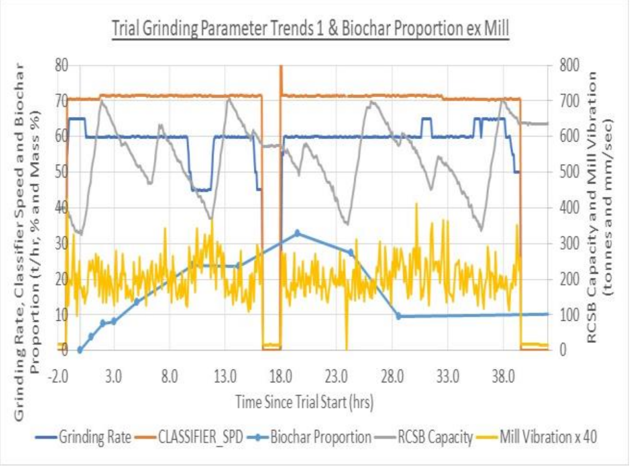


Figure 57a – Trial 4B– grinding parameters and biochar proportion

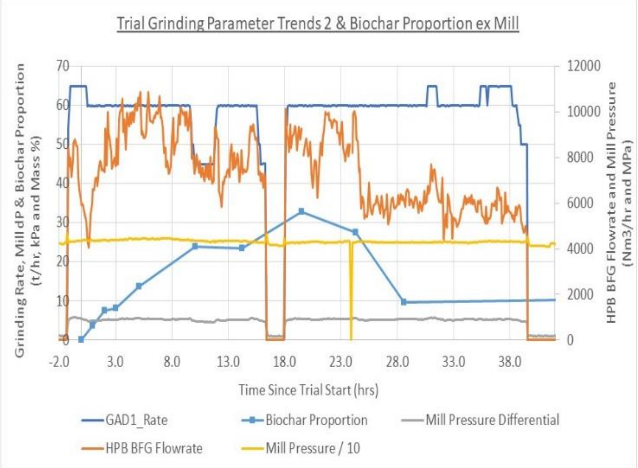


Figure 57b - Trial 4B – further grinding parameters and biochar proportion

This lack of issues was again reflected in the sizing and moisture results, where apart from the now expected changes (i.e. an increase in moisture and +200μm fraction and a decrease in the -90μm proportion), the values remained consistent throughout the trial (see Figure 58). On this occasion however, it was notable that while the measured biochar proportion reached a maximum level around the aim, it did take longer than normal to reach this level. Previous trials (Trial 4A aside) generally reached this level at around the 4-hour mark of the trial, but it wasn't until the 8 to 12-hour mark before the biochar reached close to the aim for Trial 4B. It was also notable that the peak in biochar proportion did not correlate that well with peaks in moisture or +200μm. Why this was the case is unclear, given starting levels in the RCSB were at normal levels and the flow behaviour of the biochar/coal blend should have been similar to that of Trial 4A. Again, it could be purely variation with the measurement technique bur further investigation is required.

As was now expected, injection did not experience any issues during the period of the biochar trial. Figures 59a and 59b show that in general, injection performance was steady, with no blockages or issues with the scalping plate, with dilution in normal ranges and no issues with injection hopper operation. Injection rates were also consistent at around 46t/hr reaching up to 52t/hr for short periods. There was some variation during the night in R value as one of two tuyere lines that were blocked was successfully unblocked on nightshift, however these issues pre-dated the biochar trial and were a consequence of coal use. It was notable once again that the peak biochar proportion of around 25% was only reached for a relatively short period of time, perhaps 4-8 hours after which time the biochar proportion dropped quickly, with biochar still seemingly detectable up to 50 hours after the start of the trial.

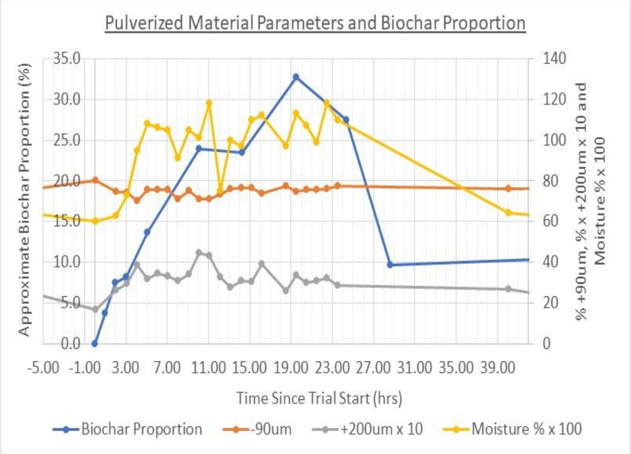


Figure 58 – Trial 4B - Biochar proportion, mass% -90um, mass% +200um x 10 and mass% moisture x 100

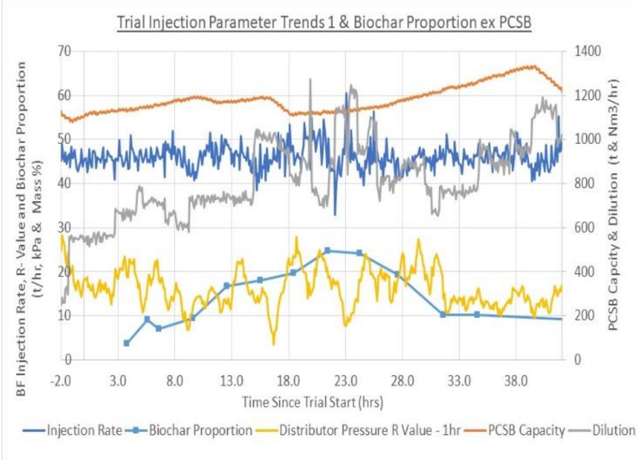


Figure 59a – Trial 4B– injection parameters and biochar proportion

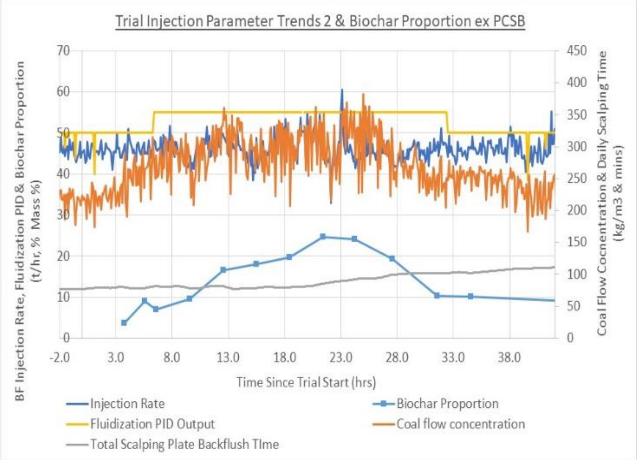


Figure 59b - Trial 4B – further injection parameters and biochar proportion

As such, while a significant quantity of biochar passed through the system, given biochar did not present at greater than 20% in the conveying line for a significant length of time, then the results seen here should only be seen as indicative of what might happen should the biochar proportion reach 30% in the conveying line. To better assess biochar proportions at 30% or greater, trials of durations longer than 24 hours are required.

It should also be noted that injection hopper fill levels were lowered considerably for this trial, to account for the lower density of biochar, thereby preventing overfilling of these units. Indeed, it was suggested that the level reductions were somewhat conservative and that this was potentially resulting in hopper change frequencies higher than necessary. As such, there is further work to be done to fully optimise the operation of the injection system for operation with higher levels of biochar, something that will have to wait until more significant supplies of biochar are found

The Blast Furnace also recorded no issues with biochar injection as per all the proceeding trials, as can be seen in Figures 60a and 60b, with standard metrics again showing little impact throughout the trial period. As noted above however, based on the measured biochar concentrations, peak levels of biochar were only achieved for a short period and as such this does detract from the results. Further trials for durations of longer than 24 hours appear to be required to ensure that the PCSB is fully saturated with biochar and biochar concentrations in the conveyed material are at the aim value for sufficiently long to give more meaningful results.

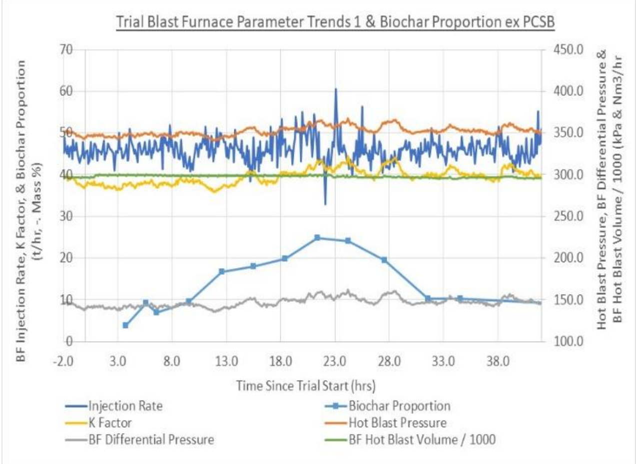


Figure 60a - Trial 4B– blast furnace parameters and biochar proportion

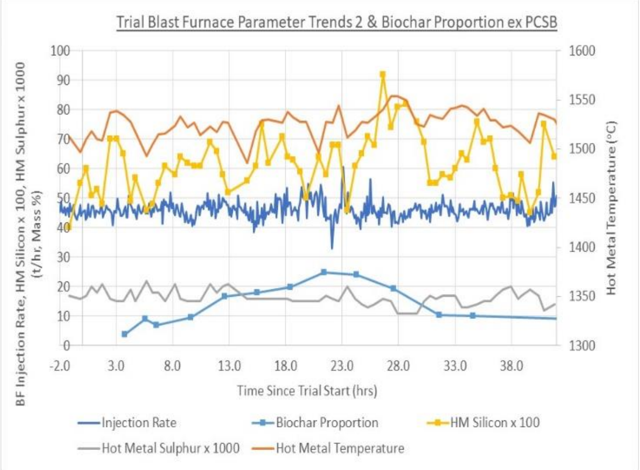


Figure 60b - Trial 4B– further blast furnace parameters and biochar proportion

6.12.15 Trials 4A-4B Summary

Overall, the 30% biochar addition trials were quite successful with virtually no problems seen during the trial period that could be directly attributable to biochar. While the effect of biochar again was evident in the sizing of the pulverised product, with small changes to classifier speed it could be controlled to the point where it was not a problem. Moisture was somewhat more of a problem, with the higher biochar proportion exacerbating the drying issues noted for all trials, however again small changes in grinding rate could accommodate higher moisture levels without too much of an issue. This was helped by the fact that injection rates and therefore grinding rates were only at a moderate level during the trials. If these were considerably higher, the impact of moisture would have been more noticeable. However, as has been noted many times now, the biochar moisture level was somewhat unusual and was required for handling purposes. It is hoped that should further biochar supplies be found, moisture can be more adequately controlled to prevent it being an issue in the future, however it was good to see during these trials that even at high moistures, the PCI Plant was still capable of processing this material, given that future biochar supplies may be exposed to rain in the PCI coal stockyard at some point.

Injection-wise, as with grinding few problems were seen, confirming the results of the pilot scale pneumatic conveying work. Coal flow concentration was a continual issue of note but ultimately it appeared controllable via an increase in fluidization nitrogen, though again this outcome was based on the output of the coal specific flowmeter and as such could be subject to calibration errors. Blast furnace and tuyere dynamics seemed to match previous laboratory work in that there were no noticeable irregularities in the operation resulting from biochar injection at a higher level and combustion performance was unaffected.

However, based on the measurements available, the trial durations and the inherent flow dynamics of the PCSB resulted in biochar proportions approaching 30% presenting to the injection system and blast furnace for a much shorter period than expected, perhaps too short to truly determine if there were any negative effects on these two parts of the process. As such further trials for longer durations, perhaps a minimum of 72 hours, are required.

Segregation Testing

As noted above, segregation of biochar and coal somewhere in the PCI Plant or injection process was a key concern. Unfortunately, evaluation of this is difficult, given it is hard to sample from different locations within the PCSB or from different injection hoppers to see if localized concentrations of biochar were occurring. However, it can be inferred from current results that in general biochar did not appear to be segregating in the process, given the relatively low level of variation within the results across all biochar trial periods. For example, with the biochar proportions at the mill exit, within the limits of the measurement technique, the general trend in biochar proportion was a logical one and there weren't any results that were over the aim biochar proportion that would suggest segregation or concentration of biochar at any point in the RCSB or grinding mill. Similarly, the results from the conveying line seemed to reflect a lack of segregation through the PCSB and injection hoppers.

Segregation along the injection line through to the Blast Furnace is something that will still require investigation in later trials but given the fact that dilution and injection line pressures were relatively stable, segregation appears unlikely, particularly in light of the results from the pilot scale testing. This leaves the distributor and tuyere lines themselves and while further work in later trials is required, some initial near-simultaneous sampling seemed to indicate that in general biochar proportions in different tuyere lines were relatively similar, at least within the accuracy limitations of the biochar measurement technique (see Figure 61). While only indicative this is still a good result, as delivery of variable biochar concentrations to selected tuyeres could potentially have resulted in significant difficulties in control of injectant combustion and therefore the blast furnace process. Further work on this in future trials is recommended.

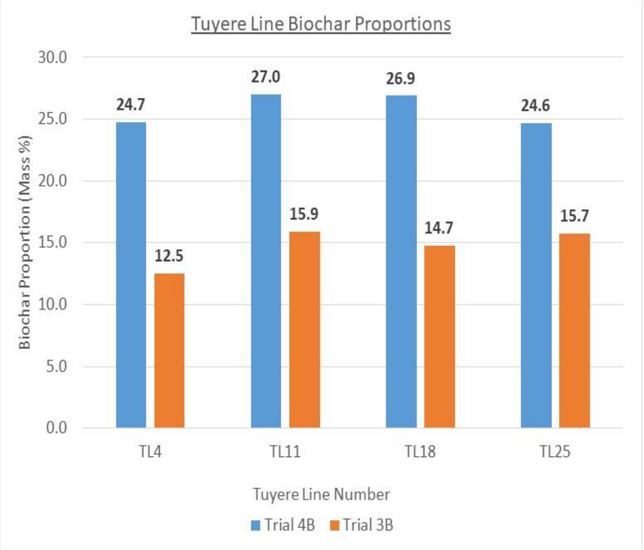


Figure 61 – Trials 3B & 4B - Biochar proportion in tuyere lines 4, 11, 18 and 25

6.13 Overall Review of the Biochar Trials

Use of biochar came with several key risks, which had the potential to result in significant negative consequences for both the PCI Plant and Blast Furnace processes. These risks primarily stemmed from the difference in physical properties, namely the lower density, propensity for moisture absorption and the difference in morphology of biochar when compared to coal. To mitigate any potential consequences, staged trials were used to gradually introduce biochar into the process such that any process changes could be observed. As has been shown above, these trials have been very successful in mitigating these risks, given at no point in any of the trials were any of the processes significantly impacted as a direct consequence of biochar addition.

Throughout the trials, only minor and easily achievable changes were made to the operating of the mixing plant to accommodate the lower density biochar and even then, the physical properties were such that the biochar performed as well, if not better than current standard coals. Elevation of biochar with coal up to and including 30% biochar addition was easily accomplished with no changes required to current equipment and no evidence of any spillage or other negative consequences. Grinding and drying in general was incident free, with the biochar/coal blends able to be ground and dried at a similar rate to coal alone, despite the differences in material properties and moisture content. While it was true that size distribution and moisture of the pulverised product was influenced by the presence of biochar, only slight changes were required to ensure that moisture and the proportion of +200µm stayed within normal operating limits, changes that were well within the scope of current control adjustments. The influence of density was apparent on the operation of the mill feeding process, in that the actual grinding rate was lower than indicated, but this did not cause issues with the process and as such was not a particular concern for the operation at the current aim injection rate. For future operations with biochar, particularly at higher aim injection rates, it should be relatively simple operation to modify the existing control system to account for lower density biochar when controlling mill feed-rate. Despite concerns about the density difference, biochar did not appear to segregate through the RCSB or grinding and drying mill, with the flow of biochar through this part of the process being quite predictable. Some mixing appeared to be apparent in the RCSB, as the measured biochar proportion increased over hours to reach the aim levels and these were sustained for somewhat less time than the planned trial duration, but still sufficiently long for representative results (see Figure 62). In addition, it was notable that biochar did reach the mill considerably faster than what might have been expected, a fact that will be of use for optimizing coal only operations. As such it would appear that the initial materials handling, grinding and drying section of the PCI Plant is fully capable of handling biochar up to levels of 30% and given the results shown here, most likely beyond.

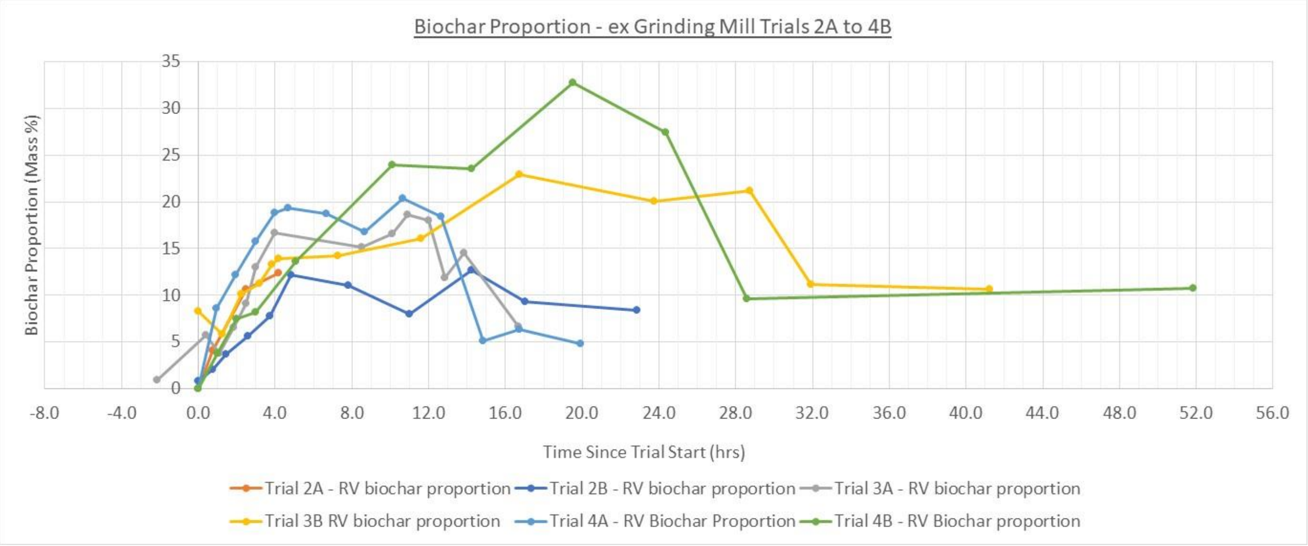


Figure 62 – Biochar proportion ex grinding mill, Trials 2A to 4B

The addition of biochar to the pulverised material also had little impact on injection parameters, with the operation of this part of the PCI Plant seemingly unaffected throughout the trials. Even at biochar input levels of ostensibly 30%, injection rates of up to 50t/hr were easily maintained, thereby validating the results of the pilot scale pneumatic conveying work. PCSB operation was unchanged and the flow of material to the three operating injection hoppers appeared unaffected by the presence of biochar.

Barring self-imposed changes to injection hopper levels, (something that could be further optimised when more biochar is available), hopper operation was as per normal. Biochar did obviously impact the coal flow concentration, however as with grinding, only a small process change was required to bring this back into normal range. It could be argued however, that the variation in concentration was merely an artefact of the measurement device as opposed to a real change. Further work on re-calibration of the flowmeter is recommended as is optimization of the control of injection hoppers based on this value when biochar is reintroduced. As with the RCSB, on the basis of analysis to date, while further work is required, there appears to be few indications that segregation was an issue through the PCSB or indeed the PCI line, distributor or tuyere lines, again validating laboratory work undertaken previously.

Unlike the RCSB however, considerable mixing and dilution of biochar appeared to occur in the PCSB as shown by the measured biochar proportion in the conveying line (see Figure 63), most likely because of the flow dynamics and quantity of retained material within the PCSB itself. This dilution was to the point where in reality, the injection system most likely saw only biochar proportions of up to around 20% for sufficient lengths of times for the results outlined here to be representative. However, this shouldn’t take away from the positives of this trial, which indicate that biochar proportions of up to 20% should be able to be pneumatically conveyed with confidence.

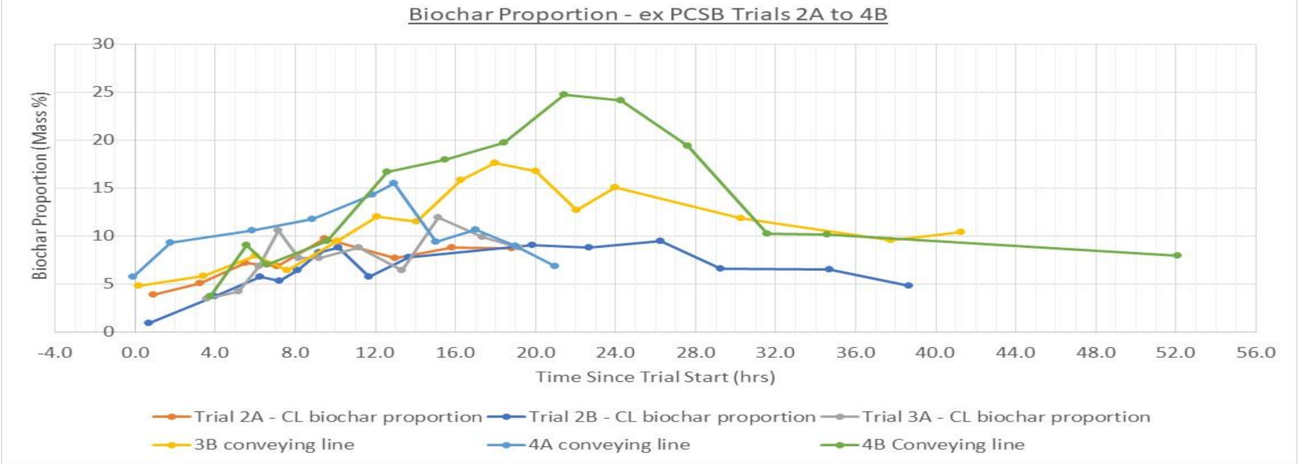


Figure 63 – Biochar proportion in the conveying lines, Trials 2A to 4B

As with many aspects of the biochar trial, blast furnace operation was unaffected using biochar at any level, with all process parameters monitored generally stable with no negative impacts on tuyeres that were apparent. Where variation did occur, at no time was biochar implicated in any of these changes. As such, the lack of issues with biochar combustion and blast furnace operation validates previous laboratory work with the single tuyere rig. As noted above however, due to the dilution of biochar through the PCSB, blast furnace operation was only exposed to biochar proportions of up to 20% for sufficiently long to be representative, rather than 30% as originally planned. Overall, this was a somewhat disappointing result, however given the limitations of biochar supply it was one that wasn’t wholly unexpected. Given the scale of ironmaking processes, 965dmt is a very small amount, with raw materials trials generally based on quantities in the thousands, if not tens of thousands of tonnes. As such, future work should focus on establishing further biochar supply sufficient to fund a minimum of 72 hours of trialling. In this way it is hoped the dilution aspect through the RCSB will be overcome and meaningful injection results for biochar proportions greater than 20% will be generated.

In addition to the further work noted above, additional efforts should be directed towards further developing the technique for measurement of biochar proportion. While sufficiently accurate to provide a good indication of biochar proportion for these trials, future optimization of the process will need an even more accurate, reliable, and more rapid measure of biochar concentration in coal.

6.14 Trials - Summary and Recommendations

From November 2021 until February 2023 biochar, purchased with funding from ARENA, was delivered and stored at BlueScope’s Port Kembla Steelworks. This was followed in February and March 2023 with biochar trials at the PCI Plant. These industrial-scale trials consisted of 10 events in a staged series, encompassing biochar additions to coal ranging from 5 to 30% for time periods from 1 to 24 hours. The work found the following:

- Bulk biochar can be successfully handled and stored in a similar fashion to most bulk materials used at the PKSW, albeit that it requires more water to reduce dust emissions to an acceptable level.
- Biochar and biochar/coal blends up to a maximum of 30% can be proportioned, elevated, and stored with the existing equipment at the PCI Plant, without experiencing problems with material flow, excessive spillage or segregation.
- Grinding and drying of biochar/coal blends, up to a maximum of 30% biochar can be undertaken successfully and safely with current equipment at the PCI Plant, with only minimal changes made to the process to achieve standard moisture and sizing aims.
- Pneumatic handling of the biochar/coal blends, up to a maximum of approximately 20% can be successfully conveyed and proportioned to the 28 tuyere lines at up to 50t/hr without experiencing unstable flow, blockages, or segregation.
- Biochar/coal blends of up to approximately 20% biochar can be successfully used to replace pulverised coal in blast furnace operations, without detriment to the stability, productivity of the process or indeed the quality of the hot metal.

- Given the positive results of these trials the following is recommended:
    - Source large quantities of biochar, sufficient in the shorter term to fund several trials of 30% biochar addition to coal for a minimum of 72 hours or indeed for normal operations at levels up to 20% biochar in coal.
    - Further optimise grinding control, with reference to the effect of biochar bulk density on calculated grinding rate.
    - Review the calibration of the coal flowmeter and determine the effect of biochar on the output of this device, with the view to ensuring that an accurate measure of coal flow concentration can be done for future operations with biochar
    - Further optimise control of injection hopper operation, again to account for the lower density of biochar on hopper fill levels and control sequencing
    - Continue to refine the biochar proportion measurement technique, to assist with future optimization of operations with biochar.

7 Conclusions

As part of the ARENA funded “Port Kembla Steelworks Renewables and Emissions Reduction Study”, BlueScope has investigated a number of aspects relating to the potential usage of biochar at the Port Kembla Steelworks.

Biochar sourcing was examined, and the work found that the status of the Australian biochar production industry was too small and insufficiently focussed on commodity biochar production to supply enough biochar to fund a potential BlueScope demand of 130,000t per annum. This would equate to replacing approximately 30% of coal for pulverized injection in the short to medium term. Importation of biochar was also examined and while it remains a possibility, it was found that the difficulties and potential risks from overseas supply meant that it was unlikely that this would be a viable source of significant biochar supply. Based on the above work, should BlueScope wish to proceed with larger scale biochar usage, it would appear that investment by BlueScope in biochar production will most likely be required.

To fund larger-scale biochar production, sufficient supplies of biomass must be found. Potential sources for biomass were examined. Indications were that there were several different sources of biomass, but few are suited to large scale biochar production for the purposes of steelmaking. Of the options, forestry wastes and diversion of timber from landfill streams appear prospective, but availability and quality concerns mean that in the shorter term, commodity grade woodchips produced from less desirable timber species is the most promising feedstock for a potential larger scale biochar production operation. In the medium to longer term, other biomass sourced from things like clearing of invasive native species or Prickly Acacia along with the use of purpose grown biomass crops should be a serious consideration.

Production of large amounts of biochar requires investment in pyrolysis technology, of which investigations found there were many types. Potential feedstock type and required production levels meant that only 3 technology types were suitable in the short term, these being the multiple hearth furnace, augur or paddle reactors, or rotary kiln-based technology. Given the technology readiness level and commercial availability of these technologies, indications are should BlueScope proceed with investment in a biochar production facility, a multiple hearth furnace or a rotary kiln technology such as the Torrcoal process are perhaps the most suitable. Longer term, the CSIRO developed variant on the Badger Stafford process could also be considered. This is particularly the case if collection of by-products is required. Indications are that the pyrolysis by-products are an important part of the biochar value equation and ideally should be sold to offset the cost of biochar. However, the inherent poorer properties of the bio-oil (relative to petroleum), the difficulties in upgrading the bio-oil and the lack of ready market for these products means that in the short term, should BlueScope proceed with a biochar production project, all of the pyrolysis products will most likely have to be combusted to generate heat/steam or electricity.

Biochar usage was the focus of the second part of this report, with particular focus on larger scale trials of biochar at PKSW PCI Plant. To minimize the risk to the plant operations from the introduction of biochar, laboratory and pilot scale pneumatic conveying work was undertaken by BMEA, using biochar/coal blends containing up to 30% biochar. Laboratory test work showed that barring the inherently lower density of the biochar, there was little to distinguish between the biochar/coal blends and 100% coal in terms of flow characteristics and handleability. Pilot scale pneumatic conveying work showed similar outcomes, with little difference in the conveying behaviour for the biochar/coal blends compared to coal. The only notable difference was the lower mass flowrate of the biochar/coal blends under the same injection conditions, however the work noted that this could be overcome with only minor changes to the conveying operation.

Given the good results seen in the laboratory, industrial scale trials of biochar were carried out at PKSW PCI Plant and blast furnace during February and March 2023. These trials used a total of 965dmt of biochar from two separate sources to conduct trial runs of 1 to 24 hours with biochar addition rates ranging from 5 to 30%. Barring some minor changes to the grinding and drying process to accommodate the damp, less dense biochar, there were no significant impacts as a result of biochar addition on the proportioning, elevation, grinding or drying of the biochar/coal blends. Pneumatic conveying of biochar/coal blends was similarly problem free, whilst blast furnace operation appeared completely unaffected by the presence of biochar in the tuyere injectant. While in general all the results were good, dilution of the biochar in the coal blend through the process resulted in a lower proportion of biochar in the conveying line than expected and as such, it was concluded that the trials only demonstrated that up to 20% biochar in coal could be pneumatically conveyed with confidence, with higher proportions requiring additional biochar to support longer duration trials.

Overall, should BlueScope wish to proceed with biochar/biomass usage at PKSW, then this work indicates while no large-scale sources of biochar are available locally, suitable biomass that could be used for large-scale biochar production is available, as are commercially proven pyrolysis technologies. In addition, while the full-scale trials were limited and further trials of longer duration are required, the work has indicated that there appears to be no technical barriers to the use of biochar at addition rates of up to 20% in pulverized coal for blast furnace injection. However, the commercial aspects of the use of biochar are still complicated and further work is required to determine if biochar is commercially viable for PKSW.

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Appendix 1 - Flow Property Testing of Pulverised Coal and Biochar (BME2206-1)

Appendix 2 - Pneumatic Conveying Trials of Pulverised Coal and Biochar (BME2206-2)