BlueScope

PHASE 3 REPORT

PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY

ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS

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SYNOPSIS

This final Phase 3 report follows the Phase 1 report detailing a site-specific evaluation of potential emissions reduction opportunities at Port Kembla Steelworks (PKSW) and Phase 2 report detailing biochar investigation and trials. This report describes the potential contribution of key Prioritised Options to PKSW's decarbonisation pathway. This is based on a high-level assessment of key issues and development gaps associated with each Prioritised Option, considering operational, engineering, environmental and safety aspects. Preliminary process integration-based simulation modelling of some of the Prioritised Options relative to a baseline PKSW operation was undertaken. Based on all aspects of the project, a final assessment identified a suite of short to medium- and long-term Prioritised Options for further consideration and recommended actions to progress.

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EXECUTIVE SUMMARY

With ARENA's support, BlueScope has investigated the technical and economic feasibility of renewable energy and decarbonisation technology pathways that have the potential to decarbonise the steelmaking process at PKSW. PKSW is a traditional integrated steelmaking facility using the blast furnace ironmaking (BF)-basic oxygen furnace (BOF) route.

The first phase of the project involved; an initial investigation of current low emissions and future emerging decarbonisation technologies, a Qualitative Options Analysis (QOA), PKSW-specific technical Decision Criteria and identified a set of Prioritised Options for further assessment. A Phase 1 report describing this investigation was issued.

The second phase of the project focussed on biochar and the potential for it to replace some of the coal injected into the blast furnace. Biochar was successfully trialled in the Pulverised Coal Injection (PCI) plant at up to 30% biochar for up to 24 hours. A Phase 2 report describing biochar-pulverised coal trials and related investigations was issued.

This third and final phase builds on the Phase 1 and Phase 2 reports, by further assessing the identified Prioritised Options via:

- a qualitative assessment of operational, engineering, environmental and safety aspects for PKSW,
- a preliminary process integration-based simulation modelling of Prioritised Options relative to a baseline PKSW operation, and
- a final assessment process.

The qualitative assessment of operational, engineering, environmental and safety aspects for PKSW identified the key issues and specific development gaps for each aspect, as well as the steps required for adapting or adopting the Prioritised Options at PKSW. This assessment assisted in determining whether the specific Prioritised Option should be considered further.

Preliminary process simulation modelling of Prioritised Options relative to a baseline PKSW operation provided a quantitative evaluation of some Prioritised Options. This involved the development, validation and application of a process simulation model describing major units of PKSW's current manufacturing operations, and PKSW operations. The model was used to assess potential emissions (CO_2) reduction with the use of four alternative reductants in No. 5 Blast Furnace (5BF): biochar, torrefied biomass (TB), coke ovens gas (COG) and hydrogen. The outcomes from the modelling were used in the assessment of these Prioritised Options.

The Prioritised Options were categorised based on short-to-medium term and long-term, with the knowledge that No. 6 Blast Furnace would be relined and operated through the short-to-medium term, and that a step change would be required for the long-term to achieve a net zero goal by 2050[1].

The final assessment process drew together all relevant information on each Prioritised Option gathered throughout the study to enable a decision on the suitability to progress further as part of reducing CO_2 emissions at PKSW and ultimately supporting a decarbonisation pathway.

[1] For BlueScope, achieving our net zero goal is dependent on several enablers including the technology evolution, raw materials supply, firmed, renewable energy, hydrogen availability and policy support.

Summaries of the final assessments of the short-to-medium term and long-term Prioritised Options are shown in Tables 20 and 21, respectively. These outline whether the Prioritised Options are to be considered further for PKSW at this stage and if so, the recommended actions.

Table 20 Final Assessment Summary – short-to-medium term Prioritised Options

PRIORITISED OPTION	FURTHER INVESTIGATION	RECOMMENDATION
SHORT-TO-MEDIUM TERM		
Blast Furnace Ironmaking		
Novel charging materials to BF		
• Carbon containing agglomerates (CCA)	NO	Continue to monitor.
• Pre-reduced agglomerates (PRA)	YES	Further investigate what would be required to conduct a HBI trial.
• Ferro-coke	NO	Continue to monitor.
Biomass application in ironmaking	YES	To enable longer duration trials to be conducted, further investigate those planning to produce biochar in Australia.
Hydrogen-enriched injection		
• Natural gas	NO	Continue to monitor.
• Coke ovens gas		
• Hot reducing gas		
• Biogas (biomass pyrolysis - “syngas")		
• Hydrogen		
Sintering		
Waste heat recovery from cooler and waste gas recycling	NO	Continue to monitor.
Super-SINTER technology (SST)		
Steelmaking		
DRI and scrap utilisation in Basic Oxygen Furnace		
• DRI utilisation in Basic Oxygen Furnace	NO	Continue to monitor.
• Scrap utilisation in Basic Oxygen Furnace, including scrap preheating	YES	Continue with current trials and investigations to increasing scrap utilisation in the BOF.
Carbon Capture, Utilisation and Storage		
CCS	NO	Continue to monitor CCU.
CCU		

In terms of long-term investigations, an Options Study is now being undertaken within BlueScope to explore the large-scale decarbonisation of ironmaking in our Australian operations, which will inform next steps in terms of trials, pilot plants, partners, capital investment and timelines. Specifically, the study will test the hypothesis that a DRI process using natural gas (as an intermediate step) and then green hydrogen (once it is commercially available), is the most prospective technology for our Australian operations.

Table 21 Final Assessment Summary – long term Prioritised Options

PRIORITISED OPTION	FURTHER INVESTIGATION	RECOMMENDATION
LONG TERM		
Alternate Ironmaking		
Electrolysis of iron ore	NO	Continue to monitor.
Fluidised bed direct reduction	YES	Complete Options Study
Shaft furnace direct reduction	YES	Complete Options Study
Smelting Reduction (SR)	NO	Continue to monitor.
Steelmaking		
DRI utilisation in ESF-BOF	YES	Complete Options Study
DRI utilisation in an EAF	YES	Complete Options Study

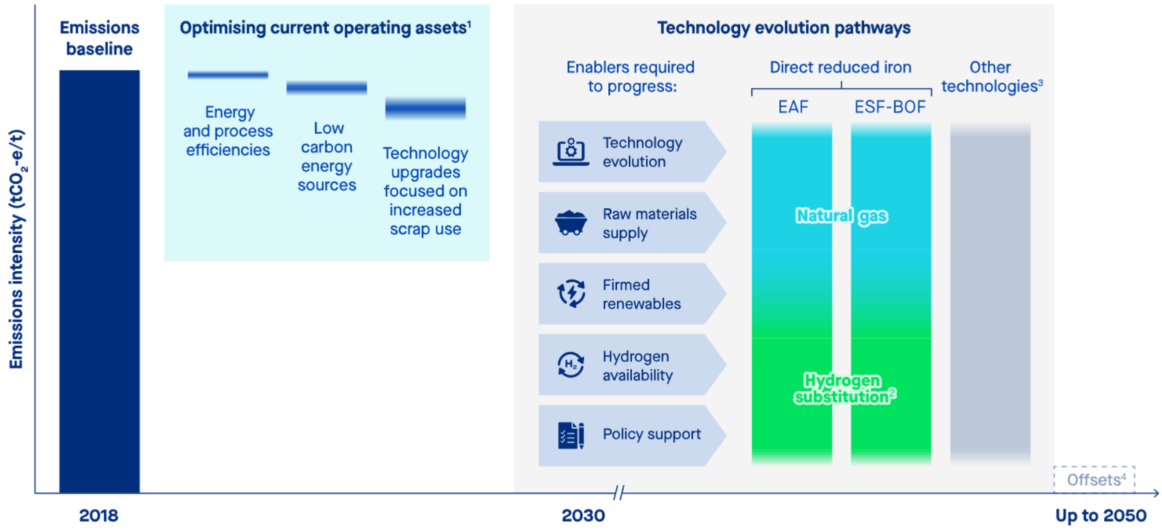
In summary, the selected PKSW-specific Prioritised Options for further action are shown in Table 22.

Table 22 Prioritised Options proposed for further action

PRIORITISED OPTION	FURTHER INVESTIGATION	RECOMMENDATION
SHORT-TO-MEDIUM TERM		
Blast Furnace Ironmaking		
Novel charging materials to BF		
• Pre-reduced agglomerates (PRA)	YES	Further investigate what would be required to conduct a HBI trial.
Biomass application in ironmaking	YES	To enable longer duration trials to be conducted, further investigate those planning to produce biochar in Australia.
Steelmaking		
DRI and scrap utilisation in Basic Oxygen Furnace		
• Scrap utilisation in Basic Oxygen Furnace, including scrap preheating	YES	Continue with current trials and investigations to increasing scrap utilisation in the BOF.
LONG TERM		
Alternate Ironmaking		
Fluidised bed direct reduction	YES	Complete Options Study.
Shaft furnace direct reduction	YES	Complete Options Study.
Steelmaking		
DRI utilisation in ESF-BOF	YES	Complete Options Study. Continue existing collaborations on the development of a DRI-ESF pathway.
DRI utilisation in an EAF	YES	Complete Options Study

BlueScope's indicative Iron and Steel decarbonisation pathway is shown in Figure 2.

Figure 2 BlueScope's indicative iron and steel decarbonising pathway.



1. Optimising current assets involves working within currently available technology options to improve the efficiency of assets and processes, including upgrading technology where there are supportive enablers.
2. Contingent upon commercial supply of hydrogen from renewable sources.
3. Other technologies include electrolysis, CCUS and biocarbon, etc.
4. We retain the option to use offsets to meet our 2050 net zero goal where direct abatement is not technically or commercially feasible.

Recently, given PKSW's short-to-medium term ironmaking process being confirmed through the major investment decision to reline No.6 BF, the outline in Figure 2 closely represents PKSW's decarbonisation pathway, which has two phases:

(i) optimising current operating assets, and
(ii) technology evolution pathways towards its 2050 net zero goal.

In the short-to-medium term, the company's focus will be on optimising its existing assets and processes and working in partnership with industry and research institutions to progress the technical and commercial viability of alternative technology options.

For the longer-term, the pathway has been updated to reflect the company's refreshed assessment of technology developments in DRI, using natural gas as a transitional step to green hydrogen to produce lower emissions steel. Five key enablers have been identified: 1) technology evolution, 2) raw materials supply, 3) firmed renewable energy, 4) hydrogen availability and 5) policy support.

For PKSW, this means that decarbonisation activities will be undertaken across two parallel streams of work. Firstly, in this next decade, activities will involve optimising existing blast furnace assets via exploring a range of initiatives to improve emissions intensity. Secondly, and in parallel, activities will involve building a pathway to meet BlueScope's goal of net zero emissions by 2050. This second future-orientated workstream includes a comprehensive technical investigation program.

For the short to medium Prioritised Options selected for further consideration, market barriers, pathway to commercialisation, timing and funding options are discussed.

Contents

List of acronyms and abbreviations

ARENA	Australian Renewable Energy Agency
AIE	Alkaline iron electrolysis
BF	Blast furnace
BFG	Blast furnace gas
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	Carbon monoxide
CO2	Carbon dioxide
COG	Coke ovens gas
DCA	Direct carbon avoidance
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
ESF	Electric smelting furnace
GHG	Greenhouse gas
H2	Hydrogen
H2-DR	Hydrogen-based direct reduction
HBI	Hot briquetted iron
HCI	Hot compacted iron
HPSR	Hydrogen plasma smelting reduction
ISEEM	Integrated steelworks energy and emissions model
ISREM	Integrated steelmaking reuse and emissions model
LCA	Life Cycle Analysis
LDG	BOF off gas, or Linz-Donawitz gas
MOE	Molten oxide electrolysis
NG-DR	Natural gas direct reduction
N2	Nitrogen
O2	Oxygen
OPEX	Operational expenditure
PCI	Pulverised coal injection
PKSW	Port Kembla Steel Works
RAFT	Raceway adiabatic flame temperature
R&D	Research and development
SAF	Submerged Arc Furnace
SCU	Smart carbon usage
SWOT	Strengths, Weaknesses, Opportunities and Threats
t	Tonne
tHM	Tonne of Hot Metal
TGR-BF	Top gas recycling – blast furnace
TRL	Technology readiness level
y	Years

1 Introduction

With the support of ARENA's Advancing Renewables Program, BlueScope, together with the University of Wollongong and Future Fuels CRC, has completed an investigation of current low emissions and future emerging decarbonisation technologies relevant to its Port Kembla Steelworks (PKSW). The overarching rationale for the Project is that climate action is central to BlueScope's purpose to strengthen communities for the future and is one of the Sustainability Outcomes that matters most to BlueScope's stakeholders.

Importantly, climate action is required to achieve the company's 2030 steelmaking greenhouse gas (GHG) emissions intensity reduction target and 2050 net zero goal.

This Project consisted of three phases:

Phase 1: Investigated potential GHG emissions reduction opportunities at PKSW and identified a set of Prioritised Options [1].

Phase 2: Investigated potential biomass and biochar supply options, pyrolysis equipment options to produce biochar from biomass, and pilot and plant trials of biochar [2].

Phase 3: This final report covering further assessments of the Prioritised Options identified in Phase 1 including:

- Qualitative assessment of operational, engineering, environmental and safety aspects for PKSW,
- Process integration (PI)-based flowsheet modelling of some Prioritised Options relative to a baseline PKSW operation,
- Final assessment process, and
- PKSW's decarbonisation roadmap, including planning for further investigations.

1.1 Phase 1 – Qualitative Options Analysis and Prioritised Options

The Phase 1 report [1] described the activities and outcomes of the initial investigation, where potential Smart Carbon Usage (SCU) and Direct Carbon Avoidance (DCA) technological pathways were assessed via a Qualitative Options Analysis (QOA) approach, using technical decision criteria relevant to PKSW. The QOA considered the impact of these technologies on BlueScope's GHG emissions intensity reduction targets.

The QOA processes and the Prioritised Options identified for PKSW considered both the short-to-medium (~5-15 years ahead) and long (more than 15 years ahead) term timeframes.

The QOA process involved:

- An evaluation of 17 current and future emerging SCU and DCA technological areas for:
    - Blast Furnace Ironmaking / Cokemaking / Sintering;
    - Alternate Ironmaking; and
    - Steelmaking
    - Carbon Capture, Utilisation and Storage (CCUS)

- Information Reviews of approximately 100 different processes and materials options across these areas, based on a general process description, material inputs and outputs, overall abatement pathway, key performance indicators, maturity and requirements to implement, and potential strengths and weaknesses.
- Utilisation of four Technical Decision Criteria for evaluation of each area, with specificity and application to PKSW:
  - Technology Readiness Level
  - Anticipated timeline and availability
  - Abatement potential (Scope 1 and Scope 2)
  - Potential production and key performance indicators impact
- A “Fatal Flaws” approach to identify (screen) non-viable technologies for PKSW, based on an inability to achieve at least one of three key objectives: BlueScope’s high-level business plans (e.g. major capital investments, including the planned No. 6 Blast Furnace reline and upgrade – more detail below), the energy sector’s future plans (e.g. renewable energy) and government policy changes.
- A project team-based evaluation.

Based on the QOA process, several Prioritised Options were identified for further assessment at PKSW. These are listed in Table a, as previously presented in the Phase 1 report [1], for the short-to-medium term and long-term timeframes.

In the short-to-medium term, the Prioritised Options were predominantly applications of SCU technological pathways, including novel charging materials for the Blast Furnace (BF), various biomass applications, hydrogen-enriched injection into the BF, waste heat recovery and waste gas recycling for the sintering plant, and increased scrap/Direct Reduced Iron (DRI) utilisation in the Basic Oxygen Furnace (BOF). These SCU pathways aligned with BlueScope’s public announcement in February 2022 that it was undertaking a feasibility study to reline and upgrade a blast furnace (No.6 Blast Furnace) at PKSW, with a final investment decision scheduled for later in 2023. Importantly, the reline and upgrade will build a bridge to future adoption of emerging technologies for lower emissions iron and steelmaking at PKSW, once these are commercially viable.

For the long-term, Prioritised Options are predominantly applications of DCA technological pathways, including electrolysis of iron ore, alternative ironmaking technologies combined with aligned steelmaking processes, hydrogen and potential CCUS (an SCU pathway).

Table a – Selected Prioritised Options for further assessment [1]

	CURRENT AND FUTURE TECHNOLOGIES	SHORT-MEDIUM TERM (5-15 YEARS)	LONG TERM (>15 YEARS)
	Blast Furnace Ironmaking		
SCU	**Novel charging materials to BF**		
	• Carbon containing agglomerates (CCA)		
	• Pre-reduced agglomerates (PRA)		
	• Ferro-coke		
SCU	**Biomass application in ironmaking**		
	• Biochar - Multiple applications		
SCU	**Hydrogen-enriched injection**		
	• Natural gas		
	• Coke ovens gas		
	• Hot reducing gas		
	• Biogas (biomass pyrolysis syngas)		
DCA	• Hydrogen		
	Sintering		
SCU	• Waste heat recovery from cooler and waste gas recycling		
	• Super-SINTER technology (SST)		
	Alternate Ironmaking		
DCA	**Electrolysis of iron ore**		
SCU/ DCA	**Fluidised bed direct reduction**		
	• Multiple equipment options		
SCU/ DCA	**Shaft furnace direct reduction**		
	• Multiple equipment options		
SCU	**Smelting Reduction (SR)**		
	• Multiple equipment options		
	Steelmaking		
SCU/ DCA	**DRI and scrap utilisation in Basic Oxygen Furnace**		
	• DRI and scrap utilisation in Basic Oxygen Furnace, including scrap preheating		
	• DRI utilisation in SAF-Basic Oxygen Furnace		
	• CONPRO (SMS)		
SCU/ DCA	**DRI and scrap utilisation in electric arc furnace**		
	• DRI-EAF or DRI-SAF		
	Carbon Capture, Utilisation and Storage		
SCU	Biological		
	Chemical		
	Absorption		
	Adsorption		
	Mineral carbonation		
Legend	Non-viable Technology	Possible Prioritised Option	Prioritised Option

1.2 Phase 2 – Biochar Investigation

The Phase 2 report [2] described the investigation of biochar and biomass supply options, pyrolysis equipment suitable for mass production of biochar, and the undertaking of pilot-scale testing and plant trials of biochar/coal mixtures injected into No. 5 Blast Furnace at PKSW. A summary of the findings is as follows:

- Biochar supply to PKSW from existing commercial suppliers within Australia appears unlikely given there is insufficient capacity in local production, and overseas supply would be difficult from sustainability and logistics perspectives.
- Several biomass supply options appear possible, either from forestry or waste sources. Forestry wastes and timber reclaimed from landfill streams appear to be the most sustainable, however the current lack of investment in utilising forestry wastes and heavy metals contamination of waste timber make these options a challenge 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.
- 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 develop further if large scale biochar usage was to proceed at PKSW.
- Pilot testing at UOW and plant trials at PKSW's No. 5 Blast Furnace showed that biochar/coal blends of up to approximately 20% biochar could be successfully used to replace pulverised coal in BF operations for at least short periods of time, without detriment to the stability, productivity of the process or the quality of the hot metal.
- Given the positive results of these trials, it was 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.

1.3 BlueScope's Steelmaking 2030 Target and 2050 net Zero Goal

BlueScope has set both a company-wide 2050 net zero goal and a 2030 steelmaking target, refer Figure 1. Achieving the net zero goal is dependent on five key enablers, as outlined in BlueScope's 2023 Sustainability Report. The 2030 steelmaking target is a 12% reduction in Scope 1 and Scope 2 emissions intensity between 2018 and 2030 across BlueScope's steelmaking activities.

Figure 1 BlueScope's 2050 Goal and 2030 Steelmaking Targets

GOAL

NET ZERO

GHG emissions across our operations by 2050[1]

$150m

In 2021 BlueScope made an inital allocation of capital for climate projects and initiatives over the next 5 years

TARGETS

12%

GHG emission intensity reduction by 2030 for our steelmaking activities[2]
(based on 2018 levels)

30%

GHG emission intensity reduction by 2030 for our non-steelmaking activities[3] (based on 2018 levels)

1. Our net zero goal covers BlueScope's Scope 1 and Scope 2 GHG emissions. Achieving our net zero goal is dependent on several enablers, see below.
2. This Target translates to a target of 1% year-on-year emissions intensity reduction (from the 2018 baseline) across our steelmaking sites.
3. The non-steelmaking target applies to our mid-stream activities that include our cold rolled, metal coating and painting lines and long and hollow sections. It excludes our downstream activities.

Technology evolution	Development and diffusion of ironmaking technologies to viable and commercial scale
Raw materials supply	Access to appropriate quality and sufficient quantities of economic raw materials
Firmed, renewable energy	Access to affordable, firmed large-scale renewable energy
Hydrogen availability	Availability of competitively priced green hydrogen, with natural gas enabling the transition to green hydrogen
Policy support	Supportive and consistent policies across all these enablers to underpin decarbonisation investment and avoid carbon leakage

1.4 BlueScope’s No. 6 Blast Furnace Reline

BlueScope’s No.5 Blast Furnace’s current campaign commenced in 2009, with an expected campaign life of approximately 17 years. On 21 August 2023, BlueScope announced that the Board had approved the $1.15 billion for a comprehensive reline and upgrade of the No.6 Blast Furnace (6BF). Implementing the reline and upgrade project will allow BlueScope the necessary time to develop, test and pilot alternative viable lower emissions ironmaking pathways. It also recognises the practical reality of the time frames required for the establishment of the critical enablers to lower emissions steelmaking; enablers that underpin BlueScope's 2050 net zero goal. The reline does not lock BlueScope in to a full 20-year blast furnace campaign. In contrast, it secures PKSW’s immediate future while enabling a transition to lower emissions steelmaking as soon as it is commercially feasible. In this sense the reline project is a bridge to the future and critical to maintaining the sovereign capability of flat steelmaking in Australia. The relined 6BF is expected to be commissioned in mid to late 2026.

The No. 6 Blast Furnace reline project scope is broader than a typical reline with comprehensive upgrade of the BF facility and related infrastructure. This includes improvements which are designed to deliver reductions in GHG emissions within existing BF technology, as well as allow for the retrofit of other prospective GHG emission reduction technologies. Technologies proposed to reduce emissions within existing processes include the installation of a Top Gas Recovery Turbine to generate electricity, a Waste Gas Heat Recovery system, and design improvements to; reduce reductant consumption, allow for potential future alternative reductants, such as hydrogen-rich Coke Ovens Gas and renewable hydrogen, and the optimisation of raw material inputs.

1.5 BlueScope’s Indicative Decarbonisation Pathway

BlueScope’s indicative iron and steelmaking decarbonisation pathway, refer Figure 2, has two phases:

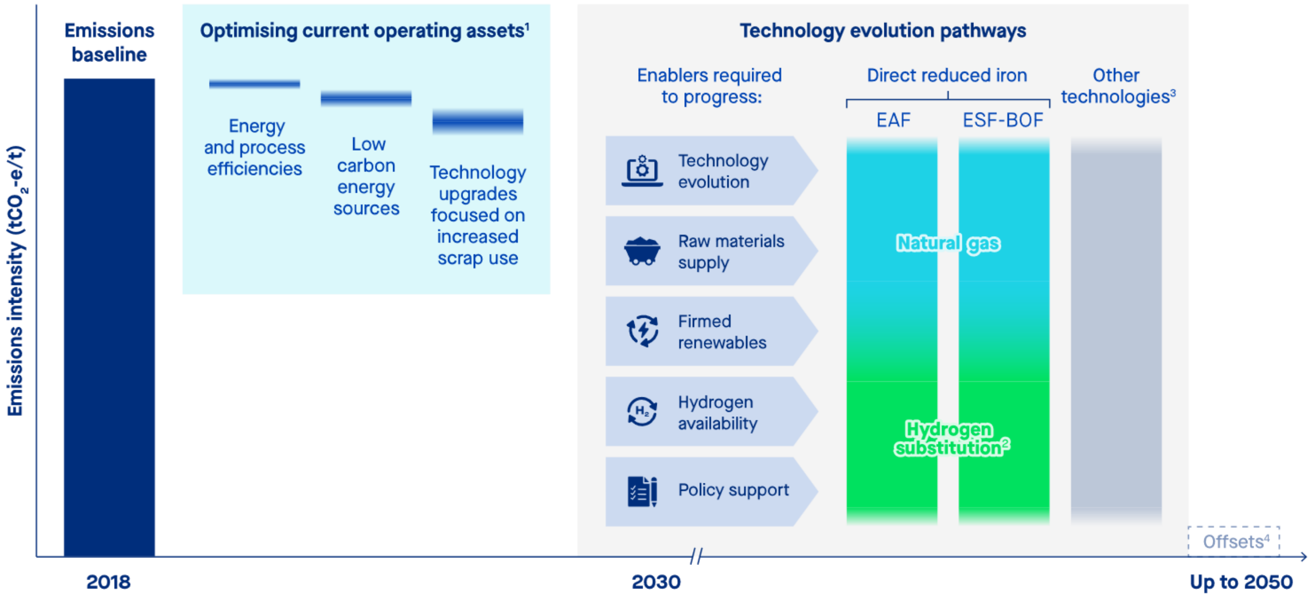
(i) optimising current operating assets
(ii) technology evolution pathways towards its 2050 net zero goal.

In the short-to-medium term, the company’s focus will be on optimising its existing assets and processes, and working in partnership with industry and research bodies to progress the technical and commercial viability of alternative technology options.

For the long term, the pathway has been updated to reflect the company’s refreshed assessment of technology developments in DRI, using natural gas as a transitional step to green hydrogen to produce lower emissions steel. Five key enablers have been identified: technology evolution, raw materials supply, firmed renewable energy, hydrogen availability and policy support.

For PKSW, this means that decarbonisation activities are undertaken in two parallel streams of work. Firstly, in this decade, optimising existing blast furnace assets via exploring a range of initiatives to improve emissions intensity. Secondly, and in parallel, looking over the horizon to the next decade, building a pathway to meet our goal of net zero emissions by 2050. This second future-orientated workstream includes a comprehensive technical investigation program.

Figure 2 BlueScope's indicative iron and steel decarbonisation pathway



1. Optimising current assets involves working within currently available technology options to improve the efficiency of assets and processes, including upgrading technology where there are supportive enablers.
2. Contingent upon commercial supply of hydrogen from renewable sources.
3. Other technologies include electrolysis, CCUS and biocarbon, etc.
4. We retain the option to use offsets to meet our 2050 net zero goal where direct abatement is not technically or commercially feasible.

2 Further Assessment of Identified Prioritised Options

Building on the Prioritised Options identified in the Phase 1 Report, BlueScope together with the University of Wollongong carried out further assessments to select those options that have the greatest potential to assist BlueScope in reducing its GHG emissions at PKSW.

A summary of key comments concerning future progression of Prioritised Options described in Table a is provided in Tables 1 and 2, for the short-to-medium term and long term, respectively. These tables provide some clarification with respect to the Prioritised Options that will be further assessed.

Table 1 – Identified short-to-medium Prioritised Options

Short-to-Medium Term Technologies	Key Comments
Novel charging materials to BF: • Carbon Containing Agglomerates (CCA) • Pre-Reduced Agglomerates (PRA) • Ferro-coke	Novel charging materials have the potential to improve process efficiencies and hence, reduce carbon consumption per tonne of hot metal produced.
Biomass application to ironmaking: • Focus on renewable biochar as an alternative and partial substitute for ~400,000 t per annum of pulverised coal injected into No. 5 Blast Furnace	As discussed in the Phase 1 report [1], there are several opportunities to use renewable biochar within an integrated steelworks. The Phase 2 report specifically investigated the use of biochar as a potential replacement for PCI, with successful trials of up to 30% biochar processed through the PKSW PCI Plant and injected into No. 5 Blast Furnace for a maximum 24-hour period.
Hydrogen-enriched injection: • Natural gas • Coke ovens gas • Hydrogen	Natural gas, coke ovens gas and hydrogen will be the focal points for progressing this Prioritised Option, potentially in both timeframes. Hot reducing gas and biogas are not significant emissions reduction options in either time frame. Hot reducing gases require gas reforming with additional facilities and equipment, adding significant complexity and cost. Biogas from biomass pyrolysis has a low hydrogen content and if available would either be used within the pyrolysis process or even fed into the integrated steelworks' gas system.
Sintering: • Waste heat recovery from cooler and waste gas recycling • Super-SINTER technology (SST)	Future sintering operations may involve additional heat recovery from the sinter cooler, followed by recycling of waste gas from sub-strand wind boxes.

Steelmaking: • DRI and scrap utilisation in the Basic Oxygen Furnace	Focus is on reducing site emissions intensity by using additional iron units in the BOF.
Carbon Capture Utilisation and Storage (CCUS): • Carbon Capture and Storage (CCS) • Carbon Capture and Use (CCU)	A higher-level split is used to classify the different CO_2 separation technologies listed in Table a from Phase 1.

Table 2 Identified long term Prioritised Options

Long term Technologies	Key Comments
Alternate Ironmaking: • Electrolysis of iron ore • Fluidised bed direct reduction • Shaft furnace direct reduction • Smelting reduction	Alternate ironmaking technologies are considered as future low emissions options for ironmaking.
Steelmaking: • DRI utilisation in the BOF • DRI utilisation in the EAF	DRI utilisation in the BOF relates to the potential to use an Electric Smelting Furnace (ESF) between a DRI plant and the BOF, which melts the DRI iron, completes the reduction of the iron and allows separation of the liquid iron product and impurities. DRI utilisation in the EAF is considered a mature technology but requires high quality iron ore (magnetite-based) feed into the DR process to be commercially viable. CONPRO, a proprietary technology, is a modified EAF, which combines the technological advantages of the BOF and EAF, providing flexibility in choice of charge materials and energy sources. However, potential adoption of this technology would be contingent on significant supply of suitable scrap which is currently unavailable in the Australian context. Note: whilst Table a from Phase 1 referred to the SAF (Submerged Arc Furnace), the descriptor, Electric Smelting Furnace (ESF) is a more accurate description of the technology.

2.1 Qualitative assessment of operational, engineering, environmental and safety aspects for PKSW

As part of the further assessment, a detailed Evaluation Framework covering each Prioritised Option was completed. Unless data was available, this was based on a qualitative assessment of operational, engineering, environmental and safety aspects as they pertain to PKSW.

The aim was to identify key issues and specific development gaps for each aspect, as well as the steps required for adapting or adopting the Prioritised Options at PKSW. The specific Technology Readiness Level for each option was previously determined in Phase 1 report. These steps serve as an initial basis for any future targeted investigations and the setting out of resources required.

Appendix 1 provides full details of this assessment, and a basis for the Final Assessment Process described in Section 3.

2.2 Preliminary process integration-based simulation modelling of Prioritised Options relative to a baseline PKSW operation

Following the identification of SCU and DCA Prioritised Options, a preliminary desktop study was undertaken for some of these options. An overall summary of the findings of this investigation follows, together with an extended outline of the methodology used, key results and discussion. A more detailed report is provided in Appendix 2.

Overall Summary

This technical evaluation involved the development, validation and application of a process simulation model describing major units of PKSW's current manufacturing operations, and PKSW operations with some Prioritised Options included. This model was used to assess potential emission (CO_2) reductions with the use of four alternative reductants in No. 5 Blast Furnace (5BF): biochar, torrefied biomass (TB), coke ovens gas (COG) and hydrogen.

The Integrated Steelmaking Reuse and Emissions Model (ISREM) is a validated process simulation model that carries out full mass and energy balances of the major steelmaking process units, allowing assessment of hypothetical scenarios as well as carrying out process and material optimisation investigations. The PKSW process units modelled include the sinter plant, coke ovens, 5BF, lime kiln and basic oxygen furnace (Figure 5). It does not include the PKSW power plant. As ISREM involves interconnections and recycles across PKSW, the numerical solution does not proceed sequentially (i.e. unit-by-unit basis) but rather, thousands of equations are solved simultaneously. ISREM was developed based on a more comprehensive process simulation model of PKSW developed by BlueScope known as the Integrated Steelworks Energy and Emissions Model (ISEEM).

For the present investigation, ISREM was initially validated based on best available historical data. This provided a baseline case. It should be noted that estimates of CO_2 emissions reduction that require the model to predict operational conditions outside of validated process conditions may be associated with a degree of uncertainty. It should also be noted that estimates of CO_2 emissions reduction are reliant on a greatly simplified representation of the interworks gas energy balance due to the exclusion of the power plant from the model. The reduction of PKSW CO_2 emissions from this baseline case resulted from either the use of carbon-neutral biomaterial (biochar and TB), or from the displacement of input carbon by hydrogen (COG and H_2).

The results showed that substitution of 30% of pulverised coal injection (PCI) with biochar and TB was predicted to result in 6.6% and 3.8% reduction of PKSW CO_2 from baseline, respectively. The two biomaterials are produced under different conditions, and 5BF responds differently to each. For example, an operational control parameter used at 5BF, the Raceway Adiabatic Flame Temperature (RAFT), increases with biochar but decreases with TB. Additional 5BF O_2 injection is required in the TB case. The energy content of the 5BF top gas is also different, decreasing for biochar and increasing for TB. The degree of carbon offset for the same input mass rate of biomaterial is related to its carbon content, being higher for biochar than TB.

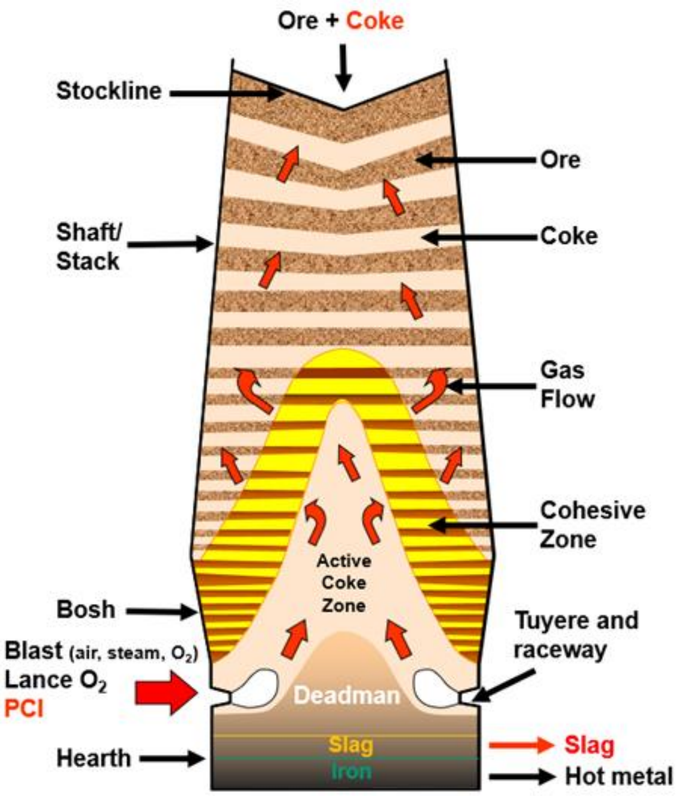
A decrease in RAFT and reduction in blast air were predicted for the injection of both COG and pure H_2. There was also a reduction in 5BF top gas carbon content, with a consequent increase in H_2 and H_2O concentrations, and an increase in the top gas energy content.

Overall, PKSW CO_2 reduction for COG injection was limited by COG availability. At 200 m^3 COG per tonne of hot metal (tHM) produced by 5BF, there was an overall PKSW CO_2 reduction of ~3% from baseline. Injection of H_2 up to a hypothetical limit of 30 kgH_2/tHM was predicted to decrease PKSW CO_2 emissions from 14 to 16% from baseline, depending on the degree of H_2 preheating. H_2 injection was modelled at 25°C, 600°C and 1200°C. The higher CO_2 reduction and most favourable carbonaceous replacement ratios were obtained at 1200°C H_2 preheating. Additional 5BF O_2 injection was required for the TB and H_2 enriched gas cases, however the total 5BF O_2 requirement was predicted to decrease for pure H_2 injection because the increased pure O_2 injection was more than offset by the reduced blast air requirement and consequent decrease in O_2 input from ambient air.

Methodology, key results, and discussion

An outline of the methodology, results and discussion is provided here, with a more detailed description in Appendix 2. By way of introducing the methodology and basis for the assessments undertaken, Figure 4 provides a basic outline of the main process attributes of a blast furnace such as 5BF.

Figure 4 Process attributes of a blast furnace e.g. 5BF



Representing a large chemical reactor and counter-current heat exchanger, 5BF is effectively the final element of the ironmaking process chain at PKSW, providing hot metal to the BOF for steelmaking. The BF can be separated into various internal zones, such as the hearth, bosh and shaft or stack, by its physical structure and the chemical processes occurring inside it. Inside the BF, the iron-bearing burden materials ("ore") and coke are introduced in alternating layers. Hot, oxygen-enriched, humidified air ("blast") is injected through specialized water-cooled nozzles called tuyeres at the BF raceway, where oxidation of descending coke occurs. Pulverised coal (PC) is also introduced and combusted within the raceway. One important measure often used for BF operational control is the calculated Raceway Adiabatic Flame Temperature (RAFT). Other measures include gas reduction efficiencies, etaCO and etaH_2, as well as stack reduction efficiency (SRE), all of which are related to BF top gas composition.

For each technological option, alternative reductants were introduced with the objective of lowering either PC or coke usage in 5BF, and subsequently decreasing carbon emissions across all evaluated operating units.

The process simulation model ISREM was used to undertake the assessment.

The options were assessed with reference to a PKSW Base Case. For this baseline case (Base Case), ISREM was validated based on yearly average data (2018 to 2019), where the production rate of 5BF was 308 tph of HM.

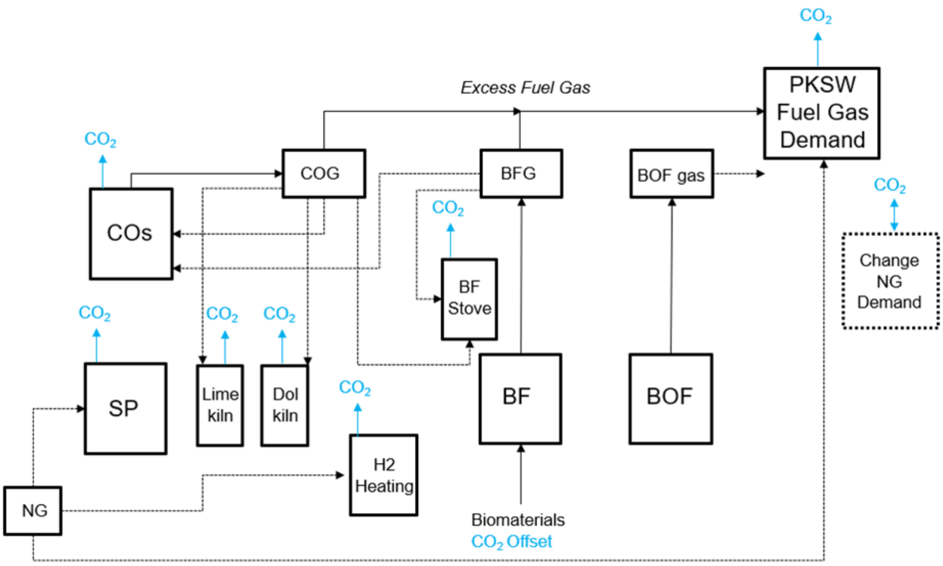
Key BF parameters for the Base Case were:

- RAFT of 2384^{o}C,
- Top gas temperature of 120^{o}C,

- Additional supplied oxygen of 20,800 Nm^3/h (added to hot blast and directly to the raceway via PC lance),
- Hot blast temperature fixed at 1200 °C,
- SRE of 91.2%

The scope of the ISREM process simulation model for CO_2 accounting purposes is shown below (Figure 5).

Figure 5 CO_2 accounting across the ISREM model



The relative change in CO_2 emissions from baseline was calculated across the ISREM flowsheet for each modelled scenario, taking into the account the utilisation and fate of internally generated fuel gases. Where excess fuel gas leaves the ISREM boundary, its energy content was considered, with an assumption of complete combustion of this stream. This excess fuel gas is used for downstream heating duty in PKSW in process units such as power plant, rolling mills etc. Since the model does not include the power plant, the CO_2 emissions impact of any variation in the total downstream energy available from this excess fuel gas stream was calculated using the simplifying assumption of a fixed energy demand beyond the model boundary, using natural gas (NG) as a balancing gas.

The reduction in net CO_2 emissions was calculated from model inputs and outputs, considering:

- Net carbon reduction from offset of PC by biochar or TB, assuming that carbon in the utilised biomaterials is net carbon neutral (Norgate et al., 2012) [4]
- Change in CO_2 emissions from heating of altered blast air in BF stoves
- CO_2 emissions that result from NG-fired heating of H_2 prior to BF injection (for applicable scenarios)
- Net CO_2 emissions from individual unit operations:
  - SP
  - CO
  - Kiln
- CO_2 emissions from combustion of excess fuel gas (COG and BFG) generated in ISREM but used elsewhere in PKSW
- CO_2 emissions from combustion of BOF gas

- Any CO_2 emissions associated with a change in NG usage as a result of altered energy content in the excess PKSW fuel gas

Each modelled scenario was set up with specific conditions for key process variables, with some fixed in value, and others set as ‘free’ allowing them to change with the problem solution. Fixed variables for 5BF included SRE, hot metal (HM) rate, top gas temperature, the input rate of pellet and lump ore, injection steam rate and blast temperature. Free variables were O_2 input to blast, bosh gas volume, sinter rate, slag rate, blast furnace gas (BFG) rate and blast volume. Other variables such as the total input rate of PC and biomaterial and the coke rate were fixed or free depending on the desired modelling outcome i.e. the combined PC and biomaterial rate to 5BF was fixed for the biomaterial scenarios with coke rate free, with these two conditions swapped for the injection of H_2-enriched gases (COG and pure H_2).

The injection of two classes of biomaterial into 5BF were assessed in the study, these being biochar and torrefied biomass (TB). These two materials are both produced from raw biomass, with TB produced at temperatures between 200-300 °C and biochar between 300-600 °C with longer residence times.

The carbon content of TB is lower than biochar, with correspondingly higher volatile matter content. These characteristics relate directly to production conditions. The biochar and TB were assumed to be renewable resources, with net zero CO_2 emissions. This is because the wood-based carbon cycle (biomass) is very short (5-10 years) compared to fossil-derived fuel (around 100 million years) (Norgate et al., 2012) [4].

Trialled biomaterial injection rates varied from 5-30% of the total PC/biomaterial input stream. The CO_2 benefit associated with the use of both biomaterials at 30% displacement of PCI was around 4-7% from baseline, being higher for biochar than TB. The major contributor to this decrease in emissions was the carbon offset inherently associated with these materials as renewable biomass-derived resources. The modelling results indicated a slight rise in RAFT with biochar injection, with a drop in RAFT for TB. This RAFT cooling effect following TB injection has been noted in literature (Babich, 2021) [5], and is likely related to its higher volatile matter content. These trends are shown in Figure 6.

The injection of H_2 rich gases (e.g. COG and pure H_2) typically leads to a decrease in both blast volume and RAFT (Chen et al., 2021) [6]. This was observed for both COG and H_2 injection. There was also an increase in both H_2 and H_2O concentration in the BFG for both COG and H_2 injection. The CO content of the BFG also increased in the COG injection cases, almost certainly related to COG’s carbon content (~24% CH_4, 6% CO and 2% CO_2).

The extent of COG utilisation is dependent on the excess available for injection. The amount of excess COG available for BF injection may change as a result of new process conditions, or, if there is an increased downstream requirement. COG injection at 200 m^3 COG/tHM was associated with a CO_2 reduction of 3% from baseline, as shown in Figure 7.

Figure 6 CO_2 reduction and RAFT with biochar and TB injection

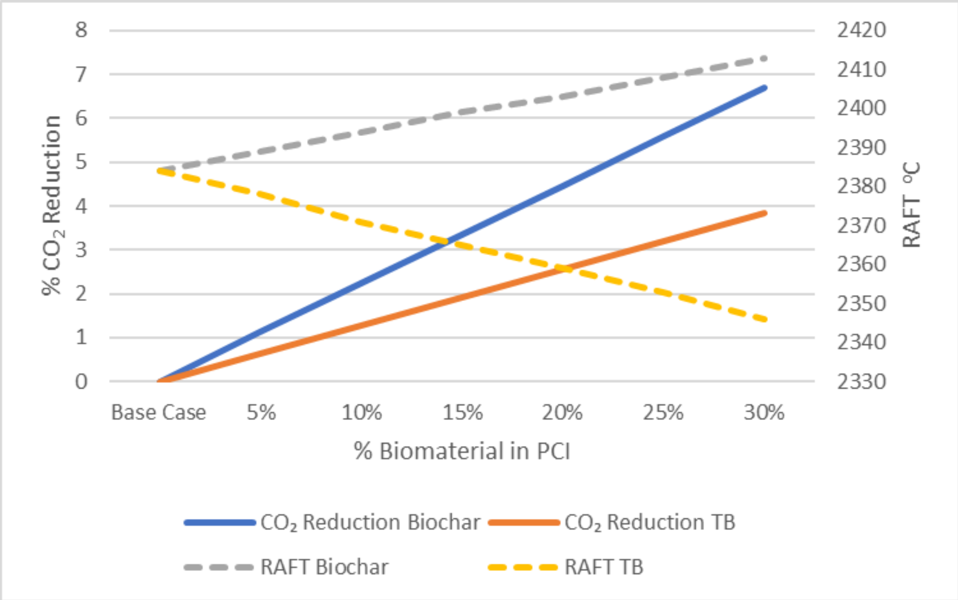
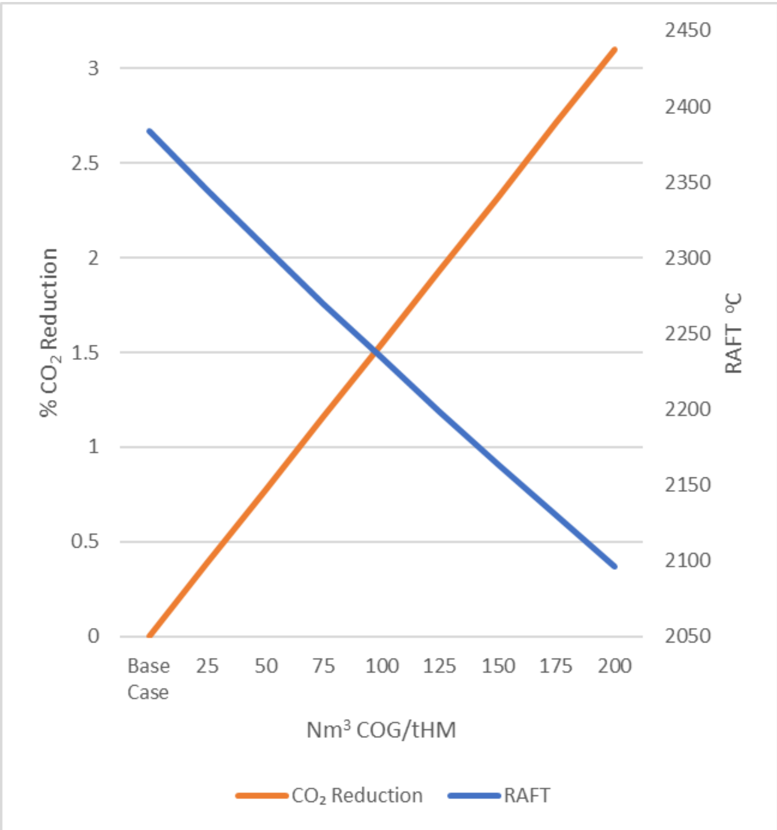
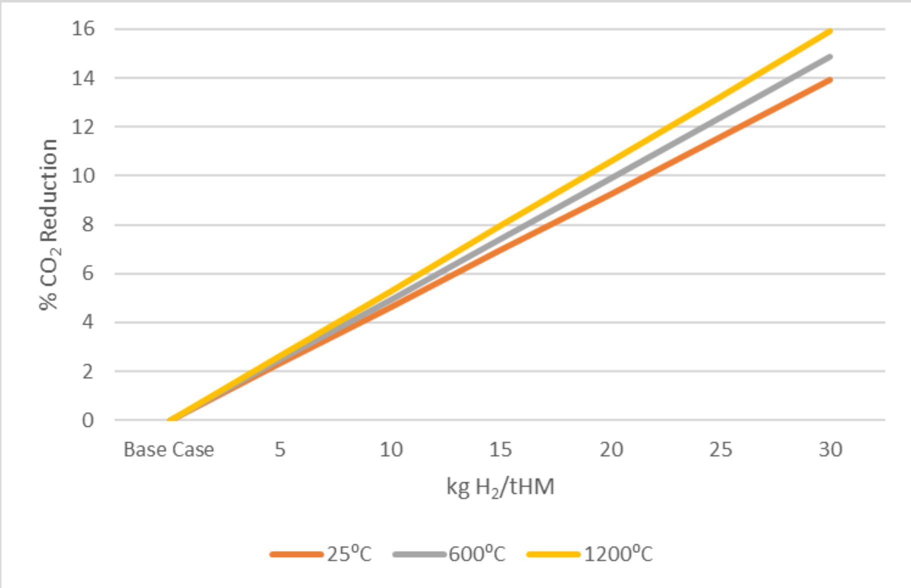


Figure 7 CO_2 reduction and RAFT with COG injection



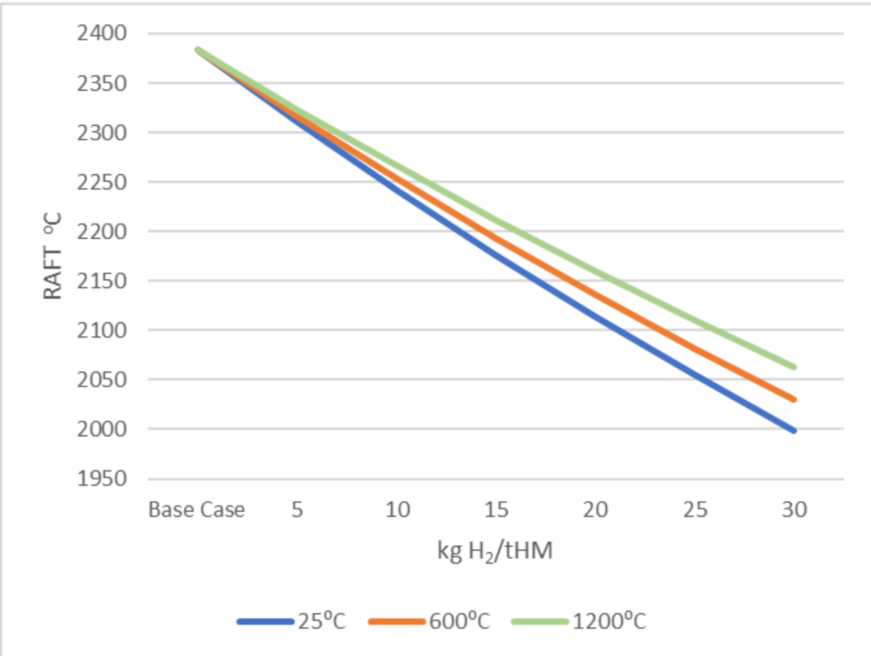
H_2 scenarios were run up to maximum injection rate 30 kgH_2/tHM for three inlet conditions: 25°C (ambient), 600°C and 1200°C (Figure 8).

Figure 8 CO_2 reduction with H_2 injection



Overall, the reduction in CO_2 emissions in the modelled scenarios varied between ~2% (at 5kg H_2/tHM and 25°C) and ~16% (at 30kg H_2/tHM and 1200°C) from the Base Case. The extent of CO_2 reduction increased with the degree of H_2 injectant heating, rising from 13.9% at 25°C to 14.9% at 600°C and 15.9% at 1200°C (all cases at 30 kg H_2/tHM). RAFT depression in the H_2 cases was less pronounced when heated H_2 was injected, again likely due to the additional sensible heat provided to 5BF in these cases (Figure 9).

Figure 9 RAFT depression with H_2 injection



The overall O_2 input to 5BF increased for all COG scenarios, but decreased in all H_2 injection scenarios, particularly for the heated cases, where the heated hydrogen provided sensible heat that would otherwise need to be supplied by coke or PCI combustion (Babich, 2021) [5].

For both COG and pure H_2 injection cases, the highest CO_2 reductions resulted from decreased PCI, decreased emissions from the BF stoves due to lower blast air, lower BFG carbon content and higher BFG CV, lower coke ovens emissions, again due to lower BFG carbon content, and reduced NG use due to higher downstream excess fuel gas energy content.

It should be noted that the ISREM process simulation model operates within certain constraints and underlying assumptions, such as steady state operation, and the thermodynamic representation of processes and chemical species. The model has been validated based on a specific yearly dataset (2018-2019), which is historical, and therefore might not fully reflect current or future production rates or feed materials. It was assumed that the use of yearly average data was sufficient to remove process variability across PKSW. Operational conditions, key parameters and fixed efficiency factors are also consistent with the validation dataset. As a consequence, estimates of carbon emissions that require the model to predict outputs outside of these validated process conditions may be associated with a degree of uncertainty.

Finally, the process simulation model does not contain all units in the PKSW, and so some complexities of cross-integration between current or future operational units may not be included e.g. power generation etc.

3 Final Assessment Process

The following section reviews each of the Prioritised Options, based on the Information Reviews gathered from Phase 1 of the Project [1] and further assessments conducted in Section 2 of this report. Consideration is given as to whether the technology is worth pursuing for PKSW and if so, recommending what actions might be taken for the short-to-medium and long term.

The assessment considers the following aspects:

- Effort to implement:
  - Current TRL, and
  - Gaps identified in Section 2
- Abatement level,
- Operational risk, and
- Cost to implement[2]:
  - CAPEX
  - OPEX
  - \$/t CO_2 reduction

In global terms, BlueScope is a relatively low volume steelmaker. PKSW has just one operating ironmaking blast furnace providing hot metal for steelmaking operations, producing approximately three million tonnes of steel per annum. The size of the PKSW operation means that:

- A conservative approach to the transition to low emissions steelmaking is required, with mature technologies being utilised to reduce operational and hence business risk, and
- With limited resources, BlueScope must focus on a select few technologies (Prioritised Options) that have the greatest potential to provide financially viable emissions reductions.

Short-to-Medium Term Prioritised Options

3.1 Novel Charging Materials to the Blast Furnace

Novel charging materials to the blast furnace include Carbon Containing Agglomerates (CCA), Pre-Reduced Agglomerates (PRA) and Ferro-coke are summarised in Tables 3-5, respectively. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.1.

Recommendations: Both CCA and Ferro-coke are carbon-bearing materials (depending on the source of the carbon, low-medium decarbonisation value), which require substantial further development. Based on this, no further development work is proposed but these technologies will continue to be monitored.

PRA in the form of Hot Briquetted Iron (HBI) produced using a DR process, is, to a limited extent, a globally traded commodity, though most production is captive to downstream users. As shown in Figure 10, Kobe

[2] As part of this project, BlueScope submitted a confidential economic model to ARENA, which provides background on the costs to implement the majority of the Prioritised Options considered.

Steel report a potential 12% reduction in overall ironmaking GHG emissions is possible [9], taking Scope 3 emissions into account. The ongoing cost/benefit of HBI will need to be monitored and included in PKSW's material selection processes. Further investigations would be required to conduct a HBI trial.

Table 3 Novel Charging Materials to BF - Carbon Containing Agglomerates (CCA)

Description	CCAs are pellets or briquettes comprised of a mixture of carbonaceous (coal, coke fine or carbon-rich materials) and iron oxide materials (iron ore fines or iron-bearing steel plant by-product fines). The close contact significantly improves carbon gasification and iron reduction kinetics, leading to a lower equilibrium temperature between reducing gas and wüstite.
TRL	8
Development activities	Cold-bonded briquettes were charged into BFs of SSAB at a rate of 100-120 kg/tHM. CCAs are currently used in six Nippon Steel BFs. However, industrial application of CCA is still limited.
Short to medium/long term	Short to medium term only
Development time frame for PKSW	5+ years Based on no CCA supply chain or a well-defined CCA product/production process.
Significance of identified gaps	Refer Table A1.1 for more detail. No current supply chain. Need to improve understanding of: CCA performance in the BF, Optimal materials for CCA, and Production process for CCA, including equipment.
Process simulation modelling	N/A
Abatement level	Given it is a carbon product, abatement level likely to be low, if carbon is from fossil sources. Use of biochar as the carbon source could improve the abatement level.
Indicative cost	Not known - not currently a globally traded commodity.
Comments	Development would require significant resources. Better alternative likely to be the use of HBI. Note there may be some synergies with biochar usage, however, which could make this more attractive, particularly if HBI supply is limited.
Consider further?	No
Recommended activities	Continue to monitor

Table 4 Novel Charging Materials to BF – Pre-Reduced Agglomerates (PRA)

Description	PRAs are partially reduced pellets and sinters, or DRI (or Hot Briquetted Iron, HBI). The latter are usually produced in shaft-based DRI processes. The focus here will be on HBI, which is a globally traded commodity.
TRL	9
Development activities	HBI produced through a DR process such as Midrex has been utilised in different BFs (AK Steel [7], Voestalpine Linz [8], and Kobe Steel [9, 10]). Kobe Steel's No. 3 blast furnace (4,844m^3) at Kakogawa Works in Hyogo Prefecture, Japan verified that the use of HBI can reduce overall ironmaking emissions (including

	upstream DRI) by approximately 12%, refer Figure 10. This level of emissions reduction is worthy of further consideration.
Short to medium/long term	Short to medium term only
Development time frame for PKSW	1 year Based on the need to run trials and evaluate performance.
Significance of identified gaps	Refer Table A1.1 for more detail. Safe transport and storage. Process to enable HBI to be fed into the BF. Trial and develop operating regime. Understand plant wide impacts. Technoeconomic assessment.
Process simulation modelling	N/A
Abatement level	Low-medium, with Kobe Steel suggesting an overall 12% reduction in ironmaking emissions (including Scope 3).
Indicative cost	A basic concept estimation [47} suggests this option would be economically challenged without a considerable carbon price, driven mainly by the cost differential between iron ore and HBI.
Comments	Has potential, particularly considering the future transition to DRI production in Australia and/or at PKSW. Very low capital cost to implement.
Consider further?	Yes
Recommended activities	Further investigate what would be required to conduct a HBI trial.

Figure 10 Kobe Steel DRI into BF approach [9]

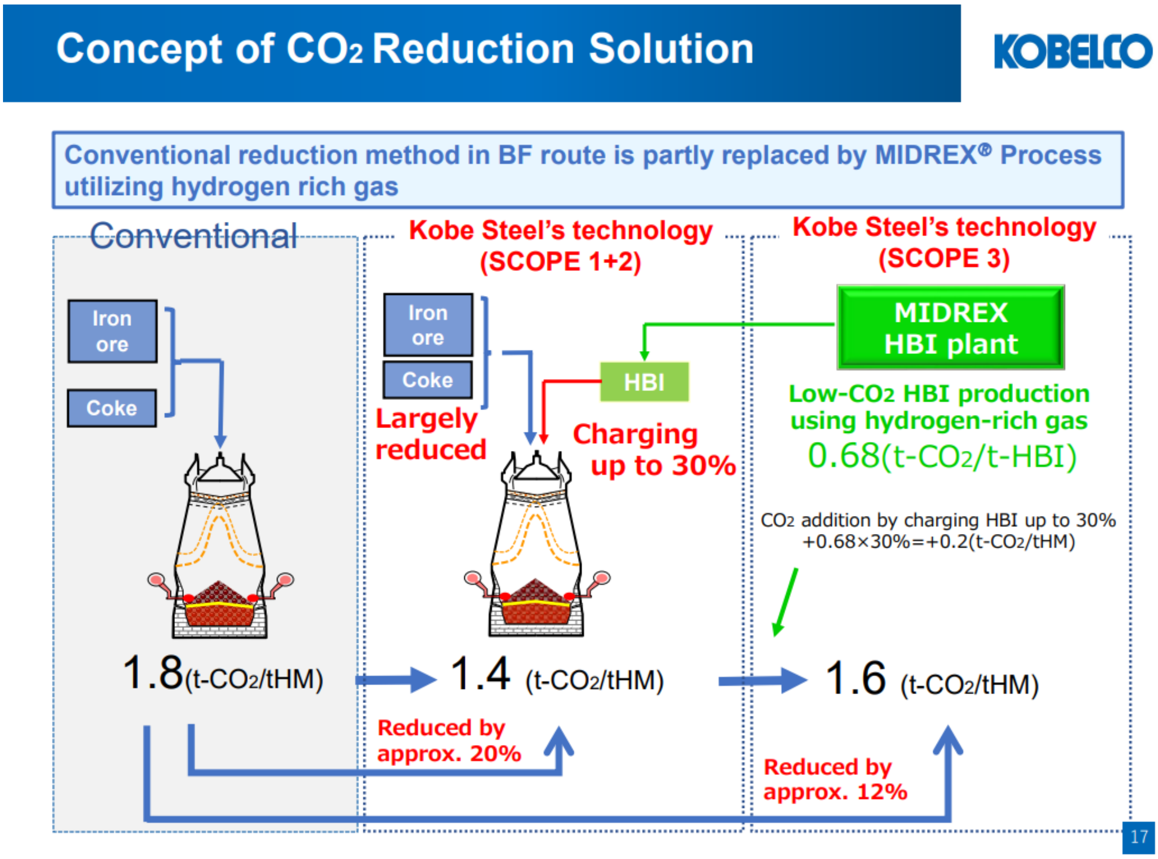


Table 5 Novel Charging Materials to BF – Ferro-coke

Description	Ferro-coke is a mixture of 70% highly-reactive coke and 30% low grade iron ores in close contact, with the latter acting as a catalyst for coke gasification.
TRL	7
Development activities	In 2020, NEDO and JFE Steel announced that they had completed a medium-scale ferro-coke production facility with a capacity of 300 t/day [11]. The new facility is a shaft-based furnace, built in cooperation with Kobe Steel and Nippon Steel. The aim is to develop ferro-coke production technology that reduces energy consumption and CO2 emissions in the ironmaking process by ~10%.
Short to medium/long term	Short to medium term only
Development time frame for PKSW	5-10 years Based on no ferro-coke supply chain or a well-defined ferro-coke product/production process.
Significance of identified gaps	Refer Table A1.1 for more detail. No current supply chain. Need to better understand: Ferro-coke performance in the BF, and Production of ferro-coke, including equipment.
Flow Sheet modelling	N/A
Abatement level	Kobe Steel and Nippon Steel aim for a 10% reduction in CO2 emissions. This may be a challenge for a coke-based product.
Indicative cost	Not known - not currently a globally traded commodity.
Comments	Would require significant resources to move forward, better alternative likely to be the use of HBI.
Consider further?	No
Recommended activities	Continue to monitor

3.2 Biomass Applications in Ironmaking - Biochar

Biochar, as an alternative or partial replacement to PCI coal, is summarised in Table 6. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.2.

Recommendations: Following successful trials of up to 30% biochar mixed with PCI coal for 24 hours at PKSW it is proposed, to enable longer duration trails to be conducted, to further investigate those potential suppliers planning to produce biochar in Australia.

Table 6 Biomass Applications in Ironmaking - Biochar

Description	Sustainably sourced biomass materials (wood, crops, animal waste, landfill gas, biofuel, etc) may be considered a carbon-neutral resource in life cycle analysis and therefore, carbon emissions reductions may be attributed to its carbon neutrality. For this study, BlueScope has focused on the use of biochar as a PCI coal alternative. Other alternative applications exist in the short-to-medium term, contingent on biomass supply and biochar properties/quality.
TRL	7-9

Development activities	Charcoal injection is employed in Brazil BFs at an injection rate of 100–190 kg/tHM. ArcelorMittal's Torero Project (Gent, Belgium) is to set up a demonstration plant to convert waste wood into biochar through torrefaction, aiming to partially replace the coal injected into the blast furnace. As of July 2023 the plant is being commissioned. As part of this study, BlueScope, with partner UOW, completed pilot tests and plant trials of up to 30% biochar for 24 hours to understand what issues, if any, would be encountered with partially replacing PCI coal with biochar. The tests and trials were successful with only minor adjustments to plant operations required.
Short to medium/long term	Both short to medium term for the BF and there is the potential for use longer term in DRI-ESF route dependent on specific biochar properties.
Development time frame for PKSW	2+ years Based on current limited biochar supply in Australia.
Significance of identified gaps	Refer Table A1.2 for more detail. 2023 biochar trials positive for PCI addition. Remaining major gaps: Understand operational impact of using biochar for significantly longer than a 24-hour trial. Supply of biomass/biochar The ideal biochar for the furnace and pyrolysis equipment. Utilisation/valorisation of pyrolysis by-products other than through use for heat/electricity generation
Process simulation modelling	Substitution of 30% of pulverised coal injection (PCI) with biochar and torrefied biomass (TB) was predicted to result in 6.6% and 3.8% reduction of PKSW CO2 from baseline, respectively. The two biomaterials are produced under different conditions, and the blast furnace (BF) responds differently to each. The Raceway Adiabatic Flame Temperature (RAFT) increases with biochar but decreases with TB. Additional BF O2 injection is also required in the TB case. The energy content of the BF top gas is also different, decreasing for biochar and increasing for TB. The degree of carbon offset for the same input mass rate of biomaterial is directly related to its carbon content, being higher for biochar than TB.
Abatement level	It is estimated that the replacement of 30% of PCI coal (105kt) by biochar would reduce PSW's emissions by approximately 309kt CO_2, or 4.3% [47].
Indicative cost	A 30ktpa pyrolysis facility at PKSW will cost in the order of $100M CAPEX[47]. Currently investigating supply of biochar from production facilities elsewhere.
Comments	Can meet both current and future needs. Ideally need in the order of 10,000t to 20,000t for further trials. Must compete with PCI coal price, incorporating the carbon price. No Australian supply chain for bulk biochar. Concerns with sustainability and social aspects of overseas supply. Current options for use of pyrolysis by-products (which could make around 40% of the pyrolysis process output) aside from combustion for energy purposes are limited, which makes the economics of biochar usage more challenging.
Consider further?	Yes

Recommended activities	To enable longer duration trials to be conducted further investigate those potential suppliers planning to produce biochar in Australia.

3.3 Hydrogen-enriched Injection

Natural gas, Coke Ovens Gas (COG) and hydrogen injection into the blast furnace are summarised in Tables 7-9 respectively. With reference to the information in these tables, it is worth noting that each gas enables the utilisation of additional hydrogen units (e.g. Natural gas is approximately 90% CH_4 and 5% C_2H_6; COG is approximately 60% H_2) into the BF process, thereby, partially replacing carbon as a reducing agent for iron-bearing materials.

Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.3.

Note that relative energy costings have a major impact on viability of the different options:

- Hydrogen @ $2/kg is $14/GJ,
- Natural gas is approximately $12/GJ and
- PCI coal approximately $8/GJ

Recommendations: As described in the summaries below, no further investigations are proposed on hydrogen-enriched injection. Investigations that have been completed could be followed up for any future implementation, should the situation change. Continue to monitor.

Table 7 Natural gas injection into the blast furnace

Description	Natural gas contains hydrogen. In general, utilisation of additional hydrogen as a reducing agent for iron-bearing materials is advantageous because of its strong diffusion and high reduction ability. More importantly, the reduction product is H_2O. Injection of additional renewable hydrogen and/or other hydrogen-enriched gases and materials into the ironmaking blast furnace (BF) can effectively reduce fossil carbon consumption (coke and pulverised coal) and assist in decarbonising the process [12, 13].
TRL	9
Development activities	NG injection into a BF is widely utilised. The former USSR first introduced NG injection into the BF in 1957 [14] and by the early 1990s, the average consumption of NG was 70-100 m^3/tHM, with 112 BFs of a total 133 in the USSR operating with NG injection [14]. In the 1990s, NG injection became popular in USA with average NG consumption of 40-110 kg/tHM (~50-150 Nm^3/tHM) [4]. NG injection was trialled in JFE Keihin No. 2 BF (5000 m^3) of Japan at a rate of 20-50 kg/tHM (~30-70 Nm^3/tHM) in Dec. 2004 and then adopted [15,16,17]. In 2007, the productivity of the same BF reached a record of 2.56 t/d-m^3 [5]. In Australia, NG was introduced at BHP's steel plants, including PKSW, after the late 1980s (e.g. Whyalla in 1990). At PKSW, natural gas was replaced by PCI in 2002. Natural gas was being injected into 5BF at a maximum of 18,000Nm^3/h (~60 Nm^3/tHM) or average 5,100Nm^3/h (~15 Nm^3/tHM), with injection rate limited by its impact on RAFT. Coal injection enabled significantly more

	energy/reductant to be injected into the furnace, resulting in cost reductions and productivity gains.
Short to medium/long term	Short to Medium term
Development time frame for PKSW	1 year Based on the need to install injection infrastructure.
Significance of identified gaps	Refer Table A1.3 for more detail. Maximum injection rates limited by impact on RAFT. Tuyere injection lance design(s) and positioning to be optimised for co-injection with PCI.
Process simulation modelling	N/A
Abatement level	A maximum 200°C drop RAFT-constrained 24,700 Nm^3/h natural gas replacing PCI would decrease PKSW's emissions by up to ~3% [47]
Indicative cost	High relative to abatement potential. CAPEX to support co-injection of PCI and NG [47]. Significant increase in OPEX when replacing PCI coal by natural gas at ~1.5x the price on an energy content basis as described above.
Comments	Limited by cost and impact on RAFT.
Consider further?	No
Recommended activities	Continue to monitor

Table 8 Coke Oven Gas injection into the blast furnace

Hydrogen-enriched Injection – Coke Ovens Gas	
Description	Coke ovens gas contains hydrogen. In general, utilisation of additional hydrogen as a reducing agent for iron-bearing materials is advantageous because of its strong diffusion and high reduction ability. More importantly, the reduction product is H_2O. Injection of additional renewable hydrogen and/or other hydrogen-enriched gases and materials into the ironmaking blast furnace (BF) can effectively reduce fossil carbon consumption (coke and pulverised coal) and assist in decarbonising the process [12, 13].
TRL	9
Development activities	Since the 1960s, COG injection technology has been trialled and implemented in several steel plants [17]. The injection rates ranged from 30-50 to 200-300 m^3/tHM at different furnaces, with a coke replacement ratio of 0.4-0.45 kg-coke/Nm3-COG [18]. In early 2000s, a trial at Linz showed a reduction in CO_2 emissions of ~78 kg/tHM with a COG injection rate of 100 Nm^3/tHM [19]. In Japan's COURSE50 project, operational trials at LKAB's Experimental BF were undertaken. COG was injected into normal tuyeres (57% H_2; 100 Nm^3/tHM) and reformed COG into lower shaft tuyeres (77.9% H2; 150 Nm^3/tHM), achieving ~3% CO_2 emissions reduction [20, 21]. More recently, industrial applications of COG injection include commissioning a system at ROGESA (Germany) in 2020; at ArcelorMittal's Gijón plant in 2021 [22]; and one to be commissioned at HKM by end 2022 [23, 24]. Despite the above applications, the replacement ratio of coke by COG is, in some cases, far lower than the theoretical value [17]. Detailed operational information from HKM, ROGESA and ArcelorMittal is not available. In Australia, COG injection was practiced at PKSW in the 1990s, up to a maximum of 100 Nm^3/tHM.

	BlueScope completed a pre-feasibility study into COG injection in 2022 [25], however, the project did not proceed to feasibility. The proposal was to utilise approximately 21,000 Nm^3/hr of COG from several sources, some of which would result in lower internal generation and thus increased Scope 2 emissions. The COG would be injected into the furnace via a second injection lance in each of the 28 tuyeres. A COG compression plant would be required to compress the COG from 4.5KPa to 1000KPa. At the time of preparing for the submission to the Board in November 2022, an estimated carbon price of $97/t would be required for the project to be NPV neutral, including 50% government funding. Based on this, BlueScope took the decision to invest in an additional turbo-alternator (23TA) to generate additional electricity, which will utilise much of the COG that would have otherwise been used for COG injection. COG injection may be implemented in the future depending on improved project economics.
Short to medium/long term	Short to medium term
Development time frame	3 years Based on need to procure and install a COG compression plant and injection infrastructure.
Significance of identified gaps	Refer Table A1.3 for more detail. Some BFs are operating with dual injection lances, one for PCI and the other for COG injection. BlueScope would still need to finalise a design that works for PKSW, which may require trialling prototypes.
Process simulation modelling	Refer Section 2.2 and Appendix 2 for more detail. A decrease in RAFT and reduction in blast volume was predicted for injection of COG. There was also a reduction in top gas carbon content, with consequent increase in H_2 and H_2O concentrations, and an increase in the top gas energy content. PKSW CO_2 reduction from COG injection was limited by COG availability. At 200m^3 COG per tonne of hot metal (tHM) there was an overall PKSW CO_2 reduction of ~3% from baseline.
Abatement level	Net Scope 1 and Scope 2 119kt CO_2-e (approximately 21,000 Nm^3/hr of COG) [25]. This equates to approximately 1.8% of PKSW's emissions.
Indicative cost	CAPEX $62M, $97/t CO_2 [25]
Comments	COG injection is not currently an economically viable option.
Consider further?	No
Recommended activities	Continue to monitor

Table 9 Hydrogen injection into the blast furnace

Description	In general, utilisation of additional hydrogen as a reducing agent for iron-bearing materials is advantageous because of its strong diffusion and high reduction ability. More importantly, the reduction product is H_2O. Injection of additional renewable hydrogen and/or other hydrogen-enriched gases and materials into the ironmaking blast furnace (BF) can effectively reduce fossil carbon consumption (coke and pulverised coal) and assist in decarbonising the process [12, 13].
TRL	6
Development activities	As steel manufacturers face challenges to reduce their greenhouse emissions, utilisation of renewable hydrogen may be an alternate

	reductant and heat source for the BF process, generating water vapor instead of CO and CO_2 [26]. Although use of reformed hydrogen-enriched off-gas to replace coke has been explored for many years [e.g. COURSE50 project [27]], use of pure hydrogen injection into an industrial BF was not undertaken until 2019, with a brief single tuyere injection trial at Thyssenkrupp Steel's Hamborn BF [28]. BlueScope proposed to install a 10MW electrolyser with funding from the NSW Government under its Hydrogen Hub Initiative [29]. Some of the hydrogen produced would be used to trial hydrogen into the No. 5 Blast Furnace. BlueScope's proposal was unsuccessful and without government funding the proposal is not economically viable. The project is now on hold.
Short to medium/long term	Short to medium term
Development time frame	5+ years
Significance of identified gaps	Refer Table A1.3 for more detail. A more complete understanding of BF hydrogen metallurgy and impact is required, including changes in mass and energy balances, evolution of iron-bearing burden physical and chemical properties, hydrogen injection into the BF, etc.
Process simulation modelling	Refer Section 2.2 and Appendix 2 for more detail. A decrease in RAFT and reduction in blast volume were predicted for injection of pure H_2. There was also a reduction in top gas carbon content, with consequent increase in H_2 and H_2O concentrations, and an increase in the top gas energy content. Injection of H_2 up to a hypothetical limit of 30 kgH_2/tHM was predicted to decrease PKSW CO_2 emissions from ~2% (at 5kg H_2/tHM and 25°C) to ~16% (at 30kg H_2/tHM and 1200°C) from baseline. H_2 injection was modelled at 25°C, 600°C and 1200°C. The higher CO_2 reduction and most favourable carbonaceous replacement ratios were obtained at 1200°C H_2 preheating. NB. 30 kgH_2/tHM is believed to be well-beyond PKSW RAFT operating limits. Also, in practice, the pre-heating of H_2 to the high temperatures proposed in the simulation (particularly above 600 °C) would require significant engineering development.
Abatement level	Based on calculations of overall energy and materials conservation, it is estimated that 100 m^3/tHM hydrogen with injection temperature of 900°C can replace 27 kg/tHM coke in the BF process [30]. Due to the role of hydrogen as a reducing agent in the BF, the replacement ratio of coke by hydrogen can vary with the change of hydrogen injection temperature and rate [1, 31]. With the injection of hydrogen, global modelling of the BF shows the softening-melting zone is likely to be narrower and lower. Although these predictions cannot be validated due to lack of operational results, they demonstrate the potential impact of hydrogen injection.
Indicative cost	Uneconomic based on estimated capital and operating cost. NB. Even at $2/kg, the cost of H2 is ~3 times the PCI coal replaced. The scale of plant required for renewable power, hydrogen production, storage and distribution is also challenging.
Comments	Given the above estimation, hydrogen injection into the BF is not likely to be economically viable in the short to medium term.

	BlueScope's proposed 10MW electrolyser (see development activities above), even with government funding, would be NPV negative. However, BlueScope considered this project as an opportunity to commence using hydrogen in preparation for potential future hydrogen-based ironmaking. Without government funding PKSW's hydrogen project is on hold.
Consider further?	No
Recommended activities	Continue to monitor, alternate sources of H_2 may become available.

3.4 Sintering

Sintering is summarised in Table 10. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.4.

Recommendations: No further action, other than to monitor microwave assisted ignition.

Table 10 Sintering

Description	This section considered the following technologies: Waste heat recovery from cooler and waste gas recycling, Emerging technologies such as low temperature sintering, microwave assisted ignition, and Super-SINTER technology.
TRL	9 (Cooler waste heat recovery and Super-SINTER) 4-5 (Microwave assisted ignition)
Development activities	Limited examples of operating plants, meaning there has not been extensive take up of these options across steelmaking.
Short to medium/long term	Short to medium term
Development time frame	5 Years Based on time to develop concept and implement.
Significance of identified gaps	Refer Table A1.4 for more detail. **Waste Heat Recovery from the cooler**, large operating plant required to capture and de-dust the waste heat, with low grade heat recovered. **Waste Gas Recycling**, Complex retrofit to existing plant with significant operational impacts to be considered. **Super-SINTER**, Sinter quality rather than emissions-focussed technology based on NG usage, with unknowns regarding operation control and stability.
Process simulation modelling	N/A
Abatement level	Likely to be low, with additional energy consuming equipment required, particularly for Super-SINTER.
Indicative cost	Not known
Comments	Microwave assisted ignition is a relatively immature technology, providing preheated airflow with higher oxygen content. Super-SINTER economic viability needs to be assessed. Waste heat recovery's high cost and viability of the lower grade energy recovered is prohibitive.
Consider further?	No
Recommended activities	Monitor Microwave assisted ignition

3.5 Steelmaking – DRI and Scrap utilisation in Basic Oxygen Furnaces

DRI and Scrap utilisation in the BOF is summarised in Table 11. This scenario is related to the short to medium term and aims to reduce GHG emissions intensity of producing steel in an integrated steel mill. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.5.

Recommendations: Continue with current trials and investigations to increasing scrap utilisation in the BOF.

Table 11 DRI and Scrap utilisation in Basic Oxygen Furnaces

Description	In the short to medium term, the BOF will remain in operation at PKSW, in line with the reline of No. 6 BF, with continuing molten iron supply from the BF. Focusing on the short to medium term, there is an opportunity to reduce PKSW's emissions intensity by increasing the amount of scrap utilised in the BOF. Melting scrap is far less energy intensive than producing iron units from raw materials. (Noting that DRI could be considered in the event of a scrap deficit, but would otherwise be more effectively utilised at the BF as HBI as detailed in Table 3 Novel charging materials to BF)
TRL	9
Development activities	Historically, BlueScope has consistently added in the order of 65 tonnes of scrap to each BOF heat of 280 tonnes (23% of steel production). In more recent times this has been increased to 76 tonnes (30% of steel production) with plant modifications made to physically enable this amount of scrap to be charged and operational improvements to manage the temperature. BlueScope is investigating options that may enable the amount of scrap charged into the BOF to be increased up to 100 tonnes per heat. Scrap charging equipment has been upgraded and during FY23 BlueScope conducted over 100 trials of above 90 tonnes of scrap per heat. BlueScope will utilise the data gathered during the trials to develop plans to increase scrap utilisation. BlueScope has also engaged a steelmaking equipment manufacturer to provide a feasibility study on increasing the amount of scrap which can be processed in the BOF plant.
Short to medium/long term	Short to medium term
Development time frame for PKSW	1+ year Based on current investigations and concept study. Longer if additional equipment is required for scrap preheating.
Significance of identified gaps	Refer Table A1.5 for more detail. Supply chain constraints, manifesting as tramp elements (Cu, Cr, Ni, Zn) entering the BOF process as the quality of available scrap decreases resulting in the need to start using poorer-quality scrap. Scrap preheating may be required to maximise scrap use.
Process simulation modelling	N/A

Abatement level	BlueScope has previously estimated a 0.3% decrease in plant intensity per tonne average scrap charge increase. However, this is dependent on the additional energy required as the amount of scrap is increased. Since FY18, BlueScope has increased the scrap rate from 65t/heat to 76t/h (FY23). During this period PKSW's CO2 intensity dropped by approximately 5%, with scrap rate increase being the major contributor to the reduction.
Indicative cost	Will depend on the final concept progressed, which is expected to be NPV positive due to resultant increased production levels. Scrap prices do vary, as does steel demand and pricing and are always a consideration in the level of scrap utilised.
Comments	Maximising the use of scrap in the BOF is an effective and efficient way of reducing the emissions intensity of PKSW.
Consider further?	Yes
Recommended activities	Continue with current trials and investigations to increasing scrap utilisation in the BOF.

3.6 Carbon Capture Utilisation and Storage

Carbon Capture and Use (CCU) and Carbon Capture and Storage (CCS) are summarised in Tables 12 and 13. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.6.

Recommendations: No further action, other than to monitor progress of MCi, Steelanol and other CCU developments.

Table 12 Carbon Capture and Use (CCU)

Description	There are two main potential uses for CCU at PKSW: 1. Carbon could be re-used directly: a. COG injection into the BF (covered in section 3.3), b. Electricity generation 2. Carbon could be re-used as a resource to produce value-added products: a. After CO_2 chemical transformation (e.g. MCi, Slag2PCC, producing $CaCO_3$) and b. After CO_2 biological transformation (e.g. Steelanol, producing ethanol). Cost-effective technologies need to be developed, with current global investigations underway.
TRL	6-9 (majority within this range)
Development activities	**Direct use:** BlueScope currently utilises the majority of the COG and BFG generated on site in various operating units, predominantly for heat. A project is underway to utilise the small amount of these gases that are currently flared, by purchasing an additional electricity generating unit that can be coupled to a redundant steam turbine (23TA). This unit will

	generate additional electricity and reduce the amount drawn from the grid. The BOF off gas, or Linz-Donawitz gas (LDG), which is approximately 70% CO, is flared. The BOF is a batch process, with the resultant gas generation varying from 0 to approximately 164,000Nm^3/h, which makes it very difficult to capture and utilise. BlueScope has repeatedly considered options to capture and utilise LDG, however, this requires special equipment and the installation of a gas holder [30] (estimated at approximately $220M), which adds significant costs and generally renders options financially non-viable. **Chemical transformation:** Australian mineral carbonation company MCi Carbon has developed a scalable carbon platform technology that safely captures and converts industrial CO_2 emissions into solid bulk materials used in new low-carbon products for construction, manufacturing, and consumer markets - enabling a circular economy. MCI are currently building an industrial scale demonstration carbon plant to be completed in 2023, co-located at Orica's AN Plant in Newcastle to lock away their captured CO_2 permanently into construction products and low carbon embodied materials. BlueScope is monitoring this development. **Biological transformation:** Carbon capture and utilisation company, LanzaTech has developed microbial gas fermentation process technology used to convert steelmaking waste gases to fuels and chemicals. A commercial facility was set up to convert LDG to ethanol in 2018 (Shougang). LanzaTech and Primetals worked on ArcelorMittal's Steelanol project to convert blast furnace emissions into ethanol, usable for sustainable fuels and other downstream products. The facility began operations in 2023. BlueScope has considered utilising the LanzaTech process to convert LDG into ethanol, however, as mentioned above, the cost of LDG collection was prohibitive. BlueScope is monitoring this development.
Short to medium/long term	Short to medium term
Development time frame for PKSW	3-5 years Based on selecting commercial technology and implementation
Significance of identified gaps	Refer Table A1.6 for more detail. CO_2 utilisation through chemical production in steel industry is still at the pilot stage. CO_2 biological transformation through fermentation has been commercialised. However, the corresponding CO_2 reduction capacity is still limited, with additional hydrogen required to improve conversion efficiency. Any fuels produced not likely to be labelled renewable due to coal origin.
Process simulation modelling	N/A
Abatement level	As described above, the main remaining opportunity, other than to repurpose BFG and COG usage, is to capture the currently flared LDG gas. The total emissions associated with LGD are approximately 480kt CO_2/a, or 7% of PKSW's emissions.

Indicative cost	The cost to capture the LDG for utilisation via a gas holder has been estimated at $220M, see above in development activities. This cost makes further use commercially unviable.
Comments	The cost associated with additional CCU options tends to be limiting and the resultant abatement modest.
Consider further?	No
Recommended activities	Monitor progress/success of current installations

Table 13 Carbon Capture and Storage

Description	In addition to new iron and steelmaking process developments, carbon capture, utilisation and storage (CCUS) technologies are considered as potential solutions to mitigate carbon emissions in the steel industry
TRL	4 - 9
Development activities	CO2CRC conducted a study for PKSW, focusing on CCS [31]. *CO_2 capture from flue gases at the coke ovens, power plant and blast furnace hot stoves were considered in this report. These are the three major CO_2 sources (Coke ovens and power plant each have 3 separate emission points) in the plant that emit 60-65% of the total CO_2 emissions. Moreover, the CO_2 content in gases from all these sources is greater than 15%, making them suitable for CO_2 capture by a solvent absorption process. To minimize the modification in the existing power plant at BlueScope, a separate natural gas combined cycle plant has been considered to fulfil the energy and process steam requirement of the capture process. With 90% capture rate, CO_2 capture could reduce the total emissions by 45%.* *To complete the assessment of CCS options, a study is included for scoping economic evaluation of Port Kembla Steelworks CO_2 transport and storage options, wherein 4 different options including pipeline transport, ship transport and pipeline transport to a pipeline hub and onto a single-sink hub were evaluated with two different storage options at Darling Basin's Pondie Range Trough and Nearshore Gippsland Basin's Barracouta Field.* *The cost of CO_2 avoidance for CO_2 capture is 142 A$/tonne of CO_2 avoided including the cost of the flue gas transport to capture facility. The cost of transport and storage of the captured CO_2 by pipeline is 31.8 A$/tonne of CO_2. Therefore, the total cost of CO_2 avoidance is 174 A$/tonne of CO2.*
Short to medium/long term	Short to medium term
Development time frame for PKSW	5-10 years Based on the need to establish infrastructure to capture the emissions, separate the CO_2, transport the CO_2 and then store the CO_2.
Significance of identified gaps	Refer Table A1.6 for more detail. The current CO_2 capture technologies are still economically suited for low volume CO_2 capture. Many on site sources of low CO_2 concentration. No local storage, so CO_2 would need to be piped long distances.
Process simulation modelling	N/A

Abatement level	The CO2CRC report [31] estimated that a total of 2.86Mt/a CO_2 could be captured and sequestered, a net reduction of 45%.
Indicative cost	Estimated at $174/t [31] to collect, concentrate, transport and store.
Comments	A complex solution and not economically viable, well in excess of expected Australian carbon pricing.
Consider further?	No
Recommended activities	Continue to monitor most prospective developments

<u>**Long Term Prioritised Options**</u>

3.7 Alternate Ironmaking – Electrolysis of Iron Ore

Electrolysis of iron ore is summarised in Table 14. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.7.

<u>**Recommendations:**</u> This technology, although promising, is at a pilot stage and being developed elsewhere. It is well supported. BlueScope's involvement in this technology would not accelerate the time taken to commercialisation. Continue to monitor.

Table 14 Electrolysis of iron ore

Description	Electrolysis of iron oxide is an electro-chemical process to produce metallic iron and oxygen, using direct electric current [32]. Principally, in an electrolytic cell, electrodes including anodes and cathodes are immersed in an electrolyte containing iron ore and then electrified. Negatively charged oxygen ions migrate to the positively charged anode where oxygen ions lose electrons and oxygen gas is evolved. Positively charged iron ions migrate to the negatively charged cathode where they are reduced to metallic iron. If the electricity used is renewably sourced (carbon-free), iron is produced without CO_2 emissions [32, 33]. Electrolysis of iron oxide has been demonstrated at laboratory scale under low and high temperature conditions. In low temperature electrolysis, i.e. "hydro"-electrolysis, aqueous electrolytes are used i.e. ~100°C. In the high temperature electrolysis, i.e. pyroelectrolysis [34], molten oxides act as the electrolyte with operating temperatures over the melting point of iron [35, 36].
TRL	4-5
Development activities	Currently, two types of electrolysis-based ironmaking technologies are being developed [35, 37]: (1) High temperature molten oxide-based electrolysis, including a) the molten oxide electrolysis (MOE) process initiated by the Massachusetts Institute of Technology (MIT) which was further developed by Boston Metal [38], and b) the ULCOLYSIS process developed through the ULCOS project [39]. (2) Low temperature alkaline based electrolysis, i.e. previously called ULCOWIN process, now the ΣIDERWIN process, using an aqueous alkaline solution as the electrolyte, developed through EU projects (currently Siderwin project) [40].
Short to medium/long term	Long term
Development time frame for PKSW	10-20 years Based on very low TRL and expected time to commercialise.
Significance of identified gaps	Refer Table A1.7 for more detail. Significant gaps and potential barriers to commercialisation still exist, particularly with respect to the amount of renewable electricity required and potential difficulties with disposal of waste oxides.
Process simulation modelling	Nil

Abatement level	Potentially very high
Indicative cost	Unknown
Comments	This technology, although promising, is at a pilot stage and being developed by others and is well supported. BlueScope's involvement in this technology would not accelerate the time taken to commercialisation.
Consider further?	No
Recommended activities	Continue to monitor

3.8 Alternate Ironmaking – Direct Reduction

Fluidised bed direct reduction and shaft furnace direct reduction are summarised in Tables 15 and 16. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendices A1.8 and A1.9.

Recommendations: Further consider direct reduction ironmaking for long-term steelmaking at PKSW. Complete an Options Study, refer Section 4.2.

Table 15 Fluidised bed direct reduction

Description	Fluidised bed direct reduction processes utilise iron ore fines, with no significant agglomeration treatment required. In this process, iron ore fines move through a series of fluidised bed reactors and are efficiently heated and reduced by gas (typically, reformed natural gas and syngas present-day; and, potentially, in the future, renewable hydrogen). Circored, Finored/Finmet and HYREX have been developed for a hematite feed and HYFOR for magnetite.
TRL	6 – 9 (Finmet/Finored)
Development activities	Circored and Finored/Finmet have been commercialised, but successful applications are very limited, due to operational and technical challenges. In the case of Finored/Finmet, two commercial plants have operated - one remains in operation, while many of the technical challenges were overcome prior to shutdown of the other [1]. Overall, these three fluidised bed DR processes are promising technologies but there are potential commercialisation risks associated with each. Both HYFOR and HYREX as the name suggests are hydrogen based processes currently under development. HYFOR is being developed by Primetals, FMG and voestalpine and have announced a pilot plant to be built at the voestalpine works in Linz, Austria in 2026. HYREX is being developed by POSCO, and they have announced a demonstration plant being built at their Pohang works by 2026.
Short to medium/long term	Long term
Development time frame for PKSW	5-10 years (for natural gas-based processes). 10-20 years for hydrogen-based processes. Based on expected time required to become fully commercialised, with all operating issues resolved.
Significance of identified gaps	Refer Table A1.8 for more detail. Although fluidised bed DR processes (e.g. Finored, Circored and Finex) have been commercially demonstrated at large scale, process stability

	and efficiency improvements are still necessary and required. These include the impact of iron ore composition and size distribution on material behaviour, particularly sticking, refractory erosion by fine particles, and potential for future use of hydrogen.
Process simulation modelling	N/A
Abatement level	Near zero emissions possible with renewable hydrogen, lower abatement potential with natural gas usage
Indicative cost	>$1.2B CAPEX [47].
Comments	Has potential and advantages with the utilisation of fines without the need for agglomeration, however, significant gaps remain to be resolved.
Consider further?	Yes
Recommended activities	Complete an options study, refer Section 4.2.

Table 16 Shaft furnace direct reduction

Alternate Ironmaking – Shaft Furnace Direct Reduction	
Description	Most direct reduction plants utilise shaft furnace reactors based on either MIDREX or HYL-ENERGIRON technologies. Shaft furnaces are moving bed, counter-current reactors with upwards flowing reducing gas and downwards flowing iron-bearing materials. Pellets and/or lump ores are charged directly at the top of the shaft. Typically, reducing gas is generated through a reformer using recycled top gas and natural gas, which is heated to a specified temperature and fed to the middle part of shaft furnace.
TRL	7 - 9
Development activities	Shaft furnace DRI is mature technology with 6% of global steel production produced via the DRI (predominantly shaft furnace)/EAF process. Both major gas-based shaft furnace DR processes, MIDREX and HYL/ENERGIRON, claim that DRI can be produced using hydrogen [41], and up to 30% of the natural gas used in these two processes can be replaced by hydrogen without major process adaptations [42]. There are several DRI plants currently being built with plans to use hydrogen. Two shaft based DRI plants are planned to be built in Sweden, H2 Green Steel and Hybrit. There are several DRI plants which have been recently publicly announced with plans to start up on natural gas and transition to hydrogen, as it becomes available. These include Arcelor Mittal Gent, Arcelor Mittal Dofasco, thyssen krupp Steel EU and more.
Short to medium/long term	Long term
Development time frame for PKSW	The development time frame for PKSW is dependent on the supportive enablers to allow transition away from BF ironmaking.
Significance of identified gaps	Refer Table A1.9 for more detail. The gaps for the shaft furnace DRI are predominantly related to raw material supply and optimising the operation based on this, given it is mature technology. Development work continues on the utilisation of lower grade ores and maximising future hydrogen utilisation.
Process simulation modelling	N/A

Abatement level	Near zero emissions possible with renewable hydrogen
Indicative cost	>$1.2B CAPEX [47].
Comments	Given the amount of further development/commercialisation required for fluidised bed DRI, the shaft furnace offers a more reliable opportunity for early movers.
Consider further?	Yes
Recommended activities	Complete an Options Study, refer Section 4.2

3.9 Alternate Ironmaking – Smelting Reduction

Smelting reduction is summarised in Table 17. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.10.

Recommendations: No further action, other than to monitor Ironarc and flash ironmaking technologies (currently TRL 5) developments.

Table 17 Smelting reduction

Description	Smelting reduction (SR) processes aim to produce liquid iron without using coke or high-grade iron ore; instead, using non-coking coal, oxygen and/or electrical energy. SR processes involve both reduction and smelting of iron-bearing materials, which can occur in single or multiple reactors. The highest rating TRL processes include Corex, Finex, and Hismelt/Hisarna [1].
TRL	Ranges from 4 to 9
Development activities	Compared to coal-based SR processes, Ironarc and flash smelting technologies offer the opportunity to use H_2-rich gases and electricity.
Short to medium/long term	Given the imminent decision to reline No. 6 BF, not a short to medium term option. Given it is a coal-based process with a maximum of 20% reduction in emissions, not a long-term option.
Development time frame	N/A
Significance of identified gaps	Refer to Table A1.10 for description of key issues and development gaps. Other then Finex and Corex, other technologies are either small scale or in the very early stages of development.
Process simulation modelling	N/A
Abatement level	20% reduction compared to BF ironmaking operation.
Indicative cost	N/A
Comments	Compared to coal-based SR processes, theoretically, Ironarc and flash ironmaking technologies (TRL 5) are more suitable for application at PKSW as H2 rich gas and electricity are used as key energy sources for these two processes. Not a viable option for short to medium-term – Would be major investment for a modest CO_2 reduction. Not an option for long-term – insufficient abatement potential.
Consider further?	No
Recommended activities	Continue to monitor Ironarc and flash ironmaking technologies (currently TRL 5) developments.

3.10 Steelmaking

For emerging ironmaking technologies utilising direct reduced iron (DRI), there are two main process routes that could be selected, and these are primarily dependent on the iron ore type feed to the plant:

- The simplest option is the use of a high-grade magnetite ore in a DRI-EAF process route.
- The second option, yet to be fully commercialised, is the use of a hematite ore in a DRI-ESF-BOF process, where ESF is an Electric Smelting Furnace.

The DRI value chain: magnetite or hematite

A key difficulty in adopting DRI technology in markets such as Australia would be domestically sourcing cost-effective iron ores of a suitable grade to produce the required pellets for DRI production. Typically, DRI plants require the iron ore to have a higher iron content (> 67 %), with low levels of contaminant materials, e.g. < 3 % (silica + alumina). The reason for this is that, unlike the BF process, the output from the DRI plant is a solid material product; so, any impurities in the iron ore remain in the product, which if too high, cannot be efficiently removed through the EAF.

To address this, the easiest option is the mining of magnetite ores. This industry in Australia sees large deposits being developed in the Pilbara and mid-west regions of Western Australia, and in South Australia. Magnetite ore deposits are typically of a lower ore grade (20 – 30 per cent iron content) but can be made into concentrates through additional beneficiation that relies on its magnetic properties, i.e. magnetic separators. This significantly increases the cost, as more than twice the amount of ore needs to be mined and processed.

Historically, proven reserves of iron ore in Australia have been thought to be around 72 % hematite and 28 % magnetite, with hematite representing most ores exported from Australian iron ore producers for BF-BOF steelmaking. Before export, these Australian ores undergo a relatively simple beneficiation process (crushing and screening) and typically, range between 56- 62 % iron and 6.2 % (silica + alumina) contents. This restricts their use in DRI production without higher order beneficiation, which substantially increases their costs and reduces their mined yield.

Using hematite ores in the DRI process

There appears to be a consensus between numerous international steelmakers and equipment manufacturers on the integration of an ESF between the DRI and BOF processes. The ESF smelts the DRI product, completing the metallisation of the iron product and separates the impurities, with the molten iron, or hot metal, being fed into the BOF.

3.11 Steelmaking – DRI-ESF-BOF

The ESF process is summarised in Table 18. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.11.

Recommendations: Complete Options Study, refer Section 4.2, and continue existing collaborations on the development of a DRI-ESF pathway.

Table 18 Electric Smelting Furnace (ESF)

Description	As described in the Phase 1 report, the two steelmaking options are the BOF and the EAF. Both are mature technologies. In the short to medium term, the BOF will remain in operation at PKSW, in line with the reline of No. 6 BF, with continuing molten iron supply from the BF. In the long term, steelmaking operations will be dependent on the selected ironmaking technology. DRI-ESF, using hematite would align with continuing BOF steelmaking, whereas DRI using magnetite would not and an EAF would be required.
TRL	2 (Pilbara ores) / 9 (New Zealand Steel)
Development activities	BlueScope's New Zealand Steel is one of the only steelmakers globally to be operating an ESF process. The ESF has also been recently selected for development by other major steelmakers ThyssenKrupp (recently announced government funding with startup in 2026), voestalpine and POSCO. Also, BHP is working with Hatch to design an Electric Smelting Furnace (ESF) pilot plant. This pilot plant is designed to evaluate the use of Australian hematite/goethite ores.
Short to medium/long term	Long term
Development time frame for PKSW	5-10 years Based on requirement for demonstration plants to prove successful. Development timeline significantly influenced by supporting enablers for the technology.
Significance of identified gaps	Refer Table A1.11 for more detail. There are significant key issues and gaps that require resolution, for the ESF to be a viable option, these include optimum size and scalability, DRI metallisation, carburization and impurities, slag formation and resistivity, and carbon addition, particularly for hydrogen based DRI (required for the BOS and steel product).
Process simulation modelling	N/A
Abatement level	Enabler - Near zero emissions possible
Indicative cost	thyssen krupp Steel EU publicly announced CAPEX of €2B
Comments	This option provides a valuable alternative to the DRI/EAF route requiring beneficiated magnetite, which enables ongoing utilisation of Australia's extensive hematite ore resources. There are considerable technology issues to overcome, however, BlueScope's New Zealand Steel plant has extensive experience with the operation of ESFs.
Consider further?	Yes
Recommended activities	Complete an Options Study, refer Section 4.2 Continue existing collaborations on the development of a DRI-ESF pathway.

3.12 Steelmaking – DRI-EAF

The EAF process is summarised in Table 19. Key issues and development gaps based on qualitative assessment of operational, engineering, environmental and safety aspects, are provided in Appendix A1.12.

Recommendation: Complete Options Study, refer Section 3.11

Table 19 DRI utilisation in Electric Arc Furnace (EAF)

Description	DRI utilisation in the EAF is mature technology with approximately 8% of global steel now being produced via this route. The main limit in applying this technology is the requirement to use high quality iron ore, as the EAF cannot efficiently manage high contaminant loads. Noting raw materials in the DRI process remain solid, meaning impurities are not removed. EAF-quality DRI requires higher grade ores, e.g. beneficiated magnetite. Magnetite represents less than 15% of current seaborne ores [1], which will only support a proportion of global steel production
TRL	9
Development activities	Given the EAF is mature technology, future developments are related to the quality and quantity of magnetite based DRI used with scrap, in order to optimise the overall EAF operation in terms of energy consumption, material charging, steel quality etc.
Short to medium/long term	Long term
Development time frame for PKSW	5-10 years This is commercial technology, however development time frames are set by the ability to put in place supportive enablers, including infrastructure, to support commercial viability.
Significance of identified gaps	Refer Table A1.12 which provides a description of the key issues and development gaps. The main gaps relate to future EAF operations involving H2-DRI, and thus low carbon and its effect on operations.
Process simulation modelling	N/A
Abatement level	Enabler - Near zero emissions possible when used in conjunction with renewable hydrogen and electricity
Indicative cost	This option was considered as part of the Port Kembla Steelworks Ironmaking Production 2026 Onwards Project [3]. At the time this option was not considered economically viable.
Comments	This is mature technology, capable of low emissions and BlueScope will include the DRI-EAF process in future ironmaking considerations.
Consider further?	Yes
Recommended activities	Complete an Options Study, refer Section 4.2

3.13 Final Assessment Summary

Summaries of the final assessment of the short-to-medium term and long term Prioritised Options are shown in Tables 20 and 21, respectively. These outline whether the Prioritised Options are to be considered further for PKSW at this stage and if so, the recommended actions.

Table 20 Final Assessment Summary – short-to-medium Prioritised Options

PRIORITISED OPTION	FURTHER INVESTIGATION	RECOMMENDATION
SHORT-TO-MEDIUM TERM		
Blast Furnace Ironmaking		
Novel charging materials to BF		
• Carbon containing agglomerates (CCA)	NO	Continue to monitor.
• Pre-reduced agglomerates (PRA)	YES	Further investigate what would be required to conduct a HBI trial.
• Ferro-coke	NO	Continue to monitor.
Biomass application in ironmaking	YES	To enable longer duration trials to be conducted, further investigate those planning to produce biochar in Australia.
Hydrogen-enriched injection		
• Natural gas • Coke ovens gas • Hot reducing gas • Biogas (biomass pyrolysis - “syngas") • Hydrogen	NO	Continue to monitor.
Sintering		
Waste heat recovery from cooler and waste gas recycling **Super-SINTER technology (SST)**	NO	Continue to monitor.
Steelmaking		
DRI and scrap utilisation in Basic Oxygen Furnace		
• DRI utilisation in Basic Oxygen Furnace	NO	Continue to monitor.
• Scrap utilisation in Basic Oxygen Furnace, including scrap preheating	YES	Continue with current trials and investigations to increasing scrap utilisation in the BOF.
Carbon Capture, Utilisation and Storage		
CCS **CCU**	NO	Continue to monitor CCU.

Table 21 Final Assessment Summary – Long-term Prioritised Options

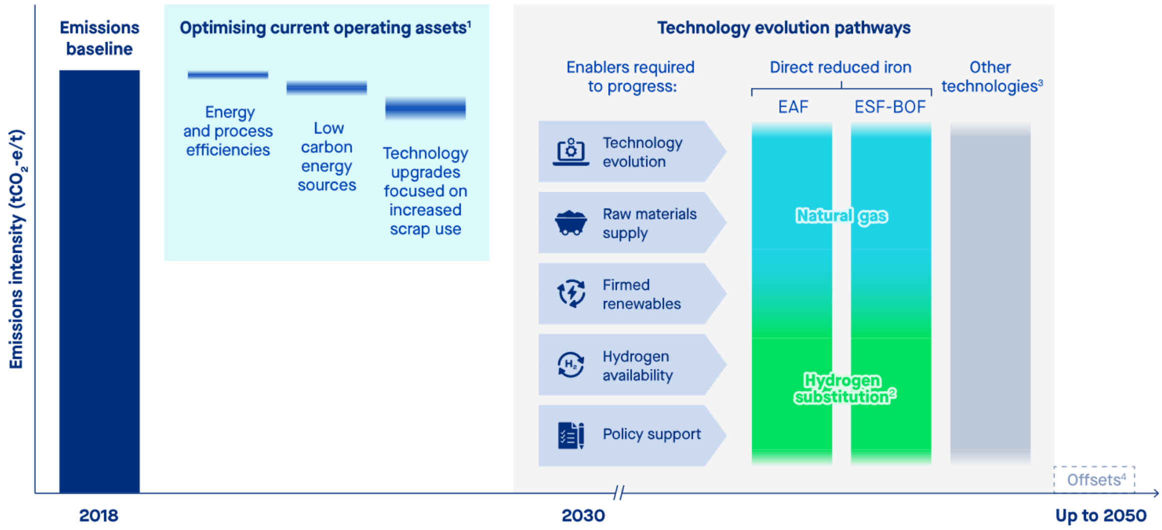
PRIORITISED OPTION	FURTHER INVESTIGATION	RECOMMENDATION
LONG TERM		
Alternate Ironmaking		
Electrolysis of iron ore	NO	Continue to monitor.
Fluidised bed direct reduction	YES	Complete Options Study.
Shaft furnace direct reduction	YES	Complete Options Study.
Smelting Reduction (SR)	NO	Continue to monitor.
Steelmaking		
DRI utilisation in ESF-BOF	YES	Complete Options Study. Continue existing collaborations on the development of a DRI-ESF pathway.
DRI utilisation in an EAF	YES	Complete Options Study.

4 PKSW Decarbonisation Pathways

As discussed previously in the Introduction, Figure 1 shows BlueScope's 2050 net zero goal and 2030 steelmaking target (12% GHG emissions intensity reduction (Scope 1 and Scope 2), based on 2018 levels).

BlueScope's indicative Iron and Steel decarbonisation pathway is shown in Figure 2.

Figure 2 BlueScope's indicative iron and steel decarbonising pathway.



1. Optimising current assets involves working within currently available technology options to improve the efficiency of assets and processes, including upgrading technology where there are supportive enablers.
2. Contingent upon commercial supply of hydrogen from renewable sources.
3. Other technologies include electrolysis, CCUS and biocarbon, etc.
4. We retain the option to use offsets to meet our 2050 net zero goal where direct abatement is not technically or commercially feasible.

Recently, given PKSW's short-to-medium term ironmaking process being confirmed through the major investment decision to reline No.6 BF, the outline in Figure 2 closely represents PKSW's decarbonisation pathway, which has two phases:

(i) optimising current operating assets, and
(ii) technology evolution pathways towards its 2050 net zero goal.

In the short-to-medium term, the company's focus will be on optimising its existing assets and processes, and working in partnership with industry and research institutions to progress the technical and commercial viability of alternative technology options.

For the longer-term, the pathway has been updated to reflect the company's refreshed assessment of technology developments in DRI, using natural gas as a transitional step to green hydrogen to produce lower emissions steel. Five key enablers have been identified: 1) technology evolution, 2) raw materials supply, 3) firmed renewable energy, 4) hydrogen availability and 5) policy support.

For PKSW, this means that decarbonisation activities will be undertaken across two parallel streams of work. Firstly, in this next decade, activities will involve optimising existing blast furnace assets via exploring a range of initiatives to improve emissions intensity. Secondly, and in parallel and decade following, activities will involve building a pathway to meet BlueScope's goal of net zero emissions by 2050. This second future-orientated workstream includes a comprehensive technical investigation program.

As described in Chapter 3, the final assessment process undertaken enabled a determination as to whether a Prioritised Option would be considered further at this point in time. For Prioritised Options with the greatest potential to be economically viable and contribute to emissions reduction at PKSW, further actions were recommended. Table 22 shows the selected Prioritised Options for further action, as summarised from Tables 20 and 21.

The next sections discuss two pathways: a) PKSW's short-to-medium term, and b) PKSW's long term.

Table 22 Prioritised Options selected for further action.

PRIORITISED OPTION	FURTHER INVESTIGATION	RECOMMENDATION
SHORT-TO-MEDIUM TERM		
Blast Furnace Ironmaking		
Novel charging materials to BF		
• Pre-reduced agglomerates (PRA)	YES	Further investigate what would be required to conduct a HBI trial.
Biomass application in ironmaking	YES	To enable longer duration trials to be conducted, further investigate those planning to produce biochar in Australia.
Steelmaking		
DRI and scrap utilisation in Basic Oxygen Furnace		
• Scrap utilisation in Basic Oxygen Furnace, including scrap preheating	YES	Continue with current trials and investigations to increasing scrap utilisation in the BOF.
LONG TERM		
Alternate Ironmaking		
Fluidized bed direct reduction	YES	Complete Options Study.
Shaft furnace direct reduction	YES	Complete Options Study.
Steelmaking		
DRI utilisation in ESF-BOF	YES	Complete Options Study. Continue existing collaborations on the development of a DRI-ESF pathway.
DRI utilisation in an EAF	YES	Complete Options Study

4.1 PKSW Short to Medium GHG Emissions Reduction Pathway

In the short-to-medium term, the focus will be on optimising existing operating assets, including a relined No. 6 BF, through energy and process efficiencies, low carbon energy sources and technology upgrades to increase scrap utilisation. PKSW is contributing to BlueScope's 2030 target, with FY23's Scope 1 and Scope 2 emissions intensity marginally above a 12% by 2030 trajectory from 2018.

BlueScope is progressing several projects that are designed to contribute to the achievement of the Company's 2030 steelmaking target. These include:

- The 23 Turbo Alternator (23TA) project that will utilise available indigenous gas to generate electricity and reduce Scope 2 emissions
- The Reline project will invest over $130m in broader environmental improvements for the No.6 BF asset before it replaces No. 5 BF in 2026, including the following emissions reduction initiatives:
    - Top Gas Recovery Turbine (TRT) – converting exiting process gas flow to deliver 12-14MW power, compared to the No. 5 BF TRT which currently delivers 7-9MW
    - Waste Gas Heat Recovery (WGHR) additional to the existing Stoves – with more efficient combustion in the stoves, liberating indigenous fuel gas (Coke Ovens Gas) that can be converted to electricity
    - High efficiency burners in stoves – replacement of existing burners with modernisedburner design – reducing CO and NOx emissions from the combustion process
    - No. 6 BF is planned to operate more energy efficiently than No.5 BF.
- The inefficient steam driven 26 Air Compressor (26AC) is to be replaced with an efficient electric driven 29AC, with overall reduced Scope 2 emissions
- Increased scrap utilisation to increase steel production and reduce emissions intensity and
- Reduced Scope 2 emissions as the grid decarbonises.

The three short-to-medium term Prioritised Options identified for further action:

- Potential use of HBI in the BF
- Biochar to as an alternative to PCI coal
- Increased scrap use in the BOF

should provide additional certainty around the 2030 target and post 2030 in preparation for the longer term.

4.1.1 Potential use of HBI in the BF

As discussed in Section 3.1, HBI could be added to the BF feed to improve efficiency and reduce emissions, including accounting for the associated Scope 3 emissions when producing the HBI. HBI use in the BF could also assist with a future transition, where HBI or DRI is produced and needs to be consumed in the existing BF process prior to a full conversion of the PKSW ironmaking production chain to low emissions ironmaking. BlueScope prefers to understand firsthand all aspects of using HBI in the BF, rather than rely on other operator's experience.

Market Barriers

The barriers to be considered include:

1. HBI availability, given the majority of HBI production is captive, with limited merchant trade

2. Challenging economics and value-in-use considerations, with the price of HBI likely to be prohibitive without an appropriatecarbon price and
3. Potential physical impacts and wear on bins, chutes and other furnace feed system equipment, as well as additional breakage to co-charged materials of charging hard HBI briquettes into the BF.

Pathway to commercialisation

A trial of approximately 20,000 tonnes of HBI into PKSW's BF would provide:

- Via engineering analysis and testing, the physical impacts and necessary modifications required across the BF raw material feed system
- A better understanding of the current availability and pricing of HBI via competitive tendering and
- Sufficient HBI to enable a trial where HBI feed could be safely ramped up to a level of around 10% of total BF feed then ramped down. Analysis would consider BF stability, efficiency potential, ability to increase throughput and changes to PKSW emissions intensity.

Timing of the above will depend on available funding to improve the economic case for conducting the trial.

4.1.2 Biochar as an alternative to PCI coal

As discussed in Section 3.2, biochar could replace PCI coal at an approximate 1:1 ratio, with a resultant 3 tonnes of CO_2 decrease overall per tonne ofbiochar for Scope 1 emissions. The successful trials completed as part of this project provide greater confidence that biochar could be used to replace up to 30% of the PCI coal.

BlueScope is working with three separate entities with plans to build and operate pyrolysis plants to produce biochar.

Market Barriers

The barriers to be considered include:

1. Conversion of biomass via pyrolysis results in a biochar yield of approximately 25%, which has cost and transport implications.
2. Some biomass sources, particularly waste timber, may produce biochar which does not meet required specifications.
3. Biochar availability, given there is no industrial level supply chain for biochar in Australia. Overseas sources could be considered but may have associated sustainability concerns and higher freight costs due to the low density of biochar.
4. Challenging economics, with biochar replacing cheaper PCI coal which has a well-established supply chain with associated economies of scale and efficiency. Onsite production using European pyrolysis equipment is currently prohibitively expensive.

Pathway to commercialisation

There are three startups, in NSW, WA and QLD, which have plans to produce biochar at industrial quantities. Two of these plan to utilise localised concentrations of invasive plant species, while the other is plantation-based. All appear to be sustainable, with local community support. BlueScope is working with these and other potential biochar manufacturers. To be successful, each of these opportunities will need Government support for the capital investment required through grant funding. Biochar will need to be cost-competitive in relation to PCI coal and any carbon pricing.

Timing will depend on availability of funding and agreement between all parties to proceed.

4.1.3 Increased Scrap utilisation in the BOF

As discussed in Section 3.5, increasing scrap utilisation in the BOF can reduce PKSW's emissions intensity. BlueScope has already increased the amount of scrap charged into the BOF. Steel demand is expected to increase as Australia moves to clean energy production, with steel a major component of the required infrastructure e.g. transmission towers.

Market Barriers

The barriers to be considered include:

1. Additional energy required to melt the scrap can increase the cost and reduce the emissions intensity gains,
2. Charging infrastructure has been a limiting factor in the amount of scrap that can be charged into the BOF,
3. Steel margins are impacted by scrap prices and steel sale prices, which can reduce the incentive to utilise additional scrap, and
4. Supply chain constraints, manifesting as additional tramp elements (Cu, Cr, Ni, Zn) entering the BOF process as the quality of available scrap decreases.

Pathway to commercialisation

BlueScope has already overcome the physical limitations on charging larger quantities of scrap into the BOF through plant modifications and is now able to physically add 100t scrap per heat. Over 100 trials have been conducted at above 90t scrap per heat. Information gathered during the trials will assist with developing plans to increase scrap utilisation, with minimal additional energy required.

A steelmaking equipment supplier has been commissioned to provide a concept study regarding options for increasing the amount of scrap that can be added to be BOF vessel.

Currently, hot metal (molten iron) loses over 170°C between the BF and the BOF, while being transported in rail torpedo ladle cars. BlueScope has developed a lid and associated opening/closing mechanism that can be mounted to the torpedo ladles. If successful, the lids could reduce the temperature loss by 40°C, which could result in increased scrap utilisation and an emissions intensity reduction of 2.4%.

It is estimated that it will take 2 - 3 years to install lids on all 31 torpedo ladles in the fleet.

4.1.4 Short- to Medium-Term Funding

There are several grant funds now available, which may provide funding, depending on the success of applications, these include:

- NSW High Emitting Industries grants, administered by Office of Energy and Climate Change
- Powering the Regions Fund – Safeguard Transformations Stream, managed by the Department of Industry, Science and Resources and
- Powering the Regions Fund – Industry Transformation Stream, managed by ARENA.

4.2 PKSW Long Term Decarbonisation Pathway

BlueScope has applied to the Safeguard Transformation Stream for the lid installation project as mentioned in Section 4.1.3.

BlueScope has also initiated discussions with both ARENA and NSW Office of Energy and Climate Change with respect to the three identified Prioritised Options for further action – HBI, biochar and ladles.

4.2 PKSW Long Term Decarbonisation Pathway

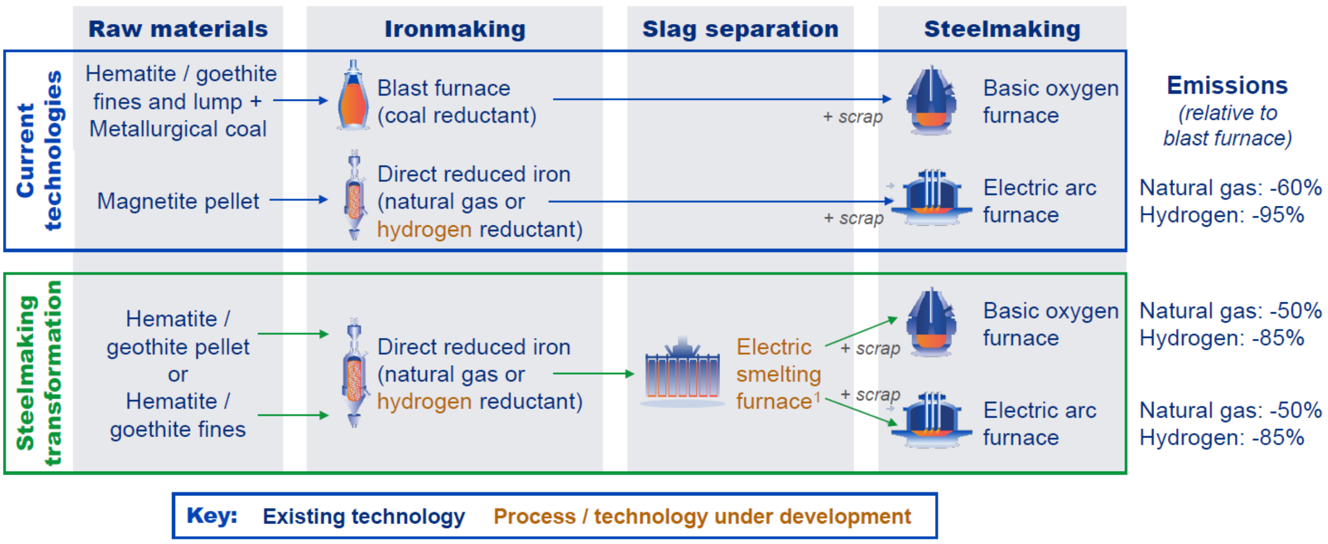
For the long-term decarbonisation pathway, BlueScope is focusing on the DRI route via a Direct Reduced Iron Options Study.

4.2.1 BlueScope's Direct Reduced Iron Options Study

In addition to and in alignment with this Study, BlueScope has completed a concept study with Rio Tinto to explore DRI and its application to Australia's Pilbara hematite ores in conjunction with Electric Smelting Furnaces.

Figure 11 provides BlueScope's view of potential pathways for primary iron and steelmaking under development and their respective emission levels relative to a blast furnace.

Figure 11 Potential pathways for primary iron and steelmaking under development



Electric Smelting Furnace is the type of furnace that processes direct reduced iron (DRI) feed and separates impurities to produce a liquid pig iron product suitable for a Basic Oxygen Furnace (BOF) that can produce a wider range of steel products.

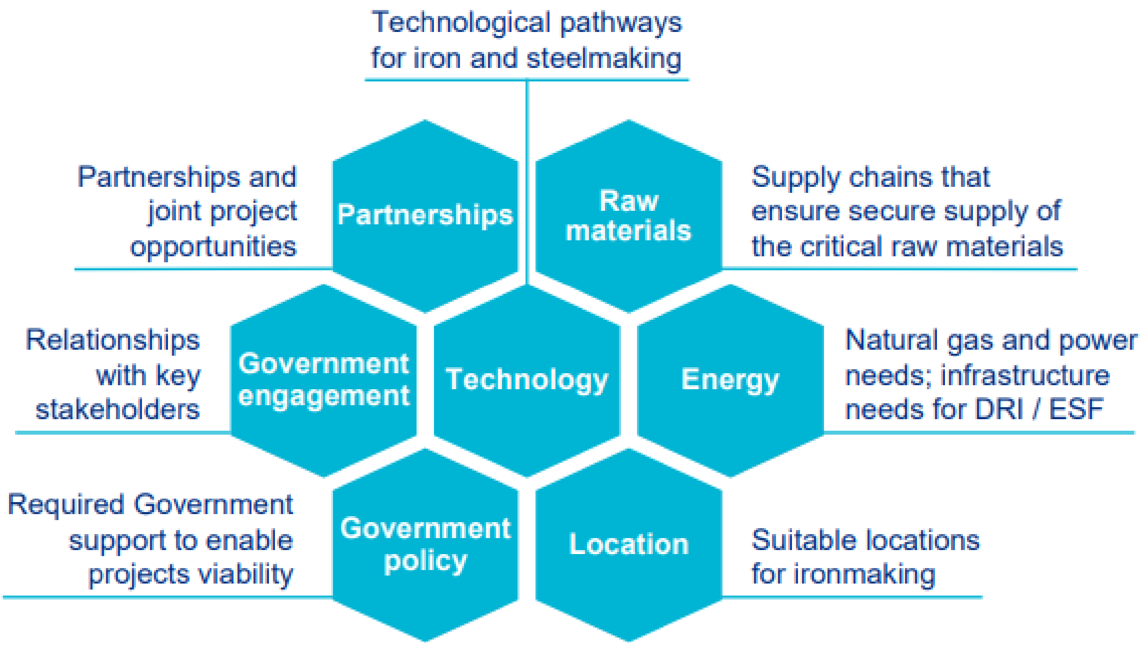
As an extension of this, BlueScope is now undertaking an expansive Direct Reduced Iron Options Study to explore the large-scale decarbonisation of ironmaking in our Australian operations. The study will inform the next steps in terms of trials, pilot plants, partners, capital investment and timelines. Specifically, the study will test the hypothesis that a DRI process using natural gas (as an intermediate step) and then green hydrogen (once it is commercially available), is the most prospective technology for our Australian operations, given the development timeframes for other nascent technology.

The study has two main objectives:

1. Identify iron and steelmaking options that provide a step-change in carbon emissions reduction, with a focus on DRI technology, and
2. Identify and qualify the enablers required for each option and any additional Government measures required to support on an economic basis.

Seven workstream teams have been deployed to progress the study, reporting to a central steering committee, refer to Figure 12.

Figure 12 Direct Reduced Iron Options Study work streams and focus areas.



The outcomes from the Direct Reduced Iron Options Study (planned to take twelve months) will form the basis of BlueScope's long-term iron and steelmaking decarbonisation pathway for steel production at PKSW.

5 Conclusions

With ARENA's support, BlueScope has investigated the technical feasibility of renewable energy and decarbonisation technology pathways that have the potential to decarbonise the steelmaking process at PKSW (Prioritised Options). PKSW is a traditional integrated steelmaking facility using the blast furnace ironmaking (BF)-basic oxygen furnace (BOF) route.

This third and final report builds on the findings and reporting for Phase 1 and Phase 2 of the Study, including further investigation of the identified Prioritised Options in Phase 1 via:

- a qualitative assessment of operational, engineering, environmental and safety aspects for PKSW,
- a preliminary process integration-based simulation modelling of Prioritised Options relative to a baseline PKSW operation,
- a final assessment process, and
- PKSW's decarbonisation pathway.

The final assessment process, Chapter 3, enabled a determination as to whether a Prioritised Option would be considered further, at this point in time. Further actions were recommended for Prioritised Options with the greatest potential to be economically viable and contribute to emissions reduction at PKSW. Chapter 4 described PKSW's decarbonisation pathway, both short- to medium-term and long-term and the Prioritised Options selected for further consideration. For each Prioritised Option, market barriers, pathway to commercialisation, and funding were considered.

6 References

1. Phase 1 report - Port Kembla Steelworks Identification of Prioritised Options Port Kembla Steelworks Identification of Prioritised Options - Australian Renewable Energy Agency (ARENA)
2. Phase 2 report – Port Kembla Steelworks Renewables and emissions Reduction Study – Biochar Investigation Bluescope Generic Report Template_v5 (arena.gov.au)
3. Internal BlueScope Concept Report - Port Kembla Steelworks Ironmaking Production 2026 Onwards Project December 2020
4. Norgate T; Haque N; Somerville M; Jahanshahi S. Biomass as a Source of Renewable Carbon for Iron and Steelmaking. ISIJ Int. 2012;52(8):1472-81.
5. Babich A. Blast furnace injection for minimizing the coke rate and CO2 emissions. Ironmaking & steelmaking. 2021;48(6):728-41.
6. Chen Y; Zuo H. Review of hydrogen-rich ironmaking technology in blast furnace. Ironmaking & steelmaking. 2021;48(6):749-68.
7. (AK steel [18],
8. https://www.midrex.com/tech-article/using-hbi-in-blast-furnaces/
9. https://www.kobelco.co.jp/english/releases/1207624_15581.html
10. https://www.kobelco.co.jp/english/releases/files/20210216_e.pdf
11. https://www.jfe-steel.co.jp/en/release/2020/201012.html
12. Yilmaz C, Wendelstorf J, Turek T. Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. Journal of Cleaner Production. 2017;154:488-501.
13. Birat JP, Patisson F, Mirgaux O. Hydrogen steelmaking, part 2: Competition with other net-zero steelmaking solutionsa-geopolitical issues. Materiaux et Techniques. 2021;109(3-4).
14. Babich A, Yaroshevskii S, Formoso A, et al. Co-injection of noncoking coal and natural gas in blast furnace. ISIJ International. 1999;39(3):229-238.
15. Zhao J, Zuo H, Wang Y, et al. Review of green and low-carbon ironmaking technology. Ironmaking and Steelmaking. 2020;47(3):296-306.
16. Miwa T, Kurihara K. Recent developments in iron-making technologies in Japan. Steel Research International. 2011;82(5):466-472.
17. Liu W, Zuo H, Wang J, et al. The production and application of hydrogen in steel industry. International Journal of Hydrogen Energy. 2021;46(17):10548-10569.
18. Babich A, Senk D, Gudenau HW. Ironmaking. Stahleisen, Germany; 2016.
19. Buergler T, Skoeld BE. The injection of ultrahigh rates of reducing gas into a modern blast furnace. Technical Report. EUR 22405 EN. European Communities. Luxembourg. 2007.
20. Watakabe S, Miyagawa K, Matsuzaki S, et al. Operation trial of hydrogenous gas injection of COURSE50 project at an experimental blast furnace. ISIJ Int. 2013;53(12):2065-2071.
21. Nishioka K, Ujisawa Y, Tonomura S, et al. Sustainable Aspects of CO2 Ultimate Reduction in the Steelmaking Process (COURSE50 Project), Part 1: Hydrogen Reduction in the Blast Furnace. Journal of Sustainable Metallurgy. 2016;2(3):200-208.
22. https://corporate.arcelormittal.com/media/news-articles/arcelormittal-asturias-starts-coke-oven-gas-injection-for-blast-furnace-b
23. https://www.sms-group.com/press-media/press-releases/press-detail/paul-wurth-books-new-order-for-coke-oven-gas-compression-and-injection-technology-at-hkm-1464
24. https://www.paulwurth.com/en/coke-oven-gas-injection-at-rogesa-blast-furnace-started-on-time/
25. BlueScope internal pre-feasibility study on Coke Ovens Gas (COG) injection 2022
26. Lebrouhi BE, Djoupo JJ, Lamrani B, et al. Global hydrogen development - A technological and geopolitical overview. International Journal of Hydrogen Energy. 2022;47(11):7016-7048.
27. Tonomura S, Kikuchi N, Ishiwata N, et al. Concept and Current State of CO2 Ultimate Reduction in the Steelmaking Process (COURSE50) Aimed at Sustainability in the Japanese Steel Industry. Journal of Sustainable Metallurgy. 2016;2(3):191-199.
28. https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/thyssenkrupp-steel-concludes-first-test-phase-successfully.html
29. BlueScope hydrogen proposal to NSW Government's Hydrogen Hubs funding program
30. BOF LDG collection proposal – Concept Study

31. Reduction of Greenhouse Gas Emissions in Steel Production, Final Report. Dr Jai Kant Pandit, Dr Max Watson & Dr Abdul Qader. March 2020, CO2CRC Report No: RPT20-6205Worldsteel.
32. Fact sheet - Electrolysis in ironmaking. Technical Report. Worldsteel Association. 2021.
33. Cavaliere P. Clean Ironmaking and Steelmaking Processes. Swutzerland: Springer; 2019.
34. Ferreira NM, Kovalevsky AV, Mikhalev SM, et al. Prospects and challenges of iron pyroelectrolysis in magnesium aluminosilicate melts near minimum liquidus temperature. Physical Chemistry Chemical Physics. 2015;17(14):9313-9325.
35. Bailera M, Lisbona P, Peña B, et al. A review on CO2mitigation in the Iron and Steel industry through Power to X processes. Journal of CO2 Utilization. 2021;46.
36. Babich A, Senk D, Gudenau HW. Ironmaking. Stahleisen, Germany; 2016.
37. Quader MA, Ahmed S, Ghazilla RAR, et al. A comprehensive review on energy efficient CO2 breakthrough technologies for sustainable green iron and steel manufacturing. Renewable and Sustainable Energy Reviews. 2015;50:594-614.
38. https://www.bostonmetal.com/
39. https://energy.nl/data/high-temperature-molten-oxide-electrolysis-steelmaking-ulcolysis/
40. https://www.siderwin-spire.eu/
41. Manenti AA. DRI Technology: Status, Trends and hydrogen use. Technical Report. METAL CONSULTING. 2021.
42. Mare CD. The 2021 AIST Howe Memorial Lecture - Why Both Hydrogen and Carbon Are Key for Net-Zero Steelmaking. Technical Report. AIST. 2021.
43. Private comms., BSL internal communications, 2023.
44. E.-H. Jeong et al., "Development of Waste Gas Recirculation System with Improvement of Sintering Productivity", DOI: 10.11159/mmme17.132.
45. https://www.sustainablesteel.org.nz/wp-content/uploads/2020/02/01146-Factsheet_Steelmaking_web-1.pdf; accessed 15 November, 2023.
46. https://www.midrex.com/tech-article/getting-the-most-from-direct-reduced-iron-operational-results-of-midrex-hot-transport-hot-charging/; accessed 15 November 2023.
47. BlueScope Econmoic Model for ARENA Project 2021/ARP011– Confidential spreadsheet detailing economics of each of the Prioritised Options. November 2023.

Appendix 1 - Quantitative assessment of operational, engineering, environmental and safety aspects

Short to Medium Term Prioritised Options

Note that information and data contained in each "General Description" below is taken from a previous investigation [1].

Table A1.1 – Key issues and development gaps: Novel charging materials to BF

BLAST FURNACE IRONMAKING	
Novel charging materials to BF (TRL range: 7-9)	**SCU**
General description: Various material improvements are available to increase the reduction efficiency of the BF process and decrease overall carbon emissions across the steelplant. These include alternatives to conventional BF raw materials, such as carbon-containing agglomerates (CCA), pre-reduced agglomerates (PRA) and ferro-coke. CCAs are pellets or briquettes comprised of a mixture of carbonaceous (coal, coke fine or carbon-rich materials) and iron oxide materials (iron ore fines or iron-bearing steel plant by-product fines). The close contact significantly improves carbon gasification and iron reduction kinetics, leading to a lower equilibrium temperature between reducing gas and wüstite. Similarly, ferro-coke is a mixture of 70% highly-reactive coke and 30% low grade iron ores in close contact, with the latter acting as a catalyst for coke gasification. PRAs are partially reduced pellets and sinters, or DRI (or Hot Briquetted Iron, HBI). The latter are usually produced in shaft-based DRI processes. With higher reduction degrees (70% or more), charging these materials into the BF increases productivity, decreases reductant requirement and potentially, overall carbon emissions of the steel plant.	
Summary of potential route(s) to progress this technology at PKSW: Development routes for "Novel charging materials to BF" are dependent on the current level of technical maturity of the three main technologies assessed i.e. CCA, HBI and Ferro-coke. Hence, while there have been many bench-scale experimental studies undertaken to assess the performance of CCA materials, especially their physical strength properties, there are few investigations involving full plant demonstration trials of these materials. The situation is very similar for JFE's Ferro-coke technology. Therefore, for PKSW, the initial key issues to resolve for both materials are similar. These pertain to establishing and understanding of the material specifications and assessing their likely performance under local BF conditions. As well, the capability to undertake pilot-scale testing would be an advantage. On the other hand, HBI is a more mature development and a traded pre-reduced agglomerate. In this case, the key issues for PKSW are to assess the impact of charging HBI in the BF on plant-wide carbon emissions reduction – initially, via a desktop study and ultimately, via a full plant demonstration.	
Key issues to resolve and the initial identified gaps for PKSW	
Carbon-containing agglomerates (CCA)	

Operational/ Technical	**Key issue:** The practical limits regarding the proportion of CCA that may be charged with the PKSW BF burden mix, with specific reference to mechanical strength and chemical behaviour. **Gap:** Initial desktop assessment of CCA performance in BF burden, based on BSL numerical models of the process including burden distribution, heat and mass balance and global models. **Gap:** Specification of CCA to achieve optimal physical strength properties for handling and further processing. This includes investigations of the type and proportion of binder to be used and the CCA post reduction strength to minimise degradation. **Gap:** Specification of CCA to optimise the thermal reserve zone temperature decrease within the BF. This includes optimising both the reactivity and fineness of ferrous (e.g. hematite, magnetite, plant dusts) and carbonaceous (e.g. fine coke, fine coal, biochar) materials. **Gap:** Behaviour of CCA under more realistic BF gaseous and thermal conditions, including reduction behaviour at low temperatures, interphase heat transfer mechanisms, reaction kinetics and mechanism, and the melting range of CCA relative to other burden materials (sinter, pellets, lump).
Engineering	**Key issue:** Production of CCA briquettes (or pellets) for large-scale piloting studies and associated technical investigations for PKSW application. CCA specifications are informed from a previous investigation [1]. **Gap:** Design/construct specific pilot-scale equipment required for preparation of material fines and the cold (or hot) pressing of briquettes (or pellets). Materials produced will be used for further technical assessment. This includes investigating cold bonding as well as briquetting at lower temperatures with appropriate binders.
Safety	None.
Environmental	**Key Issue:** Sustainably of carbonaceous sources, and process fuels. **Gap:** Assess CO2 emissions implications for both carbonaceous content of CCAs and their production.
Pre-reduced agglomerates: Hot Briquetted Iron (HBI)	
Operational/ Technical	**Key issue:** Understand the effect of charging different rates of HBI on the consumption of reducing agents particularly coke, changes in productivity and overall blast furnace operation, including hot metal quality at PKSW. **Gap:** Plant demonstration trials of HBI. This includes the logistics required to safely handle and store an alternate ferrous burden material (HBI) and experimental design of trials including the amount and placement of HBI in the BF charging sequence.
Engineering	**Key Issue:** Effect of HBI on charging equipment **Gap:** Examine the influence of HBI physical properties on materials handling and charging equipment, and any equipment modifications or HBI pre-processing (e.g. crushing) that may be required to achieve controlled feeding to the furnace without damage to the charging system.
Safety	**Key issue:** Safe handling and storage of HBI. **Gap:** Identify precautions to be taken during loading, shipment, and unloading of HBI, including fines generated during handling processes.
Environmental	**Key issue:** Feasibility study of charging HBI in the BF process to lower PKSW's overall carbon emissions. **Gap:** Assessment of the steady-state energy and materials balances of the BF process and across PKSW.

	Gap: Technoeconomic analyses of HBI use at PKSW. This includes the type of burden materials replaced, specific HBI properties and BF operational conditions.
Ferro-coke	
Operational/ Technical	**Key issue:** Understanding the performance of ferro-coke briquettes under PKSW BF conditions. [NB A possible subset of a previous investigation on CCA [1]. **Gap:** Physical properties and reactivity of ferro-coke briquettes under current BF conditions. This includes the effect of ore blending ratio on the reactivity and strength of briquettes produced using low-quality domestic ferrous materials (including PKSW iron-bearing by-products) and non-caking coals. If possible, obtain samples and compare with JFE-produced ferro-coke briquettes.
Engineering	**Key issue:** Production of ferro-coke briquettes for large-scale piloting studies and associated technical investigations for PKSW application. [NB A possible subset of a previous investigation on CCA [1]. **Gap:** Design/construct specific pilot-scale equipment required for preparation of material fines hot pressing of briquettes. Materials produced will be used for further technical assessment.
Safety	None.
Environmental	None.

Table A1.2 – Key issues and development gaps: Biomass application to ironmaking

BLAST FURNACE IRONMAKING		
Biomass application to ironmaking (TRL 5-9)	**SCU**	

General description:

Renewably sourced biomass materials (wood, crops, animal waste, landfill gas, biofuel, etc) may be considered a carbon-neutral resource in life cycle analysis and therefore, carbon emissions reductions may be attributed to its carbon neutrality. It is important to note that Life Cycle Analysis (LCA) considers the energy consumption in biomass establishment, harvesting, transport, drying and pyrolysis, and that a significant proportion of the pyrolysis co-products are captured or utilised. Furthermore, in using biomass as a partial replacement of fossil carbon across steel manufacturing, biomass serves as both a solid fuel and reductant source. Various investigations of biomass applications have been carried out across steel manufacturing processes including substitution of fossil carbon in sintering (coke breeze), cokemaking (coking coal), BF (coal injection, natural gas, coke), steelmaking (calcined anthracite) and DRI (coal). Other substitutions include in carbon-containing composites (coke, coal). In steel applications, slow or low temperature pyrolysis (torrefaction) are preferred as these maximise solids (biochar) production.

Summary of potential route(s) to progress this technology at PKSW:

There are several challenges associated with the use of biomass at PKSW. These include the availability of pyrolysis equipment of sufficient scale, geographically wide dispersion of suitable biomass sources which are quite remote, transport implications for low density and high moisture content of biomass, and the low yield of carbon per tonne of wet biomass. There is also the lack of recent industrial experience with using processed biomass (biochar), and hence, a lack of knowledge with respect to the optimum biochar attributes.

Therefore, potential routes that could be pursued for PKSW include:

Establishing links with existing aggregators of reclaimed timber from waste streams, forestry/sawmill biomass or biomass sourced from woody weeds or invasive native scrub; and establishing links with forestry/plantation companies to ensure provision of biomass through the planting of suitable species for biomass production (ideally faster growing eucalypts, mallee, etc).

Purchasing a single unit or units of an existing larger scale commercial pyrolysis technology and install these at PKSW (perhaps 20ktpa of biochar). Biomass is then purchased on an adhoc basis, which is then processed, with the resulting biochar used for longer plant trials, most likely through the PKSW Pulverised Coal Injection (PCI) Plant. Through this, optimised pyrolysis and biochar parameters are determined. Assuming these results are positive, further pyrolysis units (either of the same or different technologies depending on trial outcomes) are installed until PKSW real estate and biomass logistical limits are met (perhaps 100ktpa biochar production). Further developments may require the establishing of remote sites closer to supplies of biomass to produce biochar which is then transported to PKSW. Depending on outcomes, pyrolysis by-products could be used as a BF injectant, a renewable fuel or potentially partially condensed to produce pyrolysis oil and wood vinegar for sale.

Purchasing biochar from local and international suppliers which could then be trialled either alone or as a supplement to PKSW produced biochar and ultimately adopted as part of the normal raw materials supply for PKSW.

Setting up joint ventures with either biomass suppliers and/or biochar producers such that PKSW then has a share in biochar manufacturing closer to biomass supplies. Under this model, biomass aggregation and biochar production “hubs” could be established with logistical links to PKSW. Pyrolysis by-products in this case could be used as a source of renewable fuel for local power generation, or partially condensed to produce pyrolysis oil and wood vinegar for sale.

Key issues to resolve and the initial identified gaps for PKSW

Sourcing appropriate biomass and setting up supply/processing infrastructure	
Operational/ Technical	**Key issue:** Forestry biomass logistics are well established, however for economic and sustainability reasons, alternative supply lines of biomass need to be established, particularly reclaimed timber from landfill streams and woody weeds such as invasive native scrub (INS) or Prickly Acacia. **Gap:** Conduct surveys of alternative biomass sources and determine appropriate logistical options to transport to PKSW or remote pyrolysis plants **Gap:** Conduct pyrolysis trials on alternative biomass sources, with a focus on the partitioning of specific trace elements (arsenic; lead).
Engineering	**Key issue:** Alternative biomass sources may have different handling and processing requirements than forestry biomass. **Gap:** Conduct test work on alternative biomass to determine processing and handling requirements. **Gap:** Determine appropriate gas and dust handling equipment for treating off-gas from the pyrolysis of contaminated biomass streams.
Safety	**Key issue:** Handling/storage of particularly wet biomass can be challenging and could result in biomass degradation, potential fire and dust issues. **Gap:** Investigate current biomass handling guidelines at PKSW.
Environmental	**Key Issue:** Biomass supply needs to be sustainably certified to qualify as a zero CO_2 emissions source. **Gap:** Identify and strictly define criteria that determine the biomass sustainability requirements for ironmaking purposes and a framework for life cycle analysis of multiple biomass sources.
	Key Issue: Use of alternative biomass sources could come with higher trace metals levels, which may cause problems for steelmaking recycling streams. **Gap:** Further develop understanding of trace element flows within iron and steelmaking with the ultimate aim of determining appropriate use of biomass with higher trace element levels.

Use of biochar as a replacement for pulverised coal in the BF	
Operational/ Technical	**Key issue:** The practical limits regarding the proportion and properties of biochar that may be combined with coal for processing and pneumatic conveying through BSL's PCI Plant and injected into the BF. This in turn determines the type and scale of pyrolysis technology required as well as any further modifications that might be required for the PCI Plant. • **Gap:** Test pneumatic conveying performance of biochar/coal blends at pilot-scale, followed by increasing scale of industrial trials. • **Gap:** Conduct small to large scale industrial trials of biochar with varying volatile contents to determine optimum biochar parameters. • **Gap:** Once optimum biochar volatile content is established use this result to determine appropriate pyrolysis technology. • **Gap:** Use results above to determine the necessary modifications to the PCI Plant and injection system.
Engineering	**Key issue:** The type and scale of pyrolysis technology required is yet to be determined as are any further modifications that might be required for the PCI Plant and associated biochar handling systems • **Gap:** Understand the scale and property requirements for biochar. • **Gap:** Identify appropriate pyrolysis and materials handling technologies to deliver biochar production at the scale and quality required. • **Gap:** Identify appropriate modifications to existing equipment to facilitate the increased use of biochar for replacement of pulverised coal. • **Gap:** Identify necessary equipment required to ensure that spontaneous combustion of biochar post pyrolysis can be prevented.
Safety	**Key issue:** Handling/storage of biochar for a period immediately post pyrolysis could result in issues with spontaneous combustion. • **Gap:** Identify conditions and biochar state/properties which result in spontaneous combustion.
Environmental	**Key Issue:** Biomass supply needs to be sustainably certified to qualify as a zero CO_2 emissions source. • **Gap:** Identify and strictly define criteria that determine the biomass sustainability requirements for ironmaking purposes and a framework for life cycle analysis of multiple biomass sources.
Use of biochar as replacement for Sinter Plant fuel (assumes biochar production is already underway for PCI)	
Operational/ Technical	**Key issue:** Use of biochar for full-scale sintering operations has yet to be tested at PKSW. • **Gap:** Use laboratory scale sinter pot testing to confirm biochar can be used with current PKSW ore blends. • **Gap:** Test the use of increasing proportions of biochar at the Sinter Plant using the results of laboratory scale testing as a basis for industrial trials.
Engineering	**Key issue:** The low density and water holding capacity of biochar means handling and crushing requirements will be different compared to coke breeze. • **Gap:** Conduct laboratory scale crushing experiments with biochar to determine optimum settings for biochar crushing at PKSW. • **Gap:** Conduct survey of breeze materials handling equipment at PKSW to determine handling capacity for lower density biochar.

	• **Gap:** Conduct studies on the appropriate densification equipment and methodologies for producing a dense biomass feed for pyrolysis, thereby producing a higher density biochar product more suited to sintering.
Safety	**Key issue:** Handling/storage of biochar for a period immediately post pyrolysis could result in issues with spontaneous combustion. • **Gap:** Identify conditions and biochar state/properties which result in spontaneous combustion.
Environmental	**Key issue:** Feasibility study of using biochar in sintering to reduce PKSW's CO_2 emissions, given expected higher fuel rate requirements. • **Gap:** Conduct LCA and techno-economic analysis for use of biochar in sintering to assess overall CO_2 emissions reduction benefit.
Use of biochar as an addition to the coking coal blend	
Operational/ Technical	**Key issue:** Understanding the performance of biochar/coal blends under PKSW coking conditions. • **Gap:** Conduct industrial scale trials of increasing biochar proportions (up to an expected maximum of 5%) at PKSW.
Engineering	**Key issue:** Use of lower density biochar could challenge current materials handling equipment. • **Gap:** Conduct survey of coal materials handling equipment at PKSW to determine handling capacity for lower density biochar.
Safety	**Key issue:** Handling/storage of biochar for a period immediately post pyrolysis could result in issues with spontaneous combustion. • **Gap:** Identify conditions and biochar state/properties which result in spontaneous combustion.
Environmental	**Key issue:** Feasibility study of using biochar in coke making to reduce PKSW's CO_2 emissions. • **Gap:** Conduct LCA and techno-economic analysis for use of biochar in coke making to assess overall CO_2 emissions reduction benefit.
Use of biochar a recarburizer for steelmaking (assumes biochar is already produced/available)	
Operational/ Technical	**Key issue:** Understanding the performance of biochar at PKSW steelmaking facilities. • **Gap:** Conduct industrial scale trials of biochar as a steelmaking recarburizer.
Engineering	**Key issue:** Use of lower density and potentially higher moisture biochar could challenge current materials handling equipment. • **Gap**: Conduct survey of handling equipment at Slabmaking to determine handling capacity for lower density biochar.
Safety	**Key issue:** Biochar volatiles and moisture content could be a problem for the PKSW steelmaking gas system. • **Gap:** Identify volatile matter and moisture limits for use in steelmaking
Environmental	**Key issue:** Feasibility study of using biochar in coke making to reduce PKSW's CO_2 emissions. • **Gap:** Conduct LCA and techno-economic analysis for use of biochar in coke making to assess overall CO2 emissions reduction benefit.
Use of biochar as a Nut coke replacement at the BF	

Operational/ Technical	**Key issue:** Understanding the performance of biochar as a Nut coke replacement under industrial conditions. • **Gap:** Assess available particle size distributions and shapes of biochar for comparison with Nut coke. • **Gap:** Industrial scale trials of biochar as a Nut coke replacement. • **Gap:** Investigate moisture holding capacity of biochar in comparison to Nut coke and establish maximum/minimum moisture requirements for handling of biochar.
Engineering	**Key issue:** Use of lower density biochar could challenge current blast furnace stockhouse materials handling equipment. • **Gap:** Conduct survey of Nut coke handling equipment at the BF stockhouse to determine handling capacity for lower density biochar.
Safety	**Key issue:** Handling/storage of biochar for a period immediately post pyrolysis could result in issues with spontaneous combustion. • **Gap:** Identify conditions and biochar state/properties which result in spontaneous combustion.
Environmental	**Key issue:** Feasibility study of using biochar in coke making to reduce PKSW's CO_2 emissions. • **Gap:** Conduct LCA and techno-economic analysis for use of biochar in coke making to assess overall CO_2 emissions reduction benefit.

Table A1.3 – Key issues and development gaps: Hydrogen-enriched injection

BLAST FURNACE IRONMAKING		
Hydrogen-enriched injection (TRL range: 6-9)	**SCU/ DCA**	
General description: Utilisation of hydrogen (H_2)-enriched injection gases in the BF is advantageous because of H_2 strong diffusion and high reduction ability. More importantly, the reduction product is H_2O (and not CO_2). Hydrogen-enriched injectants that have been trialled on operating BFs include gases such as natural gas, coke oven gas and hot reducing gas, and liquid and solid materials such as oil, waste plastics and organic wastes. While there has been limited demonstration of renewable hydrogen injection into the BF, and the injection rate will be operationally constrained, this technology may effectively reduce fossil carbon consumption (e.g. coke and pulverised coal). Co-injection of renewable hydrogen together with other hydrogen-enriched gases/materials is a likely scenario. It is important to note that at present, substitution of fossil carbon via petroleum-derived waste plastics does not change carbon accounting.		
Summary of potential route(s) to progress this technology at PKSW: Potential "Hydrogen-enriched injection" development routes for a future PKSW BF operation include: injection of available, plant-generated Coke Ovens Gas (COG), Natural Gas (NG), unlikely from a decarbonisation and cost perspective, and Hydrogen. Noting that prior to current pulverised coal injection (PCI), both natural gas and COG were injected into PKSW blast furnaces, however, not concurrently with PCI. With COG injection, there are two possible options: COG (~60% H2), introduced via injection lances into the BF blowpipe; and Reformed COG (~75% H2), introduced into lower shaft tuyeres. Requires major design modifications to the furnace proper and is considered unlikely given current 6BF reline design. A cost-effective, stable supply of hydrogen, produced via electrolysis using renewable electricity, could partially replace PCI coal. The implementation of COG and certainly hydrogen injection at PKSW still requires several levels of operational, technical, and engineering investigation.		
Key issues to resolve and the initial identified gaps for PKSW		
Natural Gas (NG), Coke Ovens Gas (COG) and Hydrogen (H2)		
Operational/ Technical	**Key issue:** To lower overall PKSW carbon emissions, specify the BF operational limits which maximise the injection rate of hydrogen-enriched gases (such as NG, COG and/or H_2) at PKSW, with or without co-injection of pulverised coal, whilst maintaining overall furnace stability and productivity. **Gap:** Overall assessment of the maximum possible levels of various hydrogen-enriched gas injection at PKSW. Operational aspects to identify include optimising the furnace process conditions and settings, such as the minimum adiabatic flame temperature, minimum top gas temperature, optimal heat flow ratio, bosh gas volume, etc. Injection aspects include to understand any synergistic effect of combining hydrogen-enriched gas and pulverised coal injection, particularly on the burnout of coal. **Gap:** Evaluate the alternate equipment designs and configurations which help mitigate the risks associated with introducing H_2 and H_2-containing gases into the PKSW BF hot blast system and furnace proper. Computational models will be used to evaluate key design features for the PKSW set up such as the positioning and configuration of the various reductant supply lances or tuyere ports within the blowpipe-tuyere-raceway regions. Specific issues include optimal positioning of lances or ports delivering the H_2-	

	enriched streams, relative to the tuyere nose and oxy-coal lance; and the design of the blowpipe and tuyere, with multiple lances or ports in place. **Gap:** Understand the effects of hydrogen-enriched injection conditions on the behaviour and performance of raw materials used at PKSW, under more realistic blast furnace gaseous and thermal conditions. This would include changes in ore reduction, softening and meltdown, and changes in the reactivity of metallurgical coke at all temperatures including those greater than 1500°C at prevailing furnace gas compositions, relative to current BF reference conditions. **Gap:** Understand the impact of coke reactivity changes on coke fines generation in the BF lower zone, particularly with respect to BF productivity. This information may impact raw materials selection and production strategies that target hydrogen use in the PKSW BF.
Engineering	**Key issue:** Feasibility of safely delivering renewable hydrogen technology to partially replace carbon units in PKSW blast furnace ironmaking. **Gap:** Plant demonstration of multi-tuyere hydrogen-rich gaseous injection at PKSW's blast furnace, including either directly to the BF or for enrichment of NG to simulate COG injection. A dual lance or lance and tuyere port set up will be evaluated across multiple tuyeres, likely two adjacent tuyeres. The dual injection set up will include the existing co-axial, oxygen-coal lance system and a separate single or coaxial lance, or tuyere port, for injection of H_2 or H_2-enriched NG. The demonstration trial will involve the design modification and installation of blowpipes and tuyeres on these adjacent tuyeres. Comparative evaluation of various elements including the safe supply of H_2 to the furnace will be included. For evaluations purposes, the demonstration trials will deploy sensing technologies and data analytical tools for in-situ thermal monitoring and assessment of all equipment performance (lances, blowpipe, etc) within the high-temperature environment of the PKSW BF. **Key issue:** Assessment of material specifications for the H_2/H_2-enriched gas supply lances/ports to enable longer life performance under the harsh, high temperature conditions in the PKSW blast furnace blowpipe. **Gap:** Materials testing of candidate lance materials under thermal and gaseous conditions within the blowpipe, when supplying H_2 gas, or H_2-enriched NG or COG mixtures, compared to benchmark materials for lances supplying pulverised coal and cooled with oxygen gas, as currently used at PKSW. Laboratory metallurgical investigations of potential steel alloys (Stainless Steel 253 MA and ASTM 310 Stainless Steel) will be undertaken at high temperatures, using encapsulation of the steel samples in quartz tubes with the required gas content (99.9% hydrogen, mixture of hydrogen and natural gas) and subsequent continuous and cyclic exposure to high temperatures (800 and 1100°C), 60s to 24hs. Materials will be assessed according to H_2 pickup and degradation of their surface and mechanical properties. Optical microscopy, scanning electron microscopy, hardness and tensile properties testing will be undertaken. These data will be benchmarked against the performance of the same steel samples under oxygen atmosphere.
Safety	**Key issue:** Feasibility of safely delivering renewable hydrogen technology to partially replace carbon units in PKSW blast furnace ironmaking. **Gap:** As per Engineering key issues above, **a** plant demonstration of multi-tuyere hydrogen injection at PKSW's blast furnace.
Environmental	None.

Table A1.4 – Key issues and development gaps: Sintering related energy saving and emission reduction

SINTERING		
Sintering related energy saving and emission reduction (TRL 9)	**SCU/ DCA**	
General description: Sintering is a key agglomeration process for iron ores at many steel plants, representing ~10% of the total energy consumption of the overall steel plant. Consequently, measures to recover and appropriately utilise waste heat from the sinter cooler, recycle waste gas back into the sinter strand, utilise microwave technology for heating recycled air for ignition, use of hydrocarbon gases for sintering or to decrease the sintering bed temperature, have been considered or are under development.		
Summary of potential route(s) to progress this technology at PKSW: Initial development routes for a future PKSW sintering operation would likely involve more heat recovery from the sinter cooler. Three options are possible: (1) electricity generation for general usage; (2) gas recirculation system; and (3) preheating of ignition air. Waste gas recycling from wind boxes beneath the rear part of sinter strand is a potential next implementable step. The recycled waste gas needs oxygen enrichment (using fresh air supplement or exhaust air from the cooler). The design of the extraction location of the waste gas and the supply location on the strand is required. Depending on the availability of natural gas and coke ovens gas (COG), the super-sinter technology could be further applied at PKSW. This is expected to reduce the carbonaceous materials up to 13%. Due to the extra facilities needed for gaseous reductant injection, it could be reasonable to introduce the surface steam injection before any reducing gas is used. The implementation of the heat recovery and gas injection system at PKSW requires system design, process assessment, operational control guidance, facilities setup, and relevant operational, technical and engineering investigations.		
Key issues to resolve and the initial identified gaps for PKSW		
Waste heat recovery from cooler		
Operational/ Technical	**Key issue:** Recovered heat from cooler is used for most valuable application. **Gap:** PKSW economic and technical feasibility analysis and comparison of three options for heat application including electricity generation, preheating and gas recirculation, is required. **Key issue:** The maximum heat recovery rate should be consistently achieved. **Gap:** The design for efficient and consistent high and low grade heat recovery through low and high-temperature exhaust sections is required. **Key issue:** Process stability and sintering bed uniformity should be guaranteed as the recovered cooler air is injected back to sinter strand. **Gap:** Assessment and determination of injection location of cooling air on the sinter strand. Trials on the uniform heating and burn-through point control. Assessment of solid fuels distribution in the bed for heating and non-heating regions.	
Engineering	**Key issue:** Waste heat recovery is a high cost. Optimal design of waste heat transportation system is required. **Gap:** Consistent and uniform recovery of waste heat from the cooler is important for process stability. If the recovered heat is used to produce power, the energy conversion efficiency is also an important performance indicator. Assessment of technologies provided by different suppliers is critical although payback time of heat recovery facilities is reported to be over 5 years) [27].	
Safety	None.	
Environmental	**Key issue:** De-dusting of cooling air.	

	Gap: As part of heat recovery system, it is necessary to construct a closed cycle facility for de-dusting of cooling air to avoid the emission of a high concentration of dust into the atmosphere.
Waste gas recycling	
Operational/ Technical	**Key issue:** Optimal extraction and injection locations of waste gas. **Gap:** Evaluation of partial waste gas recycling at PKSW needs to be done in terms of extraction and injection locations of waste gas. Due to the high sensible heat and high amount of pollutants in the waste gas from the last wind boxes, most existing technology is more likely to recycle the waste gas from the rear part of sinter strand and apply the waste gas into the front part of sinter strand. The optimal arrangement of waste gas recycling needs critical judgement. **Key issue:** To maximise the waste gas recycling rate, the optimal waste gas temperature for the electrostatic precipitator (EP) should be maintained. **Gap:** Partial recycling of waste gas from wind boxes must consider the temperature of waste gas entering the EP to avoid the condensation and corrosion in the EP. In this regard, optimal recycling arrangement needs to be assessed to consider the EP requirement. **Key issue:** Similar to cooling air application into the sinter strand, process stability, sintering bed uniformity, consistent hot zone formation should be guaranteed as the recycled waste gas is injected back to this part of sinter strand. **Gap:** Recycled waste gas helps the reduction of solid fuel and pollutants from the strand, however, it also causes uncertainties such as delayed steady-state operation after restart of sintering machine from stops, change of solid fuel requirement in the different height of sintering bed, potential step change of internal sintering bed condition in relation to the partial heating region. All these require more advanced process control and operational guidance.
Engineering	**Key issue:** Proper adjustment of suction control of sinter strand and oxygen enrichment for the recycled waste gas. **Gap:** Extra EP and suction system might be required, which needs an assessment. Oxygen in waste gas can be enriched through ambient air or recycled cooling air, depending on PKSW cooler heat recovery program.
Safety	**Key issue:** Safe handling of dusty and harmful elements contained in waste gas. **Gap:** Minimisation of leakage of injection system.
Environmental	**Key issue:** Decreased pollutant release from sintering process. **Gap:** The recycling of waste gas can lead to 45-50% decrease of the waste gas emitted to the atmosphere. However, it also potentially causes more sulphur to be retained in the sinter.
Super-sinter technology	
Operational/ Technical	**Key issue:** As an emerging technology, its economic viability needs to be assessed. **Gap:** Super-sinter technology requires hydrocarbon gases for the replacement of solid fuel, which heavily depends on the availability of hydrocarbon gases. Together with the evaluation of operational cost, its economic viability needs to be assessed in the PKSW integrated steel work environment.

	Key issue: Evaluation of super-sinter technology to improve the sinter quality and reduce the fuel consumption using the PKSW raw materials and granulation condition. **Gap:** Super-sinter technology is expected to cause a broader hot zone region with the sintering temperature below the maximum combustion temperature. Evaluation of this technology's influence on sinter quality, bed permeability and fuel consumption needs trials in PKSW sintering process. **Key issue:** Similar to the waste gas recirculation, it is uncertain whether a specified solid fuel distribution in the sintering bed is required corresponding to part of the sintering bed with the injection of hydrocarbon gases. **Gap:** Partial bed injection of hydrocarbon gases may cause the step change of sintering bed condition. How do the changes in suction control, the sintering bed speed and granulation correspond to the gas injection? In terms of reported reduction of solid fuel consumption (~4.7 kg/t-sinter), what is the payback time of heat recovery facilities for PKSW? In spite of this technology having TRL 9, on-line and off-line studies are necessary before its implementation at PKSW.
Engineering	**Key issue:** Adjustment of suction control of sinter strand, additional air flow for the gas injection, and extra water generation in the waste gas. **Gap:** Further evaluation of the injection system above the strand is required, and suction and waste gas temperature control below the strand
Safety	**Key issue:** Safe transportation of natural gas and COG for gas injection. **Gap:** System design of gas transportation and injection.
Environmental	None.

BlueScope

Table A1.5 – Key issues and development gaps: DRI and scrap utilisation in Basic Oxygen Furnace

<table>
<tr><td colspan="3">STEELMAKING</td></tr>
<tr><td colspan="2">DRI and scrap utilisation in Basic Oxygen Furnace (BOF)</td><td>SCU/DCA</td></tr>
<tr><td colspan="3">General description:
The BOF is a widely used metallurgical reactor to produce molten steel, using oxygen blown through a central lance to lower carbon content and other impurities (silicon, sulphur and phosphorus) in molten iron (hot metal). Within BOF process constraints, steel scrap (~25% - 30%) and other iron-bearing materials, such as DRI, may be used as a coolant and to increase steel output. In the case of DRI, it has been charged directly into the BOF as HBI, at lower levels.</td></tr>
<tr><td colspan="3">Summary of potential route(s) to progress technology at PKSW:

In the short to medium term, with molten iron into the BOF at PKSW expected to be from the BF, it may be possible to increase scrap/HBI utilisation in BOF to decrease the overall steelmaking GHG intensity. Noting that HBI could be considered in the event of a scrap deficit but would otherwise be more effectively utilised at the BF as detailed in Table A1.1: Novel charging materials to BF. In the BOF, HBI would need to be melted and reduced, with contaminants managed, whereas scrap just needs to be melted.
Given the sufficient availability of scrap on the East Coast of Australia, the following key issues focus on increasing scrap into the BOF to increase output and reduce GHG emissions intensity. This is comparable with using an EAF to recycle scrap steel.</td></tr>
<tr><td colspan="3">Key issues to resolve and the initial identified gaps for PKSW</td></tr>
<tr><td>Operational/ Technical</td><td colspan="2">Key Issue: BOF heat balance. Scrap is used in the BOF vessel both as an iron source and as a coolant to control the BOF steelmaking temperature [1]. There is a finite amount of scrap that can be melted in a BOF, currently limited to around 25-30%. If more scrap is to be used in the furnace, consideration needs to be given to maintaining the temperature.
• Gap: Development of a scrap preheating system. Pre-heating of scrap can allow an increase of scrap to be charged to the BOF. In a study looking at preheating scrap in an existing BOF vessel, an increase of 8.2% in carbon abatement per tonne crude steel could be achieved [2]. The choice of fuel and heating method is critical to any abatement method.
• Gap: Iron temperature loss between the BF and the BOF impacts the amount of scrap that can be utilised. Investigate ways to maintain the temperature.
• Gap: Having to add significant amounts of heat raiser to maintain the temperature reduces the emissions reduction and increases costs. Understand the relationship between increased scrap charge and required heat raiser.
• Gap: In the event of insufficient supply of high-grade scrap, lower-grade scrap will increase the loads of tramp elements on the process such as Cu, Cr, Ni and Zn. This will present challenges to achieving steel grade chemistries.</td></tr>
<tr><td>Engineering</td><td colspan="2">Key issue: Being able to consistently charge the desired amount of scrap into the BOF.
• Gap: Scrap handling and BOF charging equipment is not designed to charge >30% scrap per heat. Investigate bottlenecks that limit the amount of scrap that can physically be charged.</td></tr>
<tr><td>Safety</td><td colspan="2">None</td></tr>
</table>

Environmental	None.

1. Turkdogan, E.T, Fundamentals of Steelmaking, The Institute of Materials, 1996.
2. Beca. Scrap melting concept study. Technical Report. Beca. 2022.

Table A1.6 – Key issues and development gaps: Carbon Capture, Utilisation and Storage

<table>
<tr><td colspan="3">Carbon Capture, Utilisation and Storage</td></tr>
<tr><td>Carbon Capture and Storage/Carbon Capture and Utilisation (TRL range: 4-9)</td><td>SCU</td><td></td></tr>
<tr><td colspan="3">General description:

In addition to new iron and steelmaking process developments, carbon capture, utilisation and storage (CCUS) technologies are considered as potential solutions to mitigate carbon emissions in the steel industry. The various options for carbon capture for the industry are like other industries and include chemical/physical absorption, adsorption, cryogenic separation and membrane physical separation. A number of steelmakers have completed trials and built pilot plants [1]. While some options have been commercialised at small scale (e.g. Emirates Steel Industries 0.8 Mt CO_2 per year), none are widely and commercially available at large industrial scale, particularly for CO_2 capture from a number of very high volume, dusty flue/off-gas sources that are widely dispersed across an integrated plant e.g. BF top gas and BOF off-gas. Following capture, large volumes of CO_2 would be transported to a suitable storage/geological location (e.g. oil reservoir, depleted oil and gas reservoir, coal beds and deep aquifers) and isolated for a long term (CCS); or, in the case of CCU, CO_2 would be re-used either directly or as a carbon resource for the production of value-added products. Cost-effective technologies need to be developed [1], with current investigations underway based on how CO_2 changes during its utilisation i.e. without CO_2 transformation (e.g. BF top gas recycling), after CO_2 chemical transformation (e.g. Slag2PCC, producing $CaCO_3$) and after CO_2 biological transformation (e.g. STEELANOL, producing ethanol).</td></tr>
<tr><td colspan="3">Summary of potential route(s) to progress technology at PKSW:

Chemical absorption and adsorption are two key CO_2 capture technologies which can be potentially applied at PKSW. The capture capacity and operating cost in the future development of these technologies need to be monitored. CO_2 utilisation through chemical or biological approaches can be potentially applied at PKSW. There are two major CO_2 biological transformation technologies that could be used at PKSW: (1) biological fermentation and (2) biological carbon sequestration by microalgae. The former transforms CO_2 contained flue gas and other gases into ethanol and the latter converts CO_2 into organic matter via photosynthesis. The biogas or biomass material produced by biological transformation potentially forms a closed carbon cycle in the steelworks.</td></tr>
<tr><td colspan="3">Key issues to resolve and the initial identified gaps for PKSW</td></tr>
<tr><td colspan="3">Carbon Capture and Storage (CCS)</td></tr>
<tr><td>Operational/ Technical</td><td colspan="2">Key issue: Selection of optimal chemical solvent for chemical absorption technology used in the iron and steel industry.
Gap: Common chemical solvents used in chemical absorption are amine-based solvents such as MEA (monoethanol amine), DEA (diethanol amine), etc. For optimisation, new solvents are being continuously developed (see [1] for more details) . The proper selection of chemical solvent can help improve the CO_2 absorption capacity and decrease subsequent desorption energy consumption. Thus, it is necessary to continuously monitor and evaluate the development and application of solvents.

Key issue: Industrial application of adsorption technology for CO_2 capture.
Gap: Currently, in steel industry, CO_2 capture by adsorption is still limited at the pilot level. The main adsorption processes are pressure swing adsorption, vacuum pressure swing adsorption, temperature swing adsorption and electric swing adsorption. The differences in</td></tr>
</table>

	these processes are the usage and regeneration of adsorbents. The large-scale application of adsorption in the steel industry is worth to be monitored. **Key issue:** The current CO_2 capture technologies are still economically suited for low volume CO_2 capture. **Gap:** Currently, the maximum CO_2 capture capacity is 0.8 Mt per year at Emirates Steel Industries (ESI) based on chemical absorption using MEA absorbent. The operating cost at ESI is unknown and the flue gas is from DRI process. ~20 $/t_$CO_2$ is a normal cost in the other pilot tests. For PKSW, both capture capacity and operating cost of developing CO_2 capture technology will be monitored for future application. **Key Issue:** Collection of CO_2 sources for CO2 capture **Gap:** PKSW is an integrated steelworks with over 100 discharge stacks, separated across a large facility. Even selecting the few highest CO_2 discharges for CO_2 capture, would require a significant amount of infrastructure. **Key issue:** PKSW is located in the Sydney Basin, which geologically is unsuitable for storage. **Gap:** Any collected CO_2 for storage would need to be transported long distances to a suitable storage location.
Engineering	None.
Safety	None.
Environmental	**Key issue:** Chemical absorption can cause high equipment corrosion rate and the leaked amines can affect the environment. **Gap:** The improvement of the absorbents and optimal process configuration can reduce the risks in both equipment corrosion and environment pollution.
Carbon capture and utilisation (CCU)	
Operational/ Technical	**Key issue:** CO_2 utilisation through chemical production in steel industry is still at the pilot stage. **Gap:** CO_2 utilisation through producing chemical products such as ethanol, methanol, ethylene etc has been demonstrated to be possible [1]. However, for industrial-level CO_2 utilisation, this technology still needs more developments. The renewable energy and hydrogen sources for chemical production are also required to help achieve large-scale CO_2 utilisation. **Key issue:** CO_2 biological transformation through fermentation has been commercialised. However, the corresponding CO_2 reduction capacity is still limited. **Gap:** It is worth monitoring the progress of the STEELANOL project as this project is planned to reduce annual carbon emissions from the Ghent plant by 125,000t through biological fermentation technology (Lanzatech). **Key issue:** Limited understanding of the potential disadvantages of biofuels produced through biological transformation.

	Gap: It is requested to systematically evaluate the quality of biofuel produced from fermentation or different algae species. **Key issue:** Categorisation of fuels produced. **Gap:** Even though utilisation of fuels is a means of recycling, fuels produced are unlikely to be categorised as biofuel due to their fossil carbon origin. **Key issue:** Limited understanding of culturing process of microalgae for the treatment of large amount of flue gases. **Gap:** Research and development activities are requested to help understand carbon fixation rate and algae growth law, and select suitable algae species, etc in the realistic outdoor pond for treating flue gases at a large scale.
Engineering	None.
Safety	None.
Environmental	**Key issue:** Microalgae pond used for biological sequestration could potentially lose the pond's biodiversity. **Gap:** Intensive research is required to understand the influence of biological sequestration on the environment and optimise the growth and harvesting of microalgae.

Long Term Prioritised Options

Note that, as for the short-to-medium term Prioritised Options, information and data contained in each "General Description" below is taken from a previous investigation [1].

Table A1.7 – Key issues and development gaps: Electrolysis of iron ore

<table>
<tr><td colspan="3">ALTERNATE IRONMAKING</td></tr>
<tr><td colspan="1">Electrolysis of iron ore (TRL range: 4-5)</td><td>DCA</td><td></td></tr>
<tr><td colspan="3">General description:

Electrolysis of iron oxide is an electro-chemical process to produce metallic iron and oxygen in an electrolytic cell, using direct electric current. If renewably sourced electricity is used, iron is produced without carbon emissions. Electrolysis of iron oxide has been demonstrated at laboratory scale, under low and high temperature conditions [1]. In low temperature electrolysis, aqueous electrolytes are used, while in high temperature electrolysis, molten oxides act as the electrolyte, with operating temperatures over the melting point of iron. There are many challenges to resolve: suitable anode materials, selection of electrolyte, optimal electrolysis cell configuration, control of process temperature and electrical current, acceptable iron ore properties and sustainable cell materials in highly corrosive environment.</td></tr>
<tr><td colspan="3">Summary of potential route(s) to progress this technology at PKSW:

Both high and low temperature processes are proven at laboratory scale, significant development is required before electrolysis becomes economically and practically viable.</td></tr>
<tr><td colspan="3">Key issues to resolve and the initial identified gaps for PKSW</td></tr>
<tr><td>Operational/ Technical</td><td colspan="2">Key issue: Significant research and development required prior to process scale up and demonstration at industrial scale (maximum cell size, arrangement of multiple cells, etc).
Gap: Evaluation of materials such as a cheap, carbon-free inert electrodes and cell refractories that are resistant to the corrosive conditions in the scaled up electrolysis condition. Automated, large-scale harvesting of metal plates.
Gap: Understanding of electrochemical mechanisms at large-scale operation and their influence on the efficiency of energy utilisation, and reliable process control in terms of continuous operation and product uniformity.
Gap: Assessment of secondary raw materials as iron source (e.g. plant by-products, etc.)
Gap: Understanding the integration of electrolysis plants to the power grid, recovery of oxygen, purification, and compression.</td></tr>
<tr><td>Engineering</td><td colspan="2">Key issue – Engineering challenges associated with scale up.
Gap: There will be significant engineering challenges to construct vessels large enough when scaled up from current lab scale demonstrated operation.

Gap: There are significant engineering challenges to overcome given that plant engineering has not really begun in earnest, ref Boston Metals and Arcelor Mittal have only just begun FEED for their electrolysis tech too.</td></tr>
<tr><td>Safety</td><td colspan="2">None</td></tr>
<tr><td>Environment</td><td colspan="2">None</td></tr>
</table>

Table A1.8 – Key issues and development gaps: Fluidised bed direct reduction

ALTERNATE IRONMAKING			
Fluidised bed direct reduction (TRL 6-9)		**SCU/ DCA**	
General description: Fluidised bed direct reduction processes utilise iron ore fines, with no significant agglomeration treatment required. In this process, iron ore fines move through a series of fluidised bed reactors and are efficiently heated and reduced by gas (typically, reformed natural gas and syngas present-day; and, potentially, in the future, renewable hydrogen). In a fluidised bed reactor, the fluid (gas) velocity distribution and particle properties are key factors and closely related to mass, heat transfer and chemical reaction, mixing and fluidisation efficiency. Compared to other reactors, the heat and mass transfer rates between gas and fines are high; however, for continuous operations, the residence time of the fines may be different causing non-uniform product and overall poor performance. Hence, staging design with multiple fluidised bed reactors is normally applied. Fluidised bed reactors may vary in bed design, raw material inputs, reducing gas compositions and operational conditions. Various new processes have been developed for production of direct reduced iron, including Finored (previously Finmet), Circored and Circofer (coal-based). HYFOR, and HYREX which are under development, will use hydrogen-rich gas or even 100% hydrogen. Some fluidised bed reactors have been used in the pre-reduction stage of smelting-reduction processes such as Finex. HYREX, Circored and Finored have been developed for a hematite feed and HYFOR for magnetite [1].			
Summary of potential route(s) to progress this technology at PKSW: Three potential routes for integration of fluidised bed direct reduction technology (e.g. Finex) at PKSW include: (1) DRI produced by fluidised beds, partially replaces steel scrap in the BF-BOF furnace route; (2) DRI produced by fluidised beds, charged into electric smelting furnaces and finally BOF route; (3) DRI produced by fluidised beds, briquetted and charged with scrap into EAF (replacing the BF-BOF route). Note: Options 1 and 3 relate to low gangue DRI produced from high-grade ores, i.e. with Fe typically above ~67%. Each of these potential routes have differing upstream requirements for raw materials and downstream implications for smelting and steelmaking. Selection of the appropriate route and location mainly depends on technico-economic analysis of the wide range of overall steelmaking process chain options and the long-term outlook of BSL, including product quality limitations of EAFs. Apart from these general considerations, the implementation of the fluidised beds at PKSW still requires further assessment of process performance in different bed reactors/configurations and availability of raw materials and reducing gas, a feasibility analysis of the technology integrated into the whole steelworks system, infrastructure preparation of upstream and downstream facilities, and training of relevant operational, technical and engineering workforce. The operating Finex process is the main focus for the Key Issues/Development Gaps in this Prioritised Option. Circored, which had a projected capacity of 500,000t-HBI p.a., remains non-operational.			
Key issues to resolve and the initial identified gaps for PKSW			
Operational/ Technical	**Key issue:** Impact of iron ore composition on the fluidised bed reduction process operations, including high/low grade, variability and particle size distribution (PSD).		

	Gap: Assessment of fluidised bed reduction processes- with high- and low-grade iron ore fine materials. Understand the key issues in maintaining stable fluidisation throughout the transformation (reduction) of the iron fines to final product, and investigate the sticking related surface morphology of the iron ore fines and prolonged reduction time e.g. due to the formation of a dense iron layer around the particles. Noting that there has been a significant amount of research into this topic for typical syngas in FINEX, but less has been done when H_2 used as the reducing gas. **Gap:** Evaluation of sticking behaviour linked to thermodynamic and kinetic conditions of ore fines, which may determine stability of fluidisation and reduction efficiency. **Key issue:** To operate fluidised beds in a stable and efficient manner, and produce direct reduced iron of uniform quality, the size distribution of the iron ore fines needs to be optimised. **Gap:** For each specific iron ore to be used, an assessment is required to evaluate different size distributions (within bed operational limits) versus the energy consumption required for grinding or agglomerating these ores. NB Processes operate with size distribution ranges e.g. Finored: 50 µm to 8 mm; Finex: < 8 mm; Circored: 0.1 to 2.0 mm. **Gap:** The optimal level of fluidisation (e.g. optimal superficial fluidising velocity) across a broad size distribution must be determined, whether through pre-treatment such as grinding and/or micro-agglomeration. **Key issue:** Although fluidised bed DR processes (e.g. Finored, Circored and Finex) have been commercially demonstrated at large scale, process stability and efficiency improvements are still necessary and required. **Gap:** Identification of the operating boundaries for efficient mass and heat transfer, as well as optimal chemical reaction, fines mixing and fluidisation efficiency. The objective is to promote more uniform distribution of heating and reducing conditions, thereby producing better quality direct reduced iron (DRI) product. **Gap:** Assessment and comparison of fluidised bed operating conditions and ranges, including reducing gas composition (natural gas : hydrogen ratio), reactor temperatures (650-800°C), reactor pressure (10-14 bar) and metallisation ratio for each stage (e.g. 91-92% for last stage). **Gap:** Investigation on lowering fuel consumption under various operating conditions (Finex plant is 750-800 kg/tHM). **Gap:** Evaluation of how to effectively adjust carbon content of the DRI product e.g. using the composition of reducing gas entering the final reactor. Understand metallisation degree and carburization implications for downstream processing. **Gap:** Temperature control and heat input when using pure hydrogen. **Gap:** Investigate minimisation of decrepitation and dust losses from fluidbeds. **Gap:** Potential issues associated with pure hydrogen in reducing gas, eg zero carbon DRI stability, optimisation of reactor metallisation ratios, temperatures/pressures. Noting that Circored is already configured for pure hydrogen.
Engineering	**Key issue:** Selection of an optimal fluidised bed reduction process, in terms of efficiency, stability and product quality. **Gap:** Deeper understanding of fluidised bed operations and their design with increasing levels of hydrogen, including staging design i.e. multiple fluidised bed reactors (e.g. Finex's most recent design was 3 reactors).

	Gap: Feasibility analysis and comparison of different fluidised bed processes considering PKSW's raw materials and gas resources will be critical to select the proper fluidised bed process in terms of process stability, DRI productivity and quality. **Gap:** Prolonging the life of reactors which can be significantly eroded by fine particles. **Gap:** Evaluation of DRI product briquetting for transportation and downstream processing. **Gap:** Assessment of the Circored two-stage fluidised bed process with circulating fluidised bed and a bubbling fluidised bed reactor. Especially with high hydrogen gas levels (~100%), lower reduction temperatures (~630°C) and lower pressures (~4 bars) to minimise sticking [10]. Also, the gas preheating requirements to support the endothermic hydrogen reduction process plus use of a flash heater prior to briquetting which requires temperature of ~ 700°C. Additionally, refractory design/performance. **Gap:** Assessment of the Hyfor process using ultra-fine ore (<150 μm), with a preheating-oxidation unit (~900°C) feeding the reduction unit where ore fines are reduced and leave at ~600 °C. Energy required for grinding of ultra-fine ores. **Key issue:** DRI is susceptible to oxidation, particularly during transportation or long-term material storage. **Gap:** Engineering equipment design and logistics analysis to minimise DRI oxidation while being transported between fluid bed and chosen downstream unit. Noting there are TRL9 methods for pneumatic transport of DRI in an inert atmosphere.
Safety	**Key issue:** Safe handling of hydrogen rich reducing gas generation and transport. **Gap:** Minimisation of leakage of gas system.
Environmental	None

Table A1.9 – Key issues and development gaps: Shaft furnace direct reduction

<table>
<tr><td colspan="3">ALTERNATE IRONMAKING</td></tr>
<tr><td>Shaft furnace direct reduction (TRL 7-9)</td><td>SCU/ DCA</td><td></td></tr>
<tr><td colspan="3">General description:

Most direct reduction plants utilise shaft furnace reactors based on either MIDREX or HYL-ENERGIRON technologies [1]. Shaft furnaces are moving bed, counter-current reactors with upwards flowing reducing gas and downwards flowing iron-bearing materials. The product can be hot DRI directly charged to downstream steelmaking furnaces, cold DRI stored and transported off-site for downstream processing, or hot briquetted iron (HBI, hotly pressed into a high-density pillow-shaped briquette). For the shaft-based DR process, pellets and/or lump ores are charged directly at the top of the shaft. Typically, in the commercial scale operation, reducing gas is generated through a reformer using recycled top gas and natural gas, which is heated to a specified temperature and fed to the middle part of shaft furnace. Depending on the individual process, reducing gas can be reformed coke oven gas or syngas generated through coal gasification; in one case, natural gas is directly injected to the furnace without reforming. Shaft furnace DR processes vary according to reducing gas composition, reducing temperature, injection location, burden distribution pattern, furnace structure, top pressure, outlet, etc.</td></tr>
<tr><td colspan="3">Summary of potential route(s) to progress this technology at PKSW:

Similar to fluidised bed direct reduction, three potential routes for integration of shaft furnace direct reduction technology at PKSW include:

(1) DRI produced by shaft furnaces, partially replaces steel scrap in the BF-BOF furnace route;

(2) DRI produced by shaft furnaces, charged into electric smelting furnaces and finally BOF route;

(3) DRI produced by shaft furnace, charged with scrap into EAF (replacing the BF-BOF route).

Note: Options 1 and 3 relates to low gangue DRI produced from magnetite ores.

Selection of the appropriate route mainly depends on technico-economic analysis of the overall steelmaking process chain, product quality requirements and the long-term goal of BSL. Fundamentally, as the production capacity of shaft furnaces units has increased, ironmaking based on shaft furnace technology is a more viable option.

Apart from these general considerations, the implementation of the shaft furnace at PKSW still requires further assessment of process performance in different furnace reactors/configurations and availability of raw materials and reducing gas, a feasibility analysis of shaft furnace integrated into the whole steelworks system, infrastructure preparation of upstream and downstream facilities, and training of relevant operational, technical and engineering workforce.
A likely pathway is the installation of a shaft furnace with natural gas, then progressive replacement with hydrogen as green electricity and hydrogen become available. As the use of hydrogen for reduction increases, the carbon content of the DRI product will decrease and notionally be zero with 100% hydrogen. There are several other technical issues to be resolved as hydrogen percent increases.</td></tr>
<tr><td colspan="3">Key issues to resolve and the initial identified gaps for PKSW</td></tr>
<tr><td>Operational/ Technical</td><td colspan="2">Key issue: Carbon control in the shaft furnace process.
Gap: Carburization occurred in the lower part of the traditional shaft furnace will be changed as higher ratio of hydrogen used in the reducing gas and utilisation of biomass. Evaluation of carbon control in different situations is required.
Key issue: Raw materials flexibility.</td></tr>
</table>

	Gap: sinter, low density lump and low-grade pellets are currently not widely utilised in DRI shaft furnaces. It would be highly advantageous if at least a proportion of the blend could be substituted and more research in the area would be beneficial. **Key issue:** Optimal operating conditions for H_2 based shaft furnace process. **Gap:** In the case of 100% hydrogen used for the shaft furnace process, the operational conditions such as energy supply and furnace pressure should be optimised for the maximum hydrogen utilisation in the shaft furnace.
Engineering	**Key issue:** Selection of an optimal shaft furnace process, in terms of efficiency and stability. **Gap:** Major commercial shaft furnace processes are very different in reducing gas generation, gas injection temperature and operational pressure etc. The feasibility analysis and comparison of different furnaces considering PKSW's raw materials and gas resources will be critical to select the proper shaft furnace process in terms of process stability, DRI productivity and quality. **Key issue:** DRI is susceptible to oxidation, particularly during transportation or long-term material storage. **Gap:** Engineering equipment design and logistics analysis to minimise DRI oxidation while being transported between shaft furnace and chosen downstream unit. Noting there are TRL9 methods for pneumatic transport of DRI in an inert atmosphere. **Key issue:** Cooling section of shaft furnace needs evaluation in steelworks such as PKSW where hot DRI is the main product. **Gap:** Traditional commercial shaft furnace was designed to produce cold/hot DRI as well as HBI. As the hot DRI is the key product, the lower part of shaft furnace, i.e. cooling section design, needs to be evaluated. **Key issue:** Stable operation with high top gas pressure in shaft furnace such as HYL/ENERGIRON. **Gap:** In HYL/ENERGIRON process, the operating pressure at the top gas exit can reach ~6 bars. Efficient and stable operation of top gas recycling and reheating needs engineering evaluation. There are several operating references for HYL ZR operating at this temperature and pressure around the world [see 1]. **Key issue:** Scale-up of existing shaft furnace has a limitation so that the maximum production capacity is 2.5 Mt/year. **Gap:** Currently, only MIDREX and HYL/ENERGIRON processes claim the maximum production capacity can reach 2.5 Mt/year per module. Engineering efforts may be worth to expand the reactor for the purpose of larger capacity and higher process efficiency.
Safety	**Key issue:** Safe handling of hydrogen rich reducing gas generation and transport. **Gap:** Minimisation of leakage of gas system.
Environmental	**Key issue:** Recycling and reuse of top gas. **Gap:** Partial CO_2 and H_2O from the top gas of shaft furnace process can be used to reform the natural gas. To avoid the emission of CO_2, carbon capture and usage system could be set up to remove the excess CO_2 from the top gas. Noting HYL already has this.

Table A1.10 – Key issues and development gaps: Smelting reduction

<table>
<tr><td colspan="3">ALTERNATE IRONMAKING</td></tr>
<tr><td colspan="1">Smelting reduction (TRL 4-9)</td><td>SCU</td><td></td></tr>
<tr><td colspan="3">General description:
Smelting reduction (SR) processes differ from the traditional BF-BOF integrated route in that liquid iron (hot metal) is produced without significant amounts of metallurgical coke or high-grade iron ore requirements. Instead, commercialised SR processes use non-coking coal, oxygen and/or electrical energy. Most SR processes combine reduction (fluidised bed or shaft furnace DR) and smelting of iron-bearing materials, which can occur in single or multiple reactors. Some SR processes have been successfully commercialised at reasonable scale, such as Corex and Finex, with production capacities up to 1.5Mt per year. Others, such as HIsarna, continue to be developed. The Corex process combines a shaft furnace DR plant with a melter-gasifier; Finex replaces the shaft furnace with a fluidised bed. For other commercialised processes, such as Romelt and OxyCup, limited production capacities and high energy consumption are key challenges for future application. These processes are utilised to recover iron units etc from plant by-product streams.</td></tr>
<tr><td colspan="3">Summary of potential route(s) to progress this technology at PKSW:
Coal based SR processes would, at best, only be suitable for the transition stage of decarbonisation at PKSW. Although coal-based SR processes use non-coking coal and low-grade iron ore and have flexibility in operation, the low production, coal utilisation and pure oxygen requirement limit the application of these processes for the long term decarbonisation.
Compared to coal-based SR processes, theoretically, Ironarc and flash ironmaking technologies (TRL 5) are more suitable for application at PKSW as H_2 rich gas and electricity are used as key energy sources for these two processes. Thus, it is worth to monitor the further development of these two processes.
The Oxycup process is suitable to be applied at PKSW to handle ferrous wastes. Although this process is a carbon intensive process, the technology has been proven and a broad range of wastes can be treated using Oxycup furnace.</td></tr>
<tr><td colspan="3">Key issues to resolve and the initial identified gaps for PKSW</td></tr>
<tr><td colspan="3">In-bed smelting processes</td></tr>
<tr><td>Operational/ Technical</td><td colspan="2">Key issue: The fuel consumption of in-bed smelting processes heavily depends on the utilisation of off-gas from smelting stage.
Gap: In two-stage SR process, the smelter off-gas has to be cooled down from 1600°C to ~1000°C or lower before it can be used for pre-reduction. In one-stage SR process, high temperature gas can be used, but likely cause the increased energy carried away from off-gas. Effective utilisation and recycling of high temperature off-gas from smelting stage in different in-bed smelting processes requires necessary technical evaluation before their industrial application.
Key issue: Permeability of char bed and distribution of injected oxygen and charging materials in the smelter are critical for smooth operation of in-bed SR processes.
Gap: Optimal design of operational conditions, size of charging materials, charging positions of materials and the bed height is required to guarantee smooth operation of in-bed SR processes.</td></tr>
<tr><td>Engineering</td><td colspan="2">Key issue: Comparison of capital investments for engineering implement and maintenance of in-bed SR processes.
Gap: Corex and Finex are two key commercial in-bed SFR processes. Capital investments for these two processes need to be done considering production capacity, number of reactors, operational cost, available raw materials at PKSW and construction difficulty.</td></tr>
</table>

Safety	None.
Environmental	**Key issue:** Coal consumption of in-bed SR processes is high although there is insignificant amount of NOx, SOx and dust etc released from these SR processes. **Gap:** CCU/S facility is required to treat CO_2 emission from in-bed SR processes.
In-bath smelting processes	
Operational/ Technical	**Key issue:** Post combustion of gases released from smelting bath is important for the heat transfer in coal-based in-bath SR processes. **Gap:** Post combustion of gases released from slag/metal bath needs to be optimised considering the balance of both pre-reduction and heating function of gases in the upper part of smelting furnace. **Key issue:** Reduction of iron oxide takes place in foaming slag phase of most in-bath SR processes. **Gap:** The operation with foaming of slag needs to be reviewed considering the raw materials available at PKSW. **Key issue:** Production capacities of all available in-bath SR processes are low. **Gap:** Production capacities of both commercialised in-bath and being developed SR processes are low, signifying that multiple modules could be required for production at PKSW. This can increase the total operational cost. Thus, cost estimation of different in-bath SR processes is critical.
Engineering	**Key issue:** Campaign life of smelter used for in-bath SR processes is closely linked to the refractory lining. **Gap:** The cooling panel design of smelter is necessary, particularly for the process with higher temperature environment such as Ironarc, which significantly affects the campaign life of smelter.
Safety	**Key issue:** Safe handling of high temperature off-gas **Gap:** Systematic design of in-bath SR processes is required to treat high temperature off-gas safely.
Environmental	**Key issue:** High CO_2 emission from coal-based in-bath SR process **Gap:** CCU/S facility is required to treat CO_2 emission.
Flash ironmaking technology	
Operational/ Technical	**Key issue:** The key limitation of flash ironmaking technology is the requirement of iron ore size (<100 μm). **Gap:** To guarantee the sufficient reduction of ore fine in-flight, the size requirement of ore fine is strict, which increases the cost for ore fine screening and grinding. The preparation of raw materials can be a limitation step for the whole process. **Key issue:** The realisation of high temperature operational environment, and the recycling and utilisation of off-gas are still at the design stage. **Gap:** This technology is still in development regarding heating approach and utilisation of off-gas at a large scale. **Key issue:** Uniform reduction and melting of ore fines in a large-scale reactor. **Gap:** The current technology did not show how to realise uniform reduction and melting of ore fines in a large-scale reactor. If large amount

	of unreduced ore is mixed with molten metal, it can easily cause the process instability.
Engineering	**Key issue:** The flash ironmaking technology was tested at both laboratory and small pilot-plant scales. The feasibility of this process for large-scale production needs to be tested in practice. **Gap:** The engineering trials of this technology for large-scale production needs to be carried out in practice considering the energy utilisation efficiency, reducing gas reduction efficiency, process stability and production capacity.
Safety	**Key issue:** Safe transportation of H_2 rich reducing gas and safe operation of single reactor with combustion, key reduction and melting occurring simultaneously. **Gap:** Systematic design and tests of gas transportation and reactor operation are required.
Environmental	None.

Table A1.11 – Key issues and development gaps: DRI Utilisation in the Electric Smelting Furnace - Basic Oxygen Furnace

STEELMAKING		
DRI Utilisation in an Electric Smelting Furnace (ESF) - Basic Oxygen Furnace (TRL range: 2/9 (NZS))	**SCA/DCA**	

General description:

The electric smelting furnace (ESF) is widely used in the non-ferrous and ferro-alloy industries. Its working principle is resistance heating through the furnace burden/air gap and/or slag, i.e. the electrodes are approaching, or immersed (submerged), in the slag melt, providing the energy required for melting and reaction.

The ESF is generally operated under reducing atmosphere conditions, principally to protect the carbon-based electrodes. In the ESF, it is possible to continuously add carbon and slag conditioner with the metallic charge. Round and rectangular furnace designs are available, allowing liquid bath capacity greater than 1000 t. Thus, the ESF is suitable to melt DRI to produce a liquid iron product. The furnace shell is refractory lined and, depending on the configuration/operation, may also be water cooled.

Summary of potential route(s) to progress technology at PKSW:

A possible route for PKSW is the DRI-ESF-BOF route. Here, DRI can be DRI (NG) or H2-DRI. For a carbon free DRI (H2-DRI), carbon is required for final reduction in the ESF as well as refining and alloying in the BOF to make the steel grade [1]. To maintain carbon neutrality, such carbon will need to be sourced from a renewable supply [2]. In comparison to the DRI-EAF route, the DRI-ESF-BOF route has been estimated to be more competitive when lower grade iron ores (Fe content <~67.5%) are used for the DRI production.

Key issues to resolve and identified gaps for PKSW

Operational/ Technical	**Key Issue:** DRI metallisation on ESF performance. Optimum DRI metallisation needs to be understood. The degree of metallisation impacts reduction load and carbon requirement, as well as slag composition that in turn impacts slag electrical resistivity (furnace heating and energy performance), refractory and electrode corrosion behaviour. **Gap**: The melting behaviour of DRI. While it might be expected that the melting behaviour of low to no carbon iron (H2 reduced DRI) would be similar to low alloy scrap, the effects of the likely higher melting point of the iron have to be addressed. In addition, there is a significant amount of gangue (non-metallic material) associated with the DRI. Both its melting behaviour and that of the no to low carbon iron will have to be established. **Gap**: Slag formation, fluxing and volume during ESF smelting. Generally, slag formation practices that are optimised for melting, reduction, carburization, iron yield and/or furnace performance through the resistive behaviour of the slag and/or refractory life will have to be established. As noted previously, this will be at least a part function of the DRI metallisation. Nb. In the EAF steelmaking process, high grade DRI is used to limit slag generation [3]. **Gap**: Establishing the slag resistivity used in the ESF. The slag (both the composition and volume) is a key component of the furnace heating system. As such, its resistivity (or electrical conductivity) must be understood. Current knowledge of slag electrical resistivity is probably still represented by the data given in the Slag Atlas. It is likely that electrical resistivity values will need to be established for specific slag composition ranges encountered in the new ESF process. **Gap**: Understanding hot DRI charging of the furnace. Ideally, to make use of the sensible heat associated with the production of DRI, it would be preferred to charge it to the ESF straight from the DRI furnace i.e. use hot DRI (T>600°C). If this is not possible then storage of DRI is required and

	possible pre-heating of DRI prior to use in the ESF should be investigated. DRI is a highly reactive material and can generate significant energy on re-oxidation. This is further detailed in the Safety section and titled “DRI storage/transport/charging”. **Key Issue:** C requirement to complete reduction reactions, support BOF refining and alloying to make steel specification. If H2 DRI is used in the ESF, the iron will have to be carburized. **Gap:** Knowledge of C alloying in ESF. Given that the ESF process needs to operate under reducing conditions, there may be a need to achieve C-alloying in the ESF. The efficiency and rate of carbon pickup from carbon-neutral sources will have to be established. While this may be to some degree informed by EAF practice [4], it is also likely to be a function of the degree of metallisation of the DRI source and operation of the ESF carbon-based electrodes.
Engineering	**Key Issue:** Process scale-up/intensity. The ESF process has not been demonstrated for production of 2 million tonnes per year or greater. **Gap**: Demonstration that ESF can achieve capacities of 2 million tonnes per year or greater. NB The two furnaces operating in New Zealand are currently producing a combined total of ~0.65 million tonnes per year.
Safety	**Key Issue:** Safe use of DRI. DRI is a highly reactive material and can generate significant energy on re-oxidation that can lead to fire or explosion. **Gap**: Development of safe DRI storage/transport/charging procedures. The primary approach to deal with DRI reactivity is to minimise its exposure to air by use of a N_2 atmosphere. In the EAF industry systems have already been developed that deal with hot DRI charging (enclosed conveyor systems that operate in a N_2 atmosphere), transport or DRI storage (operating under a N_2 atmosphere). While these systems are extant, they will need to be adapted/confirmed for the ESF.
Environmental	None.

1. Madias J. Electric Furnace Steelmaking. Treatise on Process Metallurgy. Vol. 3, 2014.
2. Abel M, Melting of DRI in the electric arc furnace or submerged arc furnace. Steel Academy's 2nd international seminar on hydrogen-based reduction of iron ores. Steel Institute VDEh: Steel Academy. 3 November 2021.
3. Bohm C, Hydrogen-based direct reduction with Midrex. Steel Academy's 2nd international seminar on hydrogen-based reduction of iron ores. Steel Institute VDEh: Steel Academy. 3 November 2021.
4. Hornby SA, Hydrogen-based DRI EAF steelmaking - Fact or fiction? AISTech - Iron and Steel Technology Conference Proceedings. 2021.

Table A1.12 – Key issues and development gaps: DRI and scrap utilisation in Electric Arc Furnace

STEELMAKING		
DRI and scrap utilisation in Electric Arc Furnace (TRL 9)	**SCA/DCA**	
General description: The electric arc furnace (EAF) is a widely used metallurgical reactor that melts and heats metallic materials via an electric arc using either alternating current (AC) or direct current (DC) technology. Metallic materials used are predominantly scrap and direct reduced iron (DRI/HBI); some operations use hot metal and/or cold pig iron. Compared to the traditional BF-BOF steelmaking route, EAF steelmaking has lower energy consumption and carbon emissions due to the use of recycled scrap. However, commercial and operational issues with scrap utilisation apply, particularly around supply chain, price fluctuation and lack of high-quality scrap. Hence, use of DRI/HBI as a scrap substitute has increased, particularly in improving steel quality by diluting tramp elements/residuals such as copper.		
Summary of potential route(s) to progress technology at PKSW: A possible route for PKSW is the DRI-EAF route. Here, DRI can be DRI (NG) or H2-DRI. For a carbon free DRI (H2-DRI), carbon is required for reduction, alloying to make the steel grade and for slag conditioning (foaming) to ensure stable and efficient arc performance [1]. To maintain carbon neutrality, such carbon will need to be sourced from a renewable supply [2]. Note that carbon (oxidation) is a key energy component of EAF operation.		

Key issues to resolve and identified gaps for PKSW	
Operational/ Technical	**Key Issue:** DRI metallisation on EAF performance. Optimum DRI metallisation needs to be understood. The degree of metallisation impacts slag composition that in turn impacts steel refining, slag foaming/arc stability, refractory and electrode corrosion behaviour. **Gap**: The melting behaviour of DRI. While it might be expected that the melting behaviour of low to no carbon iron (H_2 reduced DRI) would be similar to low alloy scrap, the effects of the likely higher melting point of the iron have to be addressed. In addition, there is a significant amount of gangue (non-metallic material) associated with the DRI. Both its melting behaviour and that of the no to low carbon iron will have to be established. **Gap**: Slag formation, fluxing and volume during EAF smelting. Generally, slag formation practices that are optimised for iron yield and arc stability through slag foaming will have to be established. As noted previously, this will be at least a part function of the DRI metallisation. In the case of slag foaming, optimum slag basicity and viscosity will have to be established. While there has been a significant amount of work on slag viscosity in the past decade, it is not clear the slags generated in a high to 100% DRI process are covered. A useful starting point would be data contained with the Slag Atlas [3]. Nb. generally high grade DRI is used in an EAF to limit slag generation [4]. **Gap**: Understanding hot DRI charging of the furnace. Ideally, to make use of the sensible heat associated with the production of DRI, it would be preferred to charge it to the EAF straight from the DRI furnace i.e. use hot DRI (T>600°C). If this is not possible then storage of DRI is required and possible pre-heating of DRI prior to use in the EAF should be investigated. DRI is a highly reactive material and can generate significant energy on re-oxidation. This is further detailed in the Key issue Safety section below, titled "DRI storage//transport/charging". **Key Issue:** C requirement to support reduction, make steel grade and for slag **foaming.** Carbon is required for alloying to make steel specification and, through reaction with iron oxide in the slag, slag foaming. If H2 DRI is used in the EAF, the iron will have to be carburized.

	Gap: Knowledge of C utilisation in the EAF for high DRI charge. The efficiency and rate of carbon pickup and reaction with slag from carbon-neutral sources will have to be established. While this may be to some degree informed by current EAF practice, it is also likely to be a function of the degree of metallisation of the DRI source. Note that it is known that iron containing C, such as traditional DRI or blast furnace hot metal, is more efficiently utilised in an EAF (>95%) than charging or injecting C (24-76%). **Key Issue:** Replacing C (chemical energy) with electrical energy. Carbon oxidation is a chemical energy component of the current operational practice of an EAF. Note, this chemical energy C, is that in excess of the C required for slag foaming and alloying. Using only electrical energy for fast melting of iron (short tap to tap times), is difficult and not the most economic practice. **Gap:** Development of an optimal EAF operational practice using only electrical energy. It is likely the C will still be used for slag foaming in an EAF. Therefore, there will still be a C chemical energy contribution to the energy balance. What is being considered here is that the remainder of the energy required for melting and achieving the operational furnace temperature will be supplied by electricity.
Engineering	None.
Safety	**Key Issue:** Safe use of DRI. DRI is a highly reactive material and can generate significant energy on re-oxidation that can lead to fire or explosion. **Gap:** Development of safe DRI storage//transport/charging procedures. The primary approach is to deal with DRI reactivity is to minimise its exposure to air by use of an N_2 atmosphere. In the EAF industry systems have already been developed that deal with hot DRI charging (enclosed conveyor systems that operate in an N_2 atmosphere), transport or DRI storage (operating under an N_2 atmosphere). While these systems are extant, they will need to be adapted/confirmed for the PKSW.
Environmental	None.

1. Madias J. Electric Furnace Steelmaking. Treatise on Process Metallurgy. Vol. 3, 2014.
2. Abel M, Melting of DRI in the electric arc furnace or submerged arc furnace. Steel Academy's 2nd international seminar on hydrogen-based reduction of iron ores. Steel Institute VDEh: Steel Academy. 3 November 2021.
3. Mills K.C., Slag Atlas, 2nd ed., Verlag Stahleisen GmbH, Düsseldorf, 1995, pp. 349-402.
4. Bohm C, Hydrogen-based direct reduction with Midrex. Steel Academy's 2nd international seminar on hydrogen-based reduction of iron ores. Steel Institute VDEh: Steel Academy. 3 November 2021.

Appendix 2 – Preliminary process integration-based simulation modelling of Prioritised Options relative to a baseline PKSW operation