



PHASE 1 REPORT

PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY

IDENTIFICATION OF PRIORITISED OPTIONS

7 October 2022

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SYNOPSIS

This report describes a site-specific evaluation of potential emissions reduction opportunities at Port Kembla Steelworks including Smart Carbon Usage and Direct Carbon Avoidance technological pathways, an assessment of the technical feasibility of the identified opportunities, and a short list of prioritised options for further consideration (Prioritised Options).

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

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

EXECUTIVE SUMMARY

With the support of ARENA's Advancing Renewables Program, BlueScope, together with the University of Wollongong, has completed an initial 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. The Project is also aligned with priorities placed by the Australian Federal Government on carbon emissions from Australia's steel industry, as outlined in its Low Emissions Technology Statement, including the potential use of renewable energy and other enabling technologies relevant to future steel production in Australia.

This 13-month Project consists of three phases:

- Phase 1 Investigation of potential GHG emissions reduction opportunities at PKSW and identification of prioritised options.
- Phase 2 Assessment of Prioritised Options and potential decarbonisation pathways for PKSW, and pilot and plant trials of biochar.
- Phase 3 Final assessment and planning for further investigations.

This report presents the findings of Phase 1 and describes 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 target and goal:

- Short-to-medium term target of 12% Scope 1 and Scope 2 GHG intensity reduction by 2030 against a FY2018 baseline for tonnes CO₂-e per tonne of crude steel; and
- Long-term goal of net zero GHG emissions by 2050¹.

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, Utilization and Storage (CCUS)based on general process description, material inputs and outputs, overall abatement pathway, key performance indicators, maturity and requirements to implement, and potential strengths and weaknesses. This evaluation is included in detailed Information Reviews that have been checked by

¹ Achieving our 2050 net zero goal is dependent on several enablers including the commerciality of emerging and breakthrough technologies, the availability of affordable and reliable renewable energy and hydrogen, the availability of quality raw materials and appropriate policy settings.

the Project Team and are provided in Appendix 3. High-level summaries of the Information Reviews used for this evaluation are provided in Appendix 2.

- 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, for the short-to-medium term and long-term timeframes.

In the short-to-medium term, the Prioritised Options are 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 Direct Reduced Iron (DRI) and increased scrap utilisation in the Basic Oxygen Furnace (BOF). These SCU pathways align with BlueScope’s public announcement that it is undertaking a feasibility study to reline and upgrade a blast furnace (No.6 Blast Furnace) at PKSW. The reline and upgrade plan is based on:

- Inadequate supplies of prime scrap in Australia to enable secondary steelmaking (via Electric Arc Furnace (EAF) production),
- The relatively high cost of natural gas rendering DRI economically unviable at this time, and
- Accepted industry estimates that breakthrough, low emissions steel technology to replace the BF-BOF process is likely to be more than a decade from commercialisation.

Importantly, the reline and upgrade will build a bridge to future adoption of breakthrough lower emissions iron and steelmaking, once it is technically and commercially viable.

In the long-term, breakthrough iron and steelmaking technologies will be required to meet net zero goals. Prioritised Options are predominantly applications of DCA technological pathways, including electrolysis of iron ore, alternative ironmaking technologies combined with aligned steelmaking processes and potential CCUS (SCU).

In the meantime, there will be continued optimisation of blast furnace efficiency and building in optionality (via the No. 6 Blast Furnace reline and upgrade) to utilise future low-emissions technologies, as and when commercially and technically viable.

The next step in the Project (Phase 2) involves further evaluation of the Prioritised Options identified. This includes undertaking PKSW-site mass and energy balances, understanding the operational, engineering, environmental and safety aspects of these options, undertaking a general cost competitiveness

comparison and understanding the commercial viability of the technologies relative to a baseline PKSW operation.

Table a – Selected Prioritised Options for further assessment

	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	Fluidized 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, Utilization and Storage				
SCU	Biological			
	Chemical			
	Absorption			
	Adsorption			
	Mineral carbonation			
Legend		A non-viable technology	A possible Prioritised Option	A Prioritised Option

Contents

EXECUTIVE SUMMARY	2
List of acronyms and abbreviations	6
1 Introduction	7
1.1 Project Outline	8
1.1.1 Project Rationale and Drivers	8
1.1.2 Methodology of Investigation	10
1.2 BlueScope and PKSW Decarbonisation Strategy	11
1.3 PKSW Site - Process and Emissions Description	14
1.3.1 Raw materials preparation facilities	15
1.3.2 Ironmaking	16
1.3.3 Steelmaking	16
1.4 Relevant Previous Work	16
1.4.1 General overview	16
1.4.2 Previous work in Australia	18
2 Relevant technologies	20
2.1 Overview of relevant technologies assessed	20
2.2 Description of relevant SCU and DCA technologies assessed	24
3 Assessment Criteria for Identified Technologies	29
4 Prioritised Options for Further Evaluation	32
4.1 Blast Furnace Ironmaking, Cokemaking and Sintering	34
4.2 Steelmaking and Carbon Capture, Utilization and Storage	40
4.3 Summary	42
5 Conclusions and recommendations	45
6 References	47
7 Appendix 1:	48
7.1 Proposed Qualitative Options Analysis Matrix Approach	48
8 Appendix 2:	51
8.1 High Level Summaries of 17 Technological Areas	51
9 Appendix 3:	78
9.1 17 SCA and DCA Technology Areas	78

List of acronyms and abbreviations

ARENA	Australian Renewable Energy Agency
AIE	Alkaline iron electrolysis
BF	Blast furnace
BOF	Basic oxygen furnace
C	Carbon
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CCUS	Carbon capture and usage or storage
CO ₂	Carbon dioxide
DCA	Direct carbon avoidance
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
GHG	Greenhouse gas
H ₂	Hydrogen
H ₂ -DR	Hydrogen-based direct reduction
HBI	Hot briquetted iron
HCI	Hot compacted iron
HPSR	Hydrogen plasma smelting reduction
LCA	Life Cycle Analysis
MOE	Molten oxide electrolysis
NG-DR	Natural gas direct reduction
N ₂	Nitrogen
O ₂	Oxygen
OPEX	Operational expenditure
PKSW	Port Kembla Steel Works
R&D	Research and development
SAF	Submerged Arc Furnace
SCU	Smart carbon usage
SWOT	Strengths, Weaknesses, Opportunities and Threats
t	Tonne
TGR-BF	Top gas recycling – blast furnace
TRL	Technology readiness level
y	Years

1 Introduction

Climate change is a global issue that requires a global approach. In 2020, on average, every tonne of steel produced led to the emission of 1.89 tonnes of CO₂ into the atmosphere. In 2020, 1,860 million tonnes (Mt) of steel were produced, and total direct emissions from the steel sector were of the order of 2.6 billion tonnes, representing between 7% and 9% of global CO₂ emissions [1]. The steel sector is a hard-to-abate industry due to its capital intensity, long-lived assets and limited commercial alternatives to greenhouse intensive production technologies. Work is underway across the industry to improve the efficiency of iron and steelmaking operations to decarbonise and help the sector to transition to a low-carbon economy.

Currently, 70 per cent of the world's steel is produced via the blast furnace route, refer figure 1.

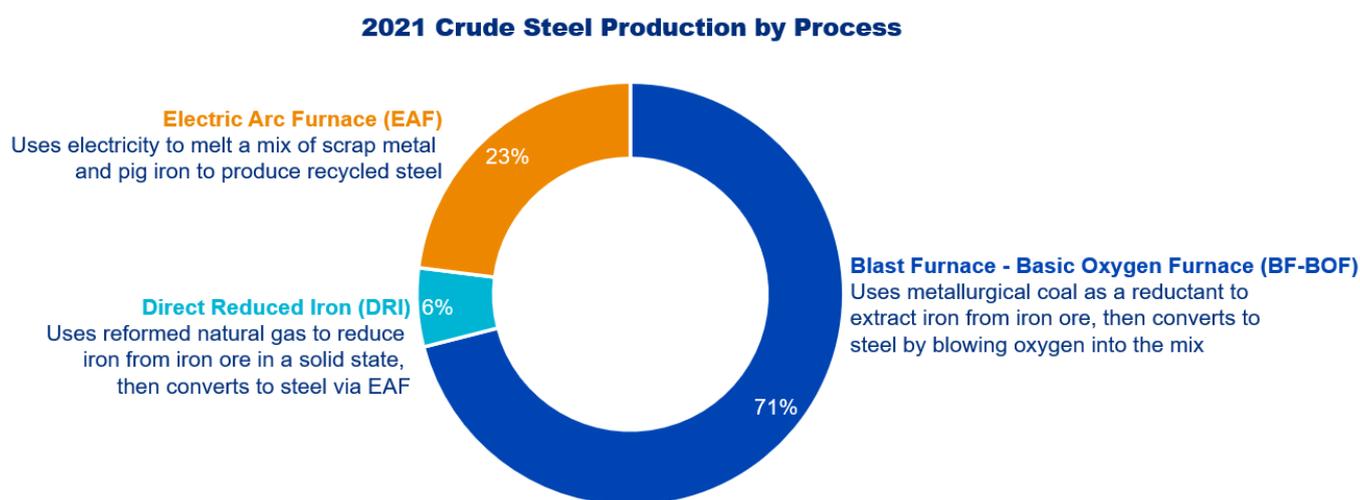


Figure 1 – 2021 World Steelmaking Production Technology

Although low emissions steel can be produced by a combination of Electric Arc Furnace (EAF) and renewable electricity, scrap availability and quality will limit this to below 50 per cent of steel production, meaning steel will still need to be manufactured from virgin iron.

In recent years, steelmakers have made considerable progress to reduce the GHG emissions intensity of their operations within existing technology and processes and these improvements continue to be optimised. However, blast furnace based ironmaking remains dependent on metallurgical coal (coke) to react with the oxygen in the iron ore and to provide the structural matrix within the furnace. To drive its decarbonisation pathway, the steel manufacturing sector is dependent on the development of breakthrough technologies [2]. While iron and steelmakers are working hard to continue to explore these breakthrough technologies, until commercially viable alternatives to current processes are available, iron and steelmaking will continue to require metallurgical coal.

Achieving future decarbonisation targets and goals for the steel sector will be extremely challenging in isolation. In fact, significant infrastructure investments are required for the generation and supply of massive amounts of renewable energy for decarbonisation of steelmaking as well as other manufacturing industries and across the economy.

As a result, to develop a long-term strategy for process technology pathways in the steel industry will require long-term engagement and commitment by governments. This includes, but is not limited to, providing investment certainty during the initial period prior to the introduction of disruptive, breakthrough technologies.

As in other countries, Australian federal and state governments have begun to work collaboratively with industries to establish low or zero emissions manufacturing roadmaps for the future including, amongst a range of opportunities, pathways for the introduction of hydrogen production and its utilisation. In this initial phase of development in Australia, government-sponsored initiatives that stimulate industrial-based R&D for advanced manufacturing are under consideration, including as part of proposed reforms to the Safeguard Mechanism in support of Australia's 2030 climate target and 2050 net zero goal.

BlueScope has publicly committed to GHG emissions reduction targets, which are covered in detail in BlueScope's decarbonisation strategy, refer section 1.3.

BlueScope's Port Kembla Steelworks (**PKSW**), the focus of this study, is an integrated steel works that takes virgin iron ore, coal and other raw materials to produce steel slabs, hot rolled coil and plate. The main operating units include: three coke ovens batteries, a sinter plant, a blast furnace, a lime kiln, two basic oxygen furnaces, three slab casters, a hot strip mill and a plate mill. According to worldsteel's CO₂ data collection program [3], PKSW is within the top 15 percent of CO₂ intensity performers. The site is further detailed in section 1.4.

1.1 [Project Outline](#)

BlueScope aims to complete a study (the Project) to investigate the technical and economic feasibility of renewable energy and decarbonisation technology pathways that have the potential to decarbonise the steelmaking process at the PKSW.

The project will be delivered through three phases:

- Phase 1 Investigation of potential emissions reduction opportunities at the PKSW and identification of prioritised options.
- Phase 2 Assessment of Prioritised Options and potential decarbonisation pathways for the PKSW, and pilot and plant trials of biochar.
- Phase 3 Final assessment and planning for further investigations.

1.1.1 [Project Rationale and Drivers](#)

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 GHG emissions intensity reduction target and 2050 net zero goal. With the support of ARENA, as part of its Advancing Renewables Program, BlueScope is seeking to complete an initial Renewables/Emissions Reduction Study to evaluate low emissions and new emerging technologies, specifically relevant to decarbonisation at PKSW. The Project also aligns with the priority placed by the Australian Federal Government on carbon emissions from Australia's steel industry, as outlined in its Low Emissions Technology Statement (LETS) [4]. Specifically, this is in respect to the potential use of

renewable energy and other enabling technologies (e.g. renewable biomass, hydrogen) relevant to future steel production in Australia.

In terms of the above and background to the key drivers for the Project, it is generally accepted that progressing new, potentially disruptive technologies for future decarbonisation of capital-intensive steel manufacturing plants requires well-targeted and carefully planned assessments. One of the main reasons for this is that steel plant configurations will vary according to locality, available raw materials and energy sources, market-driven requirements, and so on. Hence, bespoke technological solutions are likely to be required, especially with respect to the installation of new, lower emissions steelmaking processes. Moreover, as previously mentioned, achieving future decarbonisation targets in the steel industry will be very challenging, if not impossible in isolation, unless:

- Infrastructure is procured for the significant amounts of renewable energy required;
- Integration of variable renewable energy into the electricity grid is possible; and
- Coupling of energy and manufacturing sector industries (steel) occurs.

The task of decarbonising steel production in Australia, and BlueScope achieving its GHG emissions intensity reduction target at PKSW will require:

- In the short-to-medium term (~5-15 years ahead), assessment of current operating asset optimisation and transitional (emerging) technologies; and
- In the long-term (over 15 years ahead), evaluation of breakthrough iron and steelmaking technologies that are currently under development.

It is important to note that the availability of some commercialised breakthrough technologies from equipment/technology suppliers is not expected until well after 2030 and in some cases, well after 2040. This is relevant in terms of capital investment cycles as the long-lived nature of steel plant and equipment assets will influence the speed of the global rollout of such technologies.

The steel industry has identified two overarching technological pathways for future steel production. Both technological pathways are considered in the Project, *viz.*:

- Smart Carbon Usage (SCU), which is based on circular economy principles, with the aim to substantially reduce, capture and/or better utilise carbon either internally within the steel plant or externally. Invariably, this involves the plant-wide deployment of process integration methodologies or coupling of materials streams and processes.
- Direct Carbon Avoidance (DCA), which involves technologies that fully or partially avoid carbon emissions through, for example, deployment of hydrogen-based and/or electricity-based metallurgy. Ideally, hydrogen and electricity are generated from renewable sources.

As in other countries, Australian governments, both federal and state, have begun to establish technology and investment roadmaps for the future including pathways for hydrogen production and utilisation, and bioenergy. In its LETS, the Australian Federal Government identified low carbon steel and aluminium as priority low emissions technologies. The LETS recognised that whilst carbon emissions abatement in these manufacturing industries was very challenging, addressing these challenges offered significant opportunity for Australia to reduce its overall cumulative emissions and improve its economic potential. In this initial development phase in Australia, government-sponsored activities such as this Project (and potentially, extension thereof) are under consideration. As mentioned, this Project aligns with BlueScope's strategic approach to managing climate-related business risks and specifically, its plan to achieve pathways to decarbonising of its major Australian steelmaking operations at PKSW [5]. The development

and evaluation of pathways for PKSW's Scope 1 and Scope 2 carbon emissions reduction will consider various possible global and domestic drivers, as well as their impact on the company's own carbon emission intensity reduction target and goal:

- Short-to-medium term target of 12 per cent by 2030 against a FY2018 baseline for tonnes CO₂-e per tonne of crude steel; and
- Long-term goal of net zero carbon emissions by 2050.

The time-based target and goal, together with BlueScope's capital investment cycle and the availability of commercialized SCU and DCA technologies, provide a framework for the Project. For PKSW, BlueScope will continue to optimise its current assets and processes, and to partner with other relevant industry sectors and research institutions to explore and advance the technical and commercial viability of SCU and DCA options.

1.1.2 Methodology of Investigation

Based on the above rationale, Phase 1 of this Project involves exploring and assessing all potential SCU and DCA technologies for PKSW and identifying Prioritised Options for both short-to-medium (~5-15 years) and long-term (> 15 years) timeframes.

A 'Qualitative Options Analysis' (QOA) of viable SCU and DCA technologies for PKSW was conducted. The Options Analysis approach provides a listing of Prioritized Options, together with a structured overview of the challenges to overcome and possible solutions required in adapting current PKSW manufacturing processes (short to medium term) or adopting new DCA or SCU technologies (medium or long term). A more detailed description of the methodology is provided in Appendix 1 – essentially, there were six steps proposed:

1. Set up Base Case option for PKSW.
2. Systematically evaluate qualitative information on each potential technology for PKSW, providing:
 - Brief general process description
 - Material inputs and outputs
 - Overall abatement pathway
 - Key performance indicators
 - Maturity and requirements to implement
 - Potential strengths and weaknesses
 - Additional relevant comments.
3. Screen each technology to rule out non-viable technologies for PKSW (using Fatal Flaw Analysis and/or SWOT Analysis)
4. Tabulate the information in terms of Short-to-Medium- and Long-term options based on agreed Decision Criteria, including:
 - Technology Readiness Level
 - Anticipated timeline and availability
 - Production impact and key performance indicators
 - Abatement potential
5. Outline key gaps and potential challenges for each Prioritized Option identified.
6. Summarize all Prioritized Options for further evaluation in Phase 2.

1.2 [BlueScope and PKSW Decarbonisation Strategy](#)

BlueScope is an Australian-headquartered, ASX listed steel manufacturer, with operations in 18 countries. It manufactures a range of flat steel products, including commodity products such as slab, plate and hot rolled coil, as well as value-added branded products such as COLORBOND® steel, ZINCALUME® steel, and the LYSAGHT® range of building products.

BlueScope is the only domestic manufacturer of flat steel products, providing sovereign capability to supply key sectors including building and construction, manufacturing, agriculture, infrastructure, transport and defence.

BlueScope employs approximately 6,700 people in Australia, including around 3,500 people at PKSW and adjacent facilities in the Illawarra region of New South Wales. In the Illawarra, BlueScope contributes approximately \$6.5 billion of regional Total Output (Value Added) and \$1.6 billion of Gross Regional Product.

BlueScope manufactures approximately 3.2 million tonnes of steel annually in Australia, using the blast furnace - basic oxygen furnace (BF-BOF) method of primary iron and steelmaking. In this method, iron ores are smelted with coke produced from metallurgical coal (much of it sourced from the adjacent Illawarra coalfields) and limestone in the BF to produce virgin iron. The carbon in the coke acts as a chemical reductant to extract iron from the iron ore. Molten iron and scrap are then converted into steel in the BOF. While a significant amount of scrap is used (around 800,000 tonnes or 26 per cent of production in FY2021) there are thermal limits on melting scrap due to its cooling effect in the BOF.

More broadly, it should be noted that scrap can also be melted in an electric arc furnace (EAF) to manufacture new steel products – known as secondary steelmaking. However, steel demand today is higher than when products currently being recycled were produced, meaning scrap alone cannot fulfil demand. The BF-BOF process currently accounts for approximately 70 per cent of steel production worldwide, and the International Energy Agency (IEA) estimates that it will still account for between ~30–50 per cent of global production by 2050, depending on the climate change policy scenario that is adopted [2]. Given that global demand for steel is predicted to increase by more than one third through to 2050, both primary and secondary steelmaking will be required to meet demand.

BlueScope acknowledges the scientific consensus on climate change and the objectives of the Paris Agreement to limit global temperature rise this century to well below 2°C and to pursue efforts to limit the temperature increase to 1.5°C. Climate Action is a key focus of BlueScope's corporate strategy, and one of the five sustainability outcomes that matter most to its stakeholders.

BlueScope has developed an indicative decarbonisation pathway to support delivery of its climate strategy. It is based on two 2030 targets and a net zero by 2050 goal. The 2030 targets are: a 12 per cent reduction in greenhouse gas (GHG) emissions intensity for BlueScope's steelmaking operations globally; and a 30 per cent reduction in GHG intensity for BlueScope's non-steelmaking (midstream) activities. Both targets are based on FY2018 levels. The 2050 net zero goal is for all BlueScope's operations globally. All targets and goals include Scope 1 and 2 emissions.

Achieving the 2050 net zero goal is highly dependent on several enablers, including the commerciality of future breakthrough technologies, the availability of affordable and reliable renewable energy and hydrogen, the availability of quality raw materials, and appropriate policy settings.

BlueScope’s climate strategy guides activities undertaken across six focus areas:

- Reducing BlueScope’s emissions in response to science, technology availability and timing of key investment decisions;
- Creating carbon efficient and climate resilient solutions for BlueScope’s customers;
- Increasing BlueScope’s use of affordable and reliable renewable energy;
- Using quality, cost-effective carbon offsets only where direct abatement is not feasible;
- Making the case for local, sustainable steel in BlueScope’s communities; and
- Monitoring and appropriately managing climate risks and engaging with external stakeholders and partners.

Delivering the 2030 targets and progress on the 2050 net zero goal will be supported by BlueScope’s Capital Allocation Framework. On an indicative basis, BlueScope anticipates capital requirements of an estimated \$300-\$400 million between now and 2030, and to that end, it has made an initial allocation of up to \$150 million to 2026 to help deliver on its mid-term commitments and make progress on its longer-term decarbonisation journey.

BlueScope has a strong track record of implementing energy efficiency and emissions reduction opportunities where they are economic. By way of example, between FY2013 and FY2021, PKSW reduced its combined Scope 1 and Scope 2 emissions intensity from 2.45 t CO₂-e/t-raw steel to 2.14 t CO₂-e/t-raw steel i.e. a 13 per cent decrease. PKSW FY21 GHG emissions data is shown in Table 1. According to recent (2021) data from the World Steel Association (worldsteel)², the Port Kembla Steelworks has been included in the top performing 15% of world steel members that run blast furnaces.

Description	Port Kembla Steelworks
Scope 1 emissions tonnes CO ₂ -e	6,260,763
Scope 2 emission tonnes CO ₂ -e	608,085
Total site related GHG emissions tonnes CO ₂ -e	6,868,848
Production tonnes	3,209,637
Intensity tonnes CO ₂ -e / tonne steel	2.140
Up-stream Scope 3 tonnes CO ₂ -e	1,215,456

Notes: Scope 1 and Scope 2 emissions are estimated as per the requirements of the National Greenhouse and Energy Reporting Scheme (NGERS);
 Production = tonnes of accepted slab produced by the Slab Caster;
 Scope 3 emissions have been estimated based on material purchases and industry emissions factors.

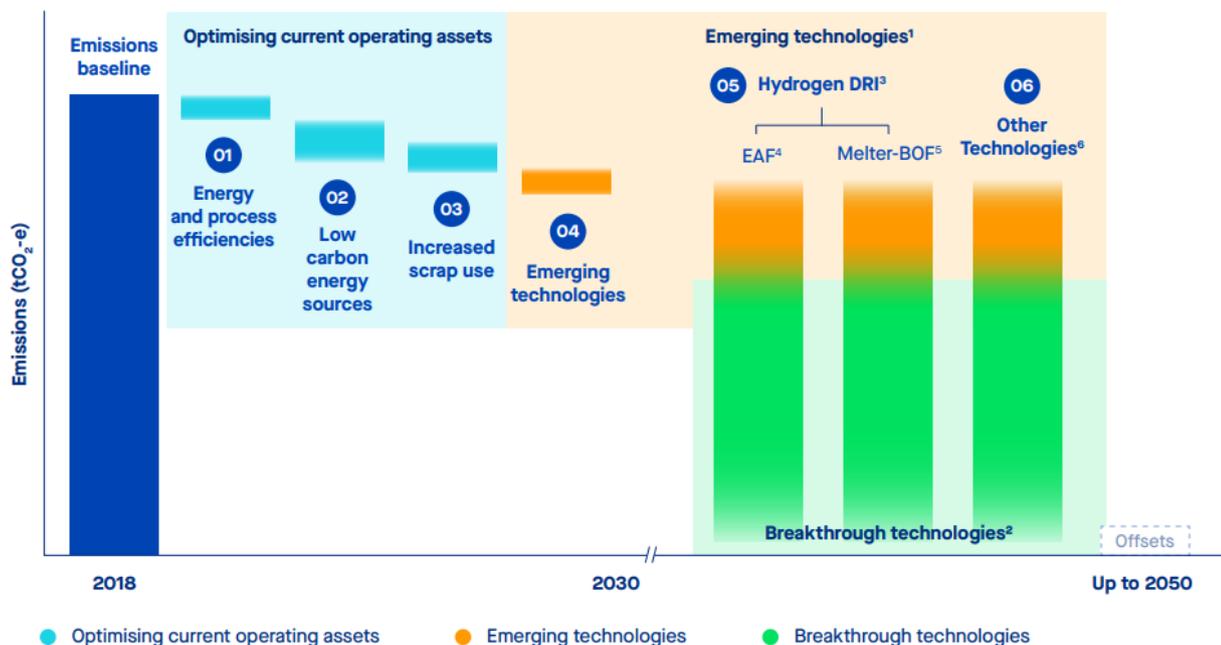
Table 1 – PKSW FY21 GHG Emissions Data

Having already achieved this significant reduction in emissions intensity and top 15% performance, further GHG emissions reductions at PKSW will be harder and more costly to achieve. In addition, BlueScope reduced its absolute Australian greenhouse gas emissions (Scope 1 and 2) by over 40 per cent since 2005, after it closed a blast furnace and associated plant at PKSW and made changes at its Western Port

² Worldsteel CO2 Data report 2022, September 2022

Works in 2011. However, without further plant closures, BlueScope does not have an opportunity to repeat this magnitude reduction in emissions without breakthrough technology.

Given this background, BlueScope has developed an indicative iron- and steelmaking decarbonisation pathway, as set out in its 2021 Climate Action Report [5] and as shown in Figure 2. The pathway provides an overview of potential emissions reduction technologies – both to optimise existing processes to meet the 2030 targets, and the breakthrough technologies that will be needed to achieve the 2050 net zero goal.



- 1 Emerging technologies refers to demonstrated technology that is commercially available but requires further application to integrated steelworks, e.g. biochar, hydrogen tuyere injection, etc.
- 2 Breakthrough technologies refers to technology not yet commercialised, currently at concept or pilot stage, or not yet applied to integrated steelworks (e.g. low Technology Readiness Level (TRL)).
- 3 Contingent upon feasible supply of hydrogen from renewable sources.
- 4 Requires suitable high-grade ores, estimated at less than 15% of available ores and access to cost-effective energy sources.
- 5 For Melter-BOF, DRI-melter replaces the blast furnace. Maintains existing BOF and caster infrastructure, and allows a wider range of ores to be used.
- 6 Other technologies include CCUS, electrolytic reduction, etc.

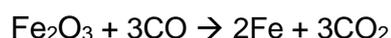
Figure 2 BlueScope's Indicative Iron- and Steelmaking Decarbonisation Pathway [5]

This indicative pathway recognises that the steel industry is often referred to as a 'hard to abate' sector. That is because carbon plays an essential role in the chemical reaction to manufacture new (virgin) iron and steel, with very limited commercial alternatives currently available. It is also because, after decades of continuous improvement, current iron and steelmaking processes are highly optimised in terms of their energy use and consumption of raw materials. Steelmakers are continuously incentivised to reduce emissions as they arise from energy use and other inputs to our production process, both of which add to production cost. Hence, to reach net zero, the industry will need major technology breakthroughs – fundamentally new processes that are currently at low levels of technical readiness and are yet to be commercialised anywhere globally. This reliance on new technologies means that decarbonisation will not be linear – but will rather involve a stepped GHG emissions reduction as such technologies are commercialised and adopted. At this stage, using renewably sourced hydrogen to make direct reduced iron (DRI) is considered the most likely technology to provide the breakthrough to very low emissions iron and steelmaking. While industry estimates of when new technologies will be commercialised vary, BlueScope currently expects it will be during the decade post 2040.

Recognising this timeframe, BlueScope's indicative decarbonisation pathway is in two phases. In the first phase (to 2030), further improvements to existing processes are to be made, together with developing and piloting emerging technologies (acknowledging that BlueScope alone is unlikely to be able to sufficiently develop and commercialise such technologies). The 2030 steelmaking and non-steelmaking targets drive these activities. Improvements to existing processes being explored include energy and process improvements. The second phase (post-2030) will be driven by BlueScope's net zero by 2050 goal. It is envisaged that BlueScope will be working on breakthrough technologies and adopting them once they are technically and commercially viable and in line with investment cycles. Again, developments of such technologies will require deep and significant collaboration across industry. By way of example, BlueScope is continuing to contribute to worldwide efforts to develop breakthrough technologies for PKSW, including a) with Rio Tinto, working towards producing low emissions iron feed via hydrogen-DRI using Pilbara ores; and b) investigating the construction of a pilot scale 10MW hydrogen electrolyser at Port Kembla which will help BlueScope to gain experience with hydrogen production, compression, storage and distribution.

1.3 PKSW Site - Process and Emissions Description

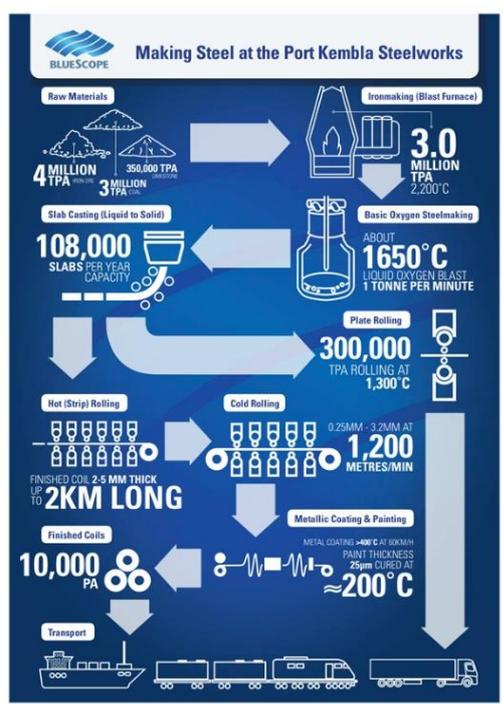
The chemical process of converting iron oxide (in iron ores) to iron is called "reduction". The basic chemical reaction is as follows, where the carbon in the coke combines with oxygen:



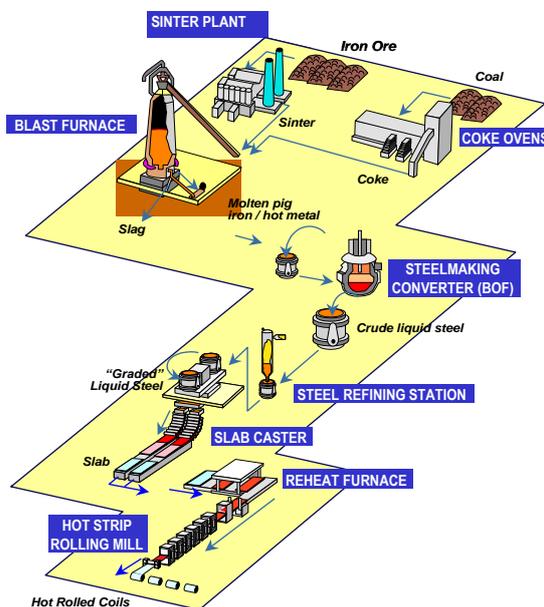
At PKSW, the traditional integrated BF-BOF steelmaking route is used to convert raw materials to liquid steel (Figure 3). The iron oxide feeds charged into the BF are predominantly composed of Australia's Pilbara iron ores. These are smelted with metallurgical coke produced at PKSW from coal mainly sourced from the adjacent Illawarra coalfields, together with pulverised coal and fluxes in the BF to produce molten iron. Molten iron and scrap are then combined and converted into steel in the BOF. Around 800,000 tonnes of scrap steel were utilised in FY2021, or 26 per cent of steel production.

Being an integrated steelmaking plant, PKSW consists of:

- Raw materials preparation facilities
 - Cokemaking, pulverized coal injection and sinter plants
- BF ironmaking
- BOF steelmaking
- Secondary refining and slab casting
- Power and utilities plant
- Product manufacturing facilities
 - Reheating furnaces, rolling mills, thermal treatment lines, coating lines)



(a)



(b)

Figure 3 - Overview of manufacturing processes at PKSW: (a) Outline of major plant production conditions [after <https://www.bluescopeillawarra.com.au/about-us/how-steel-is-made/>] and (b) Simplified flowsheet showing major processes

The key operating units relevant to this Project are the raw materials preparation facilities, ironmaking and steelmaking:

1.3.1 Raw materials preparation facilities

PKSW has three coke oven batteries, Batteries 5, 6 and 7A, which were built in 1972, 1973 and 1987, respectively. Batteries 5 and 6 are similar and a Wilputte design, with 66 and 101 ovens, respectively; Battery 7A is a Didier design, with 50 larger ovens. The coking coal blend is sequentially charged into individual ovens, where it is pyrolyzed for a set time, forming metallurgical coke product. Each oven is then sequentially pushed to remove the coke. The annual coke solids production is 1.85 million tonnes, of which 82% is lump coke with the remainder split between 3 smaller coke fractions. The BF consumes the majority of the lump coke (~1 million tonnes) and a significant proportion of one of the smaller coke fractions, whilst the sinter plant consumes all of the smallest coke fraction. The remaining coke, some 722,000 tonnes in both lump and smaller fractions is exported. Coke ovens gas (COG) produced from the coking process is cleaned in the gas processing plant, prior to reticulation within PKSW. Aside from COG, the three main products are BTX (Benzene, Toluene and Xylene), crude tar and ammonium sulphate.

A Pulverised Coal Injection plant dries and grinds a blend of non-coking coals to a very fine powder which is then pneumatically conveyed to the BF.

PKSW has a single sinter machine (SP3), which prepares an agglomerated product based on a blend of fine materials, fine iron ore, fluxes, coke breeze etc for use in the blast furnace. The single 480 m² sinter machine consumes approximately 200,000 tonnes per annum of naturally arising coke breeze, imported

anthracite or crushed nut coke. Blending of fine materials takes place in blending yards prior to granulation and feeding of the moistened mixture on to a travelling grate (or strand). An ignition furnace at the start of the strand initiates combustion, converting the green bed mixture to sinter. The hot sinter falls on to a rotating cooler bed, following which it is sent to the blast furnace or to stockpile.

1.3.2 Ironmaking

Following the decommissioning of 6BF in 2011, PKSW now operates a single, medium-size blast furnace, 5BF, which commenced its fourth campaign in 2009. 5BF has an inner volume of 3427 cubic metres, 28 tuyeres (or ports) and three tapholes. Together with coke and sinter, lump ore, iron ore pellets (externally produced) and fluxes are charged into the furnace, while hot oxygen-enriched, humidified air together with pulverised coal are injected through the tuyeres. The hot metal production range is approximately 7,500-8,000 tonnes per day. The campaign life of 5BF is expected to be complete around 2026. Following the completion of this fourth campaign and the evaluation of potential breakthrough low-emission technologies presently available, the most technically feasible and economic option is a BF reline and upgrade. BlueScope is currently working on feasibility for the option to reline the currently mothballed 6BF, including evaluation of measures to reduce carbon emissions intensity. Major long lead time items required for the reline have already been ordered.

1.3.3 Steelmaking

Two basic oxygen steelmaking vessels (bricked volume ~260 m³) are operated at PKSW, using BF hot metal (~74%) and scrap (~26%) as the metallic charge.

The above key operating units represent a baseline (or Base Case operation) for the Project.

1.4 [Relevant Previous Work](#)

1.4.1 General overview

As summarised by the worldsteel Association [6] and the International Energy Agency [2], technologies to lower carbon emissions and minimise energy consumption from steel production are at various stages of development and commercialisation. As shown in Figure 4, these future decarbonisation technologies and approaches fall under three broad categories:

- Carbon, in various forms including biomass, employed as both an energy source and reductant (i.e. a substance that reacts to become an oxide as part of the chemical reduction of the iron oxide into elemental iron), with new processes under development for its capture, utilisation and/or storage (CCUS);
- Hydrogen, renewably sourced and principally as a substitute for carbon; and
- Electricity, generated from renewable sources and utilised in electrolysis processes to produce elemental iron.

Some breakthrough technologies under development, as well as alternate approaches or concepts proposed, may dramatically transform ironmaking and minimise carbon emissions. For instance, hydrogen-based direct reduced iron (H₂-DRI), carbon capture and utilisation (CCU) from process flue gases and/or utilisation of renewable bioenergy sources are all potential levers or solutions for achieving significant emission reductions across the steel manufacturing chain. In addition, a technology often seen

as a potential 'bridging' step between steel manufactured using fossil fuels, and fossil fuel free or zero

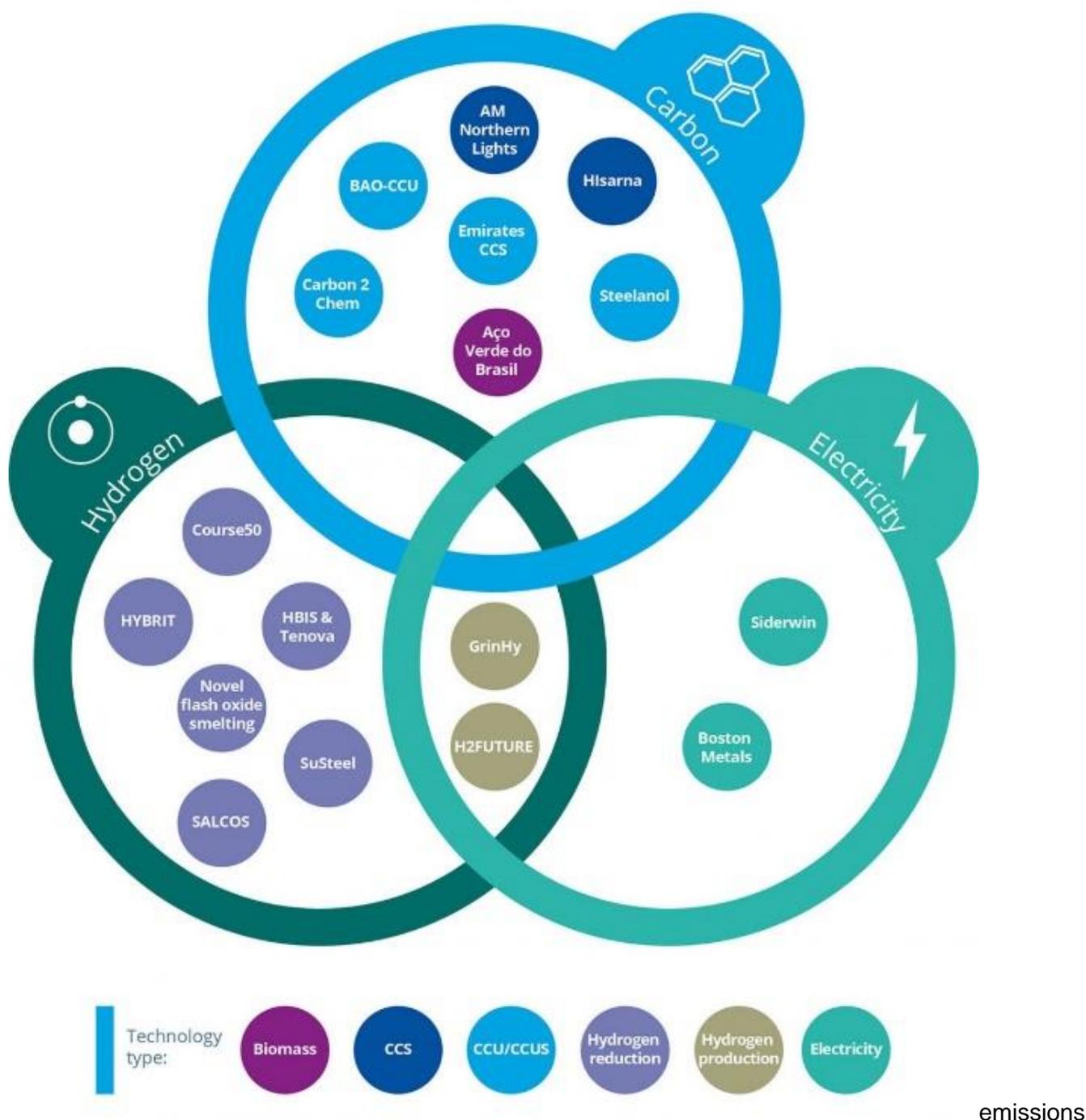


Figure 4 Breakthrough ironmaking technologies [6]

steel, is natural gas based DRI. Approximately 100 million tonnes of DRI are manufactured worldwide today, predominantly using shaft furnaces operating with natural gas. To be converted into steel, DRI is further processed e.g., in an electric arc furnace (EAF). Importantly, DRI plants have the potential for either carbon capture and storage, or phased conversion to hydrogen, which may provide a transition pathway to low emissions ironmaking. As the electricity grid is decarbonised, EAF steelmaking carbon emissions intensity will also be reduced. It should be noted that the H₂-DRI pathway remains to be proven at commercial scale using Pilbara (hematite) ores.

1.4.2 Previous work in Australia

From 2006-2014, BlueScope, Arrium and CSIRO undertook a major R&D program to develop innovative, practical technologies involving the substitution of fossil-based fuels, such as coal, with renewable biomass materials and an alternate dry slag granulation process for the blast furnace slag. Figure 5 shows the potential for biomass-derived product applications to mitigate GHG emissions for the integrated steelmaking route.

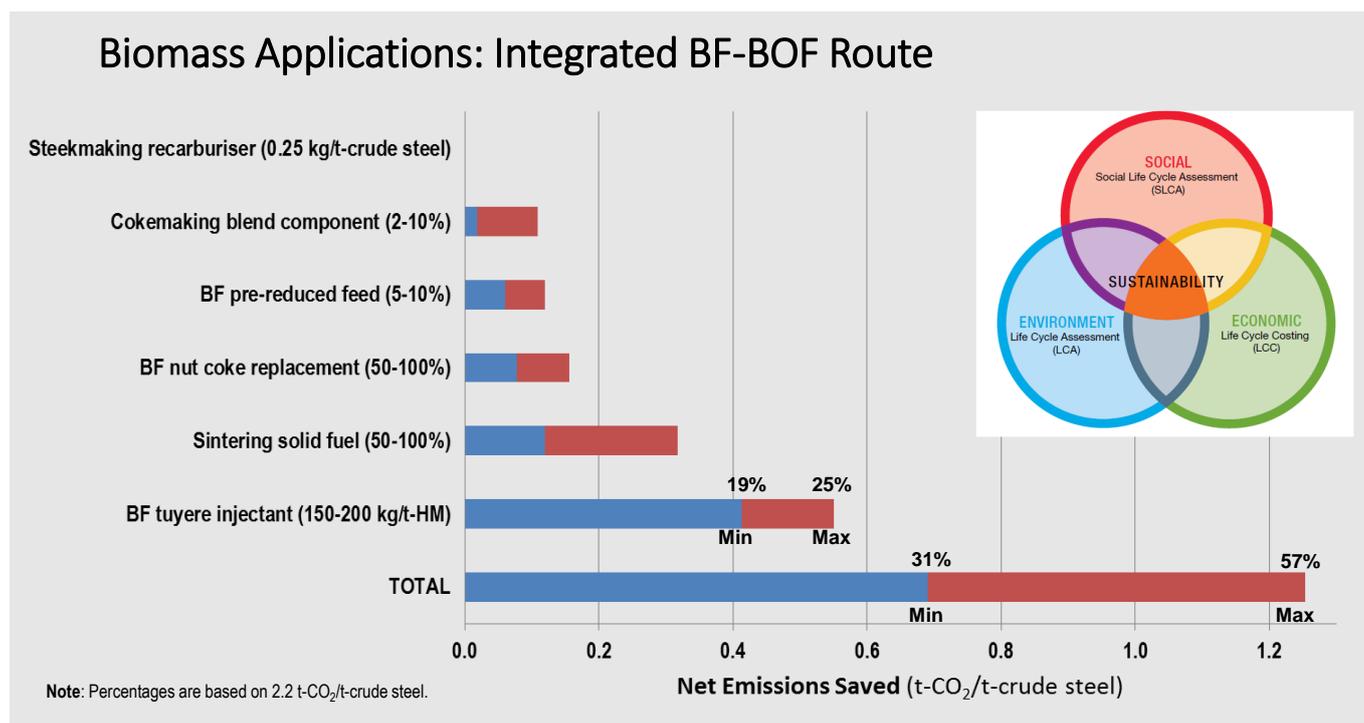


Figure 5 Australian Steel Industry CO₂ Breakthrough Program (2006-2014) (adapted, [7])

This ground-breaking R&D was recognised by worldsteel as Australia's contribution to its own CO₂ Breakthrough Program (CO₂BT). The program included bench-scale testing of a novel large-scale pyrolysis process and preliminary studies of biomass supply in Australia [7], as well as theoretical and pilot scale combustion studies showing the superior performance of biochar relative to coal for blast furnace injection, bench-scale evaluation of the limits of biochar addition to coking coal blends and the optimal specifications for these renewable materials for each process including for electric arc furnace (foam suppression) and steel ladles (steel decarburization). At the conclusion of the CO₂BT program, the suitability of biochar had been demonstrated at a technical and pilot-scale level for four applications.

More recently, projects have been undertaken or supported by BlueScope to identify ways to improve energy efficiency and reduce carbon emissions. Examples of these projects include:

- A Turbo Alternator (22TA) which was commissioned at PKSW in 2017 as a new electrical power generating machine. The 22TA was built using redundant equipment, relocated from other parts of the plant that were still in good condition and with remaining life. It provided improved efficiency and reliability of electrical power generation within PKSW; used excess by-product fuels which were previously flared to the atmosphere; and reduced electricity purchases from the New South Wales grid. The project resulted in a 28% increase in onsite electricity generation (over 57,000 MWh/yr), representing a 7.4% reduction in purchased electricity from the grid, equivalent to 46,000 t-CO₂-e/yr.

- In 2018, an energy strategy review was concluded for BlueScope's Australian operations. A key outcome included signing a seven-year, 233,000 MWh per annum Power Purchasing Agreement (PPA) with ESCO Pacific for a new 500,000 panel solar farm at Finley, New South Wales. At the time, the agreement was one of Australia's largest corporate PPA and was equivalent to 20% of BlueScope's Australian purchased electricity demand. BlueScope's support for this project emphasised its commitment to decarbonisation of the electricity supply sector.
- BlueScope also set a global target in 2018, of 12% reduction in the GHG emissions intensity (Scope 1 and 2) across its three steelmaking plants, from 2018 to 2030. To meet this ongoing target, PKSW continues to identify, analyse and in some cases, implement options for GHG intensity reduction. These include, process efficiency improvements, waste heat recovery and re-use and other incremental improvements.
- BlueScope partnered with the CO2CRC in 2018/19 to explore potential pathways for reducing GHG emissions in steel production through CCS and CCU. A high-level evaluation of the economic viability of transport (piping or shipping) and storage location options for captured CO₂ from PKSW was carried out. In addition, utilization of CO₂- and CO-rich gases to provide high-quality, value-added products using innovative biochemical and chemical processes was considered. Further work was completed on the potential to use plant-generated gases to produce ethanol, with many different scenarios considered, including hydrogen and methane. At the time, neither opportunity met financial criteria.

2 Relevant technologies

2.1 Overview of relevant technologies assessed

Current and future Smart Carbon Usage (SCU) and Direct Carbon Avoidance (DCA) technologies for steel production (as defined in Section 1.2) are based on lowering carbon intensity through modifying existing and/or implementing alternate processes, with or without carbon capture and storage (CCS). Some of these technologies include concepts and potential future processes involving partial, or near complete, replacement of fossil-derived fuels (coal, natural gas) using hydrogen as a reducing agent and energy source, and/or electrical energy from renewable sources. Tables 2-4 summarise 17 current and future SCU and DCA areas and examples of active programs that have been systematically evaluated for the main process areas relevant to PKSW's steel manufacturing chain:

- Table 2: Blast Furnace Ironmaking / Cokemaking / Sintering
- Table 3: Alternate Ironmaking
- Table 4: Steelmaking / Carbon Capture, Utilization and Storage

Section 2.2 provides a short description summarising the 17 SCU and DCA areas. A more detailed description of each relevant technology is found in the Information Reviews in Appendix 3.

In Table 2, aside from directly using renewable hydrogen injection into the BF, most technological pathways are SCU-based alternatives. For example:

- Novel raw materials charged into the BF, where carbon is in intimate contact with iron ore materials
- Renewable biochar, which allows partial replacement of pulverised coal injected into the BF, anthracite coal or coke breeze in iron ore sintering, or metallurgical coal in cokemaking with carbon from renewable/sustainable sources
- Utilising PKSW-generated gases to reduce emissions, either directly such as those with high levels of hydrogen (coke ovens gas) or with further processing such as BF top gas through water-gas shift and sorption-enhanced water-gas shift reaction.

Table 3 shows a range of potential, alternate ironmaking technologies which could replace BF ironmaking. For example:

- Electrolysis processes, which are relatively new and involve high-temperature (molten oxides) or low-temperature (alkaline) electrolytes, using renewable electricity
- Various direct reduction processes such as low production capacity processes (e.g. rotary kiln; rotary hearth) ideally suited to small steelworks (e.g. EAF-based)
- Other direct reduction processes, which utilise either fine iron ores in fluidized beds (e.g. Circored) or agglomerated iron ores in shaft furnaces (e.g. Midrex), and a range of different fuels/reductants with the future opportunity of higher levels of hydrogen
- Smelting-reduction processes, such as Finex and COREX, which convert direct reduced iron using fine coal and pure oxygen, and effectively, replacing the BF, cokemaking and iron ore sintering, whilst producing a concentrated CO₂ gas for CCS.

		CURRENT AND FUTURE TECHNOLOGIES	EXAMPLES OF ACTIVE PROGRAMS
Blast Furnace Ironmaking			
1	SCU	Novel charging materials to BF <ul style="list-style-type: none"> Carbon containing agglomerates (CCA) Pre-reduced agglomerates (PRA) Ferro-coke 	<ul style="list-style-type: none"> Ferro-coke (COURSE50, Japan)
2	SCU	Dry slag granulation <ul style="list-style-type: none"> Rotating cup/disc Air blasting Rotating drum Steel spheres in slag 	<ul style="list-style-type: none"> Primetals rotating disc DSG (Austria) CSIRO rotating disc DSG (Australia) Ecomaister / Hatch (USA)
3	SCU	Biomass application in ironmaking <ul style="list-style-type: none"> Biochar in sintering Biochar in cokemaking Biochar in blast furnace ironmaking - bio-injection into tuyeres Biochar in blast furnace ironmaking - biomass-based top charging Biochar in blast furnace ironmaking - pre-reduced agglomerates Biochar in blast furnace ironmaking - bio-composites 	<ul style="list-style-type: none"> Torero, "Smart Carbon" projects (ArcelorMittal, Ghent) (Belgium) Scope21 (Japan) COURSE50 (Japan) Brazil's continued use of charcoal in ironmaking (small BFs)
4	SCU	Top Gas Recycling with High Oxygen BF	<ul style="list-style-type: none"> NKG process, NKK (Japan) ULCOS-TGR-BF (Europe) BaoWu Group (China) COURSE50 (Japan)
5	SCU	Hydrogen-enriched injection <ul style="list-style-type: none"> Natural gas Coke ovens gas Hot reducing gas Waste plastic Biogas (associated with biomass pyrolysis "biomass syngas") 	<ul style="list-style-type: none"> COURSE 50 (Japan) COG injection (HKM and ROGESA with Paul Wurth technology, Germany) IGAR with dry reforming of CO2 using a plasma torch (ArcelorMittal, France) NG, COG and waste plastic injection are in regular use at various facilities, (TRL=9)
	DCA	<ul style="list-style-type: none"> Hydrogen 	<ul style="list-style-type: none"> H₂ injection (thyssenkrupp Stahl)
Cokemaking			
6	SCU	Coal moisture control Coke dry quenching (CDQ) Coal stamp charging Advanced control of heating walls Single chamber system	<ul style="list-style-type: none"> CDQ - SCOPE21 (Japan) CMC, DCQ and stamp charging are TRL 9 with many sites already using these technologies.
Sintering			
7	SCU	Waste heat recovery from cooler and waste gas recycling Low temperature sintering Microwave assisted ignition - iron ore sinter Super-SINTER technology (SST)	<ul style="list-style-type: none"> WHR - COURSE50 (Japan) SST - JFE (Japan)

Table 2 - List of Smart Carbon Usage (SCU) and Direct Carbon Avoidance (DCA) technologies assessed - Blast Furnace Ironmaking / Cokemaking / Sintering

		CURRENT AND FUTURE TECHNOLOGIES	EXAMPLES OF ACTIVE PROGRAMS
Alternate Ironmaking			
8	DCA	Electrolysis of iron ore	<ul style="list-style-type: none"> • Molten oxide electrolysis (Boston Metal, USA) • SIDERWIN (ArcelorMittal) • SALCOS (Salzgitter)
9	SCU	Rotary kiln furnace direct reduction	
10	SCU	Rotary hearth furnace direct reduction	<ul style="list-style-type: none"> • Fastmet/Fastmelt • Redsmelt • ITmk3 • Primus • Paired straight hearth furnace
11	SCU/ DCA	Fluidized bed direct reduction	<ul style="list-style-type: none"> • Finmet/Finored • Finex • Circored • Hyfor
	SCU		<ul style="list-style-type: none"> • Circofer (coal-based)
12	SCU/ DCA	Shaft furnace direct reduction	<ul style="list-style-type: none"> • Midrex • HYL/ENERGIRON • PERED • COREX - shaft furnace • H2 Direct Reduction
13	SCU	Smelting Reduction (SR) [Combination DR-SR processes with DRI produced via fluidised bed, shaft furnace, etc]	<ul style="list-style-type: none"> • COREX (South Africa) / COREX-MXCOL • FINEX (POSCO /Primetals) • Cyclone Converter Furnace (Tata Steel) • Hismelt (Australia) / HIsarna (Tata Steel) • Tecnoled (Brazil) • Dios (Japan) • Romelt (Russia) • AusIron (Australia) • Flash ironmaking (USA) • OxyCup (Germany) • Ironarc (Sweden)

Table 3 - List of Smart Carbon Usage (SCU) and Direct Carbon Avoidance (DCA) technologies assessed - Alternate Ironmaking

Table 4 lists future SCU/DCA-based technological pathways for an integrated BF-BOS steelworks, such as stepwise replacement or transitioning of steelmaking capacity from carbon-based BF-BOS processes. Initially, either natural gas or hydrogen-enriched natural gas-based DRI/EAF steelmaking would be used with ultimately, full hydrogen-based DRI/EAF and/or other emerging technologies being phased in. Also listed in Table 4 are the emerging “end-of-pipe” solutions involving capturing plant gases (e.g. BF, BOF) through various absorption or adsorption processes, and then reticulating the CO₂-stripped gas within the steelworks or transforming the gas by chemical or biological means, producing an alternate material.

		CURRENT AND FUTURE TECHNOLOGIES	EXAMPLES OF ACTIVE PROGRAMS
Steelmaking			
14	SCU/ DCA	DRI and scrap utilisation in Basic Oxygen Furnace	<ul style="list-style-type: none"> DRI and scrap utilisation in Basic Oxygen Furnace, including scrap preheating DRI utilisation in SAF-Basic Oxygen Furnace CONPRO (SMS)
15	SCU/ DCA	DRI and scrap utilisation in electric arc furnace	<ul style="list-style-type: none"> DRI-EAF DRI-SAF
16	DCA	Hydrogen plasma direct steel production	<ul style="list-style-type: none"> SuSteel project Hybrid hydrogen-based reduction of iron ore
Carbon Capture, Utilization and Storage			
17	SCU	Biological	<ul style="list-style-type: none"> BlueScope (New Zealand) Baosteel (China) Shougang Steel Group (China) STEELANOL (ArcelorMittal) Carbon2Value (phase 1&2) (EU) (Absorption) (+ Chemical transformation)
		Chemical	<ul style="list-style-type: none"> “Carbon2Chem” project (Thyssen Krupp Stahl) (Chemical transformation)
		Absorption	<ul style="list-style-type: none"> COURSE50 (Japan) – Option 1 (secondary amino alcohols) POSCO CO2 breakthrough framework (Korea) (Ammonia) VALORCO project (France) (MEA 30%-40%, DMX solvent) Everest (Tata steel) (+ Chemical transformation) Project3D (ArcelorMittal) (DMX) Emirates Steel Industries (Absorption MEA amine)
		Adsorption	<ul style="list-style-type: none"> COURSE50 (Japan) – Option 2 (PSA-zeolite) STEPWISE (SEWGS) C4U project (ArcelorMittal, etc) FReSMe (H2020 EU) (Belgium) (SEWGS, Chemical transformation) Carbon4PUR (ArcelorMittal) (PS-RWGS) ULCOS TGR-BF project (Adsorption [VSPA]+cryogenics)
		Mineral carbonation	<ul style="list-style-type: none"> Slag2PCC (Finland) (Chemical transformation) MCI (Australia)

Table 4 - List of Smart Carbon Usage (SCU) and Direct Carbon Avoidance (DCA) technologies assessed - Steelmaking / Carbon Capture, Utilization and Storage

2.2 Description of relevant SCU and DCA technologies assessed

A general introduction and outline are provided below for the 17 SCU and DCA technological areas, with greater detail in Appendix 3. As a guide, a range in Technology Readiness Level is also provided, based on all information assessed.

Blast Furnace Ironmaking		
1	SCU	Novel charging materials to BF (TRL range: 7-9)
<p>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 fuel rate and potentially, overall carbon emissions of the steel plant.</p>		
2	SCU	Dry slag granulation (TRL range: 5-8)
<p>Dry slag granulation (DSG) is a process involving atomization of hot molten slag which may be coupled to an integrated heat recovery system. More recent process developments and plant demonstrations use a rotating cup or disc, but others that have been developed, demonstrated and/or commercialised involve use of air blasting, rotating drums or small steel spheres that absorb energy from molten slag. Compared to conventional treatments such as air cooling in pits and water granulation, the emerging DSG processes provide opportunity for increased energy recovery and to some extent, improved slag quality and the avoidance of hydrogen sulphide and sulphur dioxide emissions.</p>		
3	SCU	Biomass application in ironmaking (TRL range: 4-9)
<p>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 fuels 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 fuels 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.</p>		

Blast Furnace Ironmaking (cont.)		
4	SCU	Top Gas Recycling with High Oxygen BF (TGR-OBF) (TRL range: 6)
<p>BF top gas recycling technology aims to fully utilise the chemical energy of a CO₂-free top gas containing reducing agents (CO and H₂), by heating and injecting the gas through tuyeres in both the lower zone and lower shaft. In this technology, pure oxygen replaces hot blast air introduced into the lower tuyeres (TGR-OBF). The captured CO₂ can be used for reforming of coke oven gas, which can also be re-injected into the lower shaft; or alternatively, it can be stored or utilized through other carbon capture utilization and storage technologies. New scale-up demonstration trials have been undertaken recently to address the operational, engineering and equipment design challenges including different TGR-OBF combinations involving injection positions, preheating of recycled gas, and the use of various combinations of injectants through tuyeres.</p>		
5	SCU/ DCA	Hydrogen-enriched injection (TRL range: 6-9)
<p>Utilisation of hydrogen (H₂)-enriched injection gases in the BF is advantageous because of H₂ strong diffusion and high reduction ability. More importantly, the reduction product is H₂O (and not CO₂). 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 fuel consumption (e.g. coke and pulverized 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 fuels via waste plastics does not change carbon accounting.</p>		
6	SCU	Cokemaking (TRL range: 9)
<p>Coke is a material fundamentally critical to the shaft-based BF process, not only as a fuel and reductant, but also as a material providing physical support for the ferrous burden and gas permeability. Consequently, coke quality as well as cokemaking productivity, energy consumption and carbon emission reduction continue to be investigated. In terms of lowering energy consumption and emissions, technologies such as coal moisture control, coke dry quenching, coke stamp charging and advanced control of heating walls have been, and continue to be, developed. Emerging technologies are under development, including a single chamber system and the utilization of biochar in the coking coal blend.</p>		
7	SCU	Sintering (TRL range: 2-9)
<p>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 utilize waste heat from the sinter cooler, recycle waste gas back into the sinter strand, utilize 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.</p>		

Alternate Ironmaking		
8	DCA	Electrolysis of iron ore (TRL range: 4-5)
<p>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. 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.</p>		

Alternate Ironmaking (Cont.)		
9	SCU	Rotary kiln furnace direct reduction (TRL range: 9)
<p>The rotary kiln process is coal-based and produces direct reduction iron using a rotating kiln as the reactor. The process is relatively flexible with the type of iron bearing materials used (e.g. lump ore, pellet, fine ore or ironsand), and carbonaceous materials (e.g. non-coking coal, coke breeze, charcoal, lignite, or anthracite). The process is a relatively mature one, with slightly different variations in operating features. The Stelco-Lurgi/Republic-National (SL/RN) rotary kiln process is the most widely used, with iron bearing materials, solid reductant and limestone/dolomite fed into the top end of the kiln and slowly travel to the discharge end, under gravity. Primary air is blown into the kiln from the discharge end, where coal is also injected and combusted to supply heat and produce the required reducing conditions. Each process unit has a relatively low production capacity, up to 200,000 tonnes per year.</p>		
10	SCU	Rotary hearth furnace direct reduction (TRL range: 4-9)
<p>Rotary hearth furnace direct reduction processes are coal-based, processing agglomerated ore fines and/or steel plant ferrous wastes (pellets or briquettes), carbonaceous materials and a binder. The large diameter furnace consists of a flat refractory hearth rotating inside a high temperature circular tunnel kiln. The agglomerates are fed continuously into the hearth with a shallow depth and remain inside the rotary hearth for one revolution. Burners located above the hearth provide energy required to heat and reduce the agglomerates in the pre-heating and reduction zones. The materials are normally heated up to 1300°C and reduced in the solid state, forming a metallized product.</p>		
11	SCU/ DCA	Fluidized bed direct reduction (TRL range: 6 [H₂], 7-9)
<p>Fluidized bed direct reduction processes utilize iron ore fines, with no significant agglomeration treatment required. In this process, iron ore fines move through a series of fluidized 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 fluidized 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 fluidization 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 fluidized bed reactors is normally applied. Fluidized 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 Finmet (Finored), Circored and Circofer (coal-based). Hyfor, which is under development, will use hydrogen-rich gas or even 100% hydrogen. Some fluidized bed reactors have been used in the pre-reduction stage of smelting-reduction processes such as Finex.</p>		
12	SCU/ DCA	Shaft furnace direct reduction (TRL range: 7 [H₂], 8-9)
<p>Most direct reduction plants utilize 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. 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 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.</p>		
13	SCU	Smelting Reduction (SR) (TRL range: 4-9)
<p>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</p>		

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 commercialized 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 fluidized 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.

Steelmaking		
14	SCU/ DCA	DRI and scrap utilisation in Basic Oxygen Furnace (TRL range: 2 [SAF], 9)
<p>The basic oxygen furnace (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 (< 25-30% of the total materials charged), steel scrap and other iron-bearing materials, such as DRI, may be used as a coolant. In the case of DRI, it has been charged directly into the BOF as HBI; or as a charging material for the DRI-BF-BOF route; or in a recently proposed DRI-melter-BOF route, melted and then charged to the BOF. Depending on DRI properties, the latter could be competitive with the DRI-EAF route. In particular, the potential for a hydrogen-based DR process, i.e. carbon-free H₂-DRI, utilizing low-grade iron ores (Fe content <~67.5%) may be highly favoured. Another alternative is a recently developed primary melter, CONPRO, which combines the technological advantages of the BOF and EAF, providing flexibility in choice of charge materials and energy sources. Recently, the submerged-arc furnace (SAF) process, a particular sub-type of electric arc furnace, was proposed to melt DRI with lower or no carbon content. The SAF has mostly been used for the continuous production of ferroalloys. Compared with the EAF, the electric energy in a SAF is delivered via electrodes immersed in the melt and converted into heat mainly through the electric resistance of the burden or molten slag. Furthermore, since the SAF is operated under reducing atmosphere conditions where there is no occurrence of oxidizing reactions and it is possible to continuously add carbon and slag builder with the metallic charge, it is suitable to melt DRI (e.g. H₂-DRI) to produce a pre-melt product prior to steelmaking. In contrast, H₂-DRI used in the EAF will likely require the addition of carbon materials, such as renewable biomass. Depending on various factors such as scrap supply, iron ore quality and steel quality, it is anticipated that iron and steelmaking will increasingly transition from the BF-BOF route to (H₂-) DRI-EAF or (H₂-) DRI-SAF-BOF routes.</p>		
15	SCU/ DCA	DRI and scrap utilisation in electric arc furnace (TRL range: 2 [SAF], 9)
<p>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 utilization 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.</p>		
16	DCA	Hydrogen plasma direct steel production (TRL range: 3-4)
<p>Hydrogen plasma direct steel production refers to the process of converting iron ore to liquid iron using a thermal hydrogen plasma, i.e. iron ore is melted and reduced simultaneously without agglomeration processing. During the thermal hydrogen plasma reduction (HPR), a plasma arc zone is generated between an electrode and the iron ore, which is melted and very efficiently reduced by hydrogen in both molecular and plasma states. Experimental observations show the iron oxide is melted and reduced simultaneously. Investigations of hydrogen plasma include smelting reduction of iron ores at laboratory/pilot scale (SuSteel project) and (H₂-) DRI at laboratory scale.</p>		

Carbon Capture, Utilization and Storage		
17	SCU	Carbon Capture and Storage/Carbon Capture and Utilization (TRL range: 4-9)
<p>In addition to new iron and steelmaking process developments, carbon capture, utilization and storage (CCUS) technologies are considered as potential solutions to mitigate carbon emissions in the steel industry – noting that ~70% of carbon emissions stem from ironmaking processes. 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. While some options have been commercialized at small scale (e.g. Emirates Steel Industries 0.8 Mt CO₂ per year), none are widely and commercially available at large industrial scale, particularly for CO₂ 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 CO₂ 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, CO₂ would be re-used either directly or as a carbon resource for the production of value-added products. For the steel industry, CCU is expected to be a potential long-term solution to treat carbon emissions. Cost-effective technologies need to be developed, with current investigations underway based on how CO₂ changes during its utilization i.e. without CO₂ transformation (e.g. BF top gas recycling), after CO₂ chemical transformation (e.g. Slag2PCC, producing CaCO₃) and after CO₂ biological transformation (e.g. STEELANOL, producing ethanol).</p>		

3 Assessment Criteria for Identified Technologies

In this section, background is provided on the appropriate criteria developed in assessing the 17 SCU and DCA technological areas (see Section 2), together with the actual assessment process utilised. As mentioned, this assessment was predominantly qualitative in nature, as it was anticipated that specific quantitative information and data for many of the SCU and DCA technologies was either limited or not available.

For each of the technological areas, relevant public domain information was systematically compiled and reviewed on current or emerging future decarbonisation technologies for steel manufacturing. The 17 sets of Information Reviews are provided in Appendix 3. The information was collected from published academic and technical conference papers, equipment manufacturer and steel plant websites, and other reference sources. The aim was to develop concise summaries for each technology identified in an area e.g. under “Novel charging materials to BF”, available information for three new materials was summarised: Carbon containing agglomerates (CCA), Pre-reduced agglomerates (PRA) and Ferro-coke.

To assist in the gathering and evaluation of primarily, qualitative information for each SCU and DCA technological area, a template was designed using the following 7 categories (with descriptor).

1. Brief general process description	• Outline of the process, material, technology
2. Material inputs and output	• List of key raw materials and end products
3. Overall abatement pathway	• Estimate of carbon emissions change
4. Key performance indicators	• Outline of potential impact on KPIs
5. Maturity and requirements to implement	• Current technical/commercial level and future pathway
6. Potential strengths and weaknesses	• Identification of advances and potential development gaps
7. Additional relevant comments	• Specific information

These categories were closely aligned with decision criteria anticipated to be used in the initial technical evaluation of each SCU and DCA area for PKSW. Specifically, the 4 Technical Decision Criteria and their descriptors were:

1. Technology Readiness Level	• Levels 1-9, defined in Table 5, based on the EU’s current TRL definitions [8]
2. Anticipated timeline and availability	• Expected commercialisation timeframe: Short 0-5y, Medium 5-10y, Long 10-15y
3. Abatement potential (Scope 1 and Scope 2)	• Relative carbon emissions reduction level: Low <10%, Medium 11-49%, High > 50%
4. Potential production and key performance indicators impact	• If deployed, the risk of impacting KPIs: Low, Medium, High

Phase	TRL	Description
Research	1	Basic principles observed
	2	Technology concept formulated
	3	Experimental proof of concept
Development	4	Technology validated in lab
	5	Technology validated in relevant environment (industrially relevant environment in the case of key technologies)
	6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key technologies)
Deployment	7	System prototype demonstration in operational environment
	8	System complete and qualified
	9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

Table 5 - EU Technology Readiness Level [8]

Following compilation and prior to undertaking the team-based evaluation and assessment sessions, the 17 sets of Information Reviews were reviewed and checked by various project team members. Members included senior officers and specialists across various process areas – technology, research, engineering and environmental. The Information Reviews were also independently endorsed by senior plant management.

In terms of the Qualitative Options Analysis (QOA) assessment process (Section 1.2.2), the first step was to rule out potential non-viable technologies for PKSW. A first-pass screening of each technology was required. A “Fatal Flaws” approach was chosen. In this project, this approach used a high-level objective (or combination of objectives) that would severely mark down and terminate consideration of any one of the specific decarbonisation technologies in the assessment.

The Fatal Flaws approach enabled the introduction of BlueScope’s high-level business plans for PKSW (e.g. major forward capital investments), the energy sector’s future plans (e.g. access to affordable and reliable renewable energy and hydrogen), and potential future changes in government policy positions or conditions that impact decarbonisation activities at PKSW (e.g. policy that supports investment in decarbonisation and avoids risk of carbon leakage). Three Fatal Flaws categorisations were used:

- Proposed plant **Investment Cycles** within BlueScope, (**‘IC’**)
- Proposed **Energy Grid** decarbonisation plans in NSW (**‘EG’**)
- Possible changes in **Government Policy** (**‘GP’**)

In conjunction with the Fatal Flaws approach, the QOA process also utilised a SWOT analysis. As well as helping to identify potential so-called opportunities and/or threats associated with each technology, the SWOT analysis enabled assessment of each technology’s capacity to support BlueScope in achieving its current climate action target and future goal [5].

Finally, based on the Information Reviews and prior to the team-based evaluation and assessment sessions, high-level summaries of all technologies for PKSW were assembled in the QOA matrix format, together with Technical Decision Criteria (see Appendix 2)). Using these summaries and QOA, key gaps

and potential challenges were discussed, identified and noted, based on technical, engineering, environmental, safety and logistics issues associated with each SCU and DCA technology.

It should be noted that Commercial Decision Criteria will be used in a later phase of the project, applied to the Prioritised Options only. These are anticipated to be:

- Commercialisation risk
- Estimated capital costs
- Estimated operational costs
- Estimated Net Present Value
- Estimated carbon price that leads to Net Present Value zero

These commercial criteria are critically important in relation to the selection of Prioritised Options for the long-term timeframe, particularly given BlueScope's 2050 goal of net zero. The reason for this is that, in the long term, the BF-BOF integrated steelmaking route will be far more dependent on the commercialisation of cost-effective, Carbon Capture and Utilisation technologies (Section 2.1, Table 4) than other steelmaking routes based on DRI.

A discussion of the results of this team based QOA assessment is provided in Section 4.

4 Prioritised Options for Further Evaluation

The QOA matrix approach, which included screening and assessment based on specific Technical Decision Criteria, permitted the identification of site-specific Prioritised Options with the potential to reduce carbon emissions at PKSW. Prioritised Options under SCU and DCA technological pathways were generated for both Short-to-Medium (~5-15 years) and Long Term (> 20 year) timeframes.

As mentioned, all high-level summaries utilised in the QOA assessment were tabulated (see Appendix 2). To illustrate how these summaries were used to identify Prioritised Options, one of the high-level summaries, *viz.* “Novel charging materials to BF”, with key elements of the QOA matrix approach, is shown in Table 6. First, the “Novel charging materials to BF” SCU pathway, which is comprised of three materials (“Carbon containing agglomerates”, “Pre-reduced agglomerates” and “Ferro-coke”), is assessed against 4 Technical Decision Criteria. Second, an overall SWOT analysis, which was based predominantly on the Information Review, assists in determining whether the SCU pathway could a) benefit PKSW (e.g. lower BF fuel consumption), b) raise issues (e.g. lower BF permeability), c) identify opportunities (e.g. more flexible materials selection) or threats (e.g. limited to BF operations only). It also informs on whether the technology has the capacity to support BlueScope in achieving its climate action target and goal. Finally, the results of the Fatal Flaws analysis provide a concise determination of whether the technology fails to address one or more overarching objective, such as a BlueScope strategic objective.

Focussing on the information relating to “Carbon containing agglomerates”, it shows a TRL of 8 (defined in Table 6). Details provided in the Information Review support this rating, *viz.* this material has been assessed elsewhere at lab-scale and evaluated at pilot scale (e.g. Sweden), but has had limited demonstration trials in a BF (e.g. SSAB Sweden). For PKSW, this material could be evaluated, first at pilot-scale and then potentially demonstrated at PKSW within the short term. However, the relatively low abatement potential (<10%) and potential production impact (Medium) suggest this requires further consideration.

Overall, the assessment of “Novel charge materials for BF” concluded that there were no Fatal Flaws in the short-medium term – not in terms of Investment Cycle (IC) nor Energy Grid decarbonisation plan impact (EG). This is an identified Prioritised Option in the short-to-medium term and as such, if a BF is operating at PKSW in the long term, this means that this SCU technological pathway could also be applied in the long term.

Based on a similar process and reasoning as described above, the team then applied the QOA matrix approach across all other SCU and DCA technological areas, for the short-to-medium- and long-term timeframes. The overall results of the QOA are detailed in Appendix 2 and are discussed and summarised in Section 4.1-4.3, including:

- Table 7 (Blast Furnace Ironmaking, Cokemaking and Sinter)
- Table 8 (Alternate Ironmaking)
- Table 9 (Steelmaking and Carbon Capture, Utilization and Storage)

A “traffic light” system is used in these tables to denote:

- A viable Prioritised Option (“green”)
- A possible Prioritised Option (“orange”).
- A non-viable technology (“red”)

BLAST FURNACE IRONMAKING				
1 Novel charging materials to BF				
Current and Future Technologies	Technology Readiness Level	Anticipated timeline	Relative abatement potential	Potential production impact
	Level 1-9	Short 0-5y Medium 5-10y Long 10-15y	Low <10% Medium 11-49% High > 50%	Low Medium High
Carbon containing agglomerates (CCA)	8	S	L	M
Pre-reduced agglomerates (PRA)	9	S	L	L
Ferro-coke	7	M	L	M
STRENGTHS				
Potential reduction of fuel consumption and CO2 emission Increased productivity by using PRAs Improved hot metal quality using PRAs due to lower coke usage Utilization of low-grade iron ores, various carbon materials and some steelplant wastes Possible lowering of the thermal reserve zone temperature by using CCAs and ferro-coke Improved reaction kinetics by using CCAs and ferro-coke				
WEAKNESSES				
Decreased gas utilization by using PRAs Possible deteriorated BF permeability Operating facilities required for pre-treatment of charging materials Requirement of sufficient strength of these agglomerates Supply chain issues, difficult to continue supply Premium \$ is variable Future situation might change over time Higher overall costs for these materials - need to understand the capex/opex Supply chain issues (continuous materials supply) where materials are not produced on steel plant Cost variability / premium makes it hard to utilise these materials commercially throughout the life of the BF				
OPPORTUNITIES				
A future deC situation might change the economics of using these materials Provide flexibility in materials selection				
THREATS				
CCA and Ferro-coke are likely to be limited to use in the BF, hence for PKSW, limited to short to medium term. Scope 3 emissions to be included in future site emissions accounting.				
FATAL FLAWS				
IC - Investment cycle EG - Energy Grid deC GP - Government policy				
CCA and Ferro-coke are materials designed to promote BF reduction efficiency (decrease fuel consumption) via improved contact between carbon and iron ore.				

In the short to medium term, no fatal flaw with producing/using these types of materials, as potential fit exists with IC and is unrelated to EG.

For the long-term, novel charging materials to the blast furnace have an IC fatal flaw related to the uncertain long-term future of blast furnace technology.

Table 6 Example of Qualitative Options Analysis matrix for “Novel charging materials to BF”

4.1 [Blast Furnace Ironmaking, Cokemaking and Sintering](#)

Table 7 shows results of the QOA for “Blast Furnace Ironmaking, Cokemaking and Sintering”, building on a PKSW Base Case. Both short-to-medium and long-term timeframes are shown.

Note: Fatal Flaws abbreviations used in the assessment for PKSW are:

IC: Proposed plant investment cycles within BlueScope

EG: Proposed energy grid decarbonisation plans in NSW

GP: Possible changes in government policy

Prioritised Options in the short-to-medium term are predominantly SCU pathways, apart from renewable hydrogen injection (DCA) into the BF:

<ul style="list-style-type: none"> Novel charging materials to BF Biomass application in ironmaking 	<ul style="list-style-type: none"> All novel carbon-iron ore materials Partial replacement of fossil fuels used in sintering (e.g. coke breeze), cokemaking (e.g. coal) and BF (e.g. pulverised coal; charged coke). Pre-reduced agglomerates and bio-composites are opportunities.
<ul style="list-style-type: none"> Hydrogen-enriched injection 	<ul style="list-style-type: none"> Injectants include natural gas, coke ovens gas, hot reducing gas, biogas and hydrogen
<ul style="list-style-type: none"> Sintering 	<ul style="list-style-type: none"> Waste heat recovery from cooler and waste gas recycling, and Super-SINTER technology.

Technologies ruled out in the short-to-medium term are listed below, together with the rationale for their non-viability:

<ul style="list-style-type: none"> Dry slag granulation (DSG) 	<ul style="list-style-type: none"> Fatal Flaw relates to the IC, as DSG technology is economically not competitive, nor commercialised at present.
<ul style="list-style-type: none"> Top Gas Recycling with High Oxygen BF (TGR-OBF) 	<ul style="list-style-type: none"> TGR-OBF is low TRL. Fatal Flaw relates to IC, given the design for a new BF is fixed well before a reline and retrofitting of new designed shaft staves/etc will not be possible given the impact on production.
<ul style="list-style-type: none"> Hydrogen-enriched injection (waste plastics) 	<ul style="list-style-type: none"> Fatal Flaw relates to GP - Australian government does not consider waste plastics as a renewable.
<ul style="list-style-type: none"> Cokemaking: Coal moisture control, Coke dry quenching, Coal stamp charging, Single chamber system 	<ul style="list-style-type: none"> All technologies have relatively low abatement potential, including Single chamber ovens with low TRL. Fatal Flaw for

	other current technologies relates to IC and the significant capital required.
<ul style="list-style-type: none"> Sintering: Low temperature sintering and Microwave assisted ignition for iron ore sintering 	<ul style="list-style-type: none"> These technologies have low TRL; hence, Fatal Flaw relates to IC.

Prioritised Options in the long term:

Breakthrough iron and steelmaking technologies will be required to meet long term, net zero goals. Adoption of high efficiency BF technology together with CCUS is considered a potential option for the future. This option will involve building on international efforts to optimise blast furnace efficiency and build in optionality to utilise future emissions reducing technologies, as and when they become commercially and technically viable.

The No. 6 BF reline and upgrade will provide a bridge to future breakthrough technologies, where identified short to medium term prioritised options may assist with the decarbonisation pathway.

For the purpose of this project, BlueScope does not intend to further investigate blast furnace ironmaking technology options, other than those selected as prioritised options in the short to medium term.

		CURRENT AND FUTURE TECHNOLOGIES	SHORT-MEDIUM TERM	LONG TERM
Blast Furnace Ironmaking				
1	SCU	Novel charging materials to BF		
		• Carbon containing agglomerates (CCA)		
		• Pre-reduced agglomerates (PRA)		
		• Ferro-coke		
2	SCU	Dry slag granulation		
		• Rotating cup/disc		
		• Air blasting		
		• Rotating drum		
		• Steel spheres in slag		
3	SCU	Biomass application in ironmaking		
		• Biochar in sintering		
		• Biochar in cokemaking		
		• Biochar in blast furnace ironmaking - bio-injection into tuyeres		
		• Biochar in blast furnace ironmaking - biomass-based top charging		
		• Biochar in blast furnace ironmaking - pre-reduced agglomerates		
		• Biochar in blast furnace ironmaking - bio-composites		
4	SCU	Top Gas Recycling with High Oxygen BF		
5	SCU	Hydrogen-enriched injection		
		• Natural gas		
		• Coke ovens gas		
		• Hot reducing gas		
		• Waste plastic		
	• Biogas (associated with biomass pyrolysis "biomass syngas")			
	DCA	• Hydrogen		
Cokemaking				
6	SCU	Coal moisture control		
		Coke dry quenching (CDQ)		
		Coal stamp charging		
		Advanced control of heating walls		
		Single chamber system		
Sintering				
7	SCU	Waste heat recovery from cooler and waste gas recycling		
		Low temperature sintering		
		Microwave assisted ignition for iron ore sintering		
		Super-SINTER technology (SST)		

Table 7 - QOA Summary for all SCU and DCA technologies assessed for Blast Furnace Ironmaking, Cokemaking and Sintering

Alternate Ironmaking

Alternative ironmaking includes technologies which could replace blast furnace technology.

Natural gas-based DRI, which is already technically proven and commercially viable where low-cost natural gas is available (unfortunately, not on the east coast of Australia), could serve as a transition path to hydrogen based DRI. Given that the most abundant ore bodies (currently used in blast furnaces - hematite) are not well suited to DRI, an intermediate refining stage after DRI such as a melter could be required.

Hydrogen-based DRI (currently at a low TRL level) produced from green hydrogen could potentially be coupled with either a Melter-Basic BOF configuration or EAF technology, once the technology is technically and commercially viable. Adoption of this technology will depend on a secure, low-cost supply of hydrogen, and substantial grid-scale renewable energy infrastructure development to support the hydrogen supply. It will also depend on long-term access to appropriate quality commercial raw materials.

Table 8 shows results of the QOA for “Alternate Ironmaking”. Some of these processes provide the opportunity for increasing use of renewable hydrogen at PKSW, e.g. in fluidised bed direct reduction. Both short-to-medium and long-term timeframes are shown.

Technologies ruled out in the short-to-medium term: The project includes an assumption for the short-to-medium term (~5–15 years) timeframe that No.6 Blast Furnace will be relined (currently planned for 2026) and thus would fulfil PKSW’s ironmaking requirements during this period. Although the final investment decision is yet to be made, all other available technologies have been assessed and rejected as part of the planning process. Refer BlueScope’s 2021 Climate Action Report [5]. A consequence of this for the short-to-medium term timeframe is that alternate ironmaking technologies have an IC (investment cycle) Fatal Flaw.

Prioritised Options in the long term are listed below, together with the rationale for their inclusion:

• Electrolysis of iron ore	• Potential long term low emissions ironmaking technology. Current low TRL.
• Fluidised bed direct reduction	• All technologies, including increasing use of supplementary hydrogen
• Shaft furnace direct reduction	• All technologies, including potentially H2 Direct Reduction
• Smelting Reduction (SR)	• Commercialised technologies, COREX / COREX-MXCOL and FINEX

Technologies ruled out in the long-term are listed below, together with the rationale for their non-viability:

<ul style="list-style-type: none"> Rotary kiln furnace direct reduction 	<ul style="list-style-type: none"> Overall, the rotary kiln Fatal Flaw relates to not meeting IC and GP objectives, given insufficient production capacity and high energy consumption.
<ul style="list-style-type: none"> Rotary hearth furnace direct reduction 	<ul style="list-style-type: none"> For Rotary Hearth Furnace processes, the Fatal Flaw relates to not meeting IC and GP objectives, with low production capacities and higher energy consumptions. For Paired Straight Hearth Furnace, the Fatal Flaw relates to IC due to the maturity of the technology and the lack of a development pathway.

		CURRENT AND FUTURE TECHNOLOGIES	SHORT-MEDIUM TERM	LONG TERM
Alternate Ironmaking				
8	DCA	Electrolysis of iron ore		
9	SCU	Rotary kiln furnace direct reduction		
10	SCU	Rotary hearth furnace direct reduction		
		• Fastmet/Fastmelt		
		• Redsmelt		
		• ITmk3		
		• Paired straight hearth furnace		
11	SCU/ DCA	Fluidized bed direct reduction		
		• Finmet/Finored		
		• Finex		
		• Circored		
	SCU	• Circofer (coal-based)		
12	SCU/ DCA	Shaft furnace direct reduction		
		• Midrex		
		• HYL/ENERGIRON		
		• PERED		
		• COREX - shaft furnace		
		• H2 Direct Reduction		
13	SCU	Smelting Reduction (SR)		
		• COREX / COREX-MXCOL		
		• FINEX		
		• Cyclone Converter Furnace		
		• HIs melt / HIsarna		
		• TecnoRed		
		• Dios		
		• Romelt		
		• AusIron		
		• Flash ironmaking		
		• OxyCup		
• Ironarc				

Table 8 - QOA Summary for all SCU and DCA Technologies Assessed for Alternate Ironmaking

4.2 Steelmaking and Carbon Capture, Utilization and Storage

Table 9 shows results of the QOA for “Steelmaking” and “Carbon Capture, Utilization and Storage”.

The “Steelmaking” processes/routes provide the opportunity for increasing use of renewable hydrogen in a future direct reduction plant at PKSW. Both short-to-medium- and long-term timeframes are shown.

Prioritised Options in the short-to-medium term for the Steelmaking technologies include both SCU and DCA pathways:

<ul style="list-style-type: none"> • DRI and scrap utilisation in Basic Oxygen Furnace 	<ul style="list-style-type: none"> • DRI in the BF-BOF routes include HBI-BOF and DRI-BF-BOF, with increasing opportunities for hydrogen use in reduction and higher levels of scrap. [In contrast, the SAF has only been commercialised at small scale, but offers opportunity to utilise low-grade iron ores. In the future, CONPRO offers operational flexibility.] • If imported DRI products are available and produced with a significantly lower carbon footprint, there are no Fatal Flaws associated with HBI-BOF nor DRI-BF-BOF routes. Without these imported, low carbon materials, Fatal Flaws relate to IC (significant capital for additional DR plant) and EG (low level of local grid deC).
<ul style="list-style-type: none"> • Carbon Capture, Utilization and Storage 	<ul style="list-style-type: none"> • CCUS could play several roles, depending on the long-term technology selected, and the level and location of CO₂ emissions. • It is included as a potential option in the short-to-medium term, however, there are several barriers to overcome for it to be viable.

Technologies ruled out in the short-to-medium term for the Steelmaking technologies are listed below, together with the rationale for their non-viability:

<ul style="list-style-type: none"> • DRI and scrap utilisation in electric arc furnace 	<ul style="list-style-type: none"> • Even with the availability of imported DRI products produced with a lower carbon footprint, Fatal Flaw relates to IC (significant capex for a new EAF plant whilst retaining the current PKSW plant configuration in place). High unit cost of gas/electricity and capex for infrastructure may be significant issues. • Fatal Flaw with SAF route relates to IC since large scale system not yet proven.
<ul style="list-style-type: none"> • Hydrogen plasma direct steel production 	<ul style="list-style-type: none"> • TRL for this technology is low. Hence, Fatal Flaw relates to IC.

Prioritised Options in the long term for the Steelmaking technologies are listed below, together with the rationale for their non-viability:

<ul style="list-style-type: none"> • DRI and scrap utilisation in Basic Oxygen Furnace 	<ul style="list-style-type: none"> • This assumes the BOF technology is retained for the long-term and there is a source of molten iron on site for the BOF to operate. The source of molten iron could be via either BF or DRI plant (with a SAF, or similar before the BOF). • CONPRO combines the technological advantages of BOF and EAF technologies, offering operational flexibility.
<ul style="list-style-type: none"> • DRI and scrap utilisation in electric arc furnace 	<ul style="list-style-type: none"> • EAF steelmaking enables both on and off-site iron production.
<ul style="list-style-type: none"> • Carbon Capture, Utilization and Storage 	<ul style="list-style-type: none"> • CCUS could play several roles, depending on the long-term technology selected and the level and location of CO₂ emissions.

Note that Hydrogen plasma direct steel production has not been included in the long term as the TRL is still too low to be considered for the project, while the technology continues to be developed.

It should also be noted that the majority of the “Carbon Capture, Utilization and Storage” applications for steel manufacturing relate to ironmaking processes and the capturing of gases with higher CO₂ concentrations, such as BF and DR gas (dependant on the reducing gas used). Most applications will involve Carbon Capture and Utilization (CCU) and currently, are low-medium TRL. Therefore:

- In the short-to-medium term, a limited number of potential applications involving biological treatment of off gases may be advanced e.g. STEELANOL. These developments involve relatively low gas volumetric rates, so the efficient capture of CO₂ from dusty, very large volumetric rates of off gas remains a critical step. Due to the medium TRL of many of the proposed CCU technologies, the assessment for PKSW indicates a potential Fatal Flaw relating to IC. There are significant uncertainties relating to plant reconfigurations and associated costs, particularly around CO₂ capture equipment, logistical challenge of CO₂, transport, given lack of geological storage close to PKSW and whether CCU is undertaken.
- In the long term, CCU technologies will likely be commercialised and adopted, regardless of processing route followed. As a minimum, even if the use of fossil carbonaceous fuels such as coal and NG can be eliminated, carbonate minerals such as limestone and dolomite will most likely still be required for fluxing during smelting, and CO₂ is released from these minerals when they are calcined prior to use. However, high capital and potentially high operating expenditures will remain significant issues in assessing these for PKSW.

		CURRENT AND FUTURE TECHNOLOGIES	SHORT-MEDIUM TERM	LONG TERM
Steelmaking				
14	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)		
15	SCU/ DCA	DRI and scrap utilisation in electric arc furnace		
		• DRI-EAF		
		• DRI-SAF		
16	DCA	Hydrogen plasma direct steel production		
		• SuSteel project		
		• Hybrid hydrogen-based reduction of iron ore		
Carbon Capture, Utilization and Storage				
17	SCU	• ULCOS TGR-BF project (Adsorption [VSPA]+cryogenics)		
		• Emirates Steel Industries (Absorption MEA amine)		
		Biological		
		• BlueScope New Zealand		
		• Baosteel		
		• Shougang Steel Group		
		• STEELANOL (ArcelorMittal)		
• Carbon2Value (EU)				
Chemical				
• "Carbon2Chem" project (TKS)				
Absorption				
• COURSE50 (Japan) – Option 1				
• POSCO CO2 breakthrough framework				
• VALORCO project (France)				
• Everest (Tata Steel)				
• Project3D (ArcelorMittal)				
Adsorption				
• COURSE50 (Japan) – Option 2				
• STEPWISE (SEWGS)				
• C4U project (ArcelorMittal, etc)				
• FReSMe (H2020 EU) (Belgium)				
• Carbon4PUR (ArcelorMittal)				
Mineral carbonation				
• Slag2PCC (Finland)				
• MCI (Australia)				

Table 9 - QOA Summary for all SCU and DCA technologies assessed for Steelmaking and Carbon Capture, Utilization and Storage

4.3 [Summary](#)

Table 10 sets out the “Prioritised Options” identified as opportunities for further assessment at PKSW, for both the short-to-medium- and long-term timeframes. These were determined using a QOA which addressed the technical feasibility of 17 SCU and DCA technological areas (as summarised in Sections 4.1-4.3) and using Technical Decision Criteria specific to PKSW.

Table 10 – Selected Prioritised Options for further assessment

		CURRENT AND FUTURE TECHNOLOGIES	SHORT-MEDIUM TERM	LONG TERM
Blast Furnace Ironmaking				
1	SCU	Novel charging materials to BF		
		• Carbon containing agglomerates (CCA)		
		• Pre-reduced agglomerates (PRA)		
		• Ferro-coke		
3	SCU	Biomass application in ironmaking		
		• Biochar - Multiple applications		
5	SCU	Hydrogen-enriched injection		
		• Natural gas		
		• Coke ovens gas		
		• Hot reducing gas		
		• Biogas (biomass pyrolysis - syngas")		
	DCA	• Hydrogen		
Sintering				
7	SCU	Waste heat recovery from cooler and waste gas recycling		
		Super-SINTER technology (SST)		
Alternate Ironmaking				
8	DCA	Electrolysis of iron ore		
11	SCU/ DCA	Fluidized bed direct reduction		
		• Multiple equipment options		
12	SCU/ DCA	Shaft furnace direct reduction		
		• Multiple equipment options		
13	SCU	Smelting Reduction (SR)		
		• Multiple equipment options		
Steelmaking				
14	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)		
15	SCU/ DCA	DRI and scrap utilisation in electric arc furnace		
		• DRI-EAF or DRI-SAF		
Carbon Capture, Utilization and Storage				
17	SCU	Biological		
		Chemical		
		Absorption		
		Adsorption		
		Mineral carbonation		

5 Conclusions and recommendations

An initial investigation of current low emissions and future emerging decarbonisation technologies was undertaken to identify a set of prioritised options (Prioritised Options) for further assessment at BlueScope's Port Kembla Steel Works (PKSW). PKSW is a traditional integrated steelmaking facility using the blast furnace ironmaking (BF)-basic oxygen furnace (BOF) route.

With ARENA's support, Bluescope is investigating the technical and economic feasibility of renewable energy and decarbonisation technology pathways that have the potential to decarbonise the steelmaking process at PKSW. The first phase of the project involves the assessment of potential Smart Carbon Usage (SCU) and Direct Carbon Avoidance (DCA) technological pathways of relevance to PKSW. A Qualitative Options Analysis (QOA) and PKSW-specific technical Decision Criteria were used. This assessment was qualitative in nature, given that specific quantitative data for many of the technologies was limited or not available. The QOA considered the impact of each technological pathway on BlueScope's carbon emission intensity reduction target and goal:

- Short-to-medium term target of 12% GHG emissions intensity reduction by 2030 against a FY2018 baseline for tonnes CO₂-e per tonne of crude steel (Scope 1 and Scope 2); and
- Long-term goal of net zero GHG emissions by 2050.

The QOA and identification of Prioritised Options was undertaken considering both short-to-medium (5-15 years ahead) or long term (greater than 15 years ahead) timeframes. A total of 17 current and future emerging SCU and DCA technological areas were systematically evaluated for the PKSW steel manufacturing chain:

- Blast Furnace Ironmaking / Cokemaking / Sintering (Table 7)
 - e.g. novel materials, biomass and hydrogen-enriched gas injection
- Alternate Ironmaking (Table 8)
 - e.g. direct reduction (DR) and smelting-reduction processes
- Steelmaking / Carbon Capture, Utilization and Storage (Table 9)
 - e.g. electric arc furnace (EAF) and submerged arc furnace (SAF) steelmaking

For each of the 17 technological areas, a detailed description was compiled using 7 categories (Information Review): general process description, material inputs and outputs, overall abatement pathway, key performance indicators, maturity and requirements to implement, and potential strengths and weaknesses (see Information Reviews in Appendix 3). Based on these reviews, high-level summaries of all technologies (see Appendix 2) were assembled in a QOA matrix format, together with 4 PKSW-specific Technical Decision Criteria. A SWOT analysis was also utilised. Potential non-viable technologies for PKSW were screened using a "Fatal Flaws" approach. A technology was eliminated based on an inability to achieve at least one of three major aspects: BlueScope's high-level business plans (e.g. major capital investments), the energy sector's future plans (e.g. renewable energy) and/or government policy changes.

Table 10 in section 4.3 provides a summary of Prioritised Options for further assessment.

In the short-to-medium term, the Prioritised Options are predominantly applications of SCU technological pathways, including novel charging materials for the BF, various biomass applications, hydrogen-enriched injection into the BF, waste heat recovery and waste gas recycling for the sintering plant, and DRI and increased scrap utilisation in the BOF. These SCU pathways align with BlueScope's public announcement that it is undertaking a feasibility study to reline and upgrade a blast furnace (No.6 Blast Furnace) at PKSW. The reline and upgrade plan is based on inadequate supplies of prime scrap in Australia to enable secondary steelmaking (via Electric Arc Furnace (EAF) production), the relatively high cost of natural gas rendering DRI economically unviable at this time and accepted industry estimates that breakthrough 'green' steel technology to replace the BF-BOF process is likely to be more than a decade from commercialisation. Importantly, the reline and upgrade will build a bridge to future adoption of breakthrough lower emissions iron and steelmaking, once these technologies are technically and commercially viable.

In the long-term, fundamental changes to current BF iron and steelmaking technologies will be required to meet net zero goals. In acknowledgement of this transition, Prioritised Options are predominantly applications of DCA technological pathways, including electrolysis of iron ore and alternate ironmaking technologies combined with aligned steelmaking processes.

The next phase of the Project involves further evaluation of the Prioritised Options identified. This includes undertaking PKSW-site mass and energy balances, understanding the operational, engineering, environmental and safety aspects of these options, undertaking a general cost competitiveness comparison and understanding the commercial viability of the technologies relative to a baseline PKSW operation.

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7 Appendix 1:

7.1 [Proposed Qualitative Options Analysis Matrix Approach](#)

Background

A “Qualitative Options Analysis” (QOA) was proposed as a framework for a systematic review, assessment, and evaluation of possible alternative Smart Carbon Usage (SCU) and Direct Carbon Avoidance (DCA) technologies that are/will be available for BlueScope’s Port Kembla Steelworks (PKSW) in achieving its specific carbon emission intensity objectives and determining which of the options - Prioritized Options – are the most effective and provide the best solution to achieve those objectives.

The QOA was intended to explore all feasible technology alternatives - conventional technologies, breakthrough technologies - and provide evidence supporting that the proposed Prioritized Options can be implemented and are the best options available among all feasible alternatives.

General Methodology and Tasks

The initial step involved completing an Information Review of potential SCU and DCA technologies for PKSW. The Information Review entailed a qualitative analysis and critique of recently published literature and other available information. This step anticipated that quantitative information for many of the SCU and DCA technologies was not available.

This high-level information was then to be assembled in an QOA matrix of viable technologies for PKSW. The matrix included a set of agreed Decision Criteria developed and was applied systematically to evaluate each viable option.

The QOA included an analysis of the fit of each technology in supporting the potential technological pathways for GHG emissions reduction at PKSW. For each option, key gaps and potential challenges were systematically identified and set out across various aspects, including technological, engineering, environmental, safety, process risks, logistics and economic.

Based on the QOA, a subset of viable technologies was evaluated in more detail in the next stages, examining the fit with current or potential future manufacturing operations.

Qualitative Options Analysis aspects included:

- 1) Business Objectives
- 2) General Methodology for QOA

Business Objectives – Carbon Emissions Reduction

For the QOA, BlueScope’s short-to-medium- and long-term objectives for carbon emissions reductions are relevant.

Long term:

Pursue net zero GHG emissions by 2050 across its business, covering operational Scope 1 and Scope 2 GHG emissions, and contingent on five key enablers:

- Evolution of emerging and breakthrough technologies to viable, commercial scale;
- Access to affordable and reliable renewable energy;
- Availability of appropriate volumes of competitively priced hydrogen from renewable sources;
- Access to appropriate quality and quantity of raw materials both ahead of and beyond the transition; and
- Public policy that supports investment in decarbonisation and avoids risk of carbon leakage.

Short-to-medium term:

Achieve a Scope 1 and 2 GHG emissions intensity reduction target of 12% by 2030 against a FY2018 baseline, measured as tonnes CO₂-e per tonne of raw steel produced from its steelmaking operations.

More SPECIFIC OBJECTIVES to consider

- *Achieve goals by reducing reliance on non-renewable energy resources, increasing renewable generating capacity, and reducing the environmental footprint.*
- *Minimize life-cycle costs of energy compared to historic costs.*
- *Rely on the implementation of commercially available technologies to ensure the objectives are not compromised.*
- *In order for the project to be viable, it is necessary to evaluate options based on their cost effectiveness over a 25-year horizon. The net present value of capital and operating costs and the economic benefits generated are estimated to evaluate options.*
- *Align short-to-medium term objective so as to support the vision for the long-term target.*

General Methodology for QOA

The original approach proposed for the QOA was as follows:

1. Initially, a Base Case option outlining PKSW's manufacturing plants and operational conditions was set up as a benchmark for all the other potential SCU and DCA options considered. This established the baseline conditions for PKSW and amongst other things, included historical GHG emissions and energy consumption data.
2. Compiled key up-to-date qualitative (and where available, quantitative) information on SCU and DCA technologies as potential options for PKSW, providing:
 - a. Brief general process description
 - b. Material inputs and outputs
 - c. Overall abatement pathway
 - d. Key performance indicators
 - e. Maturity and requirements to implement
 - f. Potential strengths and weaknesses (part of SWOT)
 - g. Additional relevant descriptors comments.
3. Assessed this information against PKSW specific site conditions and undertook a first-pass comparison or screening of each technology, using tools such as SWOT or Fatal Flaws analyses, to rule out non-viable technologies.
4. For the remaining technologies, tabulated the information in terms of Short-to-Mid term and Long term options based on agreed Decision Criteria (see example below), including:
 - a. Technology Readiness Level (Level 1-9)
 - b. Anticipated timeline and availability, including in scope or retrofit
 - c. Production impact and key performance indicators
 - d. Abatement potential
 - e. Estimated capital and operational costs
5. For each Prioritized Option identified, described in more detail key gaps and potential challenges, covering various aspects: Technological, engineering, environmental, safety, process risks, logistics, energy resources and economics.
6. Summarized and assembled all Prioritized Options for further evaluation (Phase 1.1.2).

Example: Short-to-Medium Term Objective

Decision Criterion	Prioritized Option A	Prioritized Option B	Prioritized Option C	Prioritized Option D	Prioritized Option E	Prioritized Option F
Criterion 1						
Criterion 2						
Criterion 3						
Criterion 4						
Criterion 5						
Criterion 6						
Criterion 7						

8 Appendix 2:

8.1 High Level Summaries of 17 Technological Areas

BLAST FURNACE IRONMAKING				
1 Novel charging materials to BF				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Carbon containing agglomerates (CCA)	8	S	L	M
Pre-reduced agglomerates (PRA)	9	S	L	L
Ferro-coke	7	M	L	M
STRENGTHS				
Potential reduction of fuel consumption and CO2 emission Increased productivity by using PRAs Improved hot metal quality using PRAs due to lower coke usage Utilization of low-grade iron ores, various carbon materials and some steelplant wastes Possible lowering of the thermal reserve zone temperature by using CCAs and ferro-coke Improved reaction kinetics by using CCAs and ferro-coke				
WEAKNESSES				
Decreased gas utilization by using PRAs Possible deteriorated BF permeability Operating facilities required for pre-treatment of charging materials Requirement of sufficient strength of these agglomerates Supply chain issues, difficult to continue supply Premium \$ is variable Future situation might change over time Higher overall costs for these materials - need to understand the capex/opex Supply chain issues (continuous materials supply) where materials are not produced on steel plant				
OPPORTUNITIES				
A future deC situation might change the economics of using these materials Provide flexibility in materials selection				
THREATS				
CCA and Ferro-coke are likely to be limited to use in the BF, hence for PKSW, limited to short to medium term				
FATAL FLAWS				
IC - Investment cycle EG - Energy Grid deC GP - Government policy				

CCA and Ferro-coke are materials designed to promote BF reduction efficiency (decrease fuel consumption) via improved contact between carbon and iron ore.

In the short to medium term, no fatal flaw with producing/using these types of materials, as potential fit exists with IC and is unrelated to EG.

BLAST FURNACE IRONMAKING				
2 Dry slag granulation (DSG)				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Rotating cup/disc	7	M	L	L
Air blasting	8	M	L	L
Rotating drum	6	M	L	L
Steel spheres in slag	5	M	L	L
STRENGTHS				
Product quality with excellent cementitious properties Less complex system design, low water consumption, lower steam explosion potential and pollution potential Recovery of thermal energy				
WEAKNESSES				
Scalability, cost, low energy recovery efficiencies and difficulties in energy utilization. Durability of spinning cup, production of slag wool, and handling of hot granules collected Reliability of operation and process control.				
OPPORTUNITIES				
Cement industry integration aspect Small amount of electricity generation potential				
THREATS				
Could make wet slag granulation redundant				
FATAL FLAWS				
IC - Investment cycle EG - Energy Grid deC GP - Government policy				
DSG or similar involve the recovery of molten slag sensible heat. In the short to medium term, the fatal flaw relates to the IC, as DSG technology is not economically competitive, nor commercialised at present and as a result has not been included in the scope for No.6 Blast Furnace Reline.				

BLAST FURNACE IRONMAKING				
3 Biomass application in ironmaking				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Use of biochar in sintering	4-5	M	L	L
Use of biochar in cokemaking	4	M	L	L
BF ironmaking - Bio-injection into tuyeres	7 (global) 9 (Brazil)	M	M	L
BF ironmaking - Biomass-based top charging	4 (global) 9 (Brazil)	M	L	M
BF ironmaking - Pre-reduced agglomerates	9	S	M?	L
BF ironmaking - Bio-composites	8	S	M?	M
STRENGTHS				
<p>In general, the following strengths are in comparison with utilization of conventional fuels and reductants in ironmaking processes:</p> <p>Carbon neutrality (potential reduction of CO₂ emission by 0.69–1.21 t/t-steel) Low ash and sulphur content Potential low alkalis and impurities depending on biomass source Controlled VM using different pre-processing methods Carbon will still be required as a steelmaking alloying element – biomass carbon from sustainable sources could continue to be used in a carbon-constrained economy Processing of biomass has the potential to yield other beneficial products e.g. liquid pyrolysis oils which could be processed into sustainable transport fuels, wood vinegar and syngas</p> <p>Specific areas: Sintering: Lower SO₂ and NO_x emission BF ironmaking (bio-injection): Higher combustion efficiency, given high specific surface area BF ironmaking (lump charcoal): Improved reduction efficiency due to high reactivity BF ironmaking (bio-composite): Improved reduction efficiency due to high reactivity Microwave-based direct reduced iron using biomass: Direct utilization of biomass and close contact between iron ore fine and carbonaceous materials</p>				
WEAKNESSES				

The following weaknesses are in comparison with utilization of conventional fuels and reductants in ironmaking processes:

- Extra cost for pre-processing of biomass materials
- Potential issues with sustainable and consistent biomass supply
- Competition for land use between biomass and food production
- Environmental effects of biomass production such as soil disturbance and nutrient depletion
- Low density of biomass materials
- High moisture absorption of biomass product
- Easy contamination of biomass materials
- Higher price of biomass products than fossil fuels
- Transportation and handling

Specific areas:

Sintering

- Higher moisture requirement for granulation
- Lower mechanical strength of charcoal
- Potential low production due to low density of charcoal

Cokemaking

- Potential deteriorated CSR

BF ironmaking - bio-injection

- A broad size range of charcoal if no proper sieving
- Increased oxygen enrichment
- Potential limited injection rate due to porous nature and low density of charcoal

BF ironmaking - lump charcoal/bio-composite

- Potential insufficient strength
- Potential lower productivity due to low density of biomaterials

BF ironmaking - lump charcoal/bio-composite

- Potential insufficient strength
- Potential lower productivity due to low density of biomaterials

OPPORTUNITIES

Opportunity for new industry e.g. removal and utilisation of forest waste residues
 These materials have a life beyond BF cycle
 Pyrolysis conditions may be adjusted for reducing gases
 Implement in the circular economy, including around building and constructure materials

THREATS

Perception issue related to native tree felling and potential habitat loss
 Changes in government policy, particularly in relation to carbon accounting
 Ability to provide coke breeze

FATAL FLAWS

IC - Investment cycle | EG - Energy Grid deC | GP - Government policy

The potential for utilisation of renewable biomass across the steel manufacturing processes has been evaluated and/or demonstrated.

In the short to medium term, no fatal flaw as potential fit exists with IC and is unrelated to EG. Investigations in the short term will likely assist with potential use in alternate ironmaking technologies in the future.

BLAST FURNACE IRONMAKING				
4 Top gas recycling and high oxygen blast furnace (TGR-OBF)				
Current and Future Technologies	Technology Readiness Level	Anticipated timeline	Relative abatement potential	Potential production impact
	Level 1-9	Short 0-5y Medium 5-10y Long 10-15y	Low <10% Medium 11-49% High > 50%	Low Medium High
TGR-OBF	6	M	M	M
STRENGTHS				
<p>High reducing gas concentration suppresses direct reduction, the gaseous reduction rate is high and the coke consumption can be reduced</p> <p>Furnace height can be shortened due to possibly reduced reserve zone temperature, higher reduction potential of BF gas and heating-up of the burden in the shaft by preheating gas injection</p> <p>Low grade iron ore could be used</p> <p>Low strength and high reactivity coke may be used with the shorter furnace height</p> <p>High CO₂ concentration and calorific value in the top gas is beneficial for application of CO₂ sequestration technology</p> <p>A complete utilization of coke carbon chemical energy may be done</p> <p>A higher injection rate of carbonaceous materials may be achieved</p> <p>Conventional burden materials may be used</p> <p>Reduced heat loss</p> <p>Cold oxygen replacing hot air blast may be blown into the tuyeres, without hot stoves</p> <p>Bosh gas flow rate is low with the oxygen injection, and the productivity can be increased</p> <p>For Routes 6 and 7, BFG can be utilized for re-injection to BF without CO₂ removal</p>				
WEAKNESSES				
<p>Costly modification of BF off-gas system for CO₂ capture and storage</p> <p>There are still uncertainties in technological development for TGR implementation</p> <p>Unproved process stability in a scale-up BF</p> <p>Low penetration depth of shaft gas injection, especially in a large BF</p> <p>With high CO concentration in the shaft, carbon deposition may be notable</p> <p>The energy supply to downstream processes decreases as a result of intensified top gas recycling</p> <p>A large amount of pure oxygen is required</p> <p>Penetration depth of raceway decreases</p> <p>Shaft efficiency is not clearly improved</p> <p>Large scale modifications in the existing process may be required</p> <p>For Routes 6 and 7, extra energy required for BFG reforming</p>				
OPPORTUNITIES				
THREATS				
Geological storage of massive amounts of CO ₂				
FATAL FLAWS				
IC - Investment cycle EG - Energy Grid deC GP - Government policy				
TGRBF process is designed to more fully recover CO and H ₂ from top gas and utilise in the BF.				

In the short to medium term, the technology's maturity is too low and therefore, the fatal flaw relates to IC, given the design for a new BF is fixed well before reline and retrofitting of new designed shaft staves/etc will not be possible given the impact on production.

BLAST FURNACE IRONMAKING

5 Injection of auxiliary hydrogen-enriched gases, waste plastics and biogas into the blast furnace

Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Natural gas	9	S	L	L
Coke ovens gas	9	S	L	L
Hot reducing gas	7	M	L	L
Hydrogen	6	M	L	L
Waste plastic	9	S	L	L
Biogas (associated with biomass pyrolysis "biomass syngas")	6-7 (global)	S	L	L

STRENGTHS

Natural gas

- Relatively mature technology
- Relatively low investment cost for supply and negligible pre-treatment
- HM quality improvement
- High quality and clean reducing agent

Coke ovens gas

- Availability and stability
- COG contains more than 50% hydrogen, hence a better reducing agent compared to other hydrogen-enriched gases
- HM quality improvement
- More valuable for COG to be injected to BF compared to other COG applications

Hot reducing gas

- Top gas or other waste gases recycled
- Utilization of low-grade coal and waste
- Utilization of biomass

Hydrogen

- Hydrogen injection has the highest decarbonization potential without fundamental changes in the BF process

- HM quality improvement
 - High heat capacity and diffusivity
- Waste plastics
- An auxiliary reducing agent to replace coke
 - Waste plastic recycling and reuse
 - Reducing production cost
- Biogas
- Alternative utilization of biomass pyrolysis products, without significant capex for implementation

WEAKNESSES

- Natural gas
- Soot generation if NG is poorly mixed with hot blast
 - Highest impact on flame temperature
- Coke ovens gas
- COG requires removal of condensables (tar, naphthalene, etc) and sulphur to avoid deposition in pipework and erosion of copper elements (e.g. tuyere) by hydrogen sulphide
 - COG injection can cause increased peripheral gas flow
 - Limited supply
- Hot reducing gas
- Gas reforming required
 - Additional facilities and equipment required, adding significant complexity
- Hydrogen
- Renewably sourced
 - Additional hydrogen is required to be consumed for providing the energy needed in BF process
 - Theoretically, pure hydrogen injection can cause more peripheral gas flow compared to COG injection
 - Potential tuyere design and pipeline changes required for safe transportation of hydrogen
- Waste plastic
- Australian government does not consider waste plastics a waste by-product
 - Waste plastic materials are highly heterogeneous, consisting of different chemical types, as well as contaminants
 - There are differences in thermal combustion and gasification behavior of the different types of plastics
 - Chlorine sources (PVC) need to be removed from the waste plastics due to corrosive effects
 - Potential permeability issue in BF due to un-burnt char from injected plastic
 - Low in the waste management hierarchy
- Biogas
- Composition dependent on biomass quality
 - Lower hydrogen content
 - For BF operation, maximising biochar amount is optimal

OPPORTUNITIES

- Natural gas
- A potential transitional gas towards a pathway involving H₂

THREATS

FATAL FLAWS
IC - Investment cycle | EG - Energy Grid deC | GP - Government policy

Within operational constraints limiting its consumption usage rate, the use of additional H₂ as a reducing agent in BF ironmaking is an advantage.

In the short to medium term, no major fatal flaw in using these H₂-enriched gases. There is a fatal flaw in using waste plastics, as these materials are not considered a renewable material.

COKEMAKING				
6 Cokemaking				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Coke dry quenching	9	S	L	L
Coke stamp charging	7	S	L	L
Advanced control of heating walls	6	S	L	L
Single chamber system	?	S	L	L
STRENGTHS				
<p>In general:</p> <ul style="list-style-type: none"> • Potentially improved coke quality, increased productivity, and energy saving • Utilization of lower quality coals <p>Coal moisture control</p> <ul style="list-style-type: none"> • Reduced energy consumption • Improved coke quality • Increased coke production • Usage of lower quality coal <p>Coke dry quenching</p> <ul style="list-style-type: none"> • Direct energy saving • Decreased coke moisture • Payback period of 3-5 years <p>Coal stamp charging</p> <ul style="list-style-type: none"> • Increased throughput • Decreased charging related emission <p>Advanced control of heating walls</p> <ul style="list-style-type: none"> • Reduced workload for workers • Precise automation control <p>Single chamber system</p> <ul style="list-style-type: none"> • Stress-bearing wall 				

WEAKNESSES
<p>In general:</p> <ul style="list-style-type: none"> • Additional facilities or further development required • Age of the plant means that retrofit is not viable <p>Coal moisture control</p> <ul style="list-style-type: none"> • Set up of pre-treatment plant <p>Coke dry quenching</p> <ul style="list-style-type: none"> • Long cooling time • In CDQ, real estate is an issue with logistics around charging of batteries and the non-viable utilisation of sensible heat <p>Coal stamp charging</p> <ul style="list-style-type: none"> • Potential influence on chamber wall, including stickers, particularly given the age of PKSW coke ovens batteries. <p>Advanced control of heating walls</p> <ul style="list-style-type: none"> • Continuous development required <p>Single chamber system</p> <ul style="list-style-type: none"> • Not mature
OPPORTUNITIES
<p>Advanced control of heating walls</p> <ul style="list-style-type: none"> • Energy savings with more effective heating of coking coal blend
THREATS
<p style="text-align: center;">FATAL FLAWS</p> <p style="text-align: center;">IC - Investment cycle EG - Energy Grid deC GP - Government policy</p>
<p>New emerging cokemaking technologies such as single chamber ovens, do not offer significant decarbonisation pathways, hence, a fatal flaw.</p> <p>Another fatal flaw relates to IC, due to the significant cost of large plant items, e.g. CDQ, coal drying and coal stamp charging.</p> <p>No fatal flaw, as such, with advanced control of heating walls, however, this would be considered an efficiency gain with very limited GHG emissions potential (<1% PKSW CO2 intensity reduction), thus not considered as a prioritised option. BlueScope continues to look at ways to improve battery heating performance.</p>

SINTERING				
7 Sintering				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Waste heat recovery from cooler	9	S	L	L
Low temperature sintering	2	L	L	?
Microwave assisted ignition for iron ore sintering	4-5	M-L	L	L
Super-SINTER technology (JFE Steel)	9	S	L	L
STRENGTHS				
Waste heat recovery from cooler <ul style="list-style-type: none"> • More heat recovery leading to less CO2 emission Microwave assisted ignition for iron ore sintering <ul style="list-style-type: none"> • Decreased ignition temperature • More oxygen availability for coke breeze combustion Super-SINTER technology (JFE Steel) <ul style="list-style-type: none"> • Lower sintering temperature causing less energy consumption • Long holding time of sintering above 1200 °C improves the sinter quality 				
WEAKNESSES				
Waste heat recovery from cooler <ul style="list-style-type: none"> • Additional facilities required to set up heat recovery system Microwave assisted ignition for iron ore sintering <ul style="list-style-type: none"> • Development at the early stage Super-SINTER technology (JFE Steel) <ul style="list-style-type: none"> • Depending on the availability of hydrocarbon gases 				
OPPORTUNITIES				
Waste heat recovery from cooler <ul style="list-style-type: none"> • Use biogas as an alternative fuel for ignition furnace • Use COG instead of NG for ignition furnace Super-SINTER technology (JFE Steel) <ul style="list-style-type: none"> • Utilisation of hydrogen instead of natural gas 				
THREATS				
FATAL FLAWS				
IC - Investment cycle EG - Energy Grid deC GP - Government policy				
Measure to recover and utilise waste heat from the cooler would contribute to overall energy savings and lower carbon emissions. The Super-SINTER technology refers to the				

use of secondary fuel injection on the sinter strand and is commercialised. Microwave-assisted ignition is a relatively immature technology, providing preheated airflow with higher oxygen content.

No fatal flaw with Super-SINTER, though its economic viability needs to be assessed. At present, the fatal flaw with waste heat recovery is the high cost and viability of the lower grade energy recovered, unless for preheating of materials. The other technologies have fatal flaws in terms of IC.

ALTERNATE IRONMAKING

8 Electrolysis of iron ores

Current and Future Technologies	Technology Readiness Level	Anticipated timeline	Relative abatement potential	Potential production impact
	Level 1-9	Short 0-5y Medium 5-10y Long 10-15y	Low <10% Medium 11-49% High > 50%	Low Medium High
Electrolysis of iron ores	4	S	L	L

STRENGTHS

Compared to the conventional blast furnace ironmaking, electrolysis processes have the following features:

General

- No CO₂ produced during electrolysis process
- Expected energy efficiency and process simplification due to electrification

MOE process

- Potential utilization of low- and mid-grade iron ore

ΣIDERWIN process

- Low temperature operation
- Tolerance of the power shutdown
- Flexibility of production and electricity usage to avoid the peak power usage time

WEAKNESSES

Compared to the conventional blast furnace ironmaking, electrolysis processes have the following features:

General

- Utilization of significantly more electrical energy
- Inert anode required to be developed
- Significant real estate footprint required

MOE process

- Molten electrolytes corrosive to the anode and cell refractory
- A batch process, with a significant land footprint
- Limited mechanistic understanding of high temperature electrolytic processes
- Sensitive to the power shutdown

ΣIDERWIN process

- Requirement of grinding and purification of iron ore at the current stage

<ul style="list-style-type: none"> Limited knowledge for further scale-up in terms of electrochemical mechanisms and integration with up- and down-stream processes
OPPORTUNITIES
THREATS
FATAL FLAWS
IC - Investment cycle EG - Energy Grid deC GP - Government policy
Low and high temperature electrolysis of iron ore processes are relatively low TRL. Hence, the fatal flaw relates to the IC, for the short to medium term.
For the long term, developments will likely continue but it is difficult to predict the level of technical and commercial advancement.

ALTERNATE IRONMAKING				
9 Rotary kiln furnace direct reduction				
Current and Future Technologies	Technology Readiness Level	Anticipated timeline	Relative abatement potential	Potential production impact
	Level 1-9	Short 0-5y Medium 5-10y Long 10-15y	Low <10% Medium 11-49% High > 50%	Low Medium High
Rotary kiln processes	9	S	L (Potential higher carbon consumption and CO ₂ emission)	H
STRENGTHS				
Low investment and operating cost Increased reduction efficiency by mixing coal and iron oxides in the kiln Large freeboard space in the kiln tolerant for the heavily dusted gas Utilization of low quality coal Utilization of a wide range of iron-bearing materials				
WEAKNESSES				
Potential segregation of the charge materials in the kiln, leading to product quality issues Potential formation of accretions on the kiln lining Low energy efficiency and productivity Fragmentation and clustering of charge materials in the kiln affecting the operation efficiency				
OPPORTUNITIES				
Utilization of poorer quality iron ore and non-coking coals				
THREATS				
FATAL FLAWS				
IC - Investment cycle EG - Energy Grid deC GP - Government policy				

The rotary kiln is a coal-based DR process, with relatively high flexibility with types of raw materials that may be used.

Overall, the rotary kiln's fatal flaw relates to not meeting IC and GP objectives, given insufficient production capacity and high energy consumption.

ALTERNATE IRONMAKING

10 Rotary hearth furnace direct reduction

Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Fastmet/Fastmelt	9	S	L	H
Redsmelt	9	S	L	H
ITmk3	9	S	L	H
Primus	7	M	L	H
Paired straight hearth furnace	4	L	L/M	H

STRENGTHS

Relatively simple process for operation and plant setup
 Utilization of low grade materials (ore and coal fines)
 Industrially proven reliability of equipment
 Environment friendly process
 Efficient recycling of steel plant waste containing iron and zinc
 DRI being used in BF, BOF and EAF with less zinc and dioxin
 Low fine generation due to stationary ore fine in most RHF processes
 Potential utilization of biomass and waste charcoal in the process
 Iron nuggets alleviating the demand of steel scrap
 Agglomerates with mixed iron ore and coal fines causing the occurrence of rapid carburization

WEAKNESSES

Low productivity due to limited materials thickness in relation to the heat transfer mainly by radiation
 Significant linkage between the economy of the RHF process and raw materials used
 Potential non-uniform reduction of pellets/briquettes at different layers in multi-layer bed RHF
 Actual production levels have fallen short of nameplate capacities

OPPORTUNITIES

Recycling/processing of steel plant byproducts - a complementary technology for an integrated steel plant
 Close contact between iron ore and coal fines making reduction more efficient
 For an integrated steel plant without a sinter plant processing some plant byproducts, RHF's become a key processing route for these materials

THREATS
FATAL FLAWS IC - Investment cycle EG - Energy Grid deC GP - Government policy
RHFs are DR processes with the flexibility to process different raw materials, including iron and flux containing plant byproduct streams.
For commercialised processes, the fatal flaw relates to not meeting IC and GP objectives, with low production capacities and higher energy consumptions. For the PSHF, fatal flaw relates to IC due to the maturity of the technology and the lack of a development pathway.

ALTERNATE IRONMAKING				
11 Fluidised bed direct reduction				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Finmet/Finored (Fluidised beds)	9	S	M	L
Finex (Fluidised beds)	9	S	L	M
Circored	8	M	H	H
Circofer	7	M	L	H?
Hyfor	6	M	H	H?
STRENGTHS				
Utilization of ore fines Reduction of emissions such as SOx and NOx due to no agglomeration process required e.g. sintering Flexibility in operation and selection of iron ore types Low CO2 emission due to the use of hydrogen-rich reducing gas and/or pure hydrogen If price discount is available compared with metallurgical coals, the use of low grade coals for generating the reducing gas Lower investment and operational cost Direct use of low grade iron ore fines without agglomeration High heat and mass transfer between gas and fines in the fluidization condition Low temperature reduction Using hydrogen as reductant to minimize sticking tendencies Isothermal condition leading to more precise temperature control				
WEAKNESSES				
High operating pressure Potential occurrence of de-fluidization due to sticking Difficulty in controlling gas flow due to heterogeneous fluidization phenomena Significant erosion of reactor due to mechanical attack by ore fines				

Sticking linked to complex thermodynamic and kinetic conditions of ore fines, which determines stability of fluidization and reduction efficiency
 Potential requirement for micro-agglomeration
 Incomplete reduction
 100% of gangue in product
 Limited ability to carburise product. DRI with 0% carbon after reduction by pure hydrogen as the optimum carbon level in DRI is 1.5-3% for EAF steelmaking
 Grinding of ores needs to be carefully controlled for appropriate particle size distribution of iron ore feed. Extra energy required for grinding of ultra-fine ore
 Widespread adoption of DR plants may be limited due to limited raw material supplies of sufficient quality

OPPORTUNITIES

Without need for agglomeration
 Direct utilisation of hydrogen in fluidised beds at higher gas rates is possible in fluidised beds of BF operations
 Better heat and mass transfer between reducing gas and iron fines
 DR could be produced in optimal location and transported

THREATS

Availability of significant levels of renewable hydrogen, via electrolysis

FATAL FLAWS

IC - Investment cycle | EG - Energy Grid deC | GP - Government policy

Fluidised bed DR technologies vary in materials inputs and design, and offer potential alternatives for future ironmaking capabilities, particularly with the use of increasing levels of hydrogen.

In the short to medium term, the fatal flaw for the low TRL Hyfor relates to IC and EG (renewable hydrogen availability), including understanding of fluidisation behaviour with hydrogen. The Circofer process is coal-based, hence the main fatal flaw relates to GP.

Finex fluidised bed DR units have been operated successfully; however, there are a limited number of plants in operation. Similarly, 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 the technical challenges were overcome prior to shutdown of the other. Overall, these three fluidised bed DR processes are promising technologies but there are potential commercialisation risks associated with each; hence a potential fatal flaw relates to IC. Furthermore, fatal flaw for all fluidised bed DR in the short-to-medium term relates to IC and the decision to reline No.6 Blast Furnace at PKSW.

In the long term, with further understanding of practical and operational issues, fluidised bed DR processing may offer some advantages e.g. no agglomeration requirement.

ALTERNATE IRONMAKING				
12 Shaft furnace direct reduction				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Midrex	9	S	M	M
HYL/ENERGIRON	9	S	M	M
PERED	9	S	M	?
COREX - Shaft furnace	-	-	-	-
H2 Direct Reduction	7	M	H	H
STRENGTHS				
<p>Smaller scale DR facility with less construction cost & lower investment requirement relative to BF</p> <p>Less fuel required and CO2 emission relative to BF ironmaking</p> <p>Simpler furnace design and relatively easier operation of a DRI plant relative to BF process</p> <p>Reductant source flexibility in using NG, COG, syngas or H2</p> <p>Higher process flexibility to allow quick response to the customer requirement</p> <p>Substitution of scrap by DRI in BOF or EAF</p> <p>Not necessary to be part of an integrated steel plant</p> <p>Potential viability of 100% H2-DR</p> <p>Production of low carbon steel using H2-DRI</p> <p>Favourable gas volumes relative to BF due to no air dilution</p>				
WEAKNESSES				
<p>DRI susceptible to oxidation, particularly for transportation or long-term material storage</p> <p>All gangue content left in DRI after iron ore reduction</p> <p>Low production capacity</p> <p>High cost for DRI-EAF route for steelmaking</p> <p>DRI with 0% carbon after reduction by pure hydrogen as the optimum carbon level in DRI is 1.5-3% for EAF steelmaking, and potentially similar in a HM smelter</p> <p>Long operation time, >6 hours for MIDREX process</p> <p>Potential operational issue with sticking/plating</p> <p>Pellets and lump ores required with high iron grade and low gangue contents</p> <p>High operating pressure (ENERGIRON)</p> <p>Need to supply process heat through reducing gas – more challenging as H2 content increases</p>				
OPPORTUNITIES				
<p>Production and raw materials flexibility</p> <p>Hydrogen-rich reducing gas for reduction</p>				
THREATS				
<p>Availability of significant levels of renewable hydrogen, via electrolysis</p> <p>Market needs to be able to supply high quality iron ores, which is limited (e.g. ores with higher Fe content)</p>				

FATAL FLAWS**IC - Investment cycle | EG - Energy Grid deC | GP - Government policy**

Most commercial DR plants are shaft-based, providing DR iron as a scrap substitute, particularly for electric arc steelmaking. Most of these are either Midrex or HyL/Energiron units. These processes utilise either natural gas, coke oven gas or syngas. Developments are underway to utilise increasing levels of H₂.

In the short-to-medium term, there is no potential fatal flaw given commercial technologies, although the availability of renewable hydrogen and high-quality iron ore feeds are issues. These issues currently present as potential commercialisation risks in the short to medium term.

In the long term, shaft-based DR processes will continue to be commercialised.

ALTERNATE IRONMAKING				
13 Smelting reduction				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
Corex / Corex-Mxcol	9	S	L-M	M
Finex	9	S	L-M	M
Cyclone Convertor Furnace (CCF)	4-5	M	L	H
Hismelt / Hisarna	9 / 5	S / M	L / L	H / H
Tecnored	7	M ?	L M (biomass)	M
Dios	7	L ?	L	H
Romelt	9	S	L	H
AusIron	7	L	L	M
Flash smelting technology	5	L	M	?
OxyCup	9	S	?	-
Ironarc	5	L	?	?
STRENGTHS				
<p>Compared to the traditional blast furnace ironmaking, the SR processes have the following features:</p> <p>In general</p> <ul style="list-style-type: none"> • Utilization of non-coking coal • More environmentally friendly in terms of off-gas control • Direct usage of iron ore fines in most processes • Low capital requirement for construction • Flexibility in operation and raw material selection • Low operational costs <p>Hismelt / Hisarna</p> <ul style="list-style-type: none"> • High quality of hot metal product in terms of low P, Ti, Mn and Si contents <p>Romelt</p> <ul style="list-style-type: none"> • Acceptance of a broad size of iron ore and coal <p>AusIron</p> <ul style="list-style-type: none"> • Fast reduction of iron ore concentrates • Hot metal with low P and Si contents <p>Flash smelting technology</p> <ul style="list-style-type: none"> • Complete combustion of the fuel gases in the furnace <p>OxyCup</p> <ul style="list-style-type: none"> • Handling various ferrous plant wastes • Less carbon usage and more electrical usage 				
WEAKNESSES				

Compared to the traditional blast furnace ironmaking, the SR processes have the following features:

In general

- Required large amount of oxygen in most processes
- Low production capacity
- Facilities/technologies required for the utilization of export gas
- Higher energy consumption for most processes
- High direct CO₂ emission due to the high fuel ratio

Corex / Corex-Mxcol

- Potential operational issue with sticking/plating

Finex

- Potential occurrence of de-fluidization due to sticking

Dios

- Low pre-reduction degree
- High tapping temperature, 1750-1800C

Romelt

- High energy consumption with high coal and oxygen input rate

Flash smelting technology

- Potential reduction efficiency issue

OxyCup

- Coke required for providing the energy and guaranteeing the bed permeability

Ironarc

- Potential scale-up issue

OPPORTUNITIES

Some SR processes will enable recycling/processing of steel plant byproducts - a complementary technology for an integrated steel plant

Flash smelting technology

- Utilization of H₂ rich gas

Ironarc

- Utilization of H₂ rich gas

THREATS

Development of Hismelt technology was in part based on use of lower quality raw materials (incl higher P ores), which will produce more carbon emissions

FATAL FLAWS

IC - Investment cycle | EG - Energy Grid deC | GP - Government policy

Coupled smelting-reduction processes combine production of DR products with their smelting, and in some cases, eliminating the need for coke or high quality iron ores.

In the short to medium term, there are no major fatal flaws with Corex/Corex-Mxcol technology. However, lower production capacities (against nameplate) experienced by some operations, remains a major issue.

Whilst Finex plants have been operated successfully, the fatal flaw relates to IC as there are presently very limited number of plants in operation.

In the short to medium term, other processes have fatal flaws for main production units in an integrated steel plant: e.g. Hismelt and Romelt have currently limited commercial applications (IC); others such as CCF / Hisarna and Flash smelting have low TRL (IC); others such as AusIron and OxyCup are principally for byproduct conversion.

STEELMAKING				
14 DRI and scrap utilisation in Basic Oxygen Furnace				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
DRI and scrap utilisation in Basic Oxygen Furnace, including scrap preheating	9	S	L	L
DRI utilisation in SAF-Basic Oxygen Furnace	2 / 9 (NZS)	M / S	H	M
CONPRO (SMS)	9	S	H	L
STRENGTHS				
<p>Relative to traditional BF-BOF route, DRI provides alternate sources of hot metal</p> <p>In general:</p> <ul style="list-style-type: none"> • DRI has a lower carbon footprint compared to HM • Potential utilization of DRI produced using low grade iron ore <p>DRI and scrap utilisation in Basic Oxygen Furnace, including scrap preheating</p> <ul style="list-style-type: none"> • Providing the metallic iron input as substitute for scrap • Higher cooling effect compared to scrap • Potentially less slopping occurrence • More controllable steel chemistry <p>DRI utilisation in SAF-Basic Oxygen Furnace</p> <ul style="list-style-type: none"> • Novel process to potentially achieve “Direct Carbon Avoidance” • Opportunity to utilize electrical energy for melting process • More controllable steel chemistry • Permits the use of existing BOF technology and associated equipment, to process Australian iron ores with lower Fe content <p>CONPRO (SMS)</p> <ul style="list-style-type: none"> • Flexibility with charge materials • Operational design combines EAF and BOF aspects, including efficient oxygen injection 				
WEAKNESSES				
<p>Relative to traditional BF-BOF route, DRI provides alternate sources of hot metal</p> <p>In general:</p> <ul style="list-style-type: none"> • Low production capacity of DR process compared to BF • Requires natural gas for the more relatively mature DR processes • Costly mass production of green hydrogen and green electricity Corex / Corex-Mxcol • Potential operational issue with sticking/plating <p>DRI and scrap utilisation in Basic Oxygen Furnace, including scrap preheating</p> <ul style="list-style-type: none"> • Limited input amount of DRI/HBI per heat • A high reduction degree (>91%) of DRI/HBI required to replace scrap 				

<ul style="list-style-type: none"> • Possibly high slag volume <p>DRI utilisation in SAF-Basic Oxygen Furnace</p> <ul style="list-style-type: none"> • Requirement of a smelter • Not economically feasible compared to DRI-EAF route where high grade ore is used CONPRO (SMS) • Integration of additional equipment into brownfield site
<p>OPPORTUNITIES</p>
<p>DRI and scrap utilisation in Basic Oxygen Furnace, including scrap preheating</p> <ul style="list-style-type: none"> • DRI can be produced using hydrocarbon rich gas • Biomass used for carbon source <p>DRI utilisation in SAF-Basic Oxygen Furnace</p> <ul style="list-style-type: none"> • DRI can be produced using hydrocarbon rich gas • Biomass used for carbon source
<p>THREATS</p>
<p>DRI utilisation in SAF-Basic Oxygen Furnace</p> <ul style="list-style-type: none"> • Total energy consumption and overall process efficiency for this route is unknown at large scale but will likely be higher than for DRI-EAF route • Attaining sufficient carbon in the product
<p style="text-align: center;">FATAL FLAWS</p> <p style="text-align: center;">IC - Investment cycle EG - Energy Grid deC GP - Government policy</p>
<p>There are at least 3 options relating to the utilisation of DRI in the traditional BF-BOF route: HBI-BOF, DRI-BF-BOF and DRI-SAF-BOF. Operationally, the first two have been practiced, while the route inclusive of the SAF has not at large scale. The latter offers potential opportunity to utilise lower quality iron ores that are available in Australia.</p> <p>In the short to medium term, if imported DRI products are available and produced with a significantly lower carbon footprint, there are no fatal flaws associated with the HBI-BOF nor DRI-BF-BOF routes. Without these imported, low carbon materials, fatal flaws relate to IC (significant capex with additional DR plant) and EG (low level of local grid deC).</p> <p>In the short to medium term, the SAF route's fatal flaw relates to IC as actual large scale system yet to be proven.</p>

STEELMAKING				
15 DRI and scrap utilisation in electric arc furnace				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
DRI-EAF (NB High DRI practice)	9	S	H (with H2 used)	L
DRI-SAF (NB High DRI practice)	2 / 9 (NZS)	M / S	H (with H2 used)	M
STRENGTHS				
<p>In general:</p> <ul style="list-style-type: none"> Utilization of scrap to reduce the energy consumption and CO2 emission Flexibility to vary the production Off-peak electrical power usage Less investment, quick to construct and fast cost recovery Production of different types of steels Relatively accurate control of temperature and composition of molten steel <p>DRI-EAF (NB High DRI practice)</p> <ul style="list-style-type: none"> Low content of impurity elements Controlled and consistent size of feed materials Enhanced quality of steel product With H2-DRI as feed material, potentially reduced CO2 emission" <p>DRI-SAF (NB High DRI practice)</p> <ul style="list-style-type: none"> Relatively high production 				
WEAKNESSES				
<p>In general:</p> <ul style="list-style-type: none"> Dilution losses of high-quality scrap Relatively low production Requirement of a stable power system Steel chemistry specifications for flat products are more stringent of long products <p>DRI-EAF (NB High DRI practice)</p> <ul style="list-style-type: none"> More electric energy required for DRI melting than scrap Increased slag volume Required DRI metallization >88% for better operation With H2-DRI as feed material, no in-situ carbon content in H2-DRI , affecting slag formation, FeO reduction, generation of chemical energy, and the melting temperature of metallic material <p>DRI-SAF (NB High DRI practice)</p> <ul style="list-style-type: none"> Production of hot metal only 				
OPPORTUNITIES				
<p>DRI-EAF (NB High DRI practice)</p> <ul style="list-style-type: none"> Utilization of hydrogen and green electricity <p>DRI-SAF (NB High DRI practice)</p> <ul style="list-style-type: none"> Utilization of hydrogen and green electricity Utilisation of lower quality iron ores" 				

THREATS
Total energy consumption and overall process efficiency for this route is unknown at large scale but will likely be higher than for DRI-EAF route (should be lower) (so far, large scale seems viable)
FATAL FLAWS IC - Investment cycle EG - Energy Grid deC GP - Government policy
<p>DRI in EAF is widely practiced particularly for the manufacture of steel long products. There are very limited commercial applications using DRI-SAF. The latter offers potential opportunity to utilise lower quality iron ores that are available in Australia.</p> <p>In the short to medium term, even with the availability of imported DRI products produced with a significantly lower carbon footprint, the fatal flaw relates to IC (significant capex for a new EAF plant whilst retaining the current plant configuration in place). High unit cost of gas/electricity and capex for infrastructure may be significant issues.</p> <p>In the short to medium term, the SAF route's fatal flaw relates to IC (actual large scale system yet to be proven).</p>

STEELMAKING				
16 Hydrogen plasma direct steel production				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
SuSteel project	4-5	L	H	?
Hybrid hydrogen-based reduction of iron ore	3	L	H	?
STRENGTHS				
Simultaneous melting and reduction of iron ore in hydrogen plasma furnace Potential carbon neutral steelmaking Potential utilization of existing EAF technology for operating hydrogen-based plasma-reactors Direct utilization of iron ore fines Simple separation of the reaction product water by condensation Higher reduction potential of hydrogen in plasma state				
WEAKNESSES				
Technology under development in terms of engineering implementation and economic feasibility Requires massive amounts of green electricity and hydrogen Requires design for continuous tapping of steel and slag Development of sustainable refractory and electrodes				
OPPORTUNITIES				
Utilization of hydrogen and green electricity				
THREATS				
Total energy consumption and overall process efficiency for this route is unknown at large scale but will likely be higher than for DRI-EAF route (should be lower) (so far, large scale seems viable)				
FATAL FLAWS				
IC - Investment cycle EG - Energy Grid deC GP - Government policy				
Hydrogen plasma direct steel production refers to the process of converting iron ores to liquid iron using a thermal hydrogen plasma, without the need for agglomeration processes. The TRL for this technology is low. Hence, the fatal flaw relates to the IC, for the short to medium term. For the long term, it is difficult to predict the level of technical and commercial advancement.				

CARBON CAPTURE, UTILISATION AND STORAGE				
17 CCUS with flue gases from steelworks				
Current and Future Technologies	Technology Readiness Level Level 1-9	Anticipated timeline Short 0-5y Medium 5-10y Long 10-15y	Relative abatement potential Low <10% Medium 11-49% High > 50%	Potential production impact Low Medium High
ULCOS TGR-BF project	6	M	M	L/M
Emirates Steel Industries	9	S	L	L
<i>Biological</i> BlueScope New Zealand Baosteel Shougang Steel Group STEELANOL (ArcelorMittal) Carbon2Value (EU)	6-9	S-M	L-M	L
<i>Chemical</i> "Carbon2Chem" project (TKS)	6	M	M	L
<i>Absorption</i> COURSE50 (Japan) – Option 1 POSCO CO2 breakthrough framework VALORCO project (France) Everest (Tata Steel) Project3D (ArcelorMittal)	5-6	M	L-M	L
<i>Adsorption</i> COURSE50 (Japan) – Option 2 STEPWISE (SEWGS) C4U project (ArcelorMittal) FReSMe (H2020 EU) (Belgium) Carbon4PUR (ArcelorMittal)	4-6	M	L-M	L
<i>Mineral carbonation</i> Slag2PCC (Finland) MCi (Australia)	4-5	M/L	L	L
STRENGTHS				
<p>CO2 capture</p> <ul style="list-style-type: none"> • Chemical absorption: selective separation; achievable high purity; mature process • Physical absorption: no chemical reaction; non-thermal solvent regeneration; no corrosion issue; dry gas leaving from the absorber • Adsorption: less energy required; suitable for high CO2 streams • Cryogenic separation: no chemical reaction; operation at ambient pressure; achievable high purity; liquid CO2 product • Membranes: reduced environmental impact; easy scaling; relatively low capital and operating costs; space efficiency; flexibility; minimum facility requirement; no moving parts; ease of operation and control; low energy consumption 				
CCS				

<ul style="list-style-type: none"> • Decreased CO₂ emission if renewable energy is used • Potential natural underground carbonation <p>CCU</p> <ul style="list-style-type: none"> • Convert CO₂ to add-value products • Establish a circular eco-system • Opportunities to establish a symbiosis system for chemical and metallurgical industries • Resource saving
<p>WEAKNESSES</p>
<p>CO₂ capture</p> <ul style="list-style-type: none"> • Chemical absorption: equipment corrosion (amine); environmental impact (amine); high energy consumption; large equipment sizes; partially regenerated solvent; scale up issue. • Physical absorption: elevated pressure for high efficiency; not feasible for flue gas at ambient pressure. • Adsorption: low purity; need high operating pressure; decreased adsorption capacity with elevated temperatures • Cryogenic separation: high cost for refrigeration and water removal of flue gas • Membranes: high energy requirements for gas compression; multistage separations needed to achieve high purity; aging membranes; high cost for large scale <p>CCS</p> <ul style="list-style-type: none"> • Extra investment and energy required compared to TBF process • Increased environmental impact • Transportation cost of liquid CO₂ • Potential leakage • Uncertainties of storage technology <p>CCU</p> <ul style="list-style-type: none"> • Extra investment and energy required compared to TBF process • Small scale of CO₂ usage • Technological breakthroughs required
<p>OPPORTUNITIES</p>
<p>Most CCU technologies aim to handle BF gas Wide range of potential chemical production areas e.g. urea fertilizer</p>
<p>THREATS</p>
<p>Issues with location for storage of CO₂ once captured, given constraints in using coal seams i.e. minimum 800m below surface Potential over supply of chemicals produced for market via CCU process Competition with other industries producing similar chemicals, leading to oversupply in market Most off-gases are carbon-rich and potentially, not suitable for biological transformation "</p>
<p style="text-align: center;">FATAL FLAWS IC - Investment cycle EG - Energy Grid deC GP - Government policy</p>
<p>In relation to CCUS for steel manufacturing, the majority of developments relate to ironmaking processes producing off gases with relatively higher CO₂ concentrations (BF gas, DR gas [depending on reducing gas of DR process]). Most CCU are at low TRL. A limited number of applications in the biological treatment of steelmaking off gases are further advanced. Efficient CO₂ capture (stripping) from large off gas volumes is a critical step.</p> <p>In the short to medium term, the low TRL of many of the proposed CCU technologies points to a fatal flaw relating to IC. There are significant uncertainties relating to plant</p>

reconfigurations and associated costs, particularly around CO₂ capture equipment and whether CCU is undertaken, etc.

In the long term, CCU technologies will likely be applied, regardless of processing route followed. Capex and Opex will remain significant issues.

9 Appendix 3

9.1 17 SCA and DCA Technology Areas

Blast furnace ironmaking:	1 Novel charging materials to blast furnace
<p>General technology description:</p> <p>There are many potential technical improvements available to increase reduction efficiency of the BF process and reduce overall CO₂ emissions across the steelplant, including proven Best Available Technologies [1, 2] targeting tuyere injection in the lower part of BF or adjustments in charging materials at the top.</p> <p>While there are various opportunities for lowering energy consumption and CO₂ emissions with conventional raw materials (lump ore, pellet and sinter) based on process efficiencies, lowering gangue content, etc which drive lower BF slag volume and fuel rates, this section summarizes several novel charging materials for the BF, including carbon-containing agglomerates, pre-reduced agglomerates and ferro-coke.</p> <p><u>Carbon-containing agglomerates (CCAs)</u></p> <p>CCAs are agglomerates containing carbonaceous material and iron oxide mixture, which are in the form of pellets or briquettes [3]. The carbonaceous material may be coal, coke fines, biomass-derived or carbon-rich materials while the iron oxide can be iron ore fines or steelplant by-product fines. Close contact between iron oxide and reducing material in CCAs can accelerate the gasification of carbonaceous materials and improve the reduction kinetics of iron oxide materials, which lead to a lower temperature for the carbon solution-loss reaction and the equilibrium between reducing gas and wüstite [2, 4, 5, 6]. These effects are expected to be reflected through a lower thermal reserve zone temperature and lower equilibrium ratio of CO/CO₂ in the BF, which lead to improved gas utilization efficiency and lower carbon consumption [7, 8].</p> <p>Numerous experimental studies have been undertaken to assess CCA performance. As strength is a major issue [2, 9], several binding materials were used for the preparation of CCAs, including cement [10, 11], coking tar [12] and ettringite-based binder [13] for cold briquetting, and coal for hot briquetting [14]. However, industrial application of CCA is still limited. Cold-bonded briquettes were charged into BFs of SSAB at a rate of 100-120 kg/tHM [2]; however, no specific performance information is available for these trials. In 2011, Nippon Steel carried out trials on a large BF (5775 m³ inner volume) at Oita Works [11, 15]. The maximum charging rate of CCA was 40 kg/tHM, much lower than that at SSAB. Cement was used as the bonding agent for the carbon composite-iron ore fines. The trial results show the gas reduction efficiency increases with CCA rate. During the trial, the total reducing agent rate (RAR) decreased by 2.6% and production increased by 1.9% [11]. CCAs are currently used in six Nippon Steel BFs [15].</p> <p><u>Pre-reduced agglomerates (PRAs)</u></p> <p>PRA may be pre-reduced pellets, partially reduced sinter, or DRI/HBI.</p> <p>Pre-reduced pellets and partially reduced sinter have remained concepts, with little process development in recent years. Both involve iron oxide reduction in the preparation stage of BF burden materials, with the aim to lower coke consumption through utilizing the close contact between iron oxide and carbon materials and improving reduction kinetics.</p> <p>Pre-reduced pellets would be produced through metallization of self-reducing pellets, using iron ore fines and carbon containing materials [16]. Reduction using pre-reduced pellets was studied only at laboratory scale.</p> <p>Production of partially reduced sinter [17] was proposed in the sintering machine, with partial reduction achieved by the addition of fine carbon materials in the quasi-particles as reductant. Its performance was assessed under simulated sintering and blast furnace conditions. It was estimated</p>	

that charging of partially reduced sinter with a reduction degree of $\sim 70\%$ could potentially reduce CO_2 emission from the BF by $\sim 10\%$ [16]. This needs to be verified in practice.

In contrast to pre-reduced pellet and sinter, DRI/HBI produced through a DR process such as Midrex has been utilised in different BFs (AK steel [18], voestalpine Linz [19], and Kobe Steel [20, 21]). Both theoretical estimations and practical outcomes are consistent in confirming the feasibility of HBI application in the BF process, although the actual benefit may not be the same [22]:

- Yilmaz et al. estimated that 400 kg/tHM of HBI can reduce CO_2 emissions by up to $\sim 27\%$ based on a steady-state energy and materials balance model of the process [23].
- Industrial trials at voestalpine Linz (Austria) demonstrated that when charging 100 kg/tHM of HBI to the BF, the RAR decreased by 21.9–27.5 kg/tHM and productivity increased up to 7.3–10.1% [19].
- Kobe Steel's demonstration trials show that CO_2 emissions from the BF may be reduced by $\sim 20\%$, with RAR decreasing from 518 to 415 kg/tHM when 305 kg/tHM of HBI was charged [20, 21]:
 - $\sim 20\%$ CO_2 reduction was calculated based on one-third of the ferrous materials charged being substituted with HBI ($> 90\%$ Fe).
 - If CO_2 generation during HBI production was considered, (i.e. 0.68 t- CO_2 /t-HBI), CO_2 emissions from the BF decrease by $\sim 12\%$. Note that 0.68 t- CO_2 /t-HBI was obtained assuming HBI was produced in Midrex using a hydrogen-rich reducing gas.

From an energy balance perspective, charging of hot HBI to the BF may make this process more favorable. As mentioned by Babich et al. [6], "From the metallurgical point of view, it does not make much sense to shift the reactions of indirect reduction from the blast furnace shaft to an external upstream process of direct reduction and to abuse the reduction unit blast furnace as a re-melting plant for pre-reduced materials." However, considering the flexibility in choice of iron ore and reducing agent sources, HBI utilization may be a competitive option for reducing CO_2 emission and energy consumption of the ironmaking process.

Economic and technological analyses are necessary when HBI is used in a specific integrated steelplant, as this is closely related to the type of raw materials replaced, the production and properties of DRI, BF operational conditions and so on.

Ferro-coke

Ferro-coke is a type of high-reactivity coke composed of 70% coke and 30% iron [6], which is produced from low-grade iron ore fines and non-/soft-coking coal. The iron-bearing materials in ferro-coke not only work as a catalyst for coke gasification but also increase the content of metallic iron charged into BF [24].

With increasing iron ore content, the strength of ferro-coke decreases and its reactivity increases. For ferro-coke containing 30% iron ore, the starting temperature of the gasification of ferro-coke may be 120-150°C lower than that of conventional coke and the cold strength of ferro-coke may reach the level of coke nut [25, 26, 27, 28].

The principle behind utilizing ferro-coke in the BF is that highly reactive coke could help lower the thermal reserve zone temperature and improve CO regeneration. This was expected to increase the efficiency of reduction reaction and reduce overall coke consumption [6, 28].

Although industrial trials of ferro-coke charged to BF were carried out at JFE Steel in 2013 [6], there were limited trials outside of JFE Steel. The production of ferro-coke and its deteriorated strength in BF may be major issues for its industrial application.

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 [29]. 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 CO_2 emissions in the ironmaking process by $\sim 10\%$, by 2023.

Material inputs and outputs:	
Inputs	Outputs
<ul style="list-style-type: none"> Conventional BF burden materials partially replaced by CCAs, PRAs or ferro-coke Conventional BF blast conditions with enriched cold O₂ and injection of carbonaceous materials 	<ul style="list-style-type: none"> BF gas (CO, CO₂, H₂, H₂O), BF slag, BF hot metal, BF dust
Carbon-containing agglomerates	
<ul style="list-style-type: none"> Pellets or briquettes composed of carbonaceous material such as coal, coke fine or carbon-rich materials, and iron oxide such as iron ore fines or steel plant waste fines 	
Pre-reduced agglomerates	
<ul style="list-style-type: none"> Pre-reduced pellets, partially reduced sinter, or DRI/HBI. 	
Ferro-coke	
<ul style="list-style-type: none"> Ferro-coke produced from iron ore or steel plant waste fines, and non-/soft-coking coal 	
Overall abatement pathway:	
Technologies with carbon-containing agglomerates and ferro-coke are helpful for abatement (materials, energy, environment related) through	
<ul style="list-style-type: none"> Utilization of low-grade iron ore and coal Utilisation of renewable or waste carbon sources Recycling of some steel plant wastes Improved reduction efficiency to decrease overall fuel consumption and CO₂ emission 	
Pre-reduced agglomerates are helpful for abatement through	
<ul style="list-style-type: none"> Flexibility of selecting iron ore and coal sources for producing PRAs Possibly, more efficient reduction in the pre-treatment process outside the blast furnace Improved BF performance while using pre-reduced ores Utilization of H₂ in the pre-treatment process Increased productivity due to high metallic iron charged from the top of BF 	
Based on industrial trials, the following abatement may be attained using novel charging materials:	
<ul style="list-style-type: none"> With a maximum charging rate of 40 kg/tHM of CCA, RAR may decrease by 2.6%, production increase by 1.9% and gas utilization increase by 1.7% [11] RAR may be reduced from 518 to 415 kg/tHM when charging 305 kg/tHM of HBI [20, 21] It is estimated that CO₂ emission can be reduced from 1.8 to 1.6 t-CO₂/tHM if 30% of iron ore is replaced by HBI [21] 	
Note: HBI is assumed to be produced using hydrogen-rich gas, emitting 0.68 t-CO ₂ /t-HBI.	
Key performance indicators:	
Compared to conventional BF conditions, the following changes may be estimated:	
<u>Use of carbon-containing agglomerates</u>	
<ul style="list-style-type: none"> Total RAR decreases slightly due to improved reduction efficiency Hot metal production increases [11] [cf Wang et al. [14] estimated a decrease in BF productivity] Gas utilization increases due to improved reduction kinetics Top gas temperature decreases in line with a decrease in thermal reserve zone temperature Potentially poorer BF permeability if CCA rate increases beyond a threshold level or CCA strength decreases 	
<u>Use of pre-reduced agglomerates within an allowable maximum range</u>	

<ul style="list-style-type: none"> • Total RAR decreases in relation to reduction efficiency and pre-reduced materials • Production increases due to more metallic iron charging • CO₂ emission decreases in relation to fuel consumption • Top gas utilization decreases due to a lower reduction requirement in the shaft • Top gas temperature decreases due to lower reducing gas requirements 					
<p>Maturity and requirements to implement: Except for HBI, technologies/processes for the production and utilization of the novel burden materials described are not mature. Aside from economic factors, the following improvements are required for successful implementation of each technology:</p> <ul style="list-style-type: none"> • Carbon-containing agglomerates: the improvement of CCA strength using optimal binders, and improved understanding of the relationship between CCAs and the thermal reserve zone temperature under BF conditions • Pre-reduced agglomerates: assessment of PRAs utilization in the integrated steelworks • Ferro-coke: industrial trials to confirm the feasibility of ferro-coke under BF conditions 					
<p>Potential strengths and weaknesses:</p> <table border="1"> <thead> <tr> <th style="text-align: center;"><u>Strengths</u></th> <th style="text-align: center;"><u>Weaknesses</u></th> </tr> </thead> <tbody> <tr> <td> <ul style="list-style-type: none"> • Potential reduction of fuel consumption and CO₂ emission • Increased productivity by using PRAs • Improved hot metal quality using PRAs due to lower coke usage • Utilization of low grade iron ores, various carbon materials and some steelplant wastes • Possible lowering of the thermal reserve zone temperature by using CCAs and ferro-coke • Improved reaction kinetics by using CCAs and ferro-coke </td> <td> <ul style="list-style-type: none"> • Decreased gas utilization by using PRAs • Possible deteriorated BF permeability • Operating facilities required for pre-treatment of charging materials • Requirement of sufficient strength of these agglomerates • Economics (HBI) • Supply chain issues, difficult to continue supply • Premium \$ is variable • Future situation might change over time • Higher overall costs for these materials - need to understand the capex/opex • Supply chain issues (continuous materials supply) where materials are not produced on steel plant </td> </tr> </tbody> </table>		<u>Strengths</u>	<u>Weaknesses</u>	<ul style="list-style-type: none"> • Potential reduction of fuel consumption and CO₂ emission • Increased productivity by using PRAs • Improved hot metal quality using PRAs due to lower coke usage • Utilization of low grade iron ores, various carbon materials and some steelplant wastes • Possible lowering of the thermal reserve zone temperature by using CCAs and ferro-coke • Improved reaction kinetics by using CCAs and ferro-coke 	<ul style="list-style-type: none"> • Decreased gas utilization by using PRAs • Possible deteriorated BF permeability • Operating facilities required for pre-treatment of charging materials • Requirement of sufficient strength of these agglomerates • Economics (HBI) • Supply chain issues, difficult to continue supply • Premium \$ is variable • Future situation might change over time • Higher overall costs for these materials - need to understand the capex/opex • Supply chain issues (continuous materials supply) where materials are not produced on steel plant
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<p>Additional comments:</p>					

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Blast Furnace Technology:	2 Dry Slag Granulation (DSG)
<p>General technology description:</p> <p>Dry Slag Granulation (DSG) is based on molten slag atomization, with/out a coupled integrated heat recovery system [1, 7, 9-11]. More recent process developments and plant demonstrations use a rotating cup or disc [2-5], but others that have been developed, demonstrated and/or commercialised involve use of air blasting, rotating drums or small steel spheres that absorb energy from molten slag [1].</p> <p><u>Rotating cup/disc DSG:</u> In this process, the slag is poured onto the disc enclosed in a water-cooled chamber and accelerated outwards where it is atomized [2-5]. The airborne slag is partially solidified before being collected. Heat recovery systems utilising a fluidised bed or moving packed bed heat exchanger generate hot air or steam.</p> <p><u>Air blasting DSG:</u> This involves pouring molten slag into an enclosure (gutter, chamber), which is then broken up and atomized by high pressure air nozzles from underneath and sides [1].</p> <p><u>Rotating drum DSG:</u> Development of two drum-based processes occurred in 1980s [1, 9]. The single-drum DSG involved pouring slag onto a rotating drum generating droplets that were collected, mixed with sand and cooled to solidification by air in a fluidized bed. Slag granules were then transferred to a second heat recovery unit. The twin-drum DSG was designed to freeze a layer of slag on the drum surfaces, with heat recovery achieved via the coolant circulating within the drums.</p> <p><u>Steel spheres in slag DSG:</u> Another process development involved adding contained in a caster mould [1, 9]. These spheres were evenly distributed over and penetrated the slag surface, efficiently absorbing the slag's latent heat and lowering its temperature. The steel spheres/solidified slag ingot drops onto a plate and breaks up. Magnetic separation results in separation of slag particles and steel spheres.</p>	
Material inputs and outputs:	
<u>Inputs</u>	<u>Outputs</u>
<ul style="list-style-type: none"> • Molten blast furnace slag • Air 	<ul style="list-style-type: none"> • Granulated slag product (depending on the glass content, suitable as a clinker substitute for Portland cement) • Hot air (~600°C) for heat recovery
Overall abatement pathway:	
<p>At PKSW, current blast furnace slag handling processes involve using either water to granulate the molten slag in an INBA granulating drum or air-cooled slag earth pits. In either case, there is no heat recovery. Recovery of a significant proportion of the molten slag (~1500°C) sensible heat of ~1.8 GJ/t-slag, could realise up to 1.4 PJ of potential heat recovery, reducing energy usage and hence GHG emissions.</p> <p>This adds to energy savings already achieved when granulated slag of sufficient glass content is used in cement production as a substitute for Portland cement. For the cement industry, it is estimated that partial replacement by granulated slag drops the GHG emissions by ~ 0.8 t-CO_{2e} / t-slag.</p>	

Dry slag granulation also avoids high water consumption required for the wet granulation process. It is estimated that ~1.5 t-water/t-slag processed is lost due to alternative slag process could be developed to replace water granulation to meet current and future need of steel industry.

Key performance indicators:

Compared to conventional treatments such as air cooling and water granulation, the key performance indicator for the emerging DSG processes is the energy value of the BF slag and to some extent, its material value and the avoidance of hydrogen sulphide and sulphur dioxide emissions. The extent to which the high thermal energy embodied in high temperature slags may be recovered is likely to have the most significant economic impact; hence the heat recovery efficiency for each process is critical. This recovered energy may be used for preheating materials or in some cases, electricity generation.

Maturity and requirements to implement:

Rotating disc DSG with heat recovery:

- Primetals rotating disc DSG: large-scale plant demonstration is continuing at Voest Alpine Stahl [2-3]
- CSIRO rotating disc DSG: in cooperation with Beijing MCC Equipment Research & Design Corporation, demonstrating this technology at industrial scale [5]

Air blasting DSG with heat recovery:

- Ecomaister and Hatch: Commercial scale air blast DSG plants have been installed for EAF, BOF, and LMF, two of which have waste heat recovery, reportedly recovering 30–40% of slag latent heat [9]. Promising developments for the treatment of blast furnace slag.

Potential strengths and weaknesses:

Compared to current slag handling processes, DSG have the following features:

<u>Strengths</u>	<u>Weaknesses</u>
<ul style="list-style-type: none"> • Product quality with excellent cementitious properties • Less complex system design, low water consumption, lower steam explosion potential and pollution potential • Recovery of thermal energy 	<ul style="list-style-type: none"> • Scalability, cost, low energy recovery efficiencies and difficulties in energy utilization. • Durability of spinning cup, production of slag wool, and handling of hot granules collected • Reliability of operation and process control.

Additional comments:

Reference

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Blast furnace ironmaking:	3 Biomass application to ironmaking
<p>General technology description:</p> <p>Life cycle analysis shows that renewably-sourced biomass materials (wood, crops, animal waste, landfill gas, biofuel, etc) may be considered a carbon-neutral resource [1]. The reduction in carbon emissions is therefore due to biomass’s carbon neutrality [2].</p> <p>In iron/steelmaking processes, various technical, environmental, and economical evaluations of biomass applications have been conducted [3, 4, 5, 6, 7, 8, 9]. Potential application areas range from sintering, cokemaking and blast furnace ironmaking (BF), to the production of DRI and steelmaking processes (e.g. small amounts of processed biomass (biochar) are utilized as recarburiser, replacing calcined anthracite (coal-based)).</p> <p>This section provides a brief outline of biomass pre-processing, introduces the direct application of biomass in DRI production, and summarizes the current status of the major biochar applications in sintering, cokemaking, and BF ironmaking, primarily from a technological viewpoint.</p> <p><u>Biomass pre-processing</u></p> <p>For most steel manufacturing processes, raw biomass materials cannot be utilized directly as a reducing agent or energy source because of their physical characteristics, high moisture content, low fixed carbon content and relatively low calorific value. Hence, biomass materials require some form of pre-processing prior to utilization to improve these and other properties. Aside from physical processing (e.g. for size distribution), there are two major pre-processing technologies used, viz. slow pyrolysis and torrefaction [6, 10]. These are similar in principle but differ with respect to the atmosphere, heating rate, and final temperature. Biomass materials essentially undergo thermal-chemical conversion to different extents depending on the target products, which may have different physical and chemical properties corresponding to their applications.</p> <p>Slow pyrolysis is a thermal decomposition process of biomass in the absence of air, producing charcoal and by-products such as bio-oil and combustible gas. During the operation, the biomass materials are slowly heated to between 300–600°C and then maintained at temperature for 15–30 minutes for up to several hours [6]. The solid product, charcoal, is a porous carbonaceous compound with low H/C and O/C ratios. The charcoal/biochar may have different chemical, physical, and mechanical properties depending on the pyrolysis conditions and type of biomass used. The proportions of volatile matter (VM) and ash are determined by the conditions of pyrolysis and biomass source, respectively. Almost all phosphorus, over 80% potassium and 30-80% total chlorine in the original biomass may be retained in the charcoal. Traditionally, slow pyrolysis has been carried out in batch operations using pit, mound, or brick kilns. More modern, semi-continuous or continuous processes are used including packed bed reactors, rotary kilns and screw reactors [6, 11, 12].</p> <p>Torrefaction is similar to slow pyrolysis but the operating temperatures are lower (typically between 200–300°C). Residence time for torrefaction is between a few minutes and 3 hours. Generally, compared to raw biomass, the torrefied biomass is more brittle, has higher energy density and could be easier to transport, handle and store. Compared to charcoal from pyrolysis, torrefied biomass has higher VM content, lower fixed carbon content (14–48%) [13] and lower calorific value. It is also more hydrophobic.</p> <p>As a manufactured product, the properties of charcoal/biochar can be tailored to each process [2].</p> <p><u>Microwave-based direct reduced iron using biomass</u></p> <p>Rio Tinto has developed a laboratory-based process combining renewable biomass with microwave technology to process and reduce iron ore [14]. The process involves a mixture of iron ore fines and biomass, formed into composite briquettes which are then heated to ~600°C using gases produced from the raw biomass [15]. Microwaves, potentially powered by renewable energy, are then used to heat the mixture sufficiently to reduce the iron ore fines, using remnant carbon (or biochar) in the mixture. Direct use of sustainable biomass sources including various purpose-grown agriculture by-products (e.g. wheat straw; barley straw) avoids issues with the production of biochar and</p>	

biogas. The direct reduced iron product may then be melted in an electric furnace (e.g. submerged arc furnace), prior to steelmaking. Further developments are planned at small-scale pilot level [14].

Use of biochar in the sintering process

The sintering process contributes up to 10% of the overall carbon emissions from an integrated steel plant. Hence, use of biochar in the sintering process to replace anthracite and/or coke breeze may be an attractive option. As mentioned, the original biomass material is not suitable for direct use in the sintering process [16], so pre-processing is necessary to produce charcoal or torrefied materials with high fixed carbon and low volatiles. Biochar with low volatile matter content can prevent spark fires in the electrostatic precipitator.

Based on pilot experimentation, with biochar addition, the following phenomena may be observed through partial replacement of coke breeze (or anthracite) [4, 17]:

- Higher mix moisture contents required for optimum granulation
- Increased fuel rate with increasing biochar substitution
- Less dense green sintering bed
- Higher concentration of CO and CO₂ and lower SO₂ and NO_x emission in the off-gas
- Faster flame front speed through the sinter strand bed

As biochar evaluation in sintering remains at pilot-scale test stage, some data regarding the replacement ratio are not always consistent. Regarding the replacement ratio of coke breeze, biochar usage up to 50% is shown to maintain sinter quality in terms of the sinter yield and strength [17]. However, Mousa et al. [4] reported that the replacement of up to 25% coke breeze was without significant impact on sinter quality, while Gan et al. [18] reported that the replacement ratio for coke breeze should not exceed 40% to maintain the sinter yield and strength. Differences in replacement ratio can be related to operational conditions of the sinter pot tests, iron ore properties, granulation conditions and reactivity of biochar. In particular, pyrolyzed biomass made under different conditions and using different resources can significantly affect the reactivity of charcoal/biochar and hence, replacement ratio.

Use of biochar for cokemaking

Biochar may be introduced into coking coal blends as raw, torrefied or pyrolyzed materials [4], as a partial replacement of coal.

Generally, the utilization of biochar in cokemaking is potentially beneficial for reducing ash in the product coke due to the low ash content of biochar.

Given the formation of metallurgical coke is related to the development of thermoplasticity of the coal blend during the coking process, usage of biochar most likely causes a decrease in the fluidity of the coking coal blends; hence, a potentially degrading impact on this development [6, 19, 20]. As well, the biochar also provides a more reactive carbon structure which is distributed throughout the coke matrix. In general, adding biochar to the coking coal blends alters the coke quality in terms of higher coke reactivity index (CRI) and lower coke strength after reaction (CSR) compared to the corresponding reference coke [4, 7, 9, 21].

The extent of these changes may be contained through limiting the amount of biochar added. In terms of bio-coke reactivity, a slightly increased CRI may be suitable for the BF process, as it is postulated that a higher reactive carbonaceous material lowers the temperature of the thermal reserve zone and enhances the reduction of iron oxide into metallic iron. However, too high reactivity may lead to lowering of coke strength below a threshold, which would impair the BF process performance.

Investigation of biochar utilization for cokemaking is still at the laboratory scale; industrial trials are not available. Overall, maintaining the desired coke quality necessitates an optimum biochar addition e.g. below 5% [6]. It was reported that replacing 2–10% of coking coals with biochar could reduce carbon emissions by 0.02–0.11 t-CO₂/t-steel [3].

Use of biochar in blast furnace ironmaking

Biomass-based materials may be introduced to the BF process as a partial or complete replacement for fossil fuel injectants (coal; oil; natural gas) and/or as charging materials (coke; carbon composites).

Bio-injection via tuyeres

Charcoal and/or torrefied biomaterials may be injected into the BF through tuyeres, either separately or mixed with pulverized coal, using the existing pneumatic conveying system. It is not widely practiced due to supply – industrial operations exist in Brazil [27, 28].

Multiple studies have investigated biochar (charcoal) injection as a partial/full replacement for pulverized coal (and other fuel) injection:

- Theoretical analyses: Heat and mass balance modelling, computational fluid dynamics modelling, and life cycle assessment
- Pilot- and laboratory-scale tests: LKAB experimental BF [9], drop tube furnace [22], injection rig [23], laminar flow reactor [24], and thermogravimetric analysis [25]
- Industrial trials: Bio-injection test at SSAB in Oxelösund, Sweden using one tuyere [9] and in Brahestad, Finland [26]

Selected key findings of the studies were:

- Charcoal injection was employed in Brazil BFs at an injection rate of 100–190 kg/tHM [27, 28]
- Potential application of torrefied and carbonized biomass materials used for injection in blast furnaces was confirmed [29]
- The combustion performance of charcoals greatly exceeded that for coals with the same VM content, predominantly due to its higher surface area/volume ratio [17, 22]
- The coke replacement ratio is heavily dependent on the type of biomass. Biochar is superior to other biomass-based injectants [6]

Current issues with biochar/charcoal [6] are concerned with:

- Controlling particle size and shape distribution
- Optimizing injection process for biochar injection at high rates
- Evaluating flow properties of fine powder mixtures in pneumatic conveying pipes
- Investigating upper limits of biochar injection rate
- Assessing influences of varying particle size distributions on flow and combustion behaviors
- Developing a coupled combustion model and overall HM model

Summarizing the industrial trials using medium- or large-sized BF:

- The combined charcoal and pulverized coal injection rate of up to 165kg/tHM was trialed at Arcelor Mittal’s BF A in Monlevado, Brazil [9]
- Addition of 10% charcoal to pulverized coal was shown feasible in SSAB at Oxelösund, Sweden [9] and at Brahestad, Finland [26]

Note: to achieve higher amounts of biochar addition needs further investigation on the influence of grindability and bulk density on grinding, segregation and conveying [9].

- 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. The plant is expected to be operational by the end of 2022.

In addition, the byproduct of biomass pyrolysis, such as biogas, is expected to be co-injected with charcoal to increase the total efficiency of biomass usage in the blast furnace [30, 31]. The relevant injection technology was further introduced in Section “Injection of auxiliary hydrogen-enriched gases and waste plastic into the blast furnace”.

Biomass-based top charging

Biomass-based top charging materials may be lump charcoal, pre-reduced agglomerate and bio-composite.

- Charcoal may be charged to the top of the BF as large lump material (replacing coke) or smaller size materials (replacing nut coke). Actually, the charcoal was the key reductant and fuel

material for ironmaking practices prior to the Industrial Revolution. However, due to charcoal's relatively low strength (cf coke), currently, only small-sized BFs in Brazil have used these materials as top charging materials [3]. Theoretically, for medium- to large-sized BFs, lump charcoal can partially replace metallurgical coke up to 20% [32]. Charging of 20 kg/tHM of lump charcoal could reduce the coke consumption by 30 kg/tHM due to both replacement and improved reduction of iron ore via a lower temperature of the thermal reserve zone [6, 33]. Currently, the limit of replacement ratio of coke or nut coke by charcoal requires industrial verification.

- Pre-reduced agglomerate can be pre-reduced pellets, partially reduced sinter, or DRI/HBI using biomass-derived materials. Biomass materials can partially substitute for the traditional usage of coal in pelletizing, sintering and direct reduction processes to produce pre-reduced agglomerates (as summarized in the section "Novel charging materials to blast furnace"). In terms of the high reactivity of charcoal and its lower strength, it appears the use of biomass materials in the pre-reduction process is promising, particularly in rotary hearth processes. Investigations in this area are very limited and at the conceptual stage. Further economic and technological analysis of production costs and product strength is necessary.
- Bio-composites which are composed of iron ore, biomass and binder, may be classified as carbon containing agglomerates (as summarized in section "Novel charging materials to blast furnace"). Theoretically, the biomass used may be raw solid biomaterials or pre-processed materials. The close contact between iron oxide and carbon particles in the composite can enhance the reduction kinetics of iron oxide [9]. Therefore, using the bio-composite in BF, the reduction of carbon emissions can be achieved through two ways: coke replacement and coke saving due to improved reduction efficiency.

The low crushing strength and release of volatiles of biomass at relatively low temperatures, limits the practical application of bio-composites. Some efforts to overcome these barriers include utilization of biomass lignin as a binder [34], special composite design [35], use of pyrolyzed bio-materials with low VM content, etc.

Industrial-scale trials were reported by Mousa et al. [36], where bio-composites in the form of briquettes were produced by mixing 1.8% of torrefied and pelletized sawdust, with 12% cement and 86.2% of steel mill residues.

BF trials with 38.7 kg/tHM and 64.2 kg/tHM of bio-composites, respectively were conducted in SSAB at Oxelösund, Sweden.

Heat and mass balance analysis after the trials indicated that with 64.2 kg/tHM of bio-composites charged, the carbon consumption can be reduced by about 9–11 kg/tHM due to the improved gas utilization.

Material inputs and outputs:

Inputs	Outputs
Biomass pre-processing	
<ul style="list-style-type: none"> • Biomass (incl resources from crop residues, plantation and forest residues, and waste streams) 	<ul style="list-style-type: none"> • Charcoal/biochar or torrefied materials • Exhaust gas (CO, CO₂, CH₄, NO_x, NMVOC, PIC, TSP) <p>NMVOC (non-methane volatile organic components); TSP (total solid particles); PIC (products of incomplete combustion)</p>
Microwave-based direct reduced iron using biomass	
<ul style="list-style-type: none"> • Composite briquettes composed of iron ore fines and biomass 	<ul style="list-style-type: none"> • DRI • Off gas (CO, CO₂, H₂, H₂O, etc)

<ul style="list-style-type: none"> Gas produced from the raw biomass 	
Use of biochar in the sintering process	
<ul style="list-style-type: none"> Coke breeze in conventional raw material for sintering partially replaced by charcoal Optimal charcoal – quality [23] <ul style="list-style-type: none"> Low VM: <3% High density: >700 kg/m³ Size: 0.3–3 mm 	<ul style="list-style-type: none"> Sinter Cold return fines Waste gas
Use of biomass-derived materials in coke making	
<ul style="list-style-type: none"> Coal in conventional coal blends partially replaced by raw, charcoal or torrefied bio-materials Optimal charcoal – quality [23] <ul style="list-style-type: none"> Low to mid VM: <10% High density: >700 kg/m³ Size: <1 mm Low alkalis 	<ul style="list-style-type: none"> Bio-coke Coke oven gas
Use of biochar in blast furnace ironmaking - bio-injection	
<ul style="list-style-type: none"> Conventional burden materials Pulverized coal in conventional blast conditions partially replaced by charcoal Charcoal – quality [23] <ul style="list-style-type: none"> Higher VM: 10-20% Low ash: <5% Low alkalis 	<ul style="list-style-type: none"> BF top gas (CO, CO₂, H₂, H₂O, N₂), BF slag, BF hot metal
Use of biochar in blast furnace ironmaking - lump charcoal	
<ul style="list-style-type: none"> Conventional blast operating conditions with cold O₂ enrichment and injection of carbonaceous materials Coke or nut coke in conventional burden material partially replaced by lump charcoal or small size charcoal Lump charcoal – quality [23] <ul style="list-style-type: none"> Low to high VM: 0-25% for mini-BF Higher strength Size: 30-60 mm Small size charcoal – quality [23] <ul style="list-style-type: none"> Low to mid VM: <7% Higher density Size: 20-25 mm 	<ul style="list-style-type: none"> BF top gas (CO, CO₂, H₂, H₂O, N₂), BF slag, BF hot metal
Use of biochar in blast furnace ironmaking - pre-reduced agglomerate	
<ul style="list-style-type: none"> Conventional blast conditions with enrichment, cold O₂ and injection of carbonaceous materials Iron ore in conventional burden material partially replaced by pre-reduced agglomerate Pre-reduced agglomerate – quality [23] 	<ul style="list-style-type: none"> BF top gas (CO, CO₂, H₂, H₂O, N₂), BF slag, BF hot metal

High strength: >500 N High metallization: >95%	
Use of biochar in blast furnace ironmaking - bio-composite	
<ul style="list-style-type: none"> • Conventional blast conditions with enrichment, cold O₂ and injection of carbonaceous materials • Iron ore in conventional burden material partially replaced by bio-composite • Charcoal – quality [23] <ul style="list-style-type: none"> Low VM: <5% Higher strength: >500 N Size: 80% < 75 μm 	<ul style="list-style-type: none"> • BF top gas (CO, CO₂, H₂, H₂O, N₂), BF slag, BF hot metal
<p>Overall abatement pathway: As mentioned, when source biomass materials are renewable, a life cycle assessment of biomass-derived products (biochar/charcoal and other renewable biomass-derived fuels/reductants) may be produced with net negative CO₂-e emissions [2]. There are also some other additional benefits:</p> <ul style="list-style-type: none"> • If lump charcoal and bio-composites are used for top charging materials at the BF, CO₂ emission reduction may be linked to two factors: the coke replacement by bio-materials and coke saving due to improved reduction efficiency. • More coke saving may be attributed to the improved combustion performance of the biochar in BF injection with less unburnt char and lower ash content of conventional pulverized coal. <p>Hence, the abatement potential biochar/charcoal for an integrated steel plant, is estimated to be significant e.g. for a sinter-coke-BF based plant, between ~30-50% of total CO₂ emissions [2].</p>	
<p>Key performance indicators: With reference to the overall abatement pathway, the impact of biomass applications in steelmaking processes is mainly determined by the replacement ratio of coke or coal by biomass-derived materials. The replacement ratio (coke) and injection rate (e.g. PCI) can be treated as key performance indicators, directly related to the energy consumption and CO₂ emission in each process using biochar.</p> <p>The theoretical and more practical estimations of replacement ratio or absolute biochar injection rates, are not always consistent. Theoretical predictions rely heavily on the carbon balance and equivalences. In practice, factors such as bed permeability, reaction kinetics and biochar properties require plant observations and measurements.</p> <p>The following information provides a summary of estimates across sinter, coke and BF plants. The assumption is that productivity can be maintained compared to the process prior to utilization of biochar/charcoal.</p> <ul style="list-style-type: none"> • Sintering: Replacement ratio of coke breeze with biochar may be up to 25%-50% (based on the pot test results [4, 17]). • Cokemaking: To maintain the coke quality, replacement of coal by biochar is in the range of 0–5% [6]. • BF ironmaking: <ul style="list-style-type: none"> - Bio-injection: Reported as 10% of pulverized coal replaced by biochar may be feasible [9, 26], though demonstration trials suggest 20% is viable and higher replacement rates have been achieved in Brazil - Lump charcoal: Theoretically, lump charcoal can partially replace metallurgical coke by up to 20% [32] - Pre-reduced agglomerate: Not available - Bio-composite: Industrial-scale trials indicate that with ~65 kg/tHM of bio-composites charged, the carbon consumption can be reduced by ~9–11 kg/tHM due to improved gas utilization [36]. 	

Maturity and requirements to implement:

Apart from the commercial application of charcoal charged and injected into mini-BFs in Brazil, all other applications of biomass materials in ironmaking processes are under development. Assuming sufficient supply of biomass materials, the requirements for further biochar utilization for each process are given below:

- Sintering: sufficient bed permeability, controlled total fuel consumption and maintained productivity
- Cokemaking: maintained CSR with increased addition of biochar into the coal blends
- BF ironmaking:
 - bio-injection: recognized upper limit of charcoal injection rate with optimal size distribution
 - lump charcoal: enhanced strength of bio-material in BF condition
 - pre-reduced agglomerate: agglomerate design and LCA evaluation
 - bio-composite: composite design for high strength

Overall, industrial demonstration trials are required to confirm observations in the laboratory and theoretical estimation for each biomass application.

Potential strengths and weaknesses:

The following strengths and weaknesses are in comparison with utilization of conventional fuels and reductants in ironmaking processes.

<u>Strengths</u>	<u>Weaknesses</u>
<p>General</p> <ul style="list-style-type: none"> • Carbon neutrality (potential reduction of CO₂ emission by 0.69–1.21 t/t-steel) [3] • Low ash and sulphur content • Potential low alkalis and impurities depending on biomass source • Controlled VM using different pre-processing methods • Carbon will still be required as a steelmaking alloying element – biomass carbon from sustainable sources could continue to be used in a carbon-constrained economy • Processing of biomass has the potential to yield other beneficial products e.g. liquid pyrolysis oils which could be processed into sustainable transport fuels, wood vinegar and syngas <p>More specific</p> <ul style="list-style-type: none"> • Sintering: Lower SO₂ and NO_x emission • BF ironmaking (bio-injection): Higher combustion efficiency, given high specific surface area • BF ironmaking (lump charcoal/bio-composite): Improved reduction efficiency due to high reactivity • Microwave-based direct reduced iron using biomass: Direct utilization of biomass and 	<p>General</p> <ul style="list-style-type: none"> • Extra cost for pre-processing of biomass materials • Potential issues with sustainable and consistent biomass supply • Biomass sources are not centralized and a widely spaced geographically • Low yield of solid carbon and a high yield of lower value and harder to handle byproducts • Competition for land use between biomass and food production • Environmental effects of biomass production such as soil disturbance and nutrient depletion • Low density of biomass materials • High moisture absorption of biomass product • Easy contamination of biomass materials • Higher price of biomass products than fossil fuels • Transportation and handling <p>More specific</p> <p>Sintering</p> <ul style="list-style-type: none"> • Higher moisture requirement for granulation • Lower mechanical strength of charcoal • Potential low production due to low density of charcoal

<p>close contact between iron ore fine and carbonaceous materials</p>	<p>Coke making</p> <ul style="list-style-type: none"> • Potential deteriorated CSR <p>BF ironmaking - bio-injection</p> <ul style="list-style-type: none"> • A broad size range of charcoal if no proper sieving • Increased oxygen enrichment required • Potential limited injection rate due to porous nature and low density of charcoal <p>BF ironmaking - lump charcoal/bio-composite</p> <ul style="list-style-type: none"> • Potential insufficient strength • Potential lower productivity due to low density of biomaterials
<p>Additional comments:</p>	

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Blast Furnace Technology:	4 Top gas recycling and high oxygen blast furnace
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General technology description:

To reduce the CO₂ emissions and fully utilise the chemical energy of top gas in the blast furnace (BF), top gas recycling (TGR) technology is proposed to recover CO and H₂ from the top gas, and then heat up and inject these reducing agents through the lower tuyeres in the hearth as well as the lower shaft. In this process, pure oxygen replaces hot blast air introduced into the lower tuyeres. Thus, this technology can be referred to as TGR-OBF [1, 2].

Furthermore, CO₂ in the top gas can be captured and used for reforming of coke oven gas (COG) to produce the reducing gas re-injected to the lower shaft of the blast furnace. As well, CO₂ can be removed from the top gas and then stored and utilized through other carbon capture utilization and storage (CCUS) technologies [3, 4].

Historically, various types of the top gas recycling and oxygen blast furnace were proposed to achieve low-carbon ironmaking although most of these were limited to concepts and flowsheet modelling studies. The original idea was the usage of hot reducing gas injection in the blast furnace ironmaking process (Lance, 1920). In subsequent years, other concepts were proposed: Fink nitrogen-free blast furnace (NFBF) (patent, 1970s), Lu NFBF (1984), NKK NFBF (1980s), Qin full oxygen (FO) BF (1990) and ULCOS-TGR-BF (2014) [1, 5, 6, 7].

The differences in the above TGR-OBFs are the injection positions, temperature, or preheating of recycled gas, together with the use of various combinations of injectants through tuyeres. Typical routes are listed below:

Table 1. Typical TGR-OBF routes

	Shaft tuyeres	Hearth tuyeres	Ref.
1	TGR + CO ₂ removal + Preheating	TGR + CO ₂ removal + O ₂ /Injectants	[6]
2	-	TGR + CO ₂ removal + Preheating + O ₂ /Injectants	[6, 8]
3	TGR + CO ₂ removal + Preheating	TGR + CO ₂ removal + Preheating + O ₂ /Injectants	[6, 9]
4	-	TGR + CO ₂ removal + O ₂ /Injectants	[10, 11]
5	TGR + CO ₂ removal + O ₂ /Injectants	TGR + CO ₂ removal + O ₂ /Injectants	[12]
6	TGR + Preheating + COG reforming	Hot blast	[13, 14]
7	TGR + Preheating	O ₂ /PC/Natural gas	[15]

Notes:

1) Shaft tuyeres are located below the indirect reduction region; hearth tuyeres are referring to the traditional blast furnace tuyeres; O₂ is either full oxygen or partial oxygen-enriched blast; injectants refer to pulverized coal, natural gas, H₂, charcoal, biomass or COG.

2) The injection gas temperature range: 900-1000°C (shaft tuyeres), 1200-1250°C (hearth tuyeres). Route 3 was preferred in the ULCOS TGR-BF project. Compared to Routes 1-5, top gas without CO₂ removed was used for shaft injection in Routes 6 and 7.

The definition, design and evaluation through the flowsheet and numerical modelling provided support for the feasibility of TGR technology.

Pilot trials via experimental blast furnaces and small industrial scale furnaces were carried out:

- 1) 1972: NKG experimental blast furnace (3.2 m³), NKK (Completed) (Reducing gas was used in the tests to investigate the feasibility of Route 6)[13]
- 2) 1985 – 1990: Tula OBF (1033 m³), Russia (Completed) (Route 2)[8]
- 3) 2007 – 2010: ULCOS - LKAB’s experimental blast furnace (8.2 m³), Sweden (Completed) (Routes 1, 2 and 3)[6]
- 4) 2020 – : BaoWu Group, a small industrial BF (430 m³), China (In-complete) (Route 3)[5]

Whilst this promising technology should increase productivity and reduce CO₂ emissions, the TGR-OBF process is currently not cost-effective, requiring considerable investment on facility development and systems upgrade. Technology developments remain, particularly in terms of maintaining process stability, as well as implementing effective recycled gas preheating and CCUS.

Material inputs and outputs:

Material inputs and outputs for the blast furnace still depend on the selection of routes. For a preferred route in ULCOS TGR-BF project:

Inputs	Outputs
<ul style="list-style-type: none"> • Conventional burden material • Preheated recycling top gas with CO₂ removed or reformed top gas without CO₂ removed • Cold O₂ or hot blast • Injection of carbonaceous materials 	<ul style="list-style-type: none"> • BF gas (CO, CO₂, H₂, H₂O), BF slag, BF hot metal

Overall abatement pathway:

TGR-OBF mainly reduces carbon consumption through the following pathways:

- High CO-enriched reducing gas suppresses the direct reduction and enhances indirect reduction, leading to the reduction of coke rate
- High amounts of CO and H₂ in the top gas are recycled and injected back to the BF
- Oxygen replaces the hot air blast so that the BF productivity increases, leading to the reduction of coke consumption per tonne of hot metal (tHM)
- Preheated gas injection in the shaft zone supplies the energy to maintain the heat flow ratio, helping the BF operation with less coke used
- A large amount of oxygen injection allows higher injection rate of carbonaceous materials to minimise coke consumption
- Higher CO₂ concentration in the top gas can be captured with less energy consumption
- For Routes 6 and 7, where CO₂ is injected back to the BF as CO after reforming or as a heat carrier, the carbon consumption can be reduced if the energy for reforming and preheating is from renewable resources.

Based on the industrial trials:

- Test results from the NKG experimental BF indicated that coke rate decreases up to 200 kg/tHM with 628 Nm³/tHM of reducing gas injection
- In the Tula OBF project, coke rate decreased by 39%
- In the ULCOS-TGR OBF project, being consistent with process design results from mass and energy modelling, over 21% of carbon saving can be achieved in the BF process, based on the comparison of operational results using traditional BF and TGR-OBF conditions. Reduction in the CO₂ emissions of 50-60% in the BF is feasible.

Note: For a future PKSW BF6, a 21% carbon saving could mean that the carbon consumption is reduced from ~500 kg-C/tHM to ~395 kg-C/tHM.

Key performance indicators:

Compared to current (normal) BF conditions, the following changes may occur in a TGR-OBF:

- Coke rate: a decrease by >21% (ULCOS project)
- Productivity: an increase via higher amounts of oxygen injection and lower bosh gas flow rate
- Theoretical combustion temperature (TCT): controlled by the amount of injection materials
- HM quality: maintained in relation to the control of TCT and partial pressure of CO
- Thermal level: maintained through the preheating gas injection in the shaft
- Shaft efficiency: similar or slight decrease (ULCOS project)
- Direct reduction rate: decrease due to higher CO concentration
- Injection rate of carbonaceous materials: increase
- Heat loss: decrease corresponding to higher productivity and less coke consumption at tuyere
- Permeability: Improved in regard to reduced amount of BF gas

Maturity and requirements to implement:

TGR-OBF technology is still under development. New scale-up trials were recommended by the ULCOS TGR-OBF project. To successfully implement TGR technology, it is inevitable to modify the traditional BF process and equipment design, and the following improvements are required:

- An appropriate design for all oxygen large-scale coal and gas injection system and tuyere
- Systematic design for recycled gas pre-heating
- Technology for shaft gas injection in terms of point of injection, temperature and radial gas distribution in shaft
- Process design to transform TBF to TGR-OBF in terms of operation stability
- Appropriate furnace profile
- Energy efficiency of oxygen plant and oxygen supply system design
- An appropriate CO₂ capture and sequestration system (CCS and CCUS technologies)
- Redesign of energy supply in the integrated steelworks due to less energy supply to downstream processes
- To maximize the reduction of CO₂ emissions, the energy for CO₂ capture, gas pre-heating and O₂ production should be from external renewable energy sources

Potential strengths and weaknesses:

Strengths

- High reducing gas concentration suppresses direct reduction, the gaseous reduction rate is high and the coke consumption can be reduced
- Furnace height can be shortened due to possibly reduced reserve zone temperature, higher reduction potential of BF gas and heating-up of the burden in the shaft by preheating gas injection
- Low grade iron ore could be used
- Low strength and high reactivity coke may be used with the shorter furnace height
- High CO₂ concentration and calorific value in the top gas is beneficial for application of CO₂ sequestration technology
- A complete utilization of coke carbon chemical energy may be done
- A higher injection rate of carbonaceous materials may be achieved
- Conventional burden materials may be used
- Reduced heat loss
- Cold oxygen replacing hot air blast may be blown into the tuyeres, without hot stoves
- Bosh gas flow rate is low with the oxygen injection, and the productivity can be increased
- For Routes 6 and 7, BFG can be utilized for re-injection to BF without CO₂ removal

Weaknesses

- Costly modification of BF off-gas system for CO₂ capture and storage
- There are still uncertainties in technological development for TGR implementation (listed in Maturity section)
- Unproved process stability in a scale-up BF
- Low penetration depth of shaft gas injection, especially in a large BF
- With high CO concentration in the shaft, carbon deposition may be notable
- The energy supply to downstream processes decreases as a result of intensified top gas recycling
- A large amount of pure oxygen is required
- Penetration depth of raceway decreases
- Shaft efficiency is not clearly improved
- Large scale modifications in the existing process may be required
- For Routes 6 and 7, extra energy required for BFG reforming

Additional comments:

A commercial installation proposed for MMK (10000 tpd) is currently on hold due to geopolitical issues in Europe. Paul Wurth are currently trialing dry reforming of COG and BFG at Dillinger Hutte with the aim to commercialise and inject it into HO5 at that site by 2027.

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Blast Furnace Technology:	5 Injection of auxiliary hydrogen-enriched gases and waste plastic into the blast furnace
<p>General technology description:</p> <p>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 H₂O.</p> <p>Injection of additional renewable hydrogen and/or other hydrogen-enriched gases and materials into the ironmaking blast furnace (BF) can effectively reduce fossil fuel consumption (coke and pulverized coal) and assist in decarbonizing the process [1, 2]. Hydrogen-enriched injectants 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.</p> <p>Co-injection of additional renewable hydrogen together with other hydrogen-enriched gases/materials is a likely scenario, given the supply and operational constraints of the BF.</p> <p><u>Natural gas (NG)</u></p> <p>NG injection into a BF is widely utilized. The former USSR first introduced NG injection into the BF in 1957 [3] and by the early 1990s, the average consumption of NG was 70-100 m³/tHM, with 112 BFs of a total 133 in the USSR operating with NG injection [3]. In the 1990s, NG injection became popular in USA with average NG consumption of 40-110 kg/tHM [4]. NG injection was trialed in JFE Keihin No. 2 BF (5000 m³) of Japan at a rate of 20-50 kg/tHM in Dec. 2004 and then adopted [4, 5, 6]. In 2007, the productivity of the same BF reached a record of 2.56 t/d-m³ [5]. In Australia, NG was introduced at BHP's steel plants after the late 1980s (e.g. Whyalla in 1990).</p> <p>With ~20 wt% hydrogen, NG injection can replace coke with a replacement ratio of ~1 kg-coke/kg-NG [7] (compared with coke with 87.5% carbon). The major factor limiting the maximum NG injection rate is the furnace adiabatic flame temperature so that oxygen-enriched hot blast and preheating injection technologies were applied to improve the efficiency of NG injection [6]. It was also reported that a BF can operate with a lower adiabatic flame temperature than normal by 150-200 °C while injecting NG [8].</p> <p><u>Coke ovens gas (COG)</u></p> <p>Since the 1960s, COG injection technology has been trialed and implemented in several steel plants [6]. The injection rates ranged from 30-50 to 200-300 m³/tHM at different furnaces, with a coke replacement ratio of 0.4-0.45 kg-coke/Nm³-COG [9]. In early 2000s, a trial at Linz showed a reduction in CO₂ emissions of ~78 kg/tHM with a COG injection rate of 100 Nm³/tHM [10]. In Japan's COURSE50 project, operational trials at LKAB's Experimental BF were undertaken. COG was injected into normal tuyeres (57% H₂; 100 Nm³/tHM) and reformed COG into lower shaft tuyeres (77.9% H₂; 150 Nm³/tHM), achieving ~3% CO₂ emissions reduction [11, 12]. More recently, industrial applications of COG injection include commissioning a system at ROGESA (Germany) in 2020; at ArcelorMittal's Gijón plant in 2021 [13]; and one to be commissioned at HKM by end 2022 [14, 15]. In spite of the above applications, the replacement ratio of coke by COG is, in some cases, far lower than the theoretical value [6]. Detailed operational information from HKM, ROGESA and ArcelorMittal is not available. In Australia, COG injection was practiced in the 1990s</p> <p><u>Hot reducing gas (HRG)</u></p> <p>HRG is a mixture of reducing agents H₂, CO, and other hydrocarbons (as well as CO₂ and H₂O), which can be generated from different sources such as low-grade coals, biomass, waste, reformed BF top gas, reformed NG or reuse of off gases from other processes such as COREX. Theoretical studies, as well as pilot and industrial trials, show HRG injection can decrease total reducing agent rate, particularly in co-injection situations (e.g. with pulverized coal injection) and increase productivity [1, 16]. However, HRG</p>	

injection into BF has yet to be implemented because of its complex flowsheet, and its economic cost and technology maturity compared to traditional fossil fuel injection. As an example, biogas, a type of reducing gas, can be generated from either thermal gasification or anaerobic digestion of solid/liquid biomass materials. After the upgrade/refining, methane content in the biogas can be >90% and energy content around 39 MJ/m³ [17]. In spite of the relatively mature technology for the production of biogas, there is still a reluctance to utilize biogas from an economic point of view because of investment cost for the gasification and refining facilities, transportation and storage of gas products. This situation could change with the implementation of a carbon tax and progress in recycling and reforming technology as identified through collaborative programs such as ULCOS [18] and COURSE50 [19]. Additionally, as a major byproduct of biomass pyrolysis, the biogas can be co-injected into BF with charcoal to increase the total efficiency of biomass usage and ease the investment cost [20, 21].

Hydrogen

As steel manufacturers face challenges to reduce their greenhouse emissions, utilization of renewable hydrogen may be an alternate reductant and heat source for the BF process, generating water vapor instead of CO and CO₂ [22]. Although use of reformed hydrogen-enriched off-gas to replace coke has been explored for many years [e.g. COURSE50 project [19]], use of pure hydrogen injection into an industrial BF was not undertaken until 2019, with a single tuyere injection trial at thyssenkrupp Steel's Hamborn BF [23]. A large-scale industrial trial with injection to all tuyeres is scheduled in 2022.

Various thermodynamic and kinetic studies of iron oxide reduction using hydrogen [24, 25, 26, 27, 28] show key differences in reduction behaviour in hydrogen-rich conditions compared with CO reduction. For example, different microstructure morphologies of the product iron phase occur: after hydrogen reduction, a more dense lamellar structure is formed compared with CO reduction, where the iron phase is more fragmentary [29]. The gasification rate of coke changes with hydrogen addition. It was also observed that the change in the interaction of slag-iron and coke particles in hydrogen-rich conditions helps hinder the carburization of metallic iron. All these, and other observed changes, highlight the effect of hydrogen injection on the process performance may be significant. 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.

Based on calculations of overall energy and materials conservation, it is estimated that 100 m³/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 both reducing agent and fuel in 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 application of hydrogen injection.

Waste plastic

The injection of waste plastics composed mainly of carbon and hydrogen was first investigated at No. 2 BF of Stahlwerke Bremen in 1995 and later at JFE (formerly NKK) Keihin No. 1 BF [32, 33, 34, 35]. The recycling of plastic waste as a feedstock for the BF was, and remains, a potential sustainable solution to recycling societal waste materials. The first operational results in Bremen showed that an injection level of more than 30 kg/tHM is possible [34]. The combustibility of waste plastic depends on plastic type and size [36], which requires specific separation of materials. Therefore, the cost of collection and treatment of plastic recycling is a major constraint in the utilisation of waste plastics [37]. As well, a special facility is needed for pulverization and dechlorination of waste plastic materials. In spite of these disadvantages, there has been progress on plastic injection e.g. ~20,000-30,000 t per year of waste

plastics are injected into BFs in Japan, and the total cumulative amount from 2000 reached 500,000 t in 2014 [36].

Summary

In terms of utilizing hydrogen-enriched gases, whilst the injection of NG and COG into BF has a long history with industrial trials and application, there are currently no commercial applications of pure hydrogen or HRG injection to the BF. In particular, NG injection technology is very mature. In terms of other hydrogen-enriched materials such as waste plastic, although the application was carried out at commercial scale, the selection of materials is limited and the cost may still be a constraint.

Recent active programs related to hydrogen-enriched injectants include:

- (1) COURSE 50 with reformed COG injection in Japan
- (2) Hydrogen injection to blast furnace in thyssenkrupp Steel in Germany
- (3) COG injection at HKM and ROGESA in Germany using Paul Wurth technology, and at Gijón plant in Spain
- (4) IGAR ArcelorMittal project with dry reforming of CO₂ using a plasma torch, mainly in France.

Material inputs and outputs:

Material inputs and outputs for the blast furnace process are similar with hydrogen-enriched injection. Normally, the injection is enhanced with oxygen enrichment and preheating (particularly in the case of pure hydrogen).

Inputs	Outputs
<ul style="list-style-type: none"> • Conventional burden material • Hydrogen-enriched injection • Oxygen-enriched injection • Preheating injection • Co-injection of carbonaceous materials (optional) 	<ul style="list-style-type: none"> • Hydrogen-enriched BF gas (CO, CO₂, H₂, H₂O), BF slag, BF hot metal

NG injectant:

- 90-99% CH₄, 0.1-1.0% CO₂, 0.3-4.5% C₂H₆, 0.5-3.0% N₂, 0.1-1.2% C₃H₈, 0.1-0.8% C₄H₁₀, 0-0.3% C₅H₁₂

COG injectant:

- Cleaned COG to remove benzene, tar, naphthalene etc.
- 55-63% H₂, 22-28% CH₄, 6-8% CO, 2-4% CO₂, 2-3% C_mH_n, 0-1% O₂, 2-4% N₂, 2-3% H₂O

HRG:

- A mixture of CO, H₂, H₂O, CO₂ and/or hydrocarbons generated via gasification of low grade coals, biomass and waste, or recycling top gas (CO-rich) or other process gases (e.g. LDG)

Hydrogen: Pure H₂

Waste plastic:

- PE (polyethylene), PS (polystyrene), PP (polypropylene), PVC (polyvinyl chloride), PET (polyethylene terephthalate), etc.

Overall abatement pathway:

Auxiliary, hydrogen-enriched injectants lower carbon emissions through the following pathways:

- The reducing agent, H₂ in hydrogen-enriched gases can directly lower CO₂ emission in the BF process because the reduction product of H₂ is water.
- Hydrogen-enriched injectants lead to a decrease in fuel rate, with the coke replacement ratio varying with injectant type and specific operational conditions used for stable BF conditions.
- Reduction efficiency increases due to the existence of H₂ in BF, which causes the saving of fuel consumption.
- High amount of CO and H₂ in HRG can be generated from low grade coals, waste, or top gas, reducing carbon consumption due to improved utilization efficiency of materials.

Given that the maximum injection rate is constrained by operational conditions (e.g. minimum flame temperature, minimum top gas temperature), industrial practices and calculations indicate:

- Injection rate of NG may be up to 150-170 m³/tHM (Russia and Ukraine) [9].
- Coke replacement ratio by NG can be close to ~1 [7].
- Coke replacement ratio by COG is 0.4-0.45 kg-coke/m³-COG [9].
- Complete substitution of pulverised coal and fuel oil by NG would reduce net greenhouse gas emissions by 10% for the ironmaking process i.e. cokemaking, sintering and BF on a basis of 1,650 kg CO₂/tHM [38].
- Injection of hot hydrogen (1000°C) at 42 kg/tHM could replace 140 kg/tHM coke [1], being consistent with a previously estimated value [30].
- Injection rate of plastic can be 50-70 kg/tHM (Bremen, Germany; 1995 [36]).
- An injection rate of 40 kg/tHM waste plastics would reduce the coke rate by 13.4% [39].
- Using waste plastics for syngas production and injection into BF may realize a 7% CO₂ reduction (model estimation) [40, 41].

Key performance indicators:

Compared to typical BF operating conditions, the following changes may occur with higher rates of hydrogen-enriched injectant:

- Use of hydrogen injectants can lower the fuel rate and CO₂ emission to different extents, depending on the selection of injection material.
- Hydrogen-enriched injectants tend to cause the lower flame temperature so that oxygen enrichment and preheating of injectants are normally required.
- Hot metal quality is improved due to decreased impurities from lower fuel rate.
- Hydrogen-enriched gases improve reduction efficiency of iron ore due to the high diffusivity and reduction capability of hydrogen at high temperatures.
- Total energy consumption increases with injection of hydrogen-enriched gases.

Maturity and requirements to implement:

Technologies for different hydrogen-enriched injectants for the BF are at different technological maturity levels: NG has been widely applied, while the trials with hydrogen injection have just started.

This is driven not only by the urgency of decarbonization, but also by the economic and technological viability.

To successfully implement each hydrogen-enriched injection technology, the following improvements are required:

- Natural gas: optimal raw materials and injection design, and optimal implementation of co-injection with others
- COG: proper COG cleaning technology, and industrial trial required to establish the replacement ratio of coke by COG under different operating scenarios
- Reformed COG: continuous development of COG reforming technology
- HRG: efficiency of CO₂ and H₂O removal from generated gases, and optimal injection design
- Hydrogen: reliable hydrogen production at scale, storage and transportation, tuyere design, and industrial trials
- Waste plastic: optimization of pulverization for waste size control, dechlorination to remove chlorine content from waste, impurity control with different types of waste plastic
- All: development of pre-heating technologies and optimization of injection method to avoid peripheral gas flow

Potential strengths and weaknesses:

All gaseous injectants have strengths such as coke replacement (lower direct reduction), fast combustion (relative to coal) and reduction of CO₂ emissions. As well, they share a weakness due to the less-exothermic effect of injectants in the raceway relative to coal or coke, i.e. decrease the flame temperature. This causes a narrow operating window for BF operation with hydrogen-enriched injection compared to that with PC injection. This is usually overcome via blast oxygen enrichment. Overall, heat balance requirements for stable BF operations can be adjusted for each injectant, including establishing alternate operational settings (e.g. bosh gas volume, top gas volume, flame temperature). Depending on injection rate, higher strength coke maybe required.

Strengths	Weaknesses
NG injectant	
<ul style="list-style-type: none"> • Relatively mature technology • Relatively low investment cost for supply and negligible pre-treatment • HM quality improvement • High quality and clean reducing agent 	<ul style="list-style-type: none"> • Soot generation if NG is poorly mixed with hot blast • Potential impact on flame temperature • Cost and availability
COG injectant	
<ul style="list-style-type: none"> • Availability and stability • COG contains more than 50% hydrogen, hence a better reducing agent compared to other hydrogen-enriched gases • HM quality improvement • More valuable for COG to be injected to BF compared to other COG applications 	<ul style="list-style-type: none"> • COG requires removal of condensables (tar, naphthalene, etc) and sulphur to avoid deposition in pipework and erosion of copper elements (e.g. tuyere) by hydrogen sulphide • COG injection can cause increased peripheral gas flow • Limited supply

Hot reducing gas	
<ul style="list-style-type: none"> • Top gas or other waste gases recycled • Utilization of low-grade coal and waste • Utilization of biomass 	<ul style="list-style-type: none"> • Gas reforming required • Additional facilities and equipment required, adding significant complexity
Hydrogen	
<ul style="list-style-type: none"> • Hydrogen injection has the highest decarbonization potential without fundamental changes in the BF process • HM quality improvement • High heat capacity and diffusivity 	<ul style="list-style-type: none"> • Low maturity of renewable production at sufficient scale • Additional hydrogen is required to be consumed for providing the energy needed in BF process • Theoretically, pure hydrogen injection can cause more peripheral gas flow compared to COG injection • Potential tuyere design and pipeline changes required for safe transportation of hydrogen
Waste plastic	
<ul style="list-style-type: none"> • An auxiliary reducing agent to replace coke • Waste plastic recycling and reuse • Reducing production cost 	<ul style="list-style-type: none"> • Waste plastic materials are highly heterogeneous, consisting of different chemical types, as well as contaminants • There are differences in thermal combustion and gasification behavior of the different types of plastics • Chlorine sources (PVC) need to be removed from the waste plastics due to corrosive effects • Potential permeability issue in BF due to un-burnt char from injected plastic • Low in the waste management hierarchy
Biogas	
<ul style="list-style-type: none"> • Alternative utilization of biomass pyrolysis products, without significant capex for implementation 	<ul style="list-style-type: none"> • Composition dependent on biomass quality • Lower hydrogen content • For BF operation, maximising biochar amount is optimal
Additional comments:	

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Blast furnace ironmaking:	6 Cokemaking related technologies
<p>General technology description:</p> <p>Cokemaking is the fundamental process related to the traditional blast furnace route. Many efforts have been made to improve productivity and coke quality, and reduce the energy consumption [1, 2]. This section will cover coal moisture control and emerging technologies such as single chamber system and existing technologies potentially being implemented worldwide (stamp charging; dry quenching) or developed in Port Kembla Steel Works such as battery heating control. The technologies in relation to utilization of biomass, ferrocake and COG were introduced in Sections “Biomass application to ironmaking”, “Novel charging materials to blast furnace” and “Hydrogen enriched injection to blast furnace”, respectively.</p> <p><u>Coal moisture control (CMC)</u></p> <p>The moisture content of coking coal is about 9–12%, which can lead to high energy consumption and low efficiency during cokemaking [3]. Thus, charging drier coking coals into a coke oven has various benefits, including energy saving, improved coke quality, increased coke production, and higher usage of low quality coal [4].</p> <p>There are different coal drying methods. For example, three methods were developed by Nippon Steel such as drying through steam tube dryer (STD), coal in tube (CIT), and fluidized bed (FB) (presentation). The former two methods use steam to dry the coal, and the third one uses the waste gas from the coke oven. Among them, FB drying has the lowest energy and maintenance costs. FB technology has been widely applied [1].</p> <p>As a reference, a CMC system may dry the coking coal from 10% to approximately 6% moisture content [4]. It was reported that a 4% reduction in absolute moisture content can save ~340MJ/t-coal, increase coke production by ~11%, and improve the coke quality, DI_{15}^{150}, by ~1.7% [5].</p> <p><u>Coke dry quenching</u></p> <p>Coke dry quenching (CDQ) uses an inert gas to cool the hot coke [1, 6]. The gas can be used in a closed system to recover heat from the hot coke to produce the steam for power generation. Compared to the conventional coke wet quenching (CWQ), the benefits of CDQ are summarized below:</p> <ul style="list-style-type: none"> • Utilization of the sensible heat of hot coke • Lower air-borne dust emission • CDQ coke with less moisture content • No requirement for large amounts of water • Improved coke quality in terms of strength, size and uniformity • Allowance for increased use of semi-soft coking coal etc <p>The disadvantage is a long cooling duration of 5-6 h for CDQ [7]. CDQ has been commercially applied in steel industry worldwide.</p> <p><u>Coal stamp charging</u></p> <p>Coal stamp charging is a process using stamped coal as the charged materials. The coal can be first stamped into a solid cake outside the coke oven, using a metallic box. The cake has a similar size to the coke oven chamber and is charged directly into the oven.</p> <p>Coal stamp charging has the following advantages [8, 9, 10, 11]:</p> <ul style="list-style-type: none"> • Increased charging density and productivity of the coke oven battery • Utilization of lower cost semi-soft coals • Improved coke quality in terms of CSR (Coke Strength after Reaction) • Decreased charging related emission <p>As the coal is compacted, increased bulk density of stamped charge coal may have a negative impact on the wall of oven. There is a strong relationship between bulk density and sidewall pressure [11] so that a feasible bulk density of stamped coal should be determined to avoid damaging the oven wall and subsequent influence on the campaign life of coke oven.</p> <p>The industrial application of coal stamp charging was summarized by Madias et al. [12].</p> <p><u>Advanced control of heating walls</u></p>	

In coke ovens, the heat for coking is supplied by combustion of gas (COG/BFG) in the heating flues, which is transferred through the chamber wall. Thus, controlling this is critical for thermal stability of the coke oven battery, coke quality improvement and process energy saving.

To achieve steady heating of the coke oven, thermal control methods have been continuously developed and improved in the following ways [1, 13, 14, 15, 16]:

- Optimal feedback and feed-forward control
- Utilization of intelligent methods such as neural networks
- Integrated control and management system

These efforts have been made to better control flue temperature, fuel injection, coking time, and ultimately, more stable battery operations.

As the coking coal blends vary for each plant and the structure of the charge coal changes significantly throughout the coking process, the dynamic and complex heat transfer occurring in the oven [17, 18] means more effort is required for heat control.

Single chamber system

Single chamber system [19] was developed as an alternative cokemaking technology to the conventional multi-chamber-system. It consists of single isolated chambers with a rigid wall that can better withstand high coking pressures.

Compared to the conventional oven, the single chamber has a narrower width and greater height and length. The designed dimensions are 0.45×12.5×25 m³ (W×H×L), The structure of the single chamber allows for better heating conditions of the charge coal so that more low volatile coal may be used. Due to the large volume, the charging related emission is expected to be lower than that for conventional ovens. The rigid walls also allow an increase in throughput.

This technology was supported under the EURIKA Project 500 during 1992–96. The concept was verified in a pilot plant [19, 20]. There has been no further progress since these pilot tests.

Material inputs and outputs:

<u>Inputs</u>	<u>Outputs</u>
<ul style="list-style-type: none"> • Coal blend 	<ul style="list-style-type: none"> • Coke • Coke oven gas

Overall abatement pathway:

The pathway for reduction of CO₂ emissions through the abovementioned technologies may be indirectly reflected by the heat recovery, improved production and energy saving.

Coke dry quenching

Heat recovery can be used for steam generation of 500-700 kg/t-coke or power generation of 140-185 kWh/t-coke [21].

Coal stamp charging

Coal stamp charging potentially increases the charging density up to 35% and increases the oven productivity up to 15% [1].

Advanced control of heating walls

Through optimal heating control, a reduction of fuel consumption of 10% was reported [1, 13], which is equivalent to a reduction of the CO₂ emissions of 3.8 kg-CO₂-e/t-coke [1].

Single chamber system

It was estimated that coking productivity could increase from 78,000 to 90,000 tonnes of coke per chamber per year [19].

Coal moisture control

A 4% reduction in the moisture content of coal may save the energy of ~340MJ/t-coal.

Key performance indicators:

Industrial process performance of these technologies may be indicated by direct energy saving, production change, coke quality improvement, as well as the utilization of semi-soft (and other) coal, as summarized in Table 1.

Table 1. Summary of performance indicators of technologies

Process	Direct energy saving	Increased production	Coke quality	Utilization of non-caking coal
Coke dry quenching	Yes	–	Coke moisture (0.1-0.3%)[21]	Up to 30% blending ratio of non- or slightly-caking coal [21]
Coal stamp charging	–	Up to 15% increase. Charge density >1100 kg/m ³ [10]	Increased coke strength	Usage of semi-soft coals
Advanced control of heating walls	0.17 GJ/t-coke [1]	–	Improved	–
Single chamber system	Up to 30% energy saving* [19]	Yes *	Lower CRI and higher CSR*	Usage of more low volatile coal*
Coal moisture control	~340MJ/t-coal**	Up to ~11%**	Improved	Usage of low quality coal

* Estimated without verification

** Corresponding 4% reduction of coal moisture [5]

Maturity and requirements to implement:

Except for the single chamber system, other technologies have been applied in industry. Most required retrofitting the coke oven or the addition of affiliated facilities.

For implementation, both coal stamp charging and advanced heating control need to be evaluated in terms of the specific conditions of individual steelworks because they are closely linked to coal blends, oven structure or engineering availability.

Potential strengths and weaknesses:

<u>Strengths</u>	<u>Weaknesses</u>
<p>General</p> <ul style="list-style-type: none"> • Potentially improved coke quality, increased productivity, and energy saving • Utilization of lower quality coals <p><u>Coal moisture control</u></p> <ul style="list-style-type: none"> • Reduced energy consumption • Improved coke quality • Increased coke production • Usage of lower quality coal <p><u>Coke dry quenching</u></p> <ul style="list-style-type: none"> • Direct energy saving • Decreased coke moisture • General payback period of 3-5 years <p><u>Coal stamp charging</u></p> <ul style="list-style-type: none"> • Increased throughput • Decreased charging related emission <p><u>Advanced control of heating walls</u></p> <ul style="list-style-type: none"> • Reduced workload for workers • Precise automation control <p><u>Single chamber system</u></p> <ul style="list-style-type: none"> • Stress-bearing wall 	<p>General</p> <ul style="list-style-type: none"> • Additional facilities or further development required <p><u>Coal moisture control</u></p> <ul style="list-style-type: none"> • Set up of pretreatment plant <p><u>Coke dry quenching</u></p> <ul style="list-style-type: none"> • Long cooling time <p><u>Coal stamp charging</u></p> <ul style="list-style-type: none"> • Potential influence on chamber wall <p><u>Advanced control of heating walls</u></p> <ul style="list-style-type: none"> • Continuous development required <p><u>Single chamber system</u></p> <ul style="list-style-type: none"> • Not mature

Additional comments:

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Blast furnace ironmaking:	7 Sintering related energy saving and emission reduction
<p>General technology description:</p> <p>Sintering is a key agglomeration process for iron ores at many steelworks. The energy consumption of the sintering process is ~10% of the whole steelworks [1]. Therefore, reasonable measures may be taken to recover and appropriately utilize waste heat, apply microwave technology for ignition, use hydrocarbon gases for sintering or decrease the sintering bed temperature; ultimately, these may contribute to overall energy savings and help reduce CO₂ emission. In this regard, this section will cover the following technologies:</p> <p>(1) proven technology for waste heat recovery from cooler and waste gas recycling, and</p> <p>(2) emerging technologies such as low temperature sintering, microwave assisted ignition, and Super-SINTER technology.</p> <p><u>Waste heat recovery from cooler</u></p> <p>Massive amounts of heat input used in the sintering process is released to the atmosphere [1]. The sensible heat of air from the sinter cooler is one kind of potential reusable waste heat. Along the moving direction of the sinter cooler, the cooling air temperature varies within a certain range. The measured maximum temperature of cooling air can be up to 800°C [2]. The whole cooling zone can be divided into different sectors [3]. To improve the energy recovery from this waste gas, a high-temperature exhaust section may be installed, separated from a low-temperature exhaust section. The former may be used to produce steam or electricity while the latter (low grade waste heat) for direct thermal utilization. Generally, the waste gas from cooler can be utilized in the following ways [1]:</p> <ul style="list-style-type: none"> • Steam generation in a waste gas boiler • Hot water generation for heating • Preheating combustion air in the ignition hood of the sinter plant • Preheating the sinter raw mix (current PKSW practice) • Using the waste gas in a recirculation system <p>Some industrial practices are given below:</p> <ul style="list-style-type: none"> • Up to 60% of the exhaust heat from the sinter cooler can be reused as steam or electricity through cooler waste heat recovery system (WHRS) developed by Steel Plantech [4]. 26 kW power or 132 kg-steam can be generated per ton of sinter. • Heat recovery system at Dillinger Hütte’s sinter plant in Germany allows the generation of additional electrical energy 82000 MWh, which is equivalent to a reduction in carbon emissions of ~25000 t/year [5]. • In AM’s recent study on the heat source for steam generation for their 3D project, sinter cooler ranked the first in the heat recovery source [2]. <p><u>Waste gas recycling</u></p> <p>Various recycling systems have been developed to reduce gas emissions and reuse waste heat. These include earlier developments such as Emissions Optimisation System (EOS), Low Emission and Energy Optimised Sinter Process (LEEP) and Environmental Process Optimized Sintering (EPOSINT) [6]. By way of example, EPOSINT, which was developed jointly by voestalpine Stahl Linz and SIEMENS VAI, involves waste gas from selected wind boxes being recirculated back to the sinter strand. This system provides additional operational flexibility and significantly reduces dust and other pollutants in the waste gas stream. Oxygen content of the recycled gas is increased using exhaust air from the cooler. Based on plant trials undertaken at Linz [7], reductions in ignition gas and coke breeze consumption rates were achieved (~10-20%), with improvements in sinter reducibility and cold strength but lower Reduction Disintegration Index (RDI). The system was implemented at voestalpine Linz’s No. 5 Sinter Strand.</p> <p><u>Low temperature sintering</u></p>	

Low temperature sintering was summarized in a comprehensive review of decarbonization technologies [8]. Currently, there are very few references in this area. Two key points in the concept of this technology as a patent [9] are given below:

- The sinter raw mixture consists of iron ore fines (<8 mm), coke powder and quicklime, which is granulated using water vapor.
- The thickness of green sinter bed is 500~600 mm. The ignition temperature is controlled at 1050±50°C and the maximum sintering temperature between 1250 and 1270°C. The duration of sintering with temperature above 1100°C is controlled over 6 minutes.

The implementation of these conceptual points was not provided in the review. This needs to be verified in practice, including in terms of the economics of the whole sintering process, sinter quality and production.

Microwave assisted ignition for iron ore sintering

Iron ore sintering beds are normally ignited within an ignition furnace using a high calorific value gas, such as coke oven gas or a mixture of gases. Associated carbon emissions may be decreased using microwave-heated airflow to assist the ignition of the coke breeze, at both lower temperatures and with a lower ignition energy requirement. Furthermore, sinter pot testing has shown that higher level of oxygen available (21% in air compared to gas combustion in the freeboard) improves sinter productivity and quality (higher drum strength and improved sinter microstructure) [10, 11].

Super-SINTER technology

Super-SINTER refers to a secondary fuel injection technology process, developed by JFE Steel [12]. In the sintering process, hydrocarbon gases such as natural gas is introduced into the sintering bed to partially replace coke breeze. The favorable sintering temperature, which is lower than the maximum combustion temperature, can be maintained for a longer period. The total energy consumption for sintering decreases, sinter SFCA ratio increases and bed permeability can be improved. Super-SINTER technology is another type of low temperature sintering process.

JFE Steel started to commercially utilize Super-Sinter technology in Keihin plant in 2009. It is claimed that the plant can reduce CO₂ emission by 60,000 tonnes per year. This technology was then implemented in other JFE plants, such as Kurashiki plant [13].

Similar top gas injection technology was commercially implemented in several Chinese steelworks, covering various gases, such as top COG injection at MeiSteel [14, 15], top natural gas injection at Zhongtian Steel [16], and surface steam spraying at ShouGang [16, 17, 18]. It was reported that top gas injection helps the reduction of solid fuel consumption by 4.68 kg/t-sinter at MeiSteel [14] and more recently, surface steam spraying causes a decrease in fuel consumption of 2 kg-solid fuel/t-sinter and 25% reduction in CO emissions in sintering [16].

Material inputs and outputs:

<u>Inputs</u>	<u>Outputs</u>
Waste heat recovery from cooler	
<ul style="list-style-type: none"> • Cooling air (high temperature, dusty) 	<ul style="list-style-type: none"> • Cooling air (low temperature, clean)
Waste gas recycling (EPOSINT)	
<ul style="list-style-type: none"> • Recirculated outlet gas from selected wind boxes • Sinter cooler waste gas 	<ul style="list-style-type: none"> • Waste gas (CO, CO₂, N₂, O₂, H₂O)
Low temperature sintering	
<ul style="list-style-type: none"> • Sinter raw mix (iron ore fines, coke powder, quicklime, or other flux) • Return fines • Air 	<ul style="list-style-type: none"> • Sinter • Cold return fine • Waste gas (CO, CO₂, N₂, O₂, H₂O)
Microwave assisted ignition	

<ul style="list-style-type: none"> • Air flow heated by microwave for ignition 	<ul style="list-style-type: none"> • Waste gas (CO, CO₂, N₂, O₂, etc.)
Super-SINTER technology	
<ul style="list-style-type: none"> • Sinter raw mix (iron ore fines, coke powder, quicklime, or other flux) • Return fines • Air and hydrocarbon gases 	<ul style="list-style-type: none"> • Sinter • Cold return fine • Waste gas (CO, CO₂, N₂, O₂, H₂O)
<p>Overall abatement pathway: Heat recovery from sinter cooler directly saves energy, helping reduction of CO₂ emission. Generally, the heat recovery can cause electricity savings of 22.1 kWh/t-sinter and CO₂ reduction of 19.9 kg-CO₂/t-sinter for 395t/h sinter production capacity [19]. From the viewpoint of investment, payback time of heat recovery facilities is 5.5 years [20]. Recirculated wind box off gas recycling can decrease coke breeze consumption by between 10-20%, with similar improvements in consumption of ignition gas [7]. If the sintering process can be operated in a relatively low temperature condition, it can directly decrease the consumption of solid fuel and the heat loss. Through microwave technology, the ignition can be carried out at a lower temperature, and lower energy consumption. As well, more oxygen available for ignition potentially increases the combustion efficiency of coke breeze. Super-SINTER technology has reportedly helped decrease fuel consumption by 3.1 kg/t-sinter and reduce CO₂ emissions by a maximum of ~0.17Mt per year at JFE Steel's Kurashiki No.2-4 sinter plants [12].</p>	
<p>Key performance indicators: Heat recovery rate from the cooling air is a key performance indicator. As the recovered heat is used to produce steam and further electricity, the energy conversion efficiency is also an important performance indicator. All these information depend on the technology provided by supplier and specific recovery route. Waste gas recycling KPIs include sinter quality, particularly strength and RDI. For low temperature sintering, the key performance indicators are sinter quality, production and fuel consumption. No information are available. In terms of microwave assisted ignition, the energy consumption during ignition and the influence of ignition on the permeability of sintering bed are the key performance indicators. Super-SINTER technology improves sinter quality such as tumble index and reduction index, and decreases the total energy consumption for sintering.</p>	
<p>Maturity and requirements to implement: The technology for heat recovery from sinter cooler and waste gas recycling was proved and implemented in industry. For further development, the recovery and utilization of low grade waste heat should be one of options. The technology for low temperature sintering is not well established. Fundamental study, industrial verification and detailed implementation are required. Microwave technology for ignition has been verified at the laboratory level and requires to be tested at larger scale. Super-SINTER technology has been commercially applied in JFE Steel. However, due to the utilization of hydrocarbon gases, an economic analysis is required to assess its viability. In addition, it is not clear what is the optimal length of the sintering bed with gas injection.</p>	
<p>Potential strengths and weaknesses:</p>	
Strengths	Weaknesses
<ul style="list-style-type: none"> • More heat recovery leading to less CO₂ emission 	<ul style="list-style-type: none"> • Additional facilities required to set up waste heat recovery and waste gas recycling systems

<ul style="list-style-type: none"> • Recycling waste gas (e.g. EPOSINT) may lower SO_x and NO_x, as well as carbon emissions <p>Microwave assisted ignition</p> <ul style="list-style-type: none"> • Decreased ignition temperature • More oxygen availability for coke breeze combustion <p>Super-SINTER technology</p> <ul style="list-style-type: none"> • Lower sintering temperature causing less energy consumption • Long holding time of sintering above 1200 °C improves the sinter quality 	<p>Microwave assisted ignition</p> <ul style="list-style-type: none"> • Development at the early stage <p>Super-SINTER technology</p> <ul style="list-style-type: none"> • Depending on the availability of hydrocarbon gases
<p>Additional comments:</p>	

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Alternate ironmaking:	8 Electrolysis of iron ore
<p>General technology description</p> <p>Electrolysis of iron oxide is an electro-chemical process to produce metallic iron and oxygen, using direct electric current [1].</p> <p>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 CO₂ emissions [1, 2].</p> <p>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 [3], molten oxides act as the electrolyte with operating temperatures over the melting point of iron [4, 5].</p> <p>Generally, further broad application of electrolysis of iron oxide in the ironmaking field is closely related to the availability of suitable anode materials, proper selection of electrolyte in terms of its physical and chemical properties, optimal electrolysis cell configuration, better control of process temperature and electrical current, acceptable iron ore properties and sustainable cell materials in highly corrosive environment [2, 5, 6, 7, 8, 9].</p> <p>Currently, two types of electrolysis-based ironmaking technologies are being developed [4, 10]:</p> <p>(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 [11], and b) the ULCOLYSIS process developed through the ULCOS project [12]. These processes are similar – the MOE process is mainly used in subsequent sections.</p> <p>(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) [13].</p> <p>In the <u>MOE process</u>, the iron ore is dissolved in a molten oxide mixture, such as silicon oxide and calcium oxide, at 1600°C [11]. The anode is made of a material inert to the oxide mixture [14]. Oxygen evolves as a gas at the anode, and iron is produced as a liquid metal at the cathode. The liquid iron collects at the bottom of the cell.</p> <p>The first commissioned semi-industrial MOE cell was built in 2014 and has produced a total of ~1t of metal [15]. Boston Metal is now aiming to construct a pilot scale plant [11].</p> <p>In the <u>ΣIDERWIN process</u>, super fine iron ores (10 μm) are reduced using a sodium hydroxide electrolyte at a temperature of 110°C [16, 17, 18]. At the TRL 4 stage of Siderwin project, a lamellar anode was used while the cathode materials may be based on graphite. The product is solid iron in form of plate deposited on the cathode. The purity of iron produced can reach 99% [2, 19].</p> <p>Laboratory pilot tests used to validate the feasibility of the ΣIDERWIN technology at TRL 4 has produced 4 kg iron samples. An industrial pilot plant is being developed at ArcelorMittal Maizieres Research, aiming to produce 5000 t-iron/year [19, 20]. However, it is expected that at least a decade is needed to reach a full industrial scale operation.</p> <p>A comparison between these two electrolysis processes is given in Table 1.</p>	

Table 1. Comparison of electrolysis processes

Electrolysis process	Electrolyte	Operating temperature, °C	Electrode (Anode/Cathode)	Production capacity, Mt/year	Level
MOE process	Molten oxide*	1600 [11]	Inert metallic/Fe	Up to 1***	Pilot
ΣIDERWIN process	Alkaline solution	110**	Ni/Graphite or stainless steel	Up to 1 [19]***	Pilot

* Molten oxide can be a mixture of Al₂O₃-MgO-SiO₂-CaO in different proportions [4].

** Industrial pilot scale condition [19]

*** Designed industrial production capacity

Material inputs and outputs:

Inputs	Outputs
Molten oxide electrolysis (MOE) process	
<ul style="list-style-type: none"> • Low- and mid-grade iron ore fines • Molten oxide such as Al₂O₃-MgO-SiO₂-CaO 	<ul style="list-style-type: none"> • Metallic iron • O₂
ΣIDERWIN process	
<ul style="list-style-type: none"> • Ultra fine iron ore (10 μm) • Alkaline solution (NaOH) 	<ul style="list-style-type: none"> • Metallic iron • O₂

Overall abatement pathway:

Electrolysis of iron ore would be a near carbon-free ironmaking process, with both MOE and ΣIDERWIN processes utilizing electricity generated from renewable sources.

For the ΣIDERWIN process, the estimated energy needed for the overall conversion process from iron ore to liquid steel is expected to be 13 GJ/t-iron. Considering the requirement of iron ore grinding and purification, the Siderwin project has a target to reduce CO₂ emissions and energy consumption by 87% and 31% compared to BF-BOF route, respectively [7].

In both MOE and ΣIDERWIN processes, a massive amount of oxygen may be produced as a by-product, with commercial value.

Key performance indicators:

Performance attributes of the two electrolysis processes are compared in Table 2 in terms of electrical energy consumption and operating current and voltage. Note that the current density and voltage significantly depend on electrolyte properties.

Table 2. Comparison of electrolysis processes

Process	Energy consumption, GJ/t-Fe	Current density, A/m ²	Voltage, V
MOE process	>10* [2] or 14.4* [21]	>10000 [2]	>3 [4]
ΣIDERWIN process	13* [17]	1000** [17]	1.7** [17]

* Estimated

** ΣIDERWIN process at TRL 4 stage (laboratory pilot)

Maturity and requirements to implement:

The concept of both MOE and ΣIDERWIN processes has been proved feasible at laboratory scale. However, technological development is required before electrolysis becomes economically and practically viable. This includes the development 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, understanding of electrochemical mechanisms at large-scale operation and

their influence on the efficiency of energy utilization, and reliable process control in terms of continuous operation and product uniformity.

Although the technology readiness of both MOE and ΣIDERWIN processes is currently still low, both were expected to reach some level of industrialization after a decade. [11, 19].

Potential strengths and weaknesses:

Compared to the conventional blast furnace ironmaking, electrolysis processes have the following features:

Strengths	Weaknesses
<p>General</p> <ul style="list-style-type: none"> • No CO₂ produced during electrolysis process • Expected energy efficiency and process simplification due to electrification <p>MOE process</p> <ul style="list-style-type: none"> • Potential utilization of low- and mid-grade iron ore <p>ΣIDERWIN process</p> <ul style="list-style-type: none"> • Low temperature operation • Tolerance of the power shutdown • Flexibility of production and electricity usage to avoid the peak power usage time 	<p>General</p> <ul style="list-style-type: none"> • Utilization of more electrical energy • Inert anode required to be developed <p>MOE process</p> <ul style="list-style-type: none"> • Molten electrolytes corrosive to the anode and cell refractory • Limited mechanistic understanding of high temperature electrolytic processes • Sensitive to the power shutdown <p>ΣIDERWIN process</p> <ul style="list-style-type: none"> • Requirement of grinding and purification of iron ore at the current stage • Limited knowledge for further scale-up in terms of electrochemical mechanisms and integration with upper- and down-stream processes
<p>Additional comments:</p>	

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Alternate ironmaking:		9 Rotary kiln furnace direct reduction
<p>General technology description:</p> <p>Rotary kiln (RK) processes are coal-based, direct reduction processes using a rotating kiln as the reactor. The process is relatively flexible with the type of iron bearing materials used (e.g. lump ore, pellets, fine ore or ironsands), and carbonaceous materials (e.g. non-coking coal, coke breeze, charcoal, lignite, or anthracite).</p> <p>In 2020, more than nine RK processes were in operation with a capacity greater than 50 kt/year [1], including SL/RN, JINDAL, DRC, CODIR, TISCO, SIIL, OSIL, DAV, BGRIMM, and others. These operations are similar in principle, with only slight differences [2, 3]. Among them, the SL/RN process is the most widely used, having been developed in the early 1960s by Lurgi (now Metso Outotec) [4, 5]. The SL/RN will be used to illustrate the basic RK process.</p> <p>In the standard SL/RN process, iron bearing materials, solid reductant and limestone/dolomite are fed into the top end of a rotating inclined kiln and slowly travel to the discharge end, under gravity. The residence time of the charge in the kiln is 8-12 hours [6]. The iron ore is heated and reduced as it passes down the length of the kiln. Primary air is blown into the kiln from the discharge end, where coal is also injected and combusted to supply heat and produce the required reducing conditions [2, 7]. Secondary air is provided along the entire length of the kiln through the air tubes protruding from blowers mounted to the kiln shell. Approximately 50-60% of the kiln's volume is freeboard; here, coal volatiles and surplus CO from the charge is burnt in the presence of oxygen from air, producing heat to attain a uniform temperature distribution through the kiln [8, 9]. Note that surplus CO is generated as the reduction of iron ore and coal gasification occur within the charge. A relative uniform temperature between 920°C and 1100°C can be achieved in the charge to reduce iron oxides in the solid state [4]. The final product DRI may be magnetically separated from coal ash and unreacted char, after the mixture is discharged from the kiln.</p> <p>Normal coal consumption in the SL/RN process is 450-480 kg/t-DRI [2]. The production capacity of a standard SL/RN kiln (4.8 x 80 m) and its variant, SL/RN-Xtra, can be up to 160 and 200 kt-DRI/year [4], respectively.</p> <p>The main differences in the individual processes are related to the feed ratio, charging location, kiln dimensions, air and coal injection methods and operating conditions. Differences between the three major RK processes, i.e. SL/RN, JINDAL and DRC [1], are given below.</p> <p>Compared to the SL/RN process, the Jindal process [2] has:</p> <ul style="list-style-type: none"> • ~40% of total coal charged from the inlet side and the remainder injected at the discharge end of kiln. • An innovative placement of the secondary air tubes within the kiln. • Ability to use blast furnace gas, leading to coal consumptions of 250-300 kg/t-DRI. <p>The difference in DRC process [2] relates to the secondary air injection. In the DRC process, the secondary air tubes in the pre-heating zone of the kiln are positioned to give co-current flow with the kiln gas, whereas the air tubes in the reduction zone provide counter-current flow, aimed at optimizing heat transfer in the kiln.</p> <p>Currently, most plants using rotary kiln technologies are in India.</p>		
Material inputs and outputs:		
<u>Inputs</u>		<u>Outputs</u>
<ul style="list-style-type: none"> • Lump ore or pellets, coal, dolomite/limestone • Air 		<ul style="list-style-type: none"> • DRI, char • Off gas composed of N₂, CO, CO₂, H₂, H₂O etc.
Overall abatement pathway:		

Overall energy consumption and CO₂ emission of RK processes is higher compared to the BF route, and is unlikely to be instituted in the steel industry's abatement pathway. However, RK processes may be suitable for the utilization of very low grade raw materials and non-coking coals. Potentially, biomass materials may be used as a reductant [10].

Key performance indicators:

Three major RK processes, i.e. SL/RN, JINDAL and DRC, are compared in terms of energy consumption, reduction temperature and metallization.

Table 1. Comparison of production related parameters

Process	Energy consumption, GJ/t-DRI	Production, Mt/year	Reduction Temperature, °C	Metallization, %
SL/RN	20* [2]	0.2 [1, 4]	920-1100°C [4]	93 [6]
Jindal	17.5-19 [2]	0.15 [1]	1000-1080 [2]	90 [2]
DRC	16.5-18.5 [2]	0.15 [1]	-	92-97 [2]

* There are different consumption values reported e.g. 14.6 GJ/t-DRI by Zervas et al. [5].

Maturity and requirements to implement:

Rotary kilns are commercially proven, flexible reactors using low-grade iron ore and coal. To potentially utilize the process more broadly, the following issues may need to be developed:

- Application of different reducing agents for burners
- Substitution of air with O₂ to increase the productivity and lower CO₂ emission
- Better control of accretion buildup and material segregation in the kiln
- Solution to low production capacity
- Utilization of RK to process more types of iron bearing ores, such as ferruginous manganese ores [11]

Potential strengths and weaknesses:

<u>Strengths</u>	<u>Weaknesses</u>
<ul style="list-style-type: none"> • Low investment and operating cost • Increased reduction efficiency by mixing coal and iron oxides in the kiln • Large freeboard space in the kiln tolerant for the heavily dusted gas • Utilization of low quality coal • Utilization of a wide range of iron-bearing materials 	<ul style="list-style-type: none"> • Potential segregation of the charge materials in the kiln, leading to product quality issues • Potential formation of accretions on the kiln lining [2, 12] • Low energy efficiency and productivity • Fragmentation and clustering of charge materials in the kiln affecting the operation efficiency

Additional comments:

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Alternate ironmaking:	10 Rotary hearth furnace direct reduction
<p>General technology description:</p> <p>Direct reduction (DR) processes based on a rotary hearth furnace (RHF) are coal based, processing agglomerated ore fines and/or steel plant ferrous wastes (pellets or briquettes), carbonaceous materials and a binder [1]. The RHF consists of a flat refractory hearth rotating inside a high temperature circular tunnel kiln. The agglomerates are fed continuously into the hearth with a shallow depth, and stay inside the rotary hearth for one revolution. Burners located above the hearth provide energy required to heat and reduce the agglomerates in the pre-heating and reduction zones. The materials are normally heated up to 1300°C and reduced in the solid state. The metallized product can be CDRI, HDRI, HBI or hot metal [2].</p> <p>RHF trials involving iron ore reduction were first undertaken by Midland Ross Co. (now Kobe Steel and MIDREX Technologies) [3]. A pilot plant was constructed in 1965, but further development was suspended because other technologies were more feasible due to low natural gas costs at that time. In the 1990s, development recommenced with a pilot plant built at Kobe Steel, which led to the Fastmet process [3]. The first commercial Fastmet plant, with a capacity of 0.19 Mt/year of steel plant wastes material processed, was commissioned in 2000. Later, Fastmelt was developed to melt DRI produced from Fastmet to generate hot metal. In the 1990s, Kobe Steel also developed the ItMk3 process [4] to produce iron nuggets. The ItMk3 process was initiated after it was observed that metallic iron can be easily separated from slag within ten minutes of heating. The first commercial ItMk3 plant was commissioned in 2010.</p> <p>Other RHF processes operating worldwide include Redsmelt and Primus, being developed by Paul Wurth [5] in collaboration with Severstal and ArcelorMittal, respectively.</p> <p>These RHF processes are similar - all are coal-based reduction processes. As well, they can deal with low grade iron ore fines or a variety of steel plant wastes such as BF/BOF dust, mill scale and filter cake. The major differences between them are raw material inputs, the layer thickness of solid materials in the hearth, operational conditions such as rotation speed and operating temperature, final product, and furnace design such as burner locations.</p> <p>A brief introduction of major processes is provided below.</p> <p><u>Fastmet/Fastmelt [6]</u></p> <p>In the Fastmet process, iron ore fines, steel plant wastes or other iron containing wastes are first pelletized or briquetted along with the reductant (coal) before being charged to the RHF. The feed agglomerates are charged on to the hearth with a one or two particle layer depth. As the hearth rotates, these materials are heated to 1250-1350°C [7] by burners in the RHF roof and/or sidewalls as well as energy from post combustion of CO evolved during reduction. The typical residence time of pellets on the hearth, which experience heating and pre-reduction, is 6-12 mins [6, 8]. The iron oxide is primarily reduced by carbon in the agglomerates. The metallization degree of final product is 85-92% [8, 9].</p> <p>The product, DRI/HBI, discharged out of the Fastmet process, can be used as a core or supplemental source of iron for the BF, BOF or EAF. The carbon content in DRI can be adjusted as per customer's requirement [3, 8].</p> <p>In Japan, there were six RHF facilities processing steel plant wastes by 2014, with a typical capacity of 0.2 Mt per year [1, 8]. Some facilities are also operating in other countries, such as USA and China e.g. USA plant production capacity up to 0.9 Mt per year [10].</p> <p>The Fastmelt process was developed to melt DRI produced from Fastmet to generate hot metal, using an electric ironmaking furnace [7].</p>	

Redsmelt

The Redsmelt process combines a RHF, based on Inmetco technology [1, 10], and a smelting furnace. The RDI is directly sent to the smelting furnace. Similar to Fastmet, pellets can be made from a wide variety of metallic feeds and carbonaceous materials [11, 12].

Redsmelt has two reduction steps. A RHF is used to pre-reduce iron bearing materials up to 70-90% metallization [11] and a smelting furnace complete the remaining reduction and smelting to hot metal.

Compared to the Fastmet process, the residence time of the pellets in the Redsmelt RHF is longer (10-18 mins [11]), the layer thicker (~30 mm [1]) and the operating temperature can be higher (1450°C [11]).

The process can be designed for a production capacity of 0.3 to 1.0 Mt of hot metal per year.

ItMk3

The development of ITmk3 process started by Kobe Steel in 1996 to produce iron nuggets from iron ore and coal fines [4].

Compared to Fastmet/Fastmelt, the major differences for ITmk3 [1, 4, 13, 14] are:

- Charged materials are composite pellets made from iron ore fines with pulverized non-coking coal.
- Agglomerates are heated up to 1450°C in the furnace.
- Melting is performed in the last section of the hearth, enabling metallic iron to separate from the slag (gangue).
- Iron ore fines are processed to iron nuggets with 97% iron content [6].

The first commercial plant with an annual capacity of 0.5 Mt started in 2010 [13, 14].

Primus

The Primus process is a multi-hearth furnace for the reduction of iron- and steelmaking byproducts. The process includes a specially designed EAF for melting.

In the multi-hearth furnace, the metal oxides and coal fines are first charged to the topmost hearth and are then transported to the next hearth at the lower level by scrapers [10]. The coal fines can be added at other levels of the furnace. Air is injected into the furnace at each level. The combustion of coal volatiles and the excess CO gas takes place to provide energy to dry, heat and reduce the metal oxides when they are transported from the topmost hearth to the lowest hearth. The maximum temperature is typically around 1100°C. DRI from multi-hearth furnace contains 50-80% Fe and has to be transformed to hot metal through a melting furnace prior to steelmaking.

A pilot plant was constructed in 2000 to confirm the viability of the reduction process during continuous operation. As yet, no commercial plant has been set up [10].

Paired straight hearth furnace

The paired straight hearth furnace (PSHF) was designed to reduce iron-ore/coal composite agglomerates or steel plant waste oxides in deep pellet beds. It is part of a new coal-based, coke-less hot metal production process [15].

In the PSHF, a multi-layer, nominally 120mm high bed of composite dried green balls made from iron oxide, coal and binder is set up on a refractory hearth moving in a tunnel. Two tunnel furnaces side by side with opposite movement are coupled, allowing combustibles from one furnace to be used in another parallel furnace in order to maximize fuel efficiency and also prevent oxidation of the reduced pellets.

In each tunnel, the pellet bed absorbs radiant heat energy from the high temperature refractory surfaces, with a strongly reducing gas atmosphere generated in the bed due to volatile matter released from the coal contained in the pellets. The whole reduction process produces a highly metalized DRI product.

The original concept of PSHF was completed in 2002 by McMaster University. Further tests of proposed PSHF process were done in a large batch furnace through a 5-year collaboration project from 2008 to 2013. During the project, the reaction rates obtained in the tests indicate that the productivity in a large furnace will not be as high as that observed in the small-scale furnace tests [15]. A demonstration plant with a capacity of 50,000 t-DRI/year was designed as part of project outcome. No further progress has been made since 2013.

Material inputs and outputs:

<u>Inputs</u>	<u>Outputs</u>
Fastmet/Fastmelt	
<ul style="list-style-type: none"> • Pellets/briquettes (iron ore fines, steel plant wastes, coal and binder) • Air and burner fuel (natural gas, oil or pulverized coal) 	<ul style="list-style-type: none"> • CDRI, HDRI, HBI or hot metal • Off gas composed of N₂, CO, CO₂, H₂, H₂O etc.
ItMk3	
<ul style="list-style-type: none"> • Pellets/briquettes (made from iron ore and coal fines) • Air and burner fuel (natural gas, oil or pulverized coal) 	<ul style="list-style-type: none"> • Iron nuggets • Off gas composed of N₂, CO, CO₂, H₂, H₂O, etc.
Primus	
<ul style="list-style-type: none"> • Metal oxides (iron ore, dust, sludge, mill scale) and coal fines • Air 	<ul style="list-style-type: none"> • DRI or hot metal • Off gas composed of N₂, CO, CO₂ etc.
Redsmelt	
<ul style="list-style-type: none"> • Pellets/briquettes (iron ore fines, steel plant wastes, coal, lime and binder) • Air and burner fuel (natural gas, oil or pulverized coal) 	<ul style="list-style-type: none"> • CDRI, HDRI or HBI • Off gas composed of N₂, CO, CO₂, H₂, H₂O etc.
Paired straight hearth furnace	
<ul style="list-style-type: none"> • Iron-ore/coal composite agglomerate or waste metal oxide • Air and burner fuel 	<ul style="list-style-type: none"> • CDRI, HDRI or HBI • Off gas composed of N₂, CO, CO₂, H₂, H₂O etc.

Overall abatement pathway:

RHF processes can help the abatement of emission and energy through the following pathways:

- Recycling/processing of steel plant byproducts containing iron, zinc, flux and other non-ferrous metals
- Elimination of waste disposal cost and landfill liability

- Transformation of waste to a quality source of iron (DRI)
- Agglomerates containing iron ore and coal fines making reduction more efficient
- Increased EAF productivity by 5 to 8% using Iron nuggets (ITmk3)
- Less CO₂ emissions (ITmk3) by 8–17% compared to BF [16]
- Reduction of CO₂ emission by one third compared with BF (estimated for PSHF with an electrical smelter) [15, 17]

Regarding CO₂ emissions, there are different estimates available. Theoretical model analysis from Kumar et al. [18] estimates the net total CO₂ emission through the RHF-EAF route are 1.85 t/t steel using coke oven gas and natural gas. This is similar to the BF-BOF route.

Key performance indicators:

Most RHF processes are used to process waste materials. The production related parameters for different processes are compared below.

Table 1. Comparison of production related parameters

Process	Production capacity, Mt/year	Number of layers	Residence time, minutes	Reducing T, °C
Fastmet	0.9 (max) [10]	1-2 [6]	6-12 [6]	1250-1350 [7]
Redsmelt	0.3 -1.0 (design) [11]	3 (~30 mm) [1]	10-18 [11]	- 1450 [11]
ItMk3	0.5 (max) [14]	1-2 [7]	~10 [16]	1350 – 1450 [19]

Note: Reaction time of iron ore in ItMk3 refers to residence time.

Maturity and requirements to implement:

Kobe Steel's Fastmet/Fastmelt has been commercialized worldwide to show the capability of RHF for processing the steel plant wastes. Iron nuggets produced via the ItMk3 process, provide pure iron sources for EAF with a good quality in terms of easy melting and low impurities.

For a broader application of RHF technology beyond the recycling of waste materials, the following issues are in play:

- Current production capacity of RHF needs to be scaled up
- Utilization of hydrogen for burner fuel could be a long term goal
- Economic analysis of RHF application should be assessed in the integrated steelworks context

Potential strengths and weaknesses:

Strengths	Weaknesses
<ul style="list-style-type: none"> • Relatively simple process for operation and plant setup • Utilization of low grade materials (ore and coal fines) • Industrially proven reliability of equipment • Environment friendly process • Efficient recycling of steel plant waste containing iron and zinc • DRI being used in BF, BOF and EAF with less zinc and dioxin • Low fine generation due to stationary ore fine in most RHF processes 	<ul style="list-style-type: none"> • Low productivity due to limited materials thickness in relation to the heat transfer mainly by radiation • Significant linkage between the economy of the RHF process and raw materials used • Potential non-uniform reduction of pellets/briquettes at different layers in multi-layer bed RHF [20]

<ul style="list-style-type: none"> • Potential utilization of biomass and waste charcoal in the process • Iron nuggets alleviating the demand of steel scrap • Agglomerates with mixed iron ore and coal fines causing the occurrence of rapid carburization 	
Additional comments:	

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Alternate ironmaking:	11 Fluidized bed direct reduction
<p>General technology description:</p> <p>For blast furnace ironmaking, the iron ore fines must go through an agglomeration process, either pelletizing or sintering, before they are charged into the furnace. To directly utilize iron ore fines without any agglomeration treatment, alternate ironmaking processes were developed.</p> <p>The fluidized bed direct reduction process [1] is an example where iron ore fines with a wide size distribution are used directly, without agglomeration being required. Utilization of ore fines in the ironmaking process can help decrease energy consumption and CO₂ emissions.</p> <p>In a fluidized bed reactor, bubbling and turbulent fluidization can occur depending on fluid velocity and particle properties, which are closely related to mass and heat transfer, chemical reaction, fines mixing and fluidization efficiency [2]. Industrial applications of fluidized beds for reduction of iron oxide commenced in the 1950s and reactor design has experienced a range of developments since then. In the early stages, pioneering processes such as H-iron, Nu-Iron, Stelling, Fior and FluoSolids processes were developed [2, 3]. Most were unsuccessful in achieving industrial maturity. Only a few processes such as Fior were further developed.</p> <p>Since the 1990s, Finmet [3], Circored [4] and Hyfor [5] processes have been developed. As well, fluidized bed reactors were used at the pre-reduction stage of some smelting processes such as Finex [6, 7] and Circofer [8].</p> <p>Generally, for a typical fluidized bed direct reduction process, iron ore fines go through multi-stage fluidized bed reactors where they may be more evenly heated and reduced to metallic iron, i.e. direct reduced iron (DRI), by reducing gas. Reducing gas can be reformed natural gas, syngas or pure hydrogen. In the fluidized bed reactor, iron ore fines are transformed into a fluid-like state through suspension in a reducing gas environment. The well-mixed reducing gas and ore fines can lead to near isothermal conditions throughout the reactor. 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. Thus, staging design (multiple fluidized bed reactors) is normally applied.</p> <p>Fluidized bed technologies differ in the bed design, raw material input, reducing gas composition and operational conditions. In terms of these differences, recently developed processes will be briefly introduced below, including Finmet, Finex, Circored, Circofer and Hyfor processes.</p> <p><u>Finmet</u></p> <p>Finmet is a further development of the Fior process [3] by Siemens VAI Metals Technologies (now, Primetals Technologies), which is composed of inter-linked four-stage fluidized bed reactors for producing hot briquetted iron (HBI). During operation, iron ore fines are first dried and then charged to the top reactor. Note that 95% of the total mass is in the size range of 50 µm to 8 mm [9]. The solid fines flow progressively from the upper to the lowermost reactor, undergoing pre-heating, dehydration and reduction at different stages, countercurrent to H₂-rich reducing gas. The reducing gas is mainly composed of reformed natural gas produced via steam reforming technology. Reduction of ore fines takes place within a temperature range of 650- 800°C, and the operating pressure of reactors is up to 10-14 bar [10]. Similarly, reduction progresses with each reactor stage. In the final, lowermost reactor, metallization ratio of the product can reach 91-92% [10]. The carbon content of the product can be partially adjusted via the composition of reducing gas entering the final reactor. The product DRI out of the reactor is normally briquetted for downstream processing or transport.</p> <p>Two Finmet plants, each with an annual capacity of 2 Mt HBI, commenced operation in the 1990s, one in Australia, the other in Venezuela [3, 11]. The Australian plant closed in 2005 due to operating issues while the Venezuelan plant currently operates commercially [12], producing a low metallization merchant product [13]. In general, one of the key issues to resolve in FBs reduction processes is optimal fluidization (superficial fluidizing velocity) across a reasonably broad fines size</p>	

distribution. This may require some form of pretreatment such as grinding and/or micro-agglomeration.

Finex

Finex was jointly developed by Primetals Technologies and POSCO, based on the direct use of iron ore fines and non-coking coals [9]. It includes both pre-reduction and melting processes.

In the pre-reduction process, a multi-stage bubbling fluidized-bed reactor system is used, where iron ore fine with size < 8 mm is reduced to DRI fines in a countercurrent flow with a reducing gas that is produced by coal gasification or by natural-gas reforming. Charging materials also include fluxes such as limestone or dolomite. The DRI reduction degree is between 60 and 80% [10]. The DRI product is hot-compacted and then discharged into a melter-gasifier to produce hot metal [1, 14]. The reactor system has a pressure of ~4.0 bars and the prevailing temperature in the final, lowermost reactor is in the range of 760°C [6].

The first commercial Finex plant, with an annual capacity of 1.5 Mt of hot metal (Finex 1.5M), commenced operation in April 2007. A four-stage bubbling fluidized-bed reactor system was used. The third generation Finex plant (Finex 2.0M), with an annual capacity of 2.0 Mt of hot metal, commenced operation in January 2014. Finex 2.0M consists of a three-stage fluidized bed reactor system, resulting in a decreased building height of more than 30%. Installation of a center charging system for DRI and coal allows homogeneous charging of feed materials to the melter-gasifier [6]. Fuel consumption of the Finex 2.0M plant is 750-800 kg/tHM [6]. In terms of cost-effectiveness, it was reported that the Finex 2.0M plant surpasses the POSCO blast furnaces, which are considered amongst the most modern and economic blast furnaces in the world [15].

Posco and Primetals plan to further develop the fluidized-bed reactor system of Finex to operate on 100% H₂ in the HyREX process that replaces the melter-gasifier with an electric smelter [16, 17, 18].

Circored

The Circored process was developed by Lurgi, Germany (now Metso-Outotec Oyj, Finland) for the production of DRI from iron ore fines with the size range of 0.1 to 2.0 mm [4, 19]. Development of the process was initiated in the late 1970s with pilot plant tests conducted in Sweden. The first commercial Circored process was built in 1998 by Cliffs and Associates Ltd at Trinidad. The plant which has a capacity of 500,000 tons per annum of HBI, is presently not in operation [3, 20, 21].

The Circored process is a two-stage fluidized bed process including a circulating fluidized bed (CFB) and a bubbling fluidized bed (FB) reactor. Iron ore fines (d₈₀ = 45 μm) are first dried and preheated to ~900°C [4] before being charged to the CFB where they are reduced up to 70% metallization. Iron ore fines must be sized through crushing and/or micro-agglomeration. Final reduction occurs in the FB where the metallization ratio of the product can reach more than 95% [4, 10].

Circored was designed to be run using near-pure hydrogen derived from reformed natural gas, allowing an operation with low reduction temperature. The temperature is set at 630°C to minimise sticking and the pressure is 4 bars [10]. Gas preheating is required to support the endothermic H₂ reduction process. To produce the (carbon-free) HBI, a flash heater has to be used to heat the reduced fines to the required briquetting temperature of ~700°C [10].

For the Circored-EAF route using pure renewable hydrogen, the CO₂ emission is estimated at ~0.2 t CO₂/t-steel compared to 1.8 t CO₂/t-steel based on the pelletizing-BF-BOF route [22]. This route requires high-grade fines. Alternatively, for low-grade iron ores, a combination of a single reduction stage Circored process (metallization degree of up to 85%) with smelting reduction in an electric smelter for hot metal production has been proposed.

Circofer

Circofer is a coal-based process, also developed by Lurgi (now Metso-Outotec Oyj) for the production of DRI [20]. The Circofer process works as a pre-reduction process to produce the DRI for smelting reduction reactors, such as AusIron or electric smelting furnaces [10, 23]. In this process, a heat generator is integrated with a CFB reactor. Partial coal combustion occurs in the

heat generator to supply the energy and reducing carbon/anti-sticking agent in the CFB system. Ore fines are firstly pre-heated in the heat generator and then pre-reduced in the CFB to 70% metallization. Pre-reduced fines are further reduced in a FB (fluidized bed) reactor to a metallization of ~ 93% [20].

The CFB process has been designed with operating temperatures of ~ 950°C. The size range of coal, char and iron ore fines is between 0.1 mm to 1.0 mm [20].

The Circofer process has been demonstrated at pilot plant scale with a capacity of 5 tons per day [20, 24].

Hyfor

Hydrogen-based fine-ore reduction (Hyfor) is being developed by Primetals Technologies [5]. In this process, ultra-fine ore with a size distribution of <150 µm is first heated to ~900 °C in the preheating-oxidation unit and then fed to the reduction unit where the ore fines are reduced and leave at ~600 °C [5, 25]. The Hyfor process uses a hydrogen-rich gas or even 100% hydrogen as the reducing gas [26]. The development aims to understand the key issues in maintaining stable fluidization throughout the transformation of the iron fine to final product, and investigate the sticking related surface morphology of the iron ore fines and prolonged reduction time due to the formation of a dense iron layer around the particles.

In 2021, a Hyfor pilot plant was commissioned and successfully operated at the voestalpine site in Donawitz, Austria [5]. Each test run processes in the range of 800 kg iron ore.

Material inputs and outputs:

Inputs	Outputs
Finmet [9]	
<ul style="list-style-type: none"> Iron ore fines (0.05 - 8 mm) Reducing gas: reformed NG gas and recycled top gas (H₂ 80.6%, H₂O 1.9%, CO 12.8%, CO₂ 4.7%) 	<ul style="list-style-type: none"> CDRI, HDRI or HBI Off gas composed of CO, CO₂, H₂, H₂O, etc
Finex [9, 10]	
<ul style="list-style-type: none"> Iron ore fine (< 8 m) and flux Syngas (H₂ 22.2%, H₂O 2.3%, CO 65.3%, CO₂ 10.2%) 	<ul style="list-style-type: none"> HBI Off gas composed of CO, CO₂, H₂, H₂O, etc.
Circored [4, 19]	
<ul style="list-style-type: none"> Iron ore fines (0.1 - 2 mm) Reducing gas: 100% H₂ 	<ul style="list-style-type: none"> Carbon-free CDRI, HDRI or HBI Off gas composed of H₂, H₂O, etc
Circofer [20]	
<ul style="list-style-type: none"> Iron ore fines and coal (0.1 - 1 mm) Reducing gas: Syngas 	<ul style="list-style-type: none"> CDRI, HDRI or HBI Off gas composed of CO, CO₂, H₂, H₂O, etc
Hyfor [5]	
<ul style="list-style-type: none"> Iron ore fines (<0.15 mm) Reducing gas: up to 100% H₂ 	<ul style="list-style-type: none"> Carbon-free HDRI Off gas composed of H₂, H₂O, etc.

Overall abatement pathway:

Fluidized bed DR processes can help the abatement of emissions and energy through the following pathways:

- Direct utilization of ore fines avoids the agglomeration process and hence lowers overall energy consumption.
- Hydrogen-rich reducing gas allows an immediate reduction of CO₂ emissions compared to traditional blast furnace ironmaking.
- Operation at relatively low temperature using hydrogen as reducing gas helps reduce the overall heat loss and energy consumption.

- Heat and mass transfer between reducing gas and iron fines is high and more efficient in fluidization.
- Compared to the blast furnace route, the overall Finex process demonstrates a 4% reduction in CO₂ emissions [27].

Key performance indicators:

Two major fluidized bed DR processes are compared in Table 1.

Table 1. Comparison of fluidized bed DR processes

Process	Energy consumption, GJ/t-DRI	Production capacity	Reducing T, °C	Operating pressure, bar
Finmet	~12.4 [28]	2.0 Mt/year (max) [3]	650 – 800 [10]	10-14 [10]
Circored	11.5 [29]	0.5 Mt/year (max) [20]	630 [10]	4 [10]

Maturity and requirements to implement:

Although fluidized bed DR processes (Finmet, Circored and Finex) have been commercially applied, process stability and efficiency improvements are still required. By way of example, the four-stage fluidized bed system in the Finex 1.5M plant was modified to a three-stage fluidized-bed system in the Finex 2.0M plant, which decreases the overall construction cost but maintains a similar energy consumption for the overall Finex process [6]. As a major developer of fluidized bed DR processes, Primetals Technologies continues to develop the new process, Hyfor, and investigate the stability issue of fluidized bed reactors [26], likely to be linked to sticking phenomena [30], which is a key issue for de-fluidization behavior in the reactor.

The major drivers for the implementation of fluidized bed DR process are:

- Better control of residence time of ore fines in the fluidized bed to achieve high conversion rates and continuous operation.
- Guaranteed uniform mixing between reducing gas and iron ore fines in the reactors.
- Avoidance of de-fluidization of the entire bed due to sticking.
- Better control of sintering and agglomeration of ore fines at high temperature to maintain stable fluidization throughout the reactors.
- Understanding the surface morphology of iron ore fine during reduction to better manage its influence on fluidization under different reducing gas conditions
- Prolong the life of reactors which can be significantly eroded by fine particles.
- Temperature control and heat input when using pure hydrogen
- Metallisation degree and carburization for downstream processing
- Flexibility in fines sizing, or pre-treatment processes

Potential strengths and weaknesses:

Strengths	Weaknesses
<ul style="list-style-type: none"> • Utilization of ore fines • Reduction of emissions such as SO_x and NO_x due to no agglomeration process required e.g. sintering • Flexibility in operation and selection of iron ore types • Low CO₂ emission due to the use of hydrogen-rich reducing gas and/or pure hydrogen • Use of low grade (non-metallurgical) coals for generating the reducing gas • Lower investment and operational cost 	<ul style="list-style-type: none"> • High operating pressure • Potential occurrence of de-fluidization due to sticking • Difficulty in controlling gas flow due to heterogeneous fluidization phenomena • Significant erosion of reactor due to mechanical attack by ore fines • Sticking linked to complex thermodynamic and kinetic conditions of ore fines, which determines stability of fluidization and reduction efficiency

<ul style="list-style-type: none"> • Direct use of low-grade iron ore fines without agglomeration • High heat and mass transfer between gas and fines in the fluidization process • Low temperature reduction using hydrogen as reductant to minimize sticking tendencies • Isothermal condition leading to more precise temperature control 	<ul style="list-style-type: none"> • Extra energy required for grinding of ultra-fine ore • Potential requirement for micro-agglomeration • Limited ability to carburise product • Incomplete reduction • 100% of gangue in product
Additional comments:	

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Alternate ironmaking:

12 Shaft furnace direct reduction

General technology description:

Direct reduction (DR) refers to the reaction to remove oxygen from iron ore in its solid state. The reaction product is known as direct reduced iron (DRI). Typical DRI has a metallization degree of 85-95% and carbon content of 0.5-4% [1]. Whilst the earliest processing method used to produce DRI was the bloomer method [2], intensive development of modern DR processes started in the late 1950s. In 2020, world DRI production reached 104.4 Mt [3].

DR processes can utilize a wide variety of ferrous materials, reducing agents and fuels. DRI can be a substitute for scrap used in an electric arc furnace (EAF) and basic oxygen furnace (BOF), or charged as a burden material to the blast furnace (BF) [4].

The DR processes can be categorized in terms of reactor type, reducing agent, ferrous material characteristics, and product state [1, 5]. The DR reactor is usually one of four types: shaft furnace, fluidized bed, rotary kiln and rotary hearth. The reducing agent used can be reducing gas (natural gas, coke ovens gas, syngas), coal, oil, etc. With future availability, renewable hydrogen could be used. Iron ore can be in the form of fines, lumps, pellets or briquettes. The product is known as sponge iron.

Figure 1 shows the classification of DR processes for various reactors, ferrous materials, and reducing agents used.

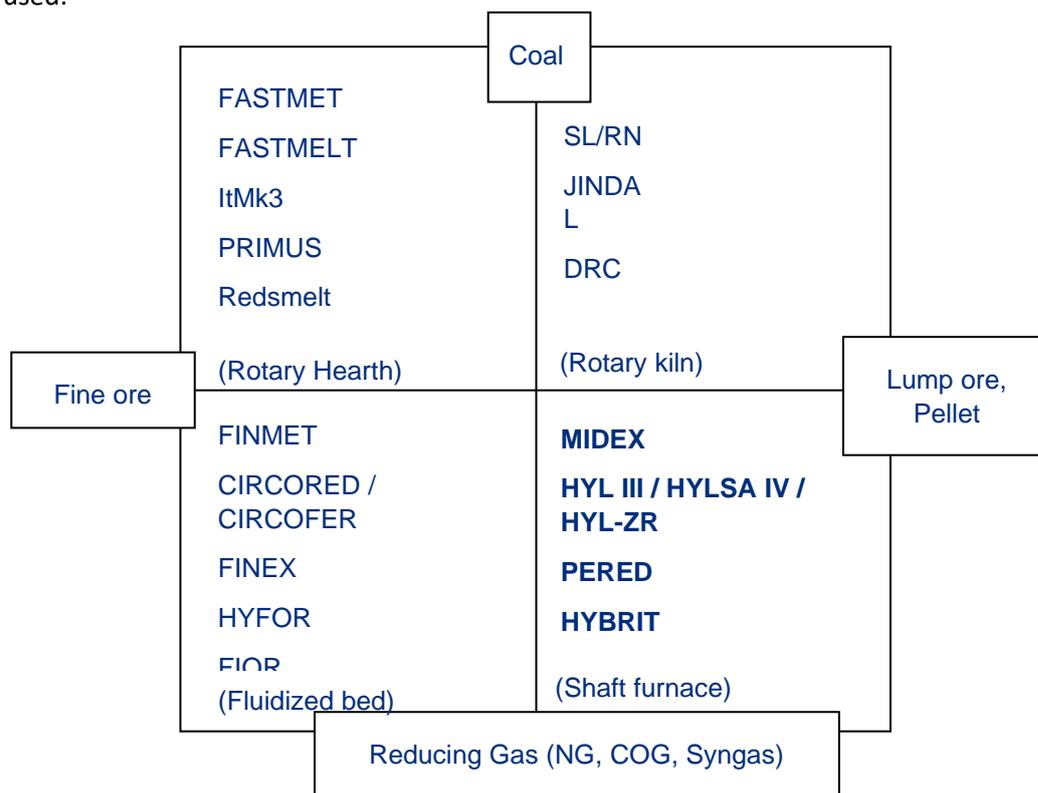


Figure 1. Classification of DR processes in terms of reactor type, reducing agent and iron ore characteristic.

This section provides an overview of the shaft furnace DR processes, including MIDREX, HYL, PERED, COREX-shaft furnace, and programs related to H2 DR.

Most commercial DR plants utilize shaft furnace reactors based on either MIDREX or HYL-ENERGIRON technologies [3]. 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 (HDRI) directly charged to the downstream furnaces (EAF, BOF or melter), cold DRI (CDRI) stored and then transported to off-site downstream steelmaking processes, or hot briquetted iron (HBI, hotly pressed into a high

density pillow-shaped briquette). In 2020, the production of HDRI and HBI made up 10.9% and 8.7% of the total global DRI production, respectively [3].

For each shaft-based DR process, pellets or lump ores are charged directly at the top of the shaft. Typically, in a commercial-scale operation such as the MIDREX NG process [6], 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 the shaft furnace. Depending on the individual process, reducing gas can be reformed coke oven gas (COG) or syngas generated through coal gasification; in the case of the HYL-ZR process, NG or other reducing gases can be directly injected to the furnace without reforming [7, 8]. Shaft furnace DR processes are different according to reducing gas composition, reducing temperature, injection location, burden distribution pattern, furnace structure, operating pressure, outlet, etc.

Table 1 lists some differences together with production capacities, and also separately lists the industrial trials undertaken with H₂ direct reduction (H₂-DR). The listed processes will be briefly introduced in regard to the process features and current status in the following section.

Table 1. Comparison of shaft furnace DR processes

Direct reduction process	Reducing agent	Reducing T, °C	Production capacity	Level
MIDREX	NG/COG/Syngas	760-930	2.5 Mt/year (max)	Commercial
HYL-ZR/ENERGIRON ZR	NG/COG/Syngas	~1050	2.5 Mt/year (max)	Commercial
PERED	NG/COG/Syngas	–	0.8 Mt/year	Commercial
COREX-shaft furnace	Syngas	~850	1.5 Mt/year (C-3000)	Commercial
ENERGIRON (Mexico)	>90% Hydrogen	–	36 t/day	Pilot
HYL-ZR (HYBRIT)	Hydrogen	–	1 t/hour	Pilot
MIDREX (Arcelormittal)	Hydrogen	–	0.1 Mt/year	Construction
ENERGIRON (HBIS Group)	Hydrogen (~70%)	–	0.6 Mt/year	On contract
HYL-ZR (Baowu Group)	H ₂ /NG/COG-NG-H ₂	–	1 Mt/year	Construction

MIDREX

The first commercial MIDREX plant started in 1969, with significant process development until the early 1980s [9]. MIDREX plants produced 62.63 Mt in 2020, occupying ~60% of 2020 world DRI production and ~80% of DRI produced via shaft furnaces [3].

The MIDREX process utilizes reducing gas modified from natural gas, top gas, coke oven gas, and/or other reducing gases derived from non-coking coal or from bottom oil generated in oil refineries [9, 10]. The typical reducing gas contains 90-95% (CO + H₂) [1]. The whole process runs without coke, and emits less CO₂ compared to blast furnace ironmaking. The MIDREX process operates at a pressure of ~1.2 bar. The total reducing time is over 6 hours. Typical MIDREX DRI has a metallization of 92-97% [11].

The maximum production capacity of the MIDREX process is 2.5 Mt/year [12] designed for Algeria's Qatari Steel.

MIDREX has developed different technologies to utilize different reducing gases and help control carbon content in DRI product, including (1) MIDREX NG with use of the patented MIDREX Reformer to convert recycled gas and fresh natural gas into a usable reducing gas [6]; (2) MxCol designed for better utilizing syngas derived from natural gas and coal sources [13]; (3) MIDREX ACT, i.e. adjustable carbon technology, used to help control carbon content of MIDREX DRI [14]; and (4) MIDREX H₂ used to enhance MIDREX NG with partial substitution of hydrogen, or up to 100% hydrogen [15].

HYL/ENERGIRON

The first commercial HYL plant was set up at Monterrey, Mexico in 1957 [16]. At the early stage, lump ore and pellets were reduced in a series of retorts. The retort is a type of fixed bed reactor. The HYL process has since undergone various improvements: from HYL I, HYL II to HYL III and HYL-ZR/ENERGIRON-ZR, where ZR refers to Zero Reformer. HYL I and HYL II are the first and second generation of HYL process based on fixed bed reactors. HYL III is the third generation process based on a moving bed reactor with high operational pressure (5-8 bar). HYL III consists of two sections: reducing gas section and moving bed reduction section. The reducing gas is generated via gas reforming. HYL-ZR is the most recent HYL process (also referred to HYLSA IV or ENERGIRON-ZR). Compared to MIDREX, the HYL-ZR process operates with higher pressure and gas temperature. Natural gas is directly injected into the furnace without gas reforming i.e. the reducing gas is formed inside the reduction region of furnace [17]. The first commercial scale HYL-ZR plant commenced in 1998 [16].

The maximum production capacity of the HYL process is 2.5 Mt/year and the relevant operational pressure is ~7 bar. Typical HYL (ENERGION) DRI has metallization of 95% and carbon content controlled in a range between 1.5 to 4% mostly in the form of cementite [18]. The carbon deposition rate in the reactor can be controlled by changing the humidity in the injected gas. The HYL-ZR process, with no external gas reformer, provides additional flexibility for using any reducing gas source in any region. The injection gas can be natural gas or other sources of reducing gas, such as COG, syngas, hydrogen and others [16].

PERED

PERED technology was registered in Germany in 2006. The first direct reduction plant based on PERED technology was commissioned in 2017 in Iran, with a design capacity of 0.8 Mt/year. The DRI product had metallization above 93%, and carbon content above 1.5% [19, 20].

The difference between PERED and other shaft furnace DR processes is reflected in areas such as the crushers, cooling system, charging system, compressors, water vapor recuperators and in-furnace structure. It was claimed that compared to similar technologies, PERED is superior in the metallization of the DRI, energy and water consumptions, operating costs and more flexible operations [20, 21].

The PERED process operates across a wide range of reduction temperature, depending on the type of iron-bearing materials [22]. With less heat, more homogeneous reducing gas, more controllable pellet feed and use of centrifugal compressors, it was claimed that PERED requires less water, electricity and gas to operate, alongside less operational and maintenance expenditure [19].

PERED plants produced ~3.5 Mt in 2020 [3], mainly in Iran. The published information is very limited.

COREX – shaft furnace

Commercial operations of the COREX process commenced in 1989 at Iscor's Pretoria Works, South Africa. Since then, the COREX process has been commissioned in other areas including Korea, India and China [23, 24].

The COREX process involves a pre-reduction shaft furnace and melter-gasifier. In the pre-reduction shaft furnace, a lump ore/pellet mix is reduced to 90-95% metallized iron [23]. The COREX shaft furnace differs from other DR processes in the furnace structure and operational conditions. Together with the ferrous materials, flux and a small amount coke are charged into the top of the shaft furnace, with coke used to avoid sticking and assist with gas permeability[1]. The typical reducing gas contains 94+% (CO + H₂) and the injection pressure is over 3 bar [1]. As an intermediate product, there is very limited information regarding DRI quality discharged from the shaft furnace. The hot DRI is then discharged into the melter-gasifier where it is further reduced and melted to hot metal. Hot syngas generated in the melter-gasifier (850°C) is used as reducing gas for the shaft furnace [1].

Industrial-scale operations using COREX C1000 and C2000 have been realized, but with the larger COREX C3000 at Baosteel, shaft furnace operations have been difficult, with high pressure drops and low DRI metallization [25]. Note C1000, C2000 and C3000 correspond to the production capacities of 0.3-0.4, 0.6-1.0 and 1.2-1.3 Mt per year, respectively.

H₂ Direct Reduction (H₂-DR)

With significant emission reductions limited by the current steel production routes, the development and, ultimately, implementation of Direct Carbon Avoidance pathways such as the H₂-DR process routes may be required. However, based on current cost analysis, H₂-DRI would be considerably more expensive than producing direct-reduced iron with natural gas [16].

In the 1990s, Tenova HYL undertook extensive tests on direct reduction of iron ore in a pilot plant at Hysla, Monterrey with more than 90% H₂. The production capacity was 36 t/day. H₂ was produced from reformed gas with CO₂ removal. A high metallization rate of 94%–96% was achieved. It was claimed that the HYL shaft furnace reactor could be easily optimized to use 100% hydrogen for the reduction of iron ore [26].

Both major gas-based DR processes, MIDREX and HYL/ENERGIRON, claim that DRI can be produced using hydrogen [27], and up to 30% of the natural gas used in these two processes can be replaced by hydrogen without major process adaptations [28]. Current shaft furnace H₂-DR trials to test the effect of 70%-100% hydrogen reduction gas are based on one of these two processes [29, 30].

The HYBRIT project initiative aims to produce DRI using renewable hydrogen using the HYL/ENERGIRON process, melting it in an EAF. Construction of the pilot plant began in Sweden in 2018, with commissioning completed late 2020. In June 2021, the plant produced the first 100 t of 100% renewable hydrogen based (and zero carbon) HBI [27]. The hydrogen was produced by water electrolysis using renewable energy [31].

In September 2019, ArcelorMittal announced that a demonstration plant to produce DRI with 100% hydrogen would be constructed at its Hamburg site, based on the MIDREX process. Production capacity will be ~0.1 Mt/y. The plant was designed to commence using hydrogen sourced from natural gas and gradually convert to renewably-sourced hydrogen [32].

In November, 2020, Tenova signed a contract with the HBIS Group to set up an ENERGIRON DRI plant with production capacity of 0.6 Mt per year. The reducing gas will contain 70% hydrogen, with a net emissions target of ~125 kg CO₂/t-DRI [33].

In May, 2021, as part of the SALCOS (Salzgitter Low CO₂ Steelmaking) project, Salzgitter AG started construction of DR plant with production capacity of 100 kg/h HBI or DRI using Tenova technology. Reduction gas will be hydrogen and natural gas. The first DRI production was scheduled in Q4 of 2022. This work aims to demonstrate the capabilities of existing technologies to reduce CO₂ emissions in integrated steel works using hydrogen [34, 35, 36]. In February, 2022, Baowu Group began building a 1 Mt/y CDRI hydrogen-based shaft furnace plant using the HYL-ZR process. Hydrogen will be produced by photovoltaic and wind energy.

Material inputs and outputs:	
<u>Inputs</u>	<u>Outputs</u>
MIDREX, HYL-ZR, PERED	
<ul style="list-style-type: none"> • Pellet or lump ore • Reducing gas 	<ul style="list-style-type: none"> • CDRI, HDRI or HBI • Off gas composed of CO, CO₂, H₂, H₂O, etc
COREX-Shaft furnace	
<ul style="list-style-type: none"> • Iron ore in pellet or lump form, coke and flux • Syngas composed of > 94% (CO + H₂) 	<ul style="list-style-type: none"> • HDRI • Off gas composed of CO, CO₂, H₂, H₂O, etc.
Reducing gas for MIDREX:	
<ul style="list-style-type: none"> • Various H₂/CO ratios in the gas related to gas source, i.e. 1.5-1.7 (for NG using MIDREX reformer), 3.2-3.9 (for NG using steam reformer, heater and MIDREX reformer) 0.3-0.6 (for COREX offgas, with CO₂ removal + heater), and 2.0 (for coal gasification gas) [10, 37] 	
Reducing gas for HYL-ZR:	
<ul style="list-style-type: none"> • NG, COG, reformed gas, syngas [18] 	
Reducing gas for PERED:	
<ul style="list-style-type: none"> • Reformed NG and COG, syngas [20, 21] 	
Overall abatement pathway:	

Shaft furnace DR processes using hydrogen-rich reducing gas can help the abatement of CO₂ emission through the following pathways:

- Hydrogen-rich reducing gas for reduction allows an immediate reduction of CO₂ emissions compared to the traditional blast furnace route.
- MIDREX and HYL/ENERGIRON processes are flexible in allowing further supplemental hydrogen injection up to 100% [15, 16].
- Application of COG in MIDREX and HYL/ENERGIRON processes has been proved at the industrial level, which helps improve utilization of off-gas [10, 12, 18].
- These processes can be easily operated in a recycling loop to utilize energy and material more efficiently.
- DRI can be hot charged into a melter, EAF, BOF or BF in an integrated steelmaking plant.
- DRI-EAF route has higher CO₂ reduction of BF-BOF route [38].

Key performance indicators:

Performances of MIDREX and HYL/ENERGIRON processes are compared in Table 2.

Table 2. Comparison of shaft furnace DR processes (using natural gas)

Process	Energy consumption, GJ/t-DRI	CO ₂ emission, t/t-steel	Operating pressure, bar
MIDREX	~10.4 [39]	1.1-1.2 (DRI-EAF total) [12]	1.2 [1]
HYL/ENERGIRON	<9.5 [16]	~1.1 (DRI-EAF total) [40]	6-8 [40]

Note: Refer to Table 1 for production capacity and reducing gas temperature.

Maturity and requirements to implement:

Shaft furnace DR processes have been commercially used world-wide and been well-proven through their production performance. Among these processes, MIDREX and HYL are dominant due to their reliability and continuous development. Both provide flexibility in terms of production and to a limited extent, raw materials (tolerance of limited amounts of BF-grade pellets and specific lump ore types), and can control product quality in terms of the carbon content and metallization degree.

Factors to be considered for broader application of shaft furnace DR processes are:

- Lower production cost of DRI-EAF route, causing DR process to be more competitive.
- Higher production capacity and better operational control without sticking.
- More reliable and effective transport of HDRI.
- Feasible life of furnace refractory and process ancillaries in hydrogen-rich environment.
- Economic and technological availability of 100% hydrogen direct reduction in terms of furnace heat balance and temperature control, carbon content of DRI and green hydrogen and electricity.
- Greater raw materials flexibility.

Potential strengths and weaknesses:

The shaft furnace DR processes have the following features:

Strengths	Weaknesses
<ul style="list-style-type: none"> • Smaller scale DR facility with less construction cost and lower investment requirement relative to BF • Less fuel required and CO₂ emission relative to BF ironmaking • Simpler furnace design and relatively easier operation of a DRI plant relative to BF process 	<ul style="list-style-type: none"> • DRI susceptible to oxidation, particularly for transportation or long-term material storage • All gangue content left in DRI after iron ore reduction • Low production capacity • High cost for DRI-EAF route for steelmaking • DRI with 0% carbon after reduction by pure hydrogen as the optimum carbon level in DRI is

<ul style="list-style-type: none"> • Reductant source flexibility in using NG, COG, syngas or H₂ • Higher process flexibility to allow quick response to the customer requirement • Substitution of scrap by DRI in BOF or EAF • Not necessary to be part of an integrated steel plant • Potential viability of 100% H₂-DR • Production of low carbon steel using H₂-DRI • Favourable gas volumes relative to BF due to no air dilution 	<p>1.5-3% for EAF steelmaking, and potentially similar in a HM smelter</p> <ul style="list-style-type: none"> • Long operation time, >6 hours for MIDREX process • Potential operational issue with sticking/plating • Pellets and lump ores required with high iron grade and low gangue contents • High operating pressure (ENERGIRON) • Need to supply process heat through reducing gas – more challenging as H₂ content increases
<p>Additional comments:</p>	

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Alternate ironmaking: 13 Smelting reduction

General technology 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. Major SR processes are summarized in Table 1; individual processes are subsequently introduced. In this section, the submerged arc furnace (an electric smelting process) is not discussed, noting this was introduced in Section “DRI utilization in electric arc furnace”.

Table 1. Comparison of smelting reduction processes

Smelting reduction process	Pre-reduction	Smelting reduction	Production capacity	Energy source	Level
Corex/Corex-Mxcol	Shaft furnace	Melter-gasifier (in-bed process)	1.5 Mt/year (Max)	Coal	Commercial
Finex	Fluidized bed	Melter-gasifier (in-bed process)	2.0 Mt/year (Max)	Coal	Commercial
Cyclone Converter Furnace	Cyclone	Converter (in-bath process)	–	Coal	Pilot
HIs melt	Fluidized bed or rotary kiln	Smelt reduction vessel (SRV) (in-bath process)	0.8 Mt/year (designed)	Coal	Commercial
HIsarna	Cyclone	Smelt reduction vessel (SRV) (in-bath process)	–	Coal	Pilot
Tecnored	–	Packed bed reactor (in-bed process)	–	Coal	Demonstration
Dios	Fluidized bed	In-bath process	–	Coal	Pilot
Romelt	–	In-bath process	0.2 Mt/year (designed)[1]	Coal	Commercial
AusIron	–	Smelter (in-bath process)	0.5 Mt/year (designed)	Coal	Pilot
Flash ironmaking technology	–	Flash reactor	1.0 Mt/year (designed)	H ₂ , CH ₄ , or coal gas	Pilot
OxyCup	–	OxyCup shaft furnace (in-bed process)	2400 t/day (JFE) [2]	Coke, carbon fine	Commercial
Ironarc	Melting and pre-reduction (in-bath process)	Final reduction* (in-bath process)	–	Electricity	Pilot

*Melting takes place in pre-reduction step

Corex/Corex-Mxcol

The commercial operation of the Corex process was launched at Iscor’s Pretoria Works, South Africa in 1989. Since then, the Corex process has been commercially applied in other countries such as Korea, India and China [3, 4]. MXCOL refers to the trademark for the utilization of syn-gas from the COREX process.

The Corex process includes a pre-reduction shaft furnace and melter-gasifier. The pre-reduction shaft furnace was introduced in Section “Shaft furnace direct reduction”. In the shaft furnace, the

charged iron ore/pellet is reduced to 90-95% metallized iron (DRI). The hot DRI is discharged into the melter-gasifier where it is melted and further reduced to hot metal. In the melter-gasifier, about 530-550 Nm³/tHM of oxygen is injected to combust a) coal which is continuously charged via a lock hopper system or b) PC injected from tuyeres for generating reducing gas and energy [5]. Typical coal consumption is 750-950 kg/tHM [5, 6]. Gas leaves the melter-gasifier at 1000-1050°C [5], mainly composed of CO, CO₂ and H₂.

Three different sized industrial-scale operations of Corex have been commercialized, named C1000, C2000 and C3000, corresponding to production capacities of 0.3-0.4, 0.6-1.0 and 1.2-1.3 Mt per year, respectively.

Finex

Finex was introduced in Section “Fluidized bed direct reduction”, as it includes multi-stage fluidized-bed reactors for pre-reduction, as well as a melter-gasifier for final reduction and melting of iron-bearing materials. The latter is identical to that used in Corex.

It should be noted that after the pre-reduction process, iron ore fines are reduced to DRI with a reduction degree between 60 and 80% [5]. The DRI product is formed into hot briquettes (HBI) before being charged to the melter-gasifier [7, 8].

The final product of Finex process is hot metal with the quality similar to Corex and BF products.

It was reported that for a combination of BF and Finex processes, both fuel consumption and CO₂ emissions can be reduced significantly, i.e. high carbon iron produced in the Finex process is charged to the BF as burden material [9].

Cyclone Converter Furnace

Cyclone converter furnace (CCF) is a single vessel with a cyclone attached to the top of a converter – a coupled process. The CCF process was developed by Hoogovens, British Steel and Ilva/CSM in the 1990s. The iron ore is pre-reduced and melted in the cyclone. The molten ore falls into the liquid bath under gravity, where final reduction and melting take place. Granulated coal and oxygen are fed to the lower part of the converter. The combustion of the rising off-gas from the bath occurs in the converter and cyclone, generating sufficient energy for melting and pre-reduction. The gas leaves the process at ~1800°C [5]. Coal consumption for the CCF is 700-750 kg/tHM [10].

A pilot sized furnace was operated in laboratory [11]. There has been no further progress in recent years.

Hismelt/Hisarna

The Hismelt (high-intensity smelting) process was originally developed by Rio Tinto in 1982 to smelt high phosphorous iron ore fines with non-coking coals [12].

- The original version of Hismelt started in the early 1980s, which was modified from bottom-blown K-OBM process. A pilot plant with a production capacity of 1 t/h was built in Germany, proving that smelting iron ore fines with coal in a bath of hot metal was feasible.
- In 1990s, a larger pilot plant with a capacity of ~10 t/h was built in Kwinana, Western Australia. The process design was improved, using a fixed, vertical furnace design to replace the original rotating design, and injecting coal and ore above the hot metal, instead of through bottom tuyeres.
- In 2000s, a commercial plant with a capacity of 0.8 Mt/year was built and operated in Kwinana; this stopped in 2008 due to the global financial crisis.
- In 2016, Hismelt was restarted and improved at Molong (Shandong Province, China), producing an average of 1600 tHM/day with an availability of >90% and a coal consumption of <900 kg/tHM. A major change was to replace the circulating fluidized bed with a rotary kiln.

In the smelting-reduction vessel (SRV), coal and pre-reduced ore fines are directly injected into the molten iron and slag bath, where the final reduction and smelting of iron ore can be completed. The energy for the process is provided by the post combustion of CO from the bath with oxygen from hot blast, which is introduced through a top central lance. Submerged injection of iron ore

strongly stirs the liquid phase, making the heat transfer between the post-combustion zone and bath very efficient. In particular, the oxidizing atmosphere and low temperature slag can remove 90-95% of the phosphorus from the input materials to the slag [5]. The typical temperature of hot metal is 1420°C [9] and silicon content in hot metal is very low (0.001%) [13]. Overall coal consumption is between 700 and 810 kg/tHM [9]. CO₂ emissions of HIs melt process are ~1.8 t-CO₂/tHM [12].

HIsarna technology combines both the cyclone converter furnace and the HIs melt technologies [14], using the cyclone for pre-reducing and melting the ore, and the SRV for final reduction and smelting. Similar to the CCF, the cyclone is attached to the top of SRV. In HIsarna, the oxygen is supplied to both the cyclone and smelter. A pilot plant with a capacity of 8 t/h hot metal was built in the Ijmuiden Works of Tata Steel Europe (formerly, Hoogovens and Corus) [15].

Tecnored

The Tecnored process consists of a moving bed, shaft furnace with a rectangular cross-section, using cold bonded self-reducing, self-fluxing and carbon-bearing agglomerates to produce hot metal [5, 16]. In the furnace, lump coal is also added to form a char bed and provide most of the energy required by the process. Both hot and cold blasts are applied: hot blast air is injected into the lower part of furnace for coal combustion and cold blast air is blown into the upper shaft for improving post-combustion of rising gas.

The height of furnace is low so that the permeability and material strength are not critical issues. The typical residence time of the charging materials in the furnace is 30-40 minutes [11]. Low grade ore fine and solid fuels may be used to produce agglomerates. The temperature of hot metal is in the range of 1380-1430°C.

A pilot plant with a capacity of 2 t/h and a demonstration plant with a 0.075 Mt/year capacity were built in Brazil in 1998 [11] and 2012 [17, 18], respectively. The industrial demonstration plant operated until 2018. It was announced that successful biomass testing had been done in 2019. Very recently, Vale commenced building Tecnored's "green" commercial plant with a production capacity of 0.25 Mt per year in Marabá, Pará [19]. The US\$345M plant was scheduled to be commissioned in 2025 using biomass to replace metallurgical coal.

Dios

The Dios (Direct Iron Ore Smelting) process is composed of two-stage, fluidized beds for preheating and pre-reduction of iron ore, and a smelter for melting and final reduction. The pre-reduction degree of iron ore is ~20%. In the smelter, the energy is generated from coal combustion and gas post-combustion. The oxygen is injected through a top lance [11].

The development of the DIOS process started in 1988 in Japan. A 500 t/day pilot plant was built and operated at JFE's (formerly NKK) Keihin plant between 1993 and 1995. The smelter was modified from a 250 t BOF. Pilot tests show that pre-reduction degree of iron ore was low and the operation of fluidized bed was not smooth [20].

There has been no further progress on the Dios process since the pilot tests although a feasibility study on a 6000 t/day commercial plant presented some benefits compared to BF process [19].

Romelt

The Romelt process consists of a single rectangular-shaped reactor where smelting and reduction take place. In this process, a broad particle size distribution of iron ore and coal is acceptable. The reactor is operated under negative pressure. During the operation, oxygen-air is injected into the reactor via the tuyeres below the slag layer. A foamy slag is formed and within this layer, reduction of iron ore occurs. The energy required for the process arises from coal combustion and post combustion of gas released from the bath. After the post-combustion, the temperature of gases may be up to 1700°C.

Since 1984, industrial practices with pilot and commercial plants have been attempted [11, 21]. The major concern was high energy consumption [21]. A new commercial industrial plant based on

Romelt technology was built and scheduled to start in 2016 at Burma, with a designed capacity of 0.2 Mt/year [22]. No further information on the performance of this plant is available.

Flash ironmaking technology

The flash ironmaking technology (FIT) process [23] is based on proven flash technology, as used for copper smelting. Iron ore fines may be magnetite or hematite concentrates (<100 µm). The concept has been proved at a laboratory scale [24]. Iron ore concentrates are directly reduced to metallic iron in-flight using hydrogen, natural gas, coal gas, or their combination. 90-99% reduction can be completed in 2-7 seconds at 1200-1500°C [25].

The scale-up process was carried out in a laboratory flash reactor and then in a pilot-plant scale flash reactor with a solid feed rate of 1-7 kg/h [26], proving the technical feasibility of the flash ironmaking technology.

Designed production capacity for the industrial flash ironmaking reactor can be up to 1 Mt, with 82% availability. If emissions from ore/coke preparation are not included, the emissions based on FIT using hydrogen or natural gas (NG) without reformer are reported as 0.04 or 1.02 t-CO₂ /tHM, respectively. Corresponding energy consumptions of FIT using hydrogen and NG without reformer are reported as 5.7 and 8.9 GJ/tHM, respectively. Note that the energy consumption of the BF process is 12.7 GJ/tHM [23].

OxyCup

The OxyCup process is a proven technology for iron recovery from ferrous waste material, which was developed by Küttner and implemented on an industrial scale by Thyssen-Krupp Steel in 2004 [2]. Ferrous wastes cover dusts, sludge, mill scale, sponge iron or ore fines [27].

The ferrous waste fines are mixed with carbon-bearing material (a reducer) and cement (a binder) to make self-reducing carbon “bricks” (C-bricks) which are the main charge materials for the OxyCup furnace [2, 28]. Carbon-bearing materials may be coke breeze, anthracite, petro coke etc. The percentage of C-bricks in the ferrous charge may be up to 100%, the balance being lumpy residues like pit scrap/skulls [29].

The major part of the OxyCup process is the furnace, which is a modified cupola combining the function of melting in a traditional cupola furnace with the function of reduction in a BF [2, 30]. The upper part of the furnace contains a charge receiving hopper, the middle part is for preheating and melting of the charge materials, and the lower part contains the cupola hearth and the iron-slag separator.

During the operation, ferrous materials, fluxes and coke are charged from the top and the metal and slag produced in the lower part are continuously discharged from the furnace. The furnace is operated with an oxygen-enriched blast (5-15% of oxygen enrichment). Most of the iron oxide is reduced by carbon in the C-bricks at 900-1400°C within 20-30 minutes.

The process has been applied in different steelworks, such as ThyssenKrupp Steel in Germany, Sicartsa in Mexico, Nippon Steel and JFE in Japan, and Taiyuan steel in China [2].

AusIron

The AusIron process consists of a single smelter for reducing and smelting iron-bearing materials. During the operation, iron ore, flux and coal are fed from the top of the vessel. Oxygen is injected into the slag bath through submerged lances. Energy is generated by submerged combustion of coal and post combustion of gases from smelting reactions, coal volatiles and residue fuel gas from coal combustion. A feature of this process is that oxygen-enriched air is injected through a shroud around the submerged lance above the slag layer, which can help complete combustion of the rising gases.

This process was developed by Ausmelt Ltd., Australia. A pilot plant with a capacity of 2 t/h was built at Whyalla. Design production capacity was reported as 0.5 Mt/year [11, 31]. There have been no further applications of this process.

Ironarc

The IronArc process as developed by ScanArc in Sweden. It utilizes an electric arc to superheat gas in a plasma generator (PG) for supplying the energy to the metallurgical process [5, 32, 33]. The designed process consists of two reactors: one for smelting and pre-reduction of iron ore, and another for final reduction.

In the first reactor, a gas mixture of air and LPG heated by PG is injected into the reactor through submerged nozzles placed on the sidewall. The injected gas has a temperature of 3500-4000°C when leaving the plasma generator. The gas is used as an energy source to heat and melt the charged iron oxide, and as a reducing agent to pre-reduce iron oxide to wustite. Note that CO and H₂ are generated when the LPG is heated together with air. Molten wustite is then transferred to the second reactor, where carbon is used as a reductant for the final reduction [32, 33, 34, 35]. In this process, it is expected that a wide range of different sized input materials may be used.

In both reactors, all the energy used for heating is from electricity, including from renewable sources. A preliminary study shows that this process has the potential to reduce the CO₂ emissions by ~ 50% [33]. Note that it is not clear whether this value considered the utilization of green electricity.

In the existing Ironarc pilot plant, only one reactor was used [33]. A demonstration-scale reactor is planned to further prove the functionality of the process using the two-reactor approach [34].

Material inputs and outputs:

Inputs	Outputs
COREX /COREX-MXCOL - Melter-gasifier	
<ul style="list-style-type: none"> • HDRI, limestone and dolomite • Lump coal, quartzite and a small amount of coke • Oxygen injection and/or PC injection 	<ul style="list-style-type: none"> • Hot metal, slag • Gas (CO, CO₂, H₂, N₂ etc.)
Finex - Melter-gasifier	
<ul style="list-style-type: none"> • HDRI, limestone and dolomite • Lump coal, quartzite and a small amount of coke • Oxygen injection and/or PC injection 	<ul style="list-style-type: none"> • Hot metal, slag • Gas (CO, CO₂, H₂, N₂ etc.)
Cyclone Converter Furnace	
<ul style="list-style-type: none"> • Iron ore fines, coal and flux • Oxygen injection 	<ul style="list-style-type: none"> • Hot metal, slag • Off gas
HIs melt/HIsarna	
<ul style="list-style-type: none"> • Iron ore fines, coal and flux • Oxygen injection 	<ul style="list-style-type: none"> • Hot metal, slag • Off gas
Dios	
<ul style="list-style-type: none"> • Iron ore fines, coal and flux • Oxygen and PC injection 	<ul style="list-style-type: none"> • Hot metal, slag • Off gas
Romelt	
<ul style="list-style-type: none"> • Iron ore fines, coal and flux • Oxygen-air injection 	<ul style="list-style-type: none"> • Hot metal, slag • Off gas
Tecno red	
<ul style="list-style-type: none"> • Self-reducing and self-fluxing agglomerates, lump coal or biomass • Hot and cold air injection 	<ul style="list-style-type: none"> • Hot metal, slag • Off gas
Flash ironmaking technology	
<ul style="list-style-type: none"> • Iron ore concentrate, flux • O₂, H₂, CH₄ or coal injection 	<ul style="list-style-type: none"> • Molten metal, slag • Off gas (CO, CO₂, H₂, H₂O)
AusIron	

<ul style="list-style-type: none"> • Lump ore, ore fines, coal and flux • Oxygen-air injection 	<ul style="list-style-type: none"> • Hot metal, slag • Gas (CO, CO₂, H₂, N₂ etc.)
Oxycup	
<ul style="list-style-type: none"> • C-brick composed of waste fines, carbon fines and binder • Coke and flux • Oxygen-air injection 	<ul style="list-style-type: none"> • Hot metal, slag • Gas (CO, CO₂, H₂, N₂ etc.)
Ironarc	
<ul style="list-style-type: none"> • Iron ore, carbon materials • Liquid natural gas or liquid petroleum gas and air injection 	<ul style="list-style-type: none"> • Hot metal, slag • Gas (CO, CO₂, H₂, N₂ etc.)

Overall abatement pathway:

CO₂ emissions for the different SR processes are compared in Table 2, noting that predictions of CO₂ emissions are limited and some processes are under development. Also, processes such as OxyCup are mainly used to for recycling of plant wastes so that the abatement of CO₂ emission is not emphasized.

Table 2. Comparison of CO₂ emission for different processes

Smelting reduction process	CO ₂ emission, t- CO ₂ /tHM	Ref.
Corex/Corex-Mxcol	2.304	[9]
Finex	4% reduction compared to BF	[9]
Cyclone Converter Furnace	—	—
Hismelt	~1.8	[12]
HIsarna	—	—
Tecnored	—	—
Dios	4-5% reduction compared to BF**	[11]
Romelt	Lower than BF emission	[36]
AusIron	—	—
Flash ironmaking technology	0.04 (H ₂ -FIT) or 1.02 (NG-FIT)*	[23]
OxyCup	—	—
Ironarc	50% reduction compared to BF**	[33]

*Theoretical estimation without considering the emission from ore/coke preparation and production of hydrogen.

**Estimated

Key performance indicators:

Performances of the different SR processes are compared in Table 3 in terms of energy and coal consumptions. For SR processes, energy consumption is closely related to the utilization of off-gas because normally the off-gas has a high reduction potential and calorific value.

Table 3. Comparison of energy and coal consumption of different SR processes

Smelting reduction process	Energy consumption, GJ/tHM	Coal consumption, kg/tHM	Operating pressure, bar	Ref.
Corex/Corex-Mxcol	18.9-21.7	750-950	5	[5, 6, 9]
Finex	N/A	700	3.0-4.5	[9]
Cyclone Converter Furnace	N/A	700-750	N/A	[10]
Hismelt	18.9-20	700-810	0.8	[9]
Hlsarna	N/A	N/A	N/A	N/A
Tecnored	N/A	N/A	N/A	N/A
Dios	3-4% reduction*	700-800	1-2	[5, 11, 36]
Romelt	Higher energy consumption*	900-1200	< 1	[5, 36]
Ausiron	N/A	N/A	< 1	[11]
Flash ironmaking technology	7.4	N/A	N/A	[36]
OxyCup	N/A	N/A	N/A	N/A
Ironarc	N/A	N/A	N/A	N/A

* Compared to BF; N/A = not available

Maturity and requirements to implement:

Some SR processes have been successfully commercialized, such as Corex, Finex, Hismelt, Romelt and OxyCup. The limited production capacity remains the key challenge for future application of these commercialized processes. Amongst these, the high energy consumption for Romelt process also must be overcome.

For other SR processes, more generally, these processes require:

- Industrial scale trials for operational feasibility
- Optimized utilization of excess gas from the processes

and specifically:

- The Dios process requires optimization of bath stirring and smooth operation of pre-reduction process
- The Ironarc process has a potential issue of penetration of heated gas in the bath after scale-up
- The Tecnored process also has issues with scale-up as the gas is laterally injected into the furnace
- Reduction efficiency of flash ironmaking process could be unpredictable as the feed rate increases

Potential strengths and weaknesses:

Compared to the traditional blast furnace ironmaking, the SR processes have the following features:

Strengths	Weaknesses
<p>General</p> <ul style="list-style-type: none"> • Utilization of non-coking coal • More environmental friendly in terms of off-gas control 	<p>General</p> <ul style="list-style-type: none"> • Required large amount of oxygen in most processes • Low production capacity

<ul style="list-style-type: none"> • Direct usage of iron ore fines in most processes • Low capital requirement for construction • Flexibility in operation and raw material selection • Low operational costs <p>Specific <u>Hismelt/HIsarna</u></p> <ul style="list-style-type: none"> • High quality of hot metal product in terms of low P, Ti, Mn and Si contents <p><u>Romelt</u></p> <ul style="list-style-type: none"> • Acceptance of a broad size of iron ore and coal <p><u>AusIron</u></p> <ul style="list-style-type: none"> • Fast reduction of iron ore concentrates • Hot metal with low P and Si contents <p><u>Flash ironmaking technology</u></p> <ul style="list-style-type: none"> • Complete combustion of the fuel gases in the furnace <p><u>OxyCup</u></p> <ul style="list-style-type: none"> • Handling various ferrous plant wastes <p><u>Ironarc</u></p> <ul style="list-style-type: none"> • Less carbon usage and more electrical usage 	<ul style="list-style-type: none"> • Facilities/technologies required for the utilization of export gas • Higher energy consumption for most processes • High direct CO₂ emission due to the high fuel ratio <p>Specific <u>Corex/Corex-MxcoI</u></p> <ul style="list-style-type: none"> • Potential operational issue with sticking/plating <p><u>Finex</u></p> <ul style="list-style-type: none"> • Potential occurrence of de-fluidization due to sticking <p><u>Dios</u></p> <ul style="list-style-type: none"> • Low pre-reduction degree • High tapping temperature, 1750-1800°C <p><u>Romelt</u></p> <ul style="list-style-type: none"> • High energy consumption with high coal and oxygen input rate <p><u>Flash ironmaking technology</u></p> <ul style="list-style-type: none"> • Potential reduction efficiency issue <p><u>OxyCup</u></p> <ul style="list-style-type: none"> • Coke required for providing the energy and guaranteeing the bed permeability <p><u>Ironarc</u></p> <ul style="list-style-type: none"> • Potential scale-up issue
<p>Additional comments:</p>	

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Steelmaking:	14 DRI and scrap utilization in Basic Oxygen Furnace
<p>General technology description:</p> <p>The basic oxygen furnace (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 such as silicon, sulphur and phosphorus.</p> <p>Compared to the scrap used in BOF as a coolant, the utilization of direct reduced iron (DRI) in BOF may be realized in three different ways:</p> <ol style="list-style-type: none"> (1) DRI in the form of hot briquetted iron (HBI) may be directly used as a coolant [1]; (2) DRI may be part of the charging materials for a DRI-BF-BOF route [1, 2, 3] ; or (3) DRI may be melted first and then charged to the BOF through a recently proposed DRI-melter-BOF route [4]. <p>For (1) and (2), the utilization of DRI as a charging material is limited.</p> <p>In the BOF operation, the major metallic material used is hot metal and other metallic materials such as scrap, DRI/HBI, or iron ore charged to BOF, are mainly used as coolants. Typically, the amount of scrap, DRI/HBI and other coolant materials is below 25-30% of the total materials charged [5]. In a recent study, different charging rates of HBI in a BOF with a charging capacity of 360 t were tested [6]. Without an evident change in operation, HBI may be charged up to 45 t per heat together with 45 t of the scrap. It was also reported that DRI can fully replace scrap in a BOF (a charging capacity of 150 t) with marginally deteriorated quality [7]. Despite these efforts, it is evident that the direct use of DRI in a BOF is limited by the energy balance and process control. In this regard, pre-heating of DRI may help the direct utilization of DRI in a BOF. Similarly, if supply is sufficient, pre-heating of scrap can also increase the its utilization in a BOF [8].</p> <p>The utilization of DRI/HBI in the BF operation (DRI-BF-BOF route) was introduced in Section “Novel charging materials to blast furnace”. Both theoretical estimations and practical outcomes are consistent in confirming the feasibility of DRI/HBI charging in the BF, although the actual benefit may not be same as reported. From the energy balance viewpoint, if HBI cannot be hot charged to the BF, the energy loss of cooling HBI makes this process less favorable. Without considering the flexible iron ore source and reducing agents, it is debatable to use the BF as a melter for pre-reduced materials such as DRI [9].</p> <p>The DRI-melter-BOF route was recently proposed [4]; it was discussed in Section “DRI utilization in electric arc furnace” in terms of DRI-SAF-BOF route [SAF refers to a Submerged Arc Furnace]. The DRI-melter-BOF route could be competitive with the DRI-EAF route depending on DRI properties [4]. In particular, H₂-DRI, i.e. carbon free DRI, and DRI produced from low-grade iron ore are favoured in this route. By way of example, it was reported that the DRI-SAF-BOF route is favored if lower grade iron ores (Fe content <~67.5%) are used for DRI production [4].</p> <p>More recently, SMS developed CONPRO, a new primary melter which combines the technological advantages of BOF and EAF [10]. CONPRO provides flexibility in choice of charge materials. The operation mode of CONPRO can easily shift between BOF and EAF modes, depending on the availability of charge materials and energy sources. Compared to a conventional EAF, the penetration depth of the injector in the EAF mode of CONPRO is greater [11]. There is limited information regarding the consumption and maintenance of electrodes in case of EAF mode. Due to the shortage of detailed information, CONPRO was not evaluated in the abatement sections.</p> <p>As discussed in Section “Novel charging materials to blast furnace”, economic and technological analysis of DRI/HBI utilization is necessary when DRI/HBI is used in a specific integrated steelworks.</p>	

This is closely related to the type of raw materials, production and properties of DRI, and availability of hydrocarbon-rich gases and electrical energy.

Material inputs and outputs:

Inputs	Outputs
Direct use of DRI/HBI/Scrap in BOF	
<ul style="list-style-type: none"> • Metallic materials: DRI, scrap, hot metal, iron ore • Slag builder: burnt lime, dolomite etc • Oxygen injection in BOF 	<ul style="list-style-type: none"> • Carbon steel • Slag • Off gas (CO, CO₂, H₂, N₂ etc.) • Dust
DRI-melter-BOF route	
<ul style="list-style-type: none"> • Metallic materials: DRI, scrap • Slag builder: burnt lime, dolomite etc • Oxygen injection in BOF 	<ul style="list-style-type: none"> • Carbon steel • Slag • Off gas (CO, CO₂, H₂, N₂ etc.) • Dust

Overall abatement pathway:

Direct use of DRI/HBI/Scrap in the BOF provides the metallic iron input. Depending on its charging rate, it may partially replace hot metal to help decrease the carbon footprint as DR processes typically use more hydrocarbon-rich gases.

As DRI is utilized through the DRI-BF-BOF route, CO₂ emissions are decreased compared to the conventional BF-BOF route. A comparison of CO₂ emissions for different routes is given in Table 1.

Table 1. Comparison of CO₂ emission for different routes

Route	CO ₂ emission, t- CO ₂ /t-crude steel
BF-BOF	1.65-2.2 [4, 12, 13, 14, 16]
DRI (NG)-BF-BOF	~1.45 [12]
DRI (NG)-EAF	~0.85 [12]

Preheating of scrap can lead to an increase of 8.2% in carbon abatement per tonne crude steel [8].

Currently, there are no reported CO₂ emissions for the DRI-melter-BOF route. It is likely that CO₂ emissions for this route are similar for the DRI-EAF route.

Key performance indicators:

There are no published energy consumption data for DRI-BF-BOF and DRI-Melter-BOF.

For the direct use of DRI/HBI/scrap in BOF, the charging amount of DRI per heat is limited by the energy balance and process control (e.g. avoiding the occurrence of slopping). The maximum charging amount is less than 25-30% of the total charged materials.

As a pre-reduced agglomerate, the effect of DRI on the BF performance is provided in Section “Novel charging materials to blast furnace”.

DRI application in the DRI-SAF-BOF route is at an early development stage, hence, monitoring this situation in terms of the total energy consumption and process efficiency is required.

Maturity and requirements to implement:

The direct utilization of DRI and scrap in the BOF process, is mature.

DRI utilization in the DRI-BF-BOF route requires a more holistic assessment of its value across an integrated steelworks.

DRI utilization via a melter before charging to BOF is less mature and must be verified through to industrial level practice [4, 15].	
Potential strengths and weaknesses:	
Strengths	Weaknesses
<p>General</p> <ul style="list-style-type: none"> • DRI has a lower carbon footprint compared to HM • Potential utilization of DRI produced using low grade iron ore <p>Utilization of scrap in BOF</p> <ul style="list-style-type: none"> • Providing the metallic iron input • Reuse of recycled materials <p>Direct use of DRI/HBI in BOF</p> <ul style="list-style-type: none"> • Providing the metallic iron input as substitute for scrap • Higher cooling effect compared to scrap • Potentially less slopping occurrence • More controllable steel chemistry <p>Use of DRI in DRI-SAF-BOF route</p> <ul style="list-style-type: none"> • Novel process to potentially achieve “Carbon Direct Avoidance” • Opportunity to utilize electrical energy for melting process <p>CONPRO</p> <ul style="list-style-type: none"> • Flexibility with charge materials • Operational design combines EAF and BOF aspects, including efficient oxygen injection 	<p>General</p> <ul style="list-style-type: none"> • <i>Low production capacity of DR process compared to BF</i> • <i>Requires natural gas for the more relatively mature DR processes</i> • <i>Costly mass production of green hydrogen and green electricity</i> • <i>Shortage of scrap and impurity contents in scrap</i> <p>Direct use of DRI/HBI in BOF</p> <ul style="list-style-type: none"> • Limited input amount of DRI/HBI per heat • A high reduction degree (>91%) of DRI/HBI required to replace scrap • Possibly high slag volume <p>Use of DRI in DRI-SAF-BOF route</p> <ul style="list-style-type: none"> • Requirement of a smelter • Not economically feasible compared to DRI-EAF route where high grade ore is used <p>CONPRO</p> <ul style="list-style-type: none"> • Integration of additional equipment into brownfield site
Additional comments:	

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Steelmaking:	15 DRI and scrap utilization in electric arc furnace
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General technology 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 in the EAF include one or more of scrap, direct reduced iron (DRI), hot briquetted iron (HBI), hot metal and cold pig iron. Worldwide, scrap and DRI/HBI cover ~75% and ~15% of the metallic materials used in EAFs, respectively, while the remainder is covered by pig iron and hot metal [1].

EAF steelmaking is the second-most prevalent steelmaking technology after the primary route of steelmaking, i.e. BF-BOF, which can be used to produce both carbon steel and alloy steel. Compared to BF-BOF steelmaking, EAF steelmaking consumes less energy and has a lower CO₂ emission due to the use of recycled scrap. On the other hand, there are commercial and operational issues with scrap viz. supply chain, price fluctuation and inhomogeneous composition. In the last few decades, the usage of DRI as a scrap substitute has increased in the EAF .

Both AC-EAF and DC-EAF can melt up to 100% DRI, with continuous- or batch- charging. DRI quality can be judged based on the content of non-metallic gangue, degree of metallization, carbon content and material temperature. Due to a lack of high-quality scrap, using DRI/HBI assists in improving EAF steel quality, since it dilutes tramp elements (residuals) e.g. copper. Hence, the usage ratio of DRI in EAF can vary depending on the target product quality, the availability and quality of the scrap. Major influences of DRI charging to the EAF may be summarized below:

- The DRI addition as a substitute of scrap potentially leads to an increase in the energy consumption, due to reducing the DRI (iron oxide)
- The amount of slag increases with increasing proportion of DRI in the charge, due to its gangue content
- Both the metallization and type of DRI affect the energy consumption of the EAF:
 - 1% increase in metallization allows an energy saving up to 25 kWh/t [2].
 - Carbon content in DRI is important in providing chemical energy, which is ~30% of the energy input to the EAF
 - 1 kg carbon in DRI may contribute > 8.6 kWh of energy [3].

Compared to the BF-BOF route, steelmaking via the production of DRI and its utilization in the EAF (with scrap) can significantly decrease CO₂ emissions whilst achieving targeted steel quality. To produce one tonne of crude steel, average CO₂ emissions for the DRI (NG)-EAF route are ~1.1 tonne compared to ~1.9 tonne via the BF-BOF route [4].

Several projects/new processes have been initiated to produce H₂-DRI in order to minimize carbon emissions. These were summarized in Section “Shaft furnace direct reduction”. It is anticipated that iron and steelmaking may make a stepwise transition from the BF–BOF route to for example, the direct hydrogen reduction–electric melting route [4]. However, the challenge remains to use carbon-free DRI (100%) in the DRI-EAF route since EAF steelmaking requires carbon for slag formation, reduction of FeO in DRI and chemical energy. As well, the melting temperature of metallic materials without in-situ carbon is high. Thus, in the case of using H₂-DRI with 0% carbon, carbon-containing materials have to be added to the process. These could be from renewable sources e.g. biomass. Considering in-situ C (contained in DRI) is more efficient (>95%) for FeO reduction and in helping slag formation, it should be noted that charging or injecting C (24% up to 76% efficient) is not advantageous in EAF steelmaking [3].

Recently, the submerged-arc furnace (SAF) process, a particular sub-type of electric arc furnace, was proposed to melt DRI with lower or no carbon content. The SAF has mainly been used for the continuous production of ferroalloys [5]. Compared with AC-EAF and DC-EAF, the electric energy converted into heat in a SAF is mainly through the electric resistance of the burden or molten slag.

The electrodes are immersed in the melt, providing the required energy exchange area between electrode and melt [6, 7].

The SAF is operated under reducing atmosphere conditions where there is no occurrence of oxidizing reactions. In the SAF, it is possible to continuously add carbon and slag builder with the metallic charge. Round and rectangular furnace designs are available, allowing liquid bath capacity greater than 1000 t. Thus, SAF is suitable to melt DRI to produce a pre-melt product [5, 8].

Due to this new development, the DRI-SAF-BOF route was proposed. Here, DRI can be DRI (NG) or H₂-DRI. By way of example, according to total cost of the technological route, it is estimated that a DRI-SAF-BOF route is more competitive than a DRI-EAF route if lower grade iron ores (Fe content <~67.5%) are used for DRI production [8].

Material inputs and outputs:

<u>Inputs</u>	<u>Outputs</u>
Scrap-EAF route	
<ul style="list-style-type: none"> • Metallic materials: scrap, hot metal, or cold pig iron • Slag builder: burnt lime, dolomite etc • Oxy-fuel injection: oxygen, coal or oil 	<ul style="list-style-type: none"> • Carbon steel • Slag • Off gas (CO, CO₂, H₂, N₂ etc.) • Dust
DRI-EAF route	
<ul style="list-style-type: none"> • Metallic materials: DRI, scrap, hot metal, or cold pig iron • Slag builder: burnt lime, dolomite etc • Oxy-fuel injection: oxygen, coal or oil 	<ul style="list-style-type: none"> • Carbon steel • Slag • Off gas (CO, CO₂, H₂, N₂ etc.) • Dust
DRI-SAF-BOF route	
<ul style="list-style-type: none"> • Metallic materials: DRI, scrap, hot metal, or cold pig iron • Slag builder: burnt lime, dolomite etc • Oxygen injection in BOF 	<ul style="list-style-type: none"> • Carbon steel • Slag • Off gas (CO, CO₂, H₂, N₂ etc.) • Dust

Overall abatement pathway:

In the EAF steelmaking process, CO₂ emissions are due to the carbon removal from the metallic materials and fuel injection/combustion. If the electric power is not generated from fossil-free resources, the indirect CO₂ emission for power generation is considered.

Normally, in the literature, the CO₂ emission is provided based on a specified route. The literature data are not always consistent because of the variety of data sources. Some of these are given in Table 1. For comparison, BF-BOF route has been listed as well.

Table 1. Comparison of CO₂ emission for different routes

Route	CO ₂ emission, t-CO ₂ /t-crude steel	CO ₂ load of electric energy	CO ₂ load of pellets	Ref.
BF-BOF	1.65-2.2	–	–	[4, 8, 10, 11]
Scrap-EAF	0.135	Excluded	–	[12]
Scrap-EAF	0.410	Included	–	[4]
Scrap-EAF	~0.5	Included	–	[10]
DRI (NG)-EAF*	1.098	Included	Included	[4]
DRI (NG, H ₂), Scrap-EAF#	0.2	Excluded	Included	[8]
DRI (NG, H ₂), Scrap-Melter-BOF#	0.33	Excluded	Included	[8]

*Re-utilization of off-gas should be applied. No details in the relevant literature.

#Estimated

Since steel scrap has already been reduced, lower CO₂ emissions intensity are associated with the Scrap-EAF route. Compared to the BF-BOF route, lower CO₂ emissions intensity for the DRI (NG)-EAF route is due to utilization of NG and electricity. Theoretically, higher utilization of H₂ in the process results in lower CO₂ emissions intensity.

EAF technology developments for emission and energy abatement

The significant developments in the EAF technologies to increase productivity, decrease heat loss and power consumption, and utilize off-gas, were summarized in different resources [1, 13, 14, 15]. The major technology advancements cover UHP operations, oxy-fuel burner, bottom tapping, hot heel operation, water cooled wall and roof, improved process control, foamy slag, continuous charging, charge materials preheating, bottom stirring, etc.

Some of these technologies are still under development e.g. preheating system. Along this direction, shaft furnace preheating system, the Consteel process, twin-shell DC arc furnace and Conarc process were developed. EAF Quantum developed by Primetal [15] is a more recent example. Note that these preheating systems may be different in structure and layout, but the fundamental operational principle is to utilize the off-gas from the EAF heat, for heating up the charging materials for the next heat.

Key performance indicators:

EAF classification

EAF can be classified based on the ratio of transformer rating in kVA to the tap weight of the furnace. Standard ultra-high power EAFs have 900–1000 kVA/t-steel in the transformers [1].

EAF production

EAF can have up to ~320t heat sizes, where steel temperature is normally around 1620°C [5]. The total furnace times per heat are in the range of 40–60 minutes [1].

Overall, total EAF production was ~523 Mt in 2019, or 28% of the total global crude steel production [16].

Energy consumption

Average electrical energy consumption of EAFs is in the range of 400-500 kWh/t-steel [17].

Maturity and requirements to implement:

In the steelmaking process, DRI is an excellent substitute for the major raw material, i.e. scrap, but further studies on the application of H₂-DRI in EAF are required in terms of overall process efficiency and energy consumption.

As an increase in DRI production can be expected in the future, the production capacity of EAF process is required to be scaled up.

EAFs are operating in an oxidizing environment; hence, elements that are higher than Fe in the Ellingham diagram cannot be removed, such as copper, nickel and tin. These residual elements remain in the steel cycle and lower the quality of steel. In the long term, the continuing accumulation of these elements remains a challenge that needs to be solved.

Potential strengths and weaknesses:

Strengths	Weaknesses
<p>General of EAF operation</p> <ul style="list-style-type: none"> • Utilization of scrap to reduce the energy consumption and CO₂ emission • Flexibility to vary the production • Off-peak electrical power usage • Less investment, quick to construct and fast cost recovery • Production of different types of steels • Relatively accurate control of temperature and composition of molten steel 	<p>General of EAF operation</p> <ul style="list-style-type: none"> • <i>Dilution losses of high quality scrap</i> • <i>Relatively low production</i> • <i>Requirement of a stable power system</i> • <i>Shortage of scrap and impurity content in scrap</i> <p>DRI as feed material</p> <ul style="list-style-type: none"> • More electric energy required for DRI melting than scrap

<p>DRI as feed material</p> <ul style="list-style-type: none"> • Low content of impurity elements • Controlled and consistent size of feed materials • Enhanced quality of steel product <p>H₂-DRI as feed material</p> <ul style="list-style-type: none"> • Potentially reduced CO₂ emission <p>DRI-SAF</p> <ul style="list-style-type: none"> • Relatively high production 	<ul style="list-style-type: none"> • Increased slag volume • Required DRI metallization >88% for better operation <p>H₂-DRI as feed material</p> <ul style="list-style-type: none"> • No in-situ carbon content in H₂-DRI , affecting slag formation, FeO reduction, generation of chemical energy, and the melting temperature of metallic material <p>DRI-SAF</p> <ul style="list-style-type: none"> • Production of hot metal only
<p>Additional comments:</p>	

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Steelmaking:	16 Hydrogen plasma direct steel production
<p>General technology description:</p> <p>Hydrogen plasma direct steel production refers to the process of converting iron ore to liquid iron using a thermal hydrogen plasma, in which the iron ore is melted and reduced simultaneously without agglomeration processing [1, 2, 3, 4, 5].</p> <p>During the thermal hydrogen plasma reduction (HPR), a plasma arc zone is generated between an electrode and the iron ore. In this zone, the ore can be melted and reduced by hydrogen in both molecular and plasma states. The reduction potential of hydrogen in the plasma state is ~15 times higher compared to gaseous molecular hydrogen [2]. At the reaction interface, hydrogen plasma can release enormous amounts of energy to support the reduction of iron oxides. All these result in a high reduction reaction rate. Experimental observations also show the iron oxide is melted and reduced simultaneously, with the hydrogen utilization degree decreasing as the concentration of hydrogen in the gas mixture increases [1, 3].</p> <p>Currently, application of hydrogen plasma in smelting reduction of iron ore has been studied in two ways:</p> <ul style="list-style-type: none"> (1) usage of hydrogen plasma alone at laboratory to pilot scales (SuSteel project), and (2) hybrid usage of hydrogen-based direct reduction (H₂-DR) and HPR at a laboratory scale. <p><u>SuSteel project</u> [2, 5, 6]</p> <p>The SuSteel project was designed to investigate the use of hydrogen plasma in a carbon-neutral steel production process. In this project, the previously studied hydrogen plasma smelting reduction (HPSR) at University of Leoben [2, 7, 8] was further investigated in a pilot plant at the Donawitz site of voestalpine, Austria.</p> <p>The mass of iron ore fines charged was 50-200 g in the laboratory and ~100 kg in the pilot plant [2, 5]. The gas mixture was composed of hydrogen and argon/nitrogen. The cathode consists of a hollow graphite electrode placed at the top of the reactor and as a transferred arc is used, a water-cooled electrode at the bottom serves as the anode. During the operation, gases, iron ore and flux additives are fed into the reactor through the hollow electrode.</p> <p>The pilot plant commenced operations in March 2021 [5]. A demonstration plant was scheduled for the next stage. The detailed pilot test results have not been reported.</p> <p><u>Hybrid hydrogen-based reduction of iron ore</u> [4]</p> <p>Hybrid reduction refers to the reduction of iron ore using both H₂-DR and HPR, aiming to combine their advantages.</p> <p>It was observed that direct reduction is efficient and fast in the early stages of reduction, and slows in the final reduction steps i.e. wüstite into iron. In contrast, hydrogen-containing plasma is potentially unstable in the early stages of HPR but more stable as the iron ore starts to be metalized.</p> <p>Therefore, during the hybrid operation, iron ore is first reduced to a defined reduction level using a DR process, and this pre-reduced iron ore is transferred to a plasma furnace to complete the final reduction and melting to liquid iron. The pre-reduced iron ore avoids the initial unstable arc and provides better electrical coupling during HPR. This treatment provides conditions for the efficient utilization of hydrogen and improved reduction kinetics over the whole process, and protects the furnace refractory and electrode from the damage of unstable plasma.</p> <p>Laboratory results show that when pure H₂ is used in DR and a gas mixture of Ar-10%H₂ used in HPR, the defined reduction level during DR should be 38% at 700°C to achieve a maximum utilization and highest potential for H₂ savings.</p>	

<p>Overall, hydrogen plasma reduction is a very promising Direct Carbon Avoidance approach to produce carbon-neutral steel. The progress of this technology should be closely followed.</p>					
<p>Material inputs and outputs:</p> <table border="1"> <thead> <tr> <th><u>Inputs</u></th> <th><u>Outputs</u></th> </tr> </thead> <tbody> <tr> <td> <ul style="list-style-type: none"> Iron ore fines/pellets, SiO₂, CaO Gas mixture of (H₂, Ar, N₂), (H₂, Ar) or (H₂, Ar, N₂, CO, CH₄) </td> <td> <ul style="list-style-type: none"> Metallic iron Slag Gas (Ar, H₂, H₂O, N₂, etc.) </td> </tr> </tbody> </table>		<u>Inputs</u>	<u>Outputs</u>	<ul style="list-style-type: none"> Iron ore fines/pellets, SiO₂, CaO Gas mixture of (H₂, Ar, N₂), (H₂, Ar) or (H₂, Ar, N₂, CO, CH₄) 	<ul style="list-style-type: none"> Metallic iron Slag Gas (Ar, H₂, H₂O, N₂, etc.)
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<p>Overall abatement pathway:</p> <p>In both potential routes, hydrogen and electrical energy are used as reducing agent and heating source. If the renewable energy is utilized to produce hydrogen and electricity, hydrogen plasma direct steel production has near-zero CO₂ emissions.</p> <p>The product of thermal hydrogen plasma reduction of iron ore is a steel-similar melt [3], which still requires final refining and finishing treatment before casting.</p>					
<p>Key performance indicators:</p> <p>The performance of thermal plasma reduction can be evaluated through the following factors:</p> <ul style="list-style-type: none"> Efficiency of H₂ utilization Energy consumption Reduction degree of iron ore Fluxing, carburization or other additive requirements and species partitioning Equipment life – electrodes, vessel, etc <p>At a laboratory scale, hybrid hydrogen-based reduction has higher H₂ utilization efficiency. However, total reduction time for hybrid reduction increases by 33% from 15 minutes (HPR alone) to 20 minutes.</p> <p>The situation regarding the energy consumption for plasma reduction is not clear because most studies were carried out in the laboratory. For reference, it was reported that the power input is 12kW for 45 minutes to reduce 100 g of iron ore fine by 82% [5].</p> <p>In the SuSteel project, the maximum power input is 250 kW [5]. The batch operation can handle 100 kg of iron ore. There is no data reported for detailed operation time.</p>					
<p>Maturity and requirements to implement:</p> <p>Hydrogen plasma may potentially overcome the thermodynamic and kinetic limitations of iron ore reduction by hydrogen at large-scale production levels. However, thermal plasma reduction of iron ore is still at a very early exploration stage, with the following critical issues to be developed or considered.</p> <ul style="list-style-type: none"> Development of industrial reactor and trials Operation with continuous charging and discharging Commercial feasibility in terms of operating cost and energy consumption Availability of renewable hydrogen and electricity generation 					
<p>Potential strengths and weaknesses:</p> <table border="1"> <thead> <tr> <th><u>Strengths</u></th> <th><u>Weaknesses</u></th> </tr> </thead> <tbody> <tr> <td> <p>General</p> <ul style="list-style-type: none"> Simultaneous melting and reduction of iron ore in hydrogen plasma furnace Potential carbon neutral steelmaking </td> <td> <p>General</p> <ul style="list-style-type: none"> Technology under development in terms of engineering implementation and economic feasibility </td> </tr> </tbody> </table>		<u>Strengths</u>	<u>Weaknesses</u>	<p>General</p> <ul style="list-style-type: none"> Simultaneous melting and reduction of iron ore in hydrogen plasma furnace Potential carbon neutral steelmaking 	<p>General</p> <ul style="list-style-type: none"> Technology under development in terms of engineering implementation and economic feasibility
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<ul style="list-style-type: none"> • Potential utilization of existing EAF technology for operating hydrogen-based plasma-reactors • Direct utilization of iron ore fines • Simple separation of the reaction product water by condensation • Higher reduction potential of hydrogen in plasma state 	<ul style="list-style-type: none"> • Requires massive amounts of green electricity and hydrogen • Requires design for continuous tapping of steel and slag • Development of sustainable refractory and electrodes
Additional comments:	

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Carbon capture utilization and storage (CCUS)	17 CCUS with flue gases from steelworks
<p>General technology description:</p> <p>Carbon capture, utilization and storage (CCUS) technologies are currently considered to provide a potential solution to mitigate carbon emissions in the steel industry [1, 2]. Note that the majority of CO₂ emissions (~70%) are from the ironmaking processes [3].</p> <p>CCUS is also considered as a hybrid of CCS (carbon capture and storage) and CCU (carbon capture and utilization), sharing one most important step - CO₂ (carbon) capture. CO₂ is firstly captured from industrial gas emissions and then either transported via pipeline/ship to a permanent and secure storage site, or utilized for a variety of industrial purposes.</p> <p>CO₂ capture is the most important step of CCUS. Currently, there are various carbon capture options, summarized into the following categories [2, 4, 5, 6]:</p> <ul style="list-style-type: none"> • Chemical/physical absorption • Adsorption • Cryogenic separation • Membrane physical separation <p>Some of these options have been commercialized to capture CO₂ from flue gases on a small scale [3, 7]. But, none of them is yet economically available for the capture of CO₂ from flue gases such as Blast Furnace top gas (BFG) on a large industrial scale due to the massive volume of BFG produced.</p> <p>Once CO₂ is captured, in the case of CCS, it is transported to a storage location and isolated for a long term; in the case of CCU, the captured CO₂ is re-used either directly or as a carbon resource for the production of value-added products.</p> <p>For CCS, captured CO₂ gas can be stored in “geosphere sinks” for long-term storage and products for future utilization, or directly used in industrial application.</p> <p>“Geosphere sinks” include oil reservoir, depleted oil and gas reservoir, coal beds and deep aquifers. Although the storage technology of CO₂ isolated from the atmosphere has been proved, there are still technical, economic, environmental and social issues to be solved, such as long-term environmental impact [4].</p> <p>Compared to storage, CCU is expected to be a more feasible solution to treat emissions in the long term. In general, there are three utilization categories [1] based on CO₂ changes during its utilization:</p> <ul style="list-style-type: none"> • Without CO₂ transformation • After CO₂ chemical transformation • After CO₂ biological transformation <p>In spite of the above utilization categories, the amount of CO₂ currently utilized remains small.</p> <p>Cost-effective technologies need to be developed to utilize pure CO₂ captured from steel plant flue gases.</p>	
Material inputs and outputs:	
Materials inputs and outputs depend on CCS and three specific CCU technologies outline:	
<u>Inputs</u>	<u>Outputs</u>
Carbon capture and storage (CCS)	
<ul style="list-style-type: none"> • Flue gases (CO, CO₂, H₂, H₂O, N₂) 	<ul style="list-style-type: none"> • Liquid CO₂ for storage, recycled CO and H₂ (processed gas)
Carbon capture and utilization (CCU)	
CCU without CO ₂ transformation	

<ul style="list-style-type: none"> Flue gases (CO, CO₂, H₂, H₂O, N₂) 	<ul style="list-style-type: none"> Separated CO₂ and reducing gas
CCU after CO ₂ chemical transformation	
<ul style="list-style-type: none"> Flue gases (CO, CO₂, H₂, H₂O, N₂) and hydrocarbons/compounds of nitrogen/minerals 	<ul style="list-style-type: none"> Chemical products (methanol CH₃OH, ethanol C₂H₆O, methane CH₄, formic acid CH₂O₂, urea CH₄NO, polymers, etc.), cement, carbonate, fuel, etc.
CCU after CO ₂ biological transformation	
<ul style="list-style-type: none"> Flue gases (CO, CO₂, H₂, H₂O, N₂) and phosphorous/starch/syngas 	<ul style="list-style-type: none"> Chemical products (methanol, methane, butanol C₄H₁₀O, etc.), biomass, biofuels, O₂, etc.

Overall abatement pathway:

The CO₂ capture was expected to account for most of the operating cost for CCUS of flue gases. According to capture media and process specifications, generally, there are four major capture technologies: absorption (chemical, physical), adsorption, cryogenics and membranes [1, 2, 4, 5, 6]. Each of them will be briefly introduced below:

- Chemical absorption

Chemical absorption technology is the most mature technology for CO₂ capture, using chemical solvents to react reversibly with a targeted gas component. The typical process flow diagram [2] is :

Flue gas → Flue gas pre-treatment → Absorption → Stripping → Compression → CO₂ product

After pre-treatment, the gas is in contact with an alkaline solvent in an absorption system to form weak intermediate compounds. Then, the CO₂ rich solution is sent to a stripping system where it is heated to break down the intermediate compounds. This regenerates the solvent and emits a concentrated CO₂ stream which is then compressed and transported for use.

Some common chemical solvents are monoethanol amine (MEA), diethanol amine (DEA), methyldiethanol amine (MDEA), and aqueous ammonia.

Amine absorption has been used by the natural gas industry for over 60 years to remove CO₂ from natural gas. Some new amines are still being developed [8].

There are three amine absorption processes which are commercially available: the Kerr-McGee /AGG Lummus Crest (KMALC) process, the Fluor Econamine FG PlusSM (EFG+) process, and the KM-CDR process [2].

Recently, some tests using ammonia and other newly developed solvents were carried out on a laboratory or pilot scale (Nippon Steel, Posco and VALORCO) [9, 10, 11, 12, 13, 14].

- Physical absorption

Compared with chemical absorption, physical solvents are used in physical absorption to capture CO₂, without the use of a chemical reaction. As well, the CO contained in the flue gas stream can be converted into CO₂ through water-gas-shift reaction under high temperature and pressure. A gas stream consisting of CO₂/H₂ is created, from which the CO₂ is separated.

Physical absorption relies on the solubility of CO₂ in solution. It is suitable for high partial pressure CO₂ gas streams because the gas solubility is proportional to its partial pressure. Absorption is favored at high partial pressures of the targeted gas component in the gas phase and low temperatures. Desorption, and thus solvent regeneration, is favored at high temperatures and low pressures.

A typical capture technology using physical absorption is Selexol technology. The physical solvent is Union Carbide Selexol solvent which is a mixture of dimethyl ethers and polyethylene glycol ($\text{CH}_3\text{O}(\text{C}_2\text{H}_4\text{O})_n\text{CH}_3$), with “n” ranging from 3 to 9 [2].

Physical absorption can only be applied economically to flue gas streams with high CO_2 partial pressures.

- Adsorption

Adsorption technology is based on the selective retention of a gaseous component from a flue gas stream on the surface of a porous solid material, i.e. adsorbent, which is considered one of the most promising technologies for CO_2 capture. The typical process flow diagram [2] is:

Flue gas → Flue gas pre-treatment → Adsorption → Desorption → Compression → CO_2 product

At the adsorption step, the gas is adsorbed by the adsorbent under controlled temperature and/or pressure conditions; and at the desorption step, the saturated adsorbent undergoes regeneration by liberating the separated gas.

Some common adsorbents for CO_2 are zeolites, activated carbon, amine functionalized adsorbents and metal-organic frameworks (MOFs) [2].

The main adsorption processes are pressure swing adsorption (PSA), vacuum pressure swing adsorption (VPSA), temperature swing adsorption (TSA) and electric swing adsorption (ESA) [1]. The difference between these processes is how the adsorbent is regenerated. The adsorbent is regenerated by reducing its pressure in PSA and vacuum is used in regeneration in VPSA. Heating and a low-voltage electric current are used for regeneration in TSA and ESA, respectively.

To date there are no operating large-scale commercial CO_2 capture processes based on adsorption technology.

- Cryogenic separation

In a cryogenic separation system, CO_2 is physically separated from flue gas stream based on dew and sublimation points.

Two cryogenic separation technologies for CO_2 capture have been proposed [2]: (1) Clodic and Younes, and (2) Tuinier and coworkers. In the former process, CO_2 is de-sublimated onto the surface of heat exchanger fins; and in the latter process, CO_2 is de-sublimated onto the packing material.

The main advantage of the cryogenic process is the absence of chemical systems and the operation at ambient pressure. However, the cryogenic process requires a very large amount of energy for refrigeration. It is often considered as an additional purification step while placed downstream of a complementary separation process responsible for CO_2 enrichment.

- Membrane physical separation

Membrane separation technology uses permeable or semi-permeable materials to separate CO_2 from the flue gas stream. The typical process flow diagram [2] is:

Flue gas → Pre-treatment → Compression → Membrane → CO_2 rich + CO_2 depleted streams

Flue gas is firstly pre-treated to remove the impurities, and is then compressed to create a driving force for gas separation within the membrane. Through the membrane, the gas stream can be separated to CO_2 rich and CO_2 depleted streams.

Main types of membranes are polymeric, carbon and recently, metallic.

Currently, only dense polymeric membranes are used commercially for CO₂ removal from natural gas on an industrial scale.

The technology mentioned above is still economically suited for low volume CO₂ capture. Scale-up of the system for the massive volumes of flue gas produced in steel plants is a significant challenge.

In the long term, CCU is expected to provide a solution for CO₂ mitigation within an ecosphere following the principles of industrial ecology.

The three categories of CO₂ utilization [1, 15] are summarized below:

- CO₂ utilization without transformation
 - enhancement of the oil, gas and coal bed methane recovery (EOR, EGR, and ECBM)
 - food and beverage product
 - BOF steelmaking in terms of mixed CO₂-O₂ injection [16]
 - COG reforming in the blast furnace ironmaking process [3]
 - geothermal energy production
 - a refrigerant applied in low temperature refrigeration applications
 - extraction in food and pharmaceutical industry
- CO₂ utilization after chemical transformation
 - polymer and fertilizer products through the reaction between CO₂ and hydrocarbon/nitrogen-containing compounds
 - carbonates through the reaction between CO₂ and some natural mineral or industrial alkaline wastes
 - waste water treatment through the formation of carbonic acid
 - chemical products such as methanol, ethanol, methane through CO₂ hydrogenation, electrolysis, photoelectrocatalysis and thermolysis
- CO₂ utilization after biological transformation
 - biomass and O₂ through the growth of microalgae
 - biofuel and chemical products through fermentation

CCUS in the iron and steel industry has been evaluated in different research programs and implemented at pilot scale or via plant demonstrations.

- NKG process [17]: Effect of BFG and COG reforming on the reduction of coke rate was investigated through reducing gas injection to an experimental blast furnace (1972).
- ULCOS TGR-BF project [18]: VPSA process coupled with a cryogenic process was applied for CO₂ capture at a pilot scale (2007 – 2010).
- Emirates Steel Industries (ESI) [7]: On a commercial scale, CO₂ captured from their DRI process through absorption technology was injected into oil reservoirs to enhance oil recovery. Amine absorption technology was used for CO₂ capture. Operation started in November 2016.
- BlueScope (New Zealand), Baosteel, Shougang Steel Group, STEELANOL (ArcelorMittal) [3, 19]: LanzaTech microbial gas fermentation process technology was used to convert the flue gas to fuels and chemicals. A commercial facility was set up to convert BOFG to ethanol in 2018 (Shougang).

- “Carbon2Chem” project (Thyssen Krupp Stahl) [20]: Steel mill gases containing CO₂ was used to produce chemical products such as methanol, ammonia etc. First project phase with a pilot plant was successfully completed. Carbon2Chem is expected to help reduce CO₂ emissions at thyssenkrupp’s steel mill by 30% by 2030.
- COURSE50 (Japan) (2008 –) [9]: Absorption technology based on a new solvent (secondary amino alcohols) was tested at a pilot plant with capacities of 1 and 30 t-CO₂/day. Results showed less regeneration energy was required in comparison with MEA absorption. In particular, it was claimed that the total thermal energy consumption for CO₂ capture can be reduced by half from 4GJ/t-CO₂ to 2GJ/t-CO₂ because of high performance of new absorbent, process optimization and usage of waste heat. In relation to this target, actual data have not been found in the literature.
- COURSE50 (Japan) (2008 –) [10]: PSA technology was used to separate CO₂ from BFG. Targets were achieved at a pilot plant with a capacity of 3 t-CO₂/day. The maximum CO₂ purity was 99.5%.
- POSCO CO₂ breakthrough framework (Korea) [12]: Ammonia absorption was applied for BFG CO₂ capture in a pilot plant (10 t-CO₂ per day). CO₂ recovery was 90%, with purity over 98%.
- VALORCO project (France) [14]: Absorption technology based on different solvents was tested in different processes (HicaptTM, Hicapt⁺TM, DMXTM) for CO₂ capture. DMX process with proprietary demixing solvents shows a better performance in terms of cost and corrosion. CO₂ recovery was over 99.5%, with purity over 99%.
- STEPWISE project (EU) [21]: SEWGS (Sorption Enhanced Water Gas Shift) technology was developed in Sweden. CO₂ in flue gas is firstly enriched by using water-gas shift reaction to convert CO to CO₂, and then CO₂ is separated from H₂ using adsorption technology. It is expected that the total emission can decrease to 1.26 t-CO₂/t-steel after 45% of BFG is treated through this technology.
- C4U project (UCL (C), ArcelorMittal, etc) [22]: Two CO₂ capture technologies, DISPLACE and CASOH, are used in C4U project. DISPLACE is based on adsorption technology to capture CO₂, and CASOH is mainly used for calcium assisted steel mill off-gas hydrogen production [23]. The project targets up to 90% of a steel plant’s CO₂ sources. An industrial pilot is being built.
- Slag2PCC (Mineral sequestration of CO₂) [24, 25]: This is a typical technology to utilize CO₂ through chemical transformation. Precipitated calcium carbonate (PCC) can be produced, utilizing steelmaking slags and CO₂. A pilot-scale test facility was set up at Aalto University. The concept was well proved. However, the economic feasibility needs to be improved for the commercialization of this technology.
- Carbon2Value (EU) [26]: In Phase 1 of this program (2017-2020), the assessment and operation of both pilot lines were used for the separation of CO/CO₂ in BFG/COG using amine based absorption technology [27]. In phase 2, the CO/CO₂ separation pilot line will be combined with downstream CO utilization pilot line. Two routes of gas utilization were proposed [26], including the production of ethylene and ethanol. A demonstration plant is planned in Phase 3 after 2027.
- MefCO₂ project (EU) [28]: MefCO₂ project demonstrated the feasibility to produce methanol from CO₂. During the project period between 2015 and 2019, a pilot plant was set up to produce 1 ton of methanol per day by capturing > 1.5 tons of CO₂ per day.
- FReSMe (EU) [29]: FReSMe project builds on the success of STEPWISE and MefCO₂ projects to develop CCU technology. 25 tons of low carbon methanol were successfully produced using BFG [30].

- Everest (Tata steel) [31, 32]: The project started in 2018 and it is currently at the stage of pilot plant construction. The project aims to produce the chemicals through utilizing CO and H₂ by-products from steelworks and capture CO₂ for storage in the North Sea gas fields. Amine based absorption technology will be used for CO₂ capture from BFG.
- Project3D (ArcelorMittal at Dunkerque) [33]: Project3D started in 2019, aiming to demonstrate the effectiveness the DMX process on an industrial pilot. DMX process was named after the solvent DMX used in chemical absorption technology for CO₂ capture. The solvent DMX was developed in the previous project “VALORCO”. The first test of the DMX industrial unit was scheduled in March 2022 at ArcelorMittal Dunkirk. It was expected that DMX process can reduce the energy intensity of CCU/S by almost 30% and capture ~4400 t-CO₂ per year from flue gases.
- Carbon4PUR (Dechema, ArcelorMittal, etc) [34]: The Carbon4PUR project has developed and demonstrated (TRL 4-6) an economically viable technology to transform the carbon from flue gases into high value polyurethane materials. This technology allows a reduction of CO₂ emissions by 10%, saves natural resources and reduces associated environmental/biological impact up to 20% [35].
- Mineral carbonation [36]: CO₂ in the flue gas can be transformed to valuable product magnesium/calcium carbonates through this technology. A demonstration plant (TRL 7) is being built by Mineral Carbonation International (MCI) and is expected to be commissioned in 2023. The final aim of MCI is to set up a carbon plant with a treatment capacity of 1 Mt-CO₂ per year.

Key performance indicators:

Different CCUS options should be under investigation considering the following indicators:

- Environmental impact
- Separation/utilization efficiency of CO₂
- Gas capacity for treatment
- Cost of implementation/utilization
- System environment
- Energy consumption
- Long term reliability and sustainability

Maturity and requirements to implement:

For CO₂ capture from flue gases, absorption, adsorption and membrane technologies may be helpful for application at production level. Cryogenic separation is more suited as an additional step in case high purity is needed as it is a high energy consuming process.

Absorption processes were largely used at commercial scale in chemical plants. Recent absorption tests using ammonia or some new solvents for CO₂ capture from flue gases in steel plants were still at a laboratory or pilot scale. Compared with absorption technology, adsorption and membrane processes are emerging technologies. They are promising processes to treat the flue gas with high CO₂ partial pressure at high capacity; although the power consumption is still high. Design and operation of a full-scale industrial process using these technologies need to be carried out.

Carbon storage is widely regarded as a potentially important CO₂ mitigation option because demonstration and commercial projects have been successfully undertaken. Although overall storage science is understood, detailed knowledge is still not clear such as the kinetics of geochemical trapping and the long-term impact of CO₂ on reservoir fluids and rocks. It still requires an evaluation of storage operations' risks for health and the local environment. There are many uncertainties regarding

leakages, such as quantification of potential leakage rates from storage sites and long-term leakage monitoring approaches. It appears that continuous improvement is required to overcome technical barriers.

Among CO₂ utilization options, the largest scale use of capture CO₂ is its geological storage for enhanced oil recovery; global geological storage capacity is ~900 Gt CO₂. The scale of CO₂ usage in industrial processes is small. Among the industrial uses of CO₂, the production of urea fertilizer accounts for a large part. However, the lifetime of urea fertilizer is only 6 months. Thus, breakthrough technologies are required to apply CO₂ in a wide range of chemical production areas, and then recycle/reuse CO₂ in an ecosphere.

Associated with technology developments, the large capital investment is another key issue. Deployment of CO₂ utilization technology on a commercial scale should be supported by government policymakers due to its economic disadvantages over conventional technologies.

Potential strengths and weaknesses:

Strengths	Weaknesses
<p>CO₂ capture</p> <ul style="list-style-type: none"> • Chemical absorption: selective separation; achievable high purity; mature process • Physical absorption: no chemical reaction; non-thermal solvent regeneration; no corrosion issue; dry gas leaving from the absorber • Adsorption: less energy required; suitable for high CO₂ streams • Cryogenic separation: no chemical reaction; operation at ambient pressure; achievable high purity; liquid CO₂ product • Membranes: reduced environmental impact; easy scaling; relatively low capital and operating costs; space efficiency; flexibility; minimum facility requirement; no moving parts; ease of operation and control; low energy consumption <p>CCS</p> <ul style="list-style-type: none"> • Decreased CO₂ emission if renewable energy is used • Potential natural underground carbonation <p>CCU</p> <ul style="list-style-type: none"> • Convert CO₂ to add-value products • Establish a circular eco-system • Opportunities to establish a symbiosis system for chemical and metallurgical industries • Resource saving 	<p>CO₂ capture</p> <ul style="list-style-type: none"> • Chemical absorption: equipment corrosion (amine); environmental impact (amine); high energy consumption; large equipment sizes; partially regenerated solvent; scale up issue. • Physical absorption: elevated pressure for high efficiency; not feasible for flue gas at ambient pressure. • Adsorption: low purity; need high operating pressure; decreased adsorption capacity with elevated temperatures • Cryogenic separation: high cost for refrigeration and water removal of flue gas • Membranes: high energy requirements for gas compression; multistage separations needed to achieve high purity; aging membranes; high cost for large scale <p>CCS</p> <ul style="list-style-type: none"> • Extra investment and energy required compared to TBF process • Increased environmental impacts • Transportation cost of liquid CO₂ • Potential leakage • Uncertainties of storage technology <p>CCU</p> <ul style="list-style-type: none"> • Extra investment and energy required compared to TBF process • Small scale of CO₂ usage • Technological breakthroughs required

Additional comments:

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