Australia's National Science Agency

The State of Energy Transition Technologies

Industry

TECHNICAL APPENDIX

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Citation and authorship

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Acknowledgement

CSIRO acknowledges the Traditional Owners of the land, sea, and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture, and we pay our respects to their Elders past and present.

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Contents

Unit conversions

UNITS	
GJ	Gigajoule (1 000 000 000 joules)
PJ	Petajoules (1 000 000 gigajoules)
GW	Gigawatt (1 000 megawatts)
GWh	Gigawatt hour (a gigawatt of power used in an hour)
kL	Kilolitres (1 000 litres)
Km	kilometre (1 000 metres)
kW	Kilowatt (1000 watts of electrical power)
MJ	Megajoule (1 000 000 joules)
Mwe	Megawatt electric (1 000 000 watts of electrical energy)
MWh	Megawatt hour (1 000 000 watts of power used in an hour)
MWth	Megawatt thermal (1 000 000 watts of thermal energy)
TWh	Terawatt hour (1 000 000 megawatt hours)

1 Executive summary

Industry

RD&D to lower the cost of electricity and low carbon fuels can help drive the economic viability of low emissions technologies for alumina digestion, iron and steelmaking, and mining heavy haulage operations.

Challenge

Australian industry is made up of a diverse range of sectors that play a crucial role in both domestic and international markets and contribute significantly to GDP, exports and employment. However, it also remains one of the largest contributors to Australia's total emissions and energy consumption. The complexity of industry decarbonisation pathways, driven by differences in individual operation asset configurations, process requirements, asset lifetimes, site location and technology availability, requires investment across the distribution or co-location of low carbon fuel production and renewable energy generation infrastructure, and energy efficiency technologies.

Scope of analysis

This analysis highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts across three Industry sub-sectors:

- **Iron and steelmaking** analyses low emission technologies that provide emissions abatement pathways for iron and steelmaking, an energy and emissions intensive high-temperature heat process. Five technologies were explored in more detail to identify RD&D opportunities.
- **Medium-temperature process steam** analyses technology options that can provide emissions abatement pathways, adopting the digestion phase of alumina refining as a use case. Alumina digestion is a process extracting alumina from bauxite ore and accounts for a significant amount of medium-temperature process steam emissions in Australia. Four technologies were explored in more detail to identify RD&D opportunities.
- **Mining heavy haulage** analyses low emissions technology options that can transport significant volumes of mined materials in open-pit operations. Due to their significant energy consumption, high emissions intensity, and demanding operational requirements, heavy-duty diesel trucks present as a decarbonisation challenge for the mining industry. Two technologies were explored in more detail to identify RD&D opportunities.

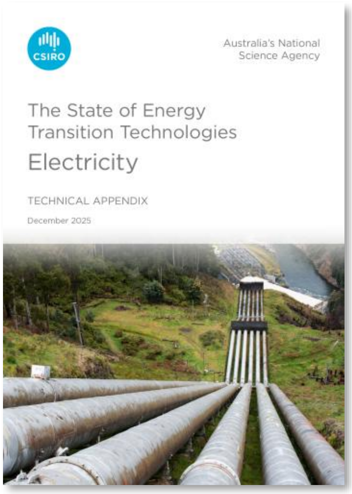
2 Industry overview

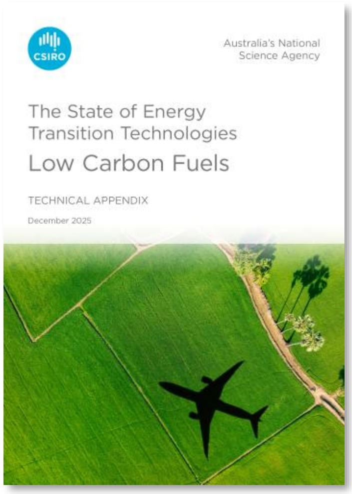
Research, development and demonstration (RD&D) will be pivotal in informing and driving the change required to achieve the energy transition and Australia's net zero ambitions. However, with limited resources and a broad array of emerging low emissions technologies, Australia faces the important task of strategically and collaboratively optimising its RD&D efforts to maximise national benefit.

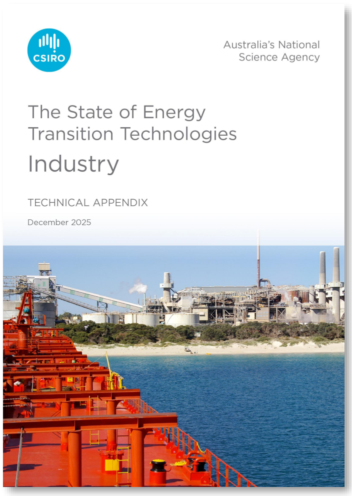
This study, *The State of Energy Transition Technologies*, highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. It is not intended to prescribe research strategies for Australia or any individual organisation. Rather, it serves as a resource to support constructive dialogue and help navigate the energy transition by leveraging the nation's RD&D strengths.

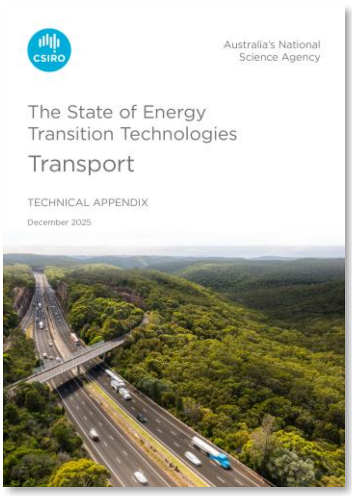
2.1 This report

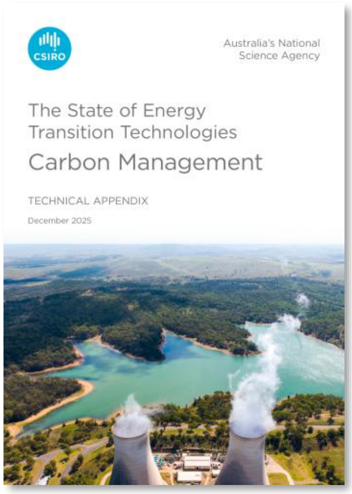
The State of Energy Transition Technologies consists of a Synthesis report and five technical appendices spanning a range of Australian energy supply and demand related sectors. This report, focused on industry, is to be considered alongside the other appendices, and aims to evaluate a diverse range of low emissions technologies to help explore opportunities for RD&D related to specific industrial activities. It leverages global literature and CSIRO expertise, designing and applying a technology analysis framework to explore RD&D opportunities.











2.2 Australia's industrial energy needs

Australian industry is made up of a diverse range of sectors that play a crucial role in both domestic and international markets and contribute significantly to GDP, exports and employment. Sectors include mining, oil and gas extraction, primary metal production, chemical manufacturing, resource processing and other essential services. Key industrial supply chains include iron and steel, aluminium, other metals, chemicals, and liquefied natural gas (LNG), which together generate substantial revenue. For example, the Australia Industry Energy Transitions initiative report states that these five supply chains contribute 17.3% of Australia's GDP and generate $236 billion in annual exports.[1]

While industry plays a vital role in both the national and global economy, it remains one of the largest contributors to Australia's total emissions and energy consumption. Heavy industry accounts for 44% of Australia's total emissions, while industrial processes consume 44% of Australia's total energy.[1] Industry emissions refers to direct combustion emissions from burning fuels, coal and gas to generate energy for stationary purposes. For example, to produce energy for industrial heat, steam and pressure and to produce energy for mobile equipment in mining, manufacturing and construction.[1]

Industry decarbonisation pathways are complex. Industry investments are often influenced by the current state and future development of global markets and supply chains. Fluctuations in resource demand, prices, and competition on an international level can affect where and how much Australia invests. Investment decisions are also intertwined with company and site-specific decisions. For example, decisions relating to the long asset lives of existing infrastructure.

Balancing economic growth with net-zero targets will require Australia to make considered investment decisions that are aligned with the transformative changes expected in Australia's energy system. Accelerating the most relevant and cost-effective of technologies will be essential for positioning Australia's industrial sector to remain globally competitive in a decarbonised future.

2.3 Scope of this report

Given the breadth and diversity of Australia's industrial sectors, this report highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies related to iron and steelmaking, mid-temperature process steam, and mining heavy haulage, advancing Australia's industrial decarbonisation efforts.

These three subsectors contribute a significant proportion of energy and emissions compared to other process-based subsectors. They also represent challenging Australian industrial subsectors which present clear opportunities for ongoing RD&D effort.

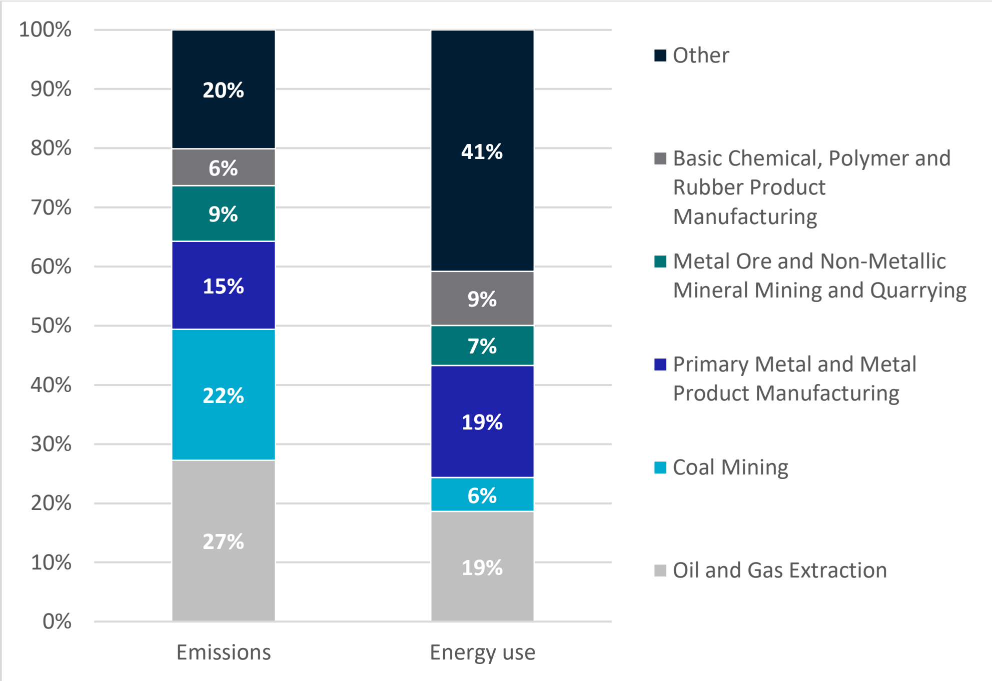
The following section provides an overview of the analysis that informed the scope of this report, including a high-level overview of iron and steelmaking, mid-temperature process steam, and mining heavy haulage.

[1] Climateworks Centre and CSIRO (2023) Pathways to industrial decarbonisation: Phase 3 technical report. Australian Industry Energy Transitions Initiative, Climateworks Centre.

Industry subsector emissions and energy use analysis

To inform the scope of the report, analysis of emissions and energy use was conducted across various industrial processes. The analysis highlighted that the top the five top emitting industry sectors[2] in 2022 represented 80% of emissions but accounted for only 59% of total industrial energy use (See Figure 1).

Figure 1: Total emissions and energy use (%) by industry sector (2022)[3]

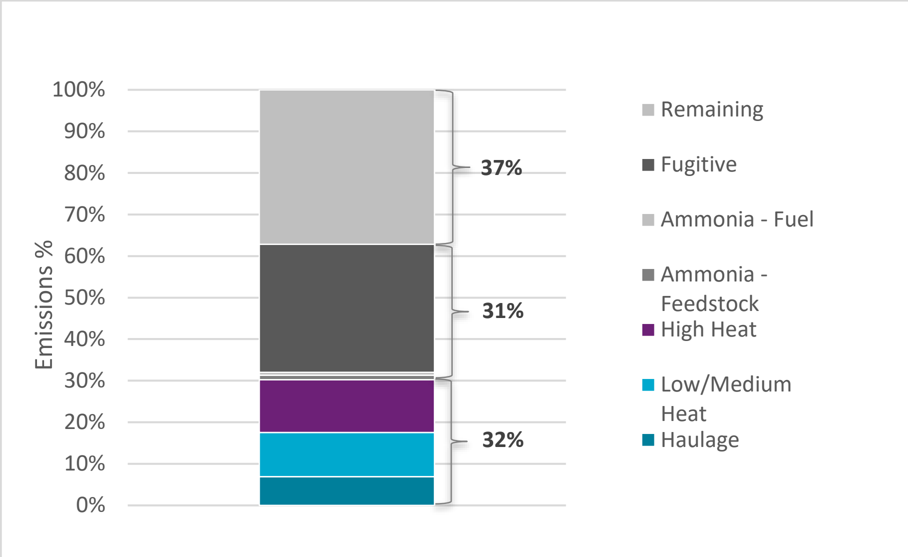


Analysis of key activities within these industrial processes show that high-temperature heat, medium-temperature process steam and mining heavy haulage contribute to a significant proportion of energy, heat and emissions intensity compared to other process-based subsectors (see Figure 2). Together, these activities account for 32% of the industry sector's total Scope 1 emissions (including fugitive emissions).

[2] Industry sectors are typically classified using the Australian and New Zealand Standard Industrial Classification (ANZIC) system, where a business is assigned to an industry based on its predominant activity. The ANZIC codes for the industry sectors used in this analysis are as follows: 07 Oil and Gas extraction, 08-10 Metal Ore and Non-Metallic Mineral Mining and Quarrying, 21 Primary Metal and Metal Product Manufacturing, 06 Coal mining and 18-19 Basic chemical, Polymer and Rubber Product manufacturing. ANZIC codes have been excluded from figures for simplicity.

[3] Emissions were sourced from the Department of Climate Change, Energy, the Environment and Water's (DCCEEW) National Inventory by economic sector.[3] Energy use was sourced from DCCEEW's Guide to Australian Energy Statistics.[3]

Figure 2: Share of emissions and energy use captured by a selection of industry subsectors (2022)[3]



A more detailed breakdown of emissions from specific industry activities is provided in the Australian Industry Energy Transitions Initiative (IET) Phase 1 and Phase 3 reports.[4] Unlike medium-temperature steam and mining heavy haulage, high temperature heat has been analysed in the context of iron and steelmaking. According to ETI emissions estimates, iron and steelmaking accounts for the largest proportion of emissions for high-temperature heat processes (57%). Given this and its importance to the Australia economy, it has been identified as a critical high-temperature heat process to focus on for analysis.

Overview of subsectors analysed within the report

Iron and steelmaking

Australia is the world's largest iron ore exporter, and the iron and steel industry plays a significant role in the Australian economy by generating export revenue, supporting domestic and international trade and creating local employment opportunities.

However, this industry is energy intensive, and the high temperature process heat (>800°C) required for extracting iron ore and converting it to steel is a significant source of CO_2 emissions. Based on ETI data, blast furnace-basic oxygen furnace (BF-BOF) steel production released 10.11 $MtCO_2e$ in 2022.[5]

To date, emissions abatement is challenged by brownfield asset lifetimes and capital-intensive processing infrastructure. Investing in the development of low emission technologies will be required to strengthen Australia's supply chain, meet rising demands for green steel and remain competitive in global markets.

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[4] Emissions estimates have been calculated via internal analysis, drawing on figures from the Australian Industry Energy Transitions Initiative Phase 1 & Phase 3 reports:Butler C, Maxwell R, Graham P, Hayward J (2021) Australian Industry Energy Transitions Initiative Phase 1 Technical Report, ClimateWorks Australia; and Climateworks Centre and CSIRO (2023) Pathways to industrial decarbonisation: Phase 3 technical report, Australian Industry Energy Transitions Initiative, Climateworks Centre. ***Note:*** Energy and emissions breakdowns were only available for a select few subsectors and processes and as such final estimates are an underestimate ofoverall energy requirements and emissions across the entire industry subsector.

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Medium-temperature process steam

Medium-temperature process steam is vital to multiple industrial sectors in Australia, including the digestion phase of alumina refining, food processing, textile manufacturing and other industrial processes that require heat at a moderate temperature range (100-300°C).

Like iron and steelmaking, medium-temperature industrial processes are energy intensive. Based on ETI data, the medium-temperature process heat required for alumina digestion released 9.75 $MtCO_2e$ in 2022.[6]

Decarbonising medium-temperature processes is challenging due to the high upfront costs of transitioning manufacturing plants, their long life span and the difficulty of sourcing thermal energy from low-or zero emission sources. While there are multiple pathways forward, such as electrification and thermal energy solutions, with clear opportunities for RD&D to support the transition toward these low emissions technologies.

Mining heavy haulage

Mining heavy haulage is essential to the operational efficiency and cost and export competitiveness of Australian mines. It refers to the transport of large volumes (100 to 400 tonnes) of mined materials, including ore, coal and overburden in open-pit or underground mining operations.

Mining heavy haulage is a key contributor to total mining emissions. Based on ETI data, heavy mining haulage in iron, bauxite, coal and other metal (copper, lithium, nickel and zinc) mines released 12.57 $MtCO_2e$ in 2022.[7]

To date, the cost of purchasing zero emission trucks and developing supporting infrastructure, such as such as charging stations, hydrogen refuelling networks, and grid upgrades in remote mining areas, is significantly higher than maintaining existing diesel fleets. This creates substantial barriers to decarbonisation for this key aspect of mining operations. Investing in RD&D to support the transition of heavy mining haulage vehicles to low emission technologies will be critical to reduce the carbon footprint of this subsector.

[6] Emissions estimates have been calculated via internal analysis, drawing on figures from the Australian Industry Energy Transitions Initiative Phase 1 & Phase 3 reports:Butler C, Maxwell R, Graham P, Hayward J (2021) Australian Industry Energy Transitions Initiative Phase 1 Technical Report, ClimateWorks Australia; and Climateworks Centre and CSIRO (2023) Pathways to industrial decarbonisation: Phase 3 technical report, Australian Industry Energy Transitions Initiative, Climateworks Centre. ***Note:*** Energy and emissions breakdowns were only available for a select few subsectors and processes and as such final estimates are an underestimate ofoverall energy requirements and emissions across the entire industry subsector.

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3 General methodology

The State of Energy Transition Technologies report methodology was designed to highlight RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. The methodology adopts a multi-stage approach (see , where prospective technology solutions were identified from a broad list through a technology analysis framework. This formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

The framework uses a structured approach to consistently filter technologies, while retaining flexibility to adapt criteria to a broad range of sectors and sub-sectors. This helps ensure technologies are fit-for-purpose and can meet the expected requirements for indicative energy- and emissions-intensive Australian use cases, while capturing a diverse range of technologies and RD&D opportunities to support Australia's sectoral and economy-wide 2050 net zero objectives.

The analysis derives technology specific RD&D opportunities that could address the technical, economic, and operational requirements of different sector applications. While extremely important, non-technical RD&D is outside of the scope of this study. This includes research related to policy and regulation, social licence and participation, communication and engagement and governance to support the energy transition.

The following is a high-level summary of the methodology and framework applied in this report.

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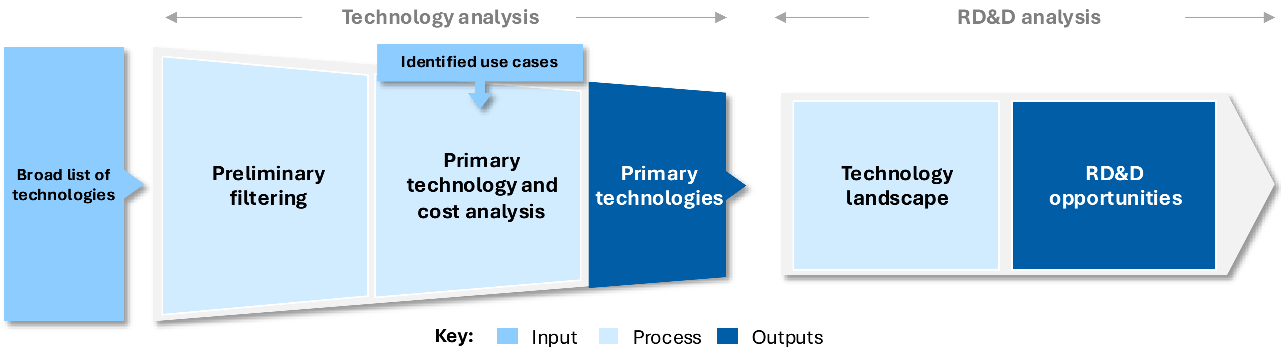
Figure 3: Summary of framework



Inputs

The broad list of technologies was compiled from most recent Australian and global literature and assigned to key (sub)sectors (see *Appendix A.3* for sources). As the level of detail varied across sources, only technologies that directly contribute to emissions reduction efforts were considered as inputs to the framework.

Use cases were defined based on energy and emissions intensive applications identified for the sector/subsector. These use cases were developed to ensure technologies were fit-for-purpose for the specific (sub)sector, and focus on opportunities with the highest abatement impact. These use cases aim to capture a diverse range of applications where possible to ensure the technologies explored provide a portfolio of solutions that align with Australia's sectoral and economy-wide decarbonisation needs.

Technology analysis

The technology broad list was filtered through a two-stage process to explore their suitability for the chosen use case(s). Filtering has been conducted on a knock-out basis, ensuring that only technologies meeting all relevant conditions progressed through the analysis. The order of filters is not indicative of a relative importance of criteria.

- **Preliminary filtering**: Three criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:
  1. Relevance to Australia;
  2. Technology maturity; and
  3. Abatement potential.[8]
- **Primary technology and cost analysis**: Specific criteria were applied to determine each technology's suitability for use case applications, followed by levelised cost analysis to provide a relative comparison of the long-term feasibility of technology options and to support RD&D opportunity analysis.
  1. The specific criteria used to evaluate suitability differed by subsector. For more detail on the criteria used across each (sub)sector in *The State of Energy Transition Technologies* reports, please refer to *Appendix A.3.*
  2. Levelised cost analysis was conducted for each use case to identify technologies that are relatively more cost competitive and therefore likely to play a role in advancing Australia's decarbonisation efforts. Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis.*

At each filter, technologies were assigned one of three ratings (see Figure 4) based on their ability to meet the criteria. Where conditions or limitations were identified but deemed surmountable for a given technology, a 'meets criteria with caveats' rating was applied.

The subset of technologies that met all filtering criteria are described as *Primary technologies*, and inform the technology landscape development and RD&D opportunity analysis.

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[8] Considers Scope 1 emissions arising from the direct use of a technology, as well as Scope 2 (indirect) emissions generated from the production of key energy inputs. Some Scope 3 emissions are considered on a case-by-case basis. See the relevant section for further detail.

Figure 4: Technology assessment rating criteria

Meets filter criteria | Meets criteria with caveats | Does not meet criteria | Not assessed further

Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the exploration of RD&D opportunities. The identified *Primary technologies* cannot exist in isolation and form one part of a broader technology landscape that must be developed in parallel. This landscape includes technologies essential for the deployment or enhanced performance of the primary technologies, described in *The State of Energy Transition Technologies* reports as *Auxiliary technologies* (see Figure 5).

Figure 5: Technology landscape components

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding *Energy efficiency solutions*, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across *Primary and/or Auxiliary technologies*. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

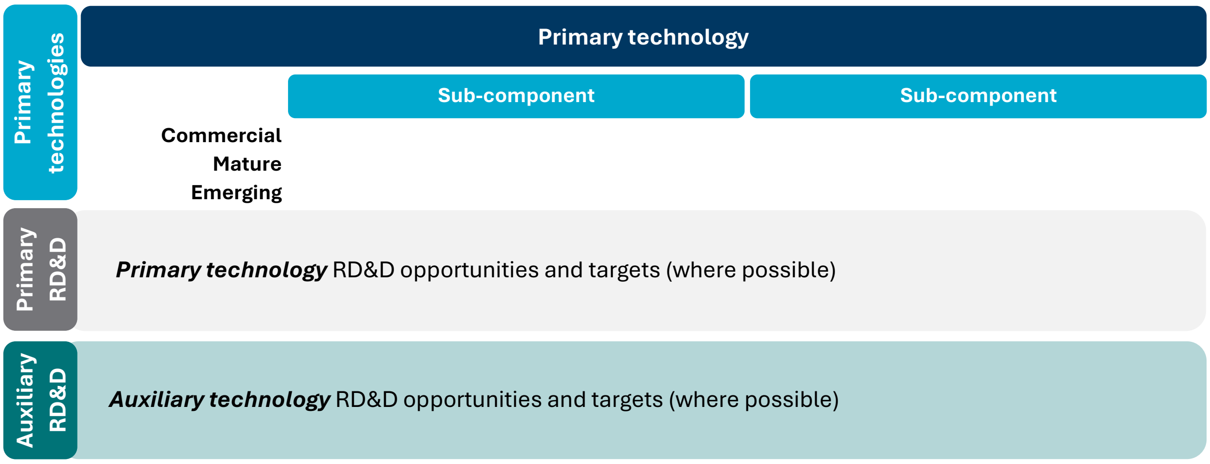
RD&D opportunity analysis

Following the development of the technology landscape, RD&D opportunities were explored. These RD&D opportunities reflect broad workstreams that are likely to help scale-up, de-risk and accelerate the deployment of low emissions technologies.

The analysis is designed to inform constructive dialogue around the role of RD&D in navigating Australia's energy transition. As such, the identified opportunities are not exhaustive of all RD&D areas for the technologies explored. Where possible, cost projections or quantitative targets for technology development were also identified, informed by model cost projections, literature reviews, and the input of subject matter experts. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of the explored low emission technologies.

Primary technologies were categorised based on their technological maturity and disaggregated into their key components where relevant (see Figure 6). These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9). Literature and stakeholder experts were consulted to determine detailed RD&D opportunities related to the identified technology landscape, spanning primary, auxiliary and energy efficiency technologies.

Figure 6: Technology RD&D opportunity overview



4 Iron and steelmaking

4.1 Executive summary

Iron and steelmaking glossary:
oxyBF: oxygen blast furnace
BOF: basic oxygen furnace
NG-DRI: natural gas direct reduced iron
H_2-DRI: hydrogen gas direct reduced iron
ESF: electric smelting furnace
EAF: electric arc furnace

Advancing Australia's low-emission iron and steelmaking will require targeted RD&D investment in technology demonstrations using Australian ores, complemented by tailored strategies to reduce energy demand across operations.

Technology Landscape: Brownfield and Greenfield pathways for a 2Mtpa BF-BOF steel mill

Iron and steelmaking involve complex processes and long asset lifetimes, requiring both brownfield and greenfield decarbonisation pathways and investment in both mature and emerging technologies.

Brownfield pathway technologies

oxyBF with coal, oxyBF with partial biomass injection

- Agglomeration
- HBI/DRI handling and transport mechanisms
- Biomass feedstock processing

BOF

- Control systems for slag optimisation

Greenfield pathway technologies

NG – DRI , H_2 – DRI

- Renewable hydrogen production, storage and distribution infrastructure
- HBI/DRI handling and transporting mechanisms
- Component modelling
- Agglomeration

ESF, EAF

- Beneficiation
- Renewable electricity generation, storage and transmission infrastructure
- HBI/DRI handling and transporting mechanisms
- Slag utilisation techniques

Carbon capture and storage (CCS) – *See Carbon Management technical appendix*

Energy efficiency solutions

- Carbon capture and utilisation
- Slag and material utilisation
- Waste heat recovery
- Beneficiation
- Sensing and analytics
- Advanced digital modelling

RD&D Opportunities

Brownfield pathway technologies

oxyBF

- As an established process, RD&D opportunities for blast furnace ironmaking centre on optimising input/output streams to improve energy and material efficiencies and reduce emissions, and enabling the use of lower energy- and emissions-intensive ores.
- Partial biomass injection as a substitute for coal and coke requires further piloting and demonstration to investigate the impacts that biomass can have on operations and steelmaking recycling streams.

BOF

- Optimisation of low carbon alloying materials and inputs, such as direct reduced iron (DRI) and alloys, will enable greater portions of scrap to be used in basic oxygen furnaces.

Greenfield pathway technologies

DRI

- Although direct reduction processes have been demonstrated at pilot scales, there is a need to demonstrate Australian ores in direct reduction processes using natural gas or hydrogen. This includes demonstrating the beneficiation and agglomeration of Australia's magnetite and hematite-goethite ores for use in shaft and fluidised bed reactors, to determine their feasibility.
- Full reactor designs require RD&D to optimise the process at commercial scales.

ESF

- Demonstrating DRI-based production routes with lower-grade Australian ores is essential to fully characterise technical and operational requirements to accurately inform costs and areas of cost improvement.

EAF

- RD&D opportunities to reduce the high energy demand of electric arc furnaces (EAFs) include process optimisation and novel instrumentation to enable data collection.

- Substituting the chemical energy component of the process with electrical energy to electrify the entire process.

Auxiliary

- CCS RD&D, across the various brownfield and greenfield production pathways is needed to improve its performance and economics as an auxiliary system.
- RD&D to improve beneficiation to address the increasing impurity content within Australia ores will support improvements in both the quality and efficiency of iron and steelmaking in Australia.
- Similarly, RD&D into agglomeration of Australian-based ores is required for shaft-based DRI routes.
- Exploring alternatives to coal for carbon supply can be employed in both electric melter types and reduce reliance on fossil fuels for carburising the metal during steelmaking.

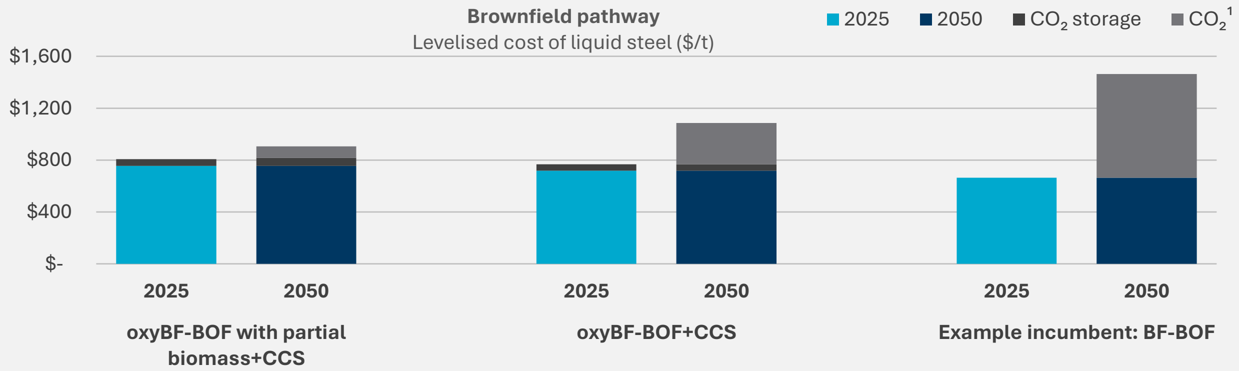
Energy efficiency solutions

- Given the inherent requirement of carbon in steelmaking processes, optimising materials efficiencies will be critical to reducing the carbon emissions and waste impacts that are attributed to steel products.
- Advanced waste heat recovery systems capable of operating under harsh operating conditions and recovering heat from high-temperature process by-products provide another opportunity to enhance process efficiency, supported by suitable energy storage systems.
- Digitalisation is expected to play a continued role in improving the energy efficiency of steelmaking operations and derisking the scale up of emerging systems, and sensors can inform operational strategies to effectively integrate variable renewable energy into increasingly electrified plants

Levelised Cost Analysis

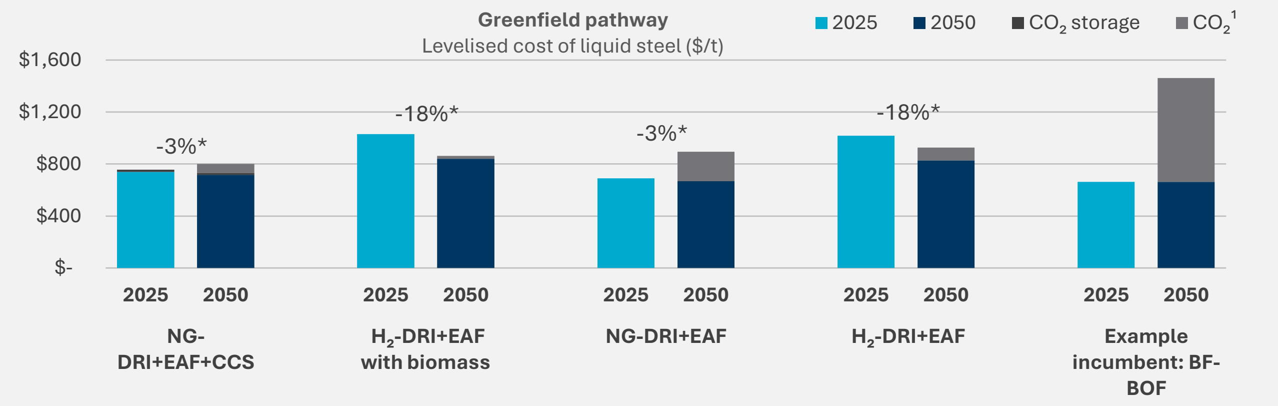
Brownfield pathway: Relining of a 2Mt/year BF-BOF steel mill

CCS with partial biomass is projected to be the lowest cost BF-BOF pathway in 2050 for brownfield sites, but is only competitive when a CO_2 emission cost is applied to the incumbent BF-BOF process.



Greenfield pathway: Retirement of a 2Mt/year brownfield BF-BOF steel mill

Emerging technologies, such as natural gas and hydrogen-based direct reduction routes are likely to offer greater long-term emissions reductions via greenfield asset end-of-life transitions and are projected to be significantly more cost competitive than incumbent BF-BOF pathways when accounting for a CO_2 emission cost.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

4.2 Introduction

Iron and steelmaking is an energy intensive and emissions intensive production process, accounting for approximately 7-9% of global greenhouse gas emissions.[9] Australia plays a key role in global steelmaking, both as a manufacturer of steel through its two steelmaking facilities (Whyalla, South Australia and Port Kembla, New South Wales) and as a key supplier of inputs into steelmaking processes in the Asia and Pacific region. This region accounts for over 75% of global steelmaking capacity and is disproportionally responsible for industry emissions.[10]

Today, 70% of global steel production is performed using the integrated blast furnace (BF)-basic oxygen furnace (BOF) route, which is heavily reliant on coal and other fossil fuels. In Australia, conventional integrated steelmaking plants typically consists of integrated sintering plants, pelletising plants, and coke ovens to produce material inputs for the steelmaking process; the BF-BOF equipment for iron and steelmaking; recovery processes; water treatment and disposal; and casting and rolling to create finished or semi-finished steel products. Upstream processes of iron ore extraction and beneficiation are generally considered part of the materials value chain. Carbon plays a pivotal role in the process, serving functions as a reducing agent, fuel source and alloying element which influences hardness, ductility (i.e., ability to stretch or deform without fracturing), and tensile strength of the steel product.

As a result of asset lifetimes, steelmakers are required to make long-term investment decisions that will ultimately shape the decarbonisation pathways of steel plants. Blast furnaces require periodic relining approximately every 20 years to maintain operational efficiency. The high capital cost incurred by relining provides a natural point in which technology investment decisions must be made, and where investment in an alternative technology solution could be more competitive compared to earlier in the existing assets lifetime.[11]

For assets that are not yet approaching end-of-life, retrofit and optimisation strategies that can make use of existing infrastructure will play a vital role in decarbonisation pathways. For new build facilities, or when the BF is retired, steel mills have the opportunity to adopt alternative technologies that present a more effective way to decarbonise the steelmaking process.

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[9] Deloitte, WWF (2025) Forging Futures: Changing the nature of iron and steel production.

[10] Figure derived from the most recent Green Steel Tracker dataset <https://www.industrytransition.org/green-steel-tracker/> (accessed 26 March 2025); Deloitte, WWF (2025) Forging Futures: Changing the nature of iron and steel production.

[11] Advisian (2021) Australian hydrogen market study: Sector analysis summary. Prepared by Advisian for the Clean Energy Finance Corporation (CEFC)

This chapter presents an analysis of low emissions technologies that are technically feasible and cost competitive, and could support the decarbonisation of the iron and steelmaking subsector for both existing facilities and new operations. This informs an exploration of RD&D opportunities that could support the scale-up, de-risking, and deployment of these technologies.

4.2.1 Iron and steelmaking use case(s)

To explore low emissions technologies in the iron and steelmaking subsector, two use cases have been defined, reflecting brownfield and greenfield pathways (see Table 1). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with these use cases.

The brownfield pathway is representative of a 2Mt/year brownfield blast furnace-basic oxygen furnace (BF-BOF) steel mill reaching the end of its blast furnace life. The BF is relined and the BF-BOF process is fitted with low emissions technologies to allow for low emissions steel production. This pathway leverages existing infrastructure, reducing upfront costs while delivering incremental emissions reductions.

The greenfield pathway is representative of a 2Mt/year brownfield BF-BOF steel mill reaching the end of its blast furnace life. Rather than relining the BF, the furnace is retired, and alternative low emissions technologies are implemented. This pathway offer higher emissions abatement but will oftentimes incur greater CAPEX costs associated with new technology deployments.

Given the fundamental differences between these pathways, directly comparing the performance of technologies across them would be misleading. Instead, the development of two use cases allows technologies to be assessed on a like-for-like basis within each pathway. This approach ensures options are considered within the appropriate investment and operational context and reflect the distinct decarbonisation strategies available to industry based on their existing assets.

These use cases are illustrative and presents requirements that technologies must be able to meet to service Australia's iron and steelmaking subsector. In reality, operations in Australia feature different production capacities and will have asset management strategies that align to their operating models.

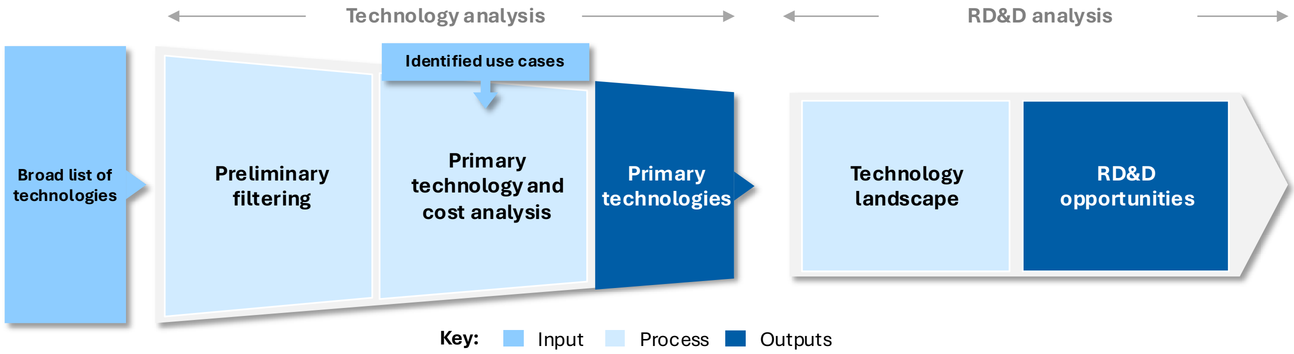
Table 1: Use case(s) – Iron and steelmaking

Use case(s)	Brownfield pathway	Greenfield pathway
Description:	A 2Mt/year brownfield blast furnace-basic oxygen furnace (BF-BOF) steel mill is reaching the end of its blast furnace life. The BF is relined and the BF-BOF process is fitted with low emissions technologies to allow for low emissions steel production.	A 2Mt/year brownfield BF-BOF steel mill is reaching the end of its blast furnace life. Rather than relining the BF, the furnace is retired, and alternative low emissions technologies are implemented.

4.3 Methodology: Iron and steelmaking inputs and criteria

The methodology is comprised of several steps (see Figure 7). Technology analysis was performed to first determine prospective technologies with the potential to contribute to decarbonisation across brownfield and greenfield sites. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress.

Figure 7: Technology and RD&D analysis framework for iron and steelmaking



4.3.1 Broad technology list

The iron and steelmaking process comprises of several steps (Box 1), each of which requires specific technologies and equipment.

Box 1: Iron and steelmaking process

Steelmaking is the process of converting iron ore (or scrap steel for secondary steelmaking) into steel by removing impurities (such as nitrogen, silicon, phosphorus, sulphur and excess carbon) and adding alloying elements (such as manganese, chromium and nickel) to produce steel of various grades.[12]

Broadly, the conversion of iron ore to steel involves the following steps:

1. **Reduction:** the iron oxide compounds in iron ore undergo chemical reactions with reducing agents (typically CO and H_2 gas) at high temperatures to strip them of oxygen and convert them into metallic, or 'reduced', iron.[13]
2. **Smelting:** the metallic iron is heated until melted, and any impurities that resisted reduction (typically silica and alumina) form a floating molten slag which can easily be separated.
3. **Refining:** excess reduced elements that are dissolved in the molten iron (i.e., carbon, phosphorus, sulphur) are removed.

Two technology lists were developed for iron and steelmaking to explore potential technology configurations suitable for both greenfield and brownfield (retrofit) facilities. Each configuration has distinct advantages and challenges and presents varying levels of disruption to conventional manufacturing processes (Figure 8). The pathway that steelmakers select will depend on the remaining operational lifetime of infrastructure assets, site-specific constraints, company decarbonisation strategies, and broader economic and operational factors.

Conventional integrated steelmaking processes involve the use of the blast furnace-basic oxygen furnace (BF-BOF) route to produce steel from iron ore. Blast furnaces require periodic refurbishing (termed *'relining'*) approximately every 20 years to maintain operational efficiency.

Broadly, steelmakers may consider brownfield technology pathways in which traditional BF equipment is relined and retrofitted with integrated low emissions technology solutions, or greenfield technology pathways in which the BF is decommissioned, and the mill switches to alternative technologies. Three brownfield technology configurations (Table 2) and 11 greenfield technology configurations (Table 3) were considered.

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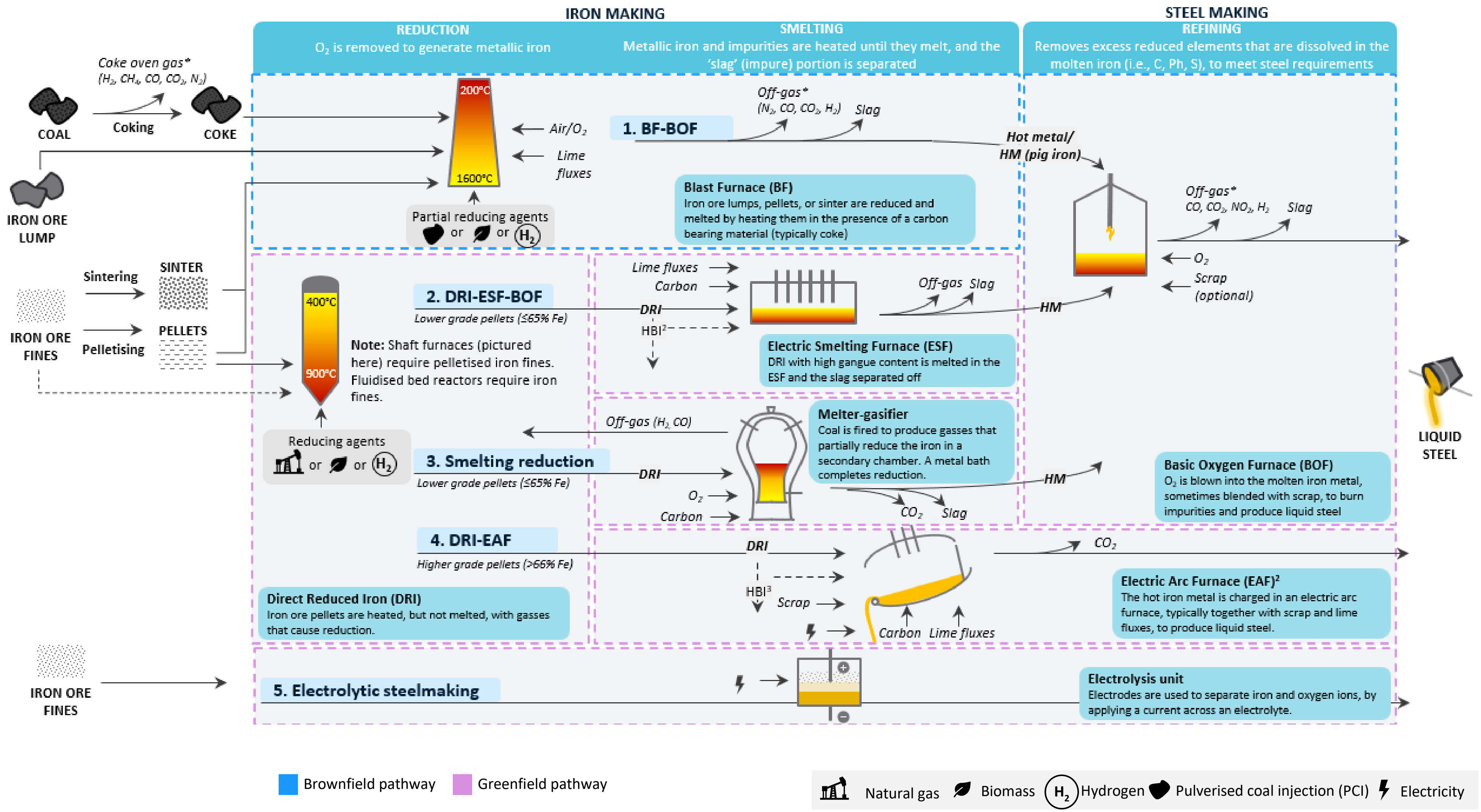
[12] Gadd A, Tame N, Liu X, Dukino R (2023) Prospect: Pathways to decarbonization episode seven. The Electric Smelting Furnace. BHP. <<https://www.bhp.com/news/bhp-insights/2023/06/pathways-to-decarbonisation-episode-seven-the-electric-smelting-furnace> (accessed 21 Janaury 2025); IEA GHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology 2024-02.

[13] These reducing gases are produced by the combustion of carbon-containing materials, like coke, natural gas or biochar. Where hydrogen is used as the reducing agent, this is injected directly as a gas into the pathway's reduction reactor.

Figure 8: Iron and steelmaking pathways



* BF-BOF off-gases (incl. from coking) are generally recycled back into the BF, BOF, and coking oven, and for power generation.

I. Scrap-based EAF is considered a discrete form of secondary steel making. While not discussed explicitly here, it is captured within the DRI-EAF pathway.

II. DRI may be converted to hot briquetted iron (HBI) for storage and transport (incl. export), where it may be used as the iron input into the smelting process.

Brownfield technologies

Three brownfield technology configurations were considered. Each configuration is a low emissions derivation of the conventional BF-BOF pathway:

- **BF (ironmaking):** Iron ore lumps, pellets or sinter are reduced to produce hot metal (or 'pig iron') by heating the ore in the presence of a carbon-bearing material in the BF. The carbon bearing material is predominantly coke, oftentimes blended with less expensive auxiliary reducing agents like pulverised coal injection (PCI). Limestone is also added as a flux agent, to remove impurities and facilitate slag formation.
- **BOF (steelmaking):** Steelmaking takes place in the BOF, or converter, where oxygen is blown into the hot metal to react with unwanted elements to form slag.

In a conventional BF-BOF steel mill, the single biggest contributor of CO_2 emissions in this process is the use of carbon (coke) as the reductant. To reduce emissions, several strategies are being considered to reduce the carbon intensity of operations, often in tandem: (1) The integration of CCS; (2) Partial substitution of fossil-based reductants with low emissions alternatives; and (3) Substituting fossil-based energy sources with low- or zero-carbon heat and electrical inputs.

Though not explored as a discrete pathway, improving the quality of feed to the BF can have material impacts on emissions reductions by reducing reductant consumption and improving efficiency. These strategies, such as switching to pellets from sinter, and adopting greater portions of DRI and scrap in BF burden, are highlighted instead as RD&D opportunities that could support decarbonisation efforts.

Table 2: Technology category descriptions – Steelmaking (brownfield)

Technology configuration	Explanation
BF-BOF	
> oxy-Blast furnace-basic oxygen furnace (oxyBF-BOF) w/ CCS + TGR	• In this configuration, an oxy-blast furnace (oxyBF) with top gas recycling (TGR) is adopted rather than a conventional BF. The oxyBF uses an oxygen stream intake rather than regular air, reducing nitrogen content in the furnace and allowing higher efficiencies to be achieved when integrated with CCS. The utilisation of TGR, where treated off-gas is treated and recycled back into the furnace, leads to a reduced coke consumption, subsequently lowering emissions.[14] • CCS (via chemical absorption) is integrated into the BF-BOF process to capture CO_2 from flue gas, for storage. The oxyBF means that furnace gas contains higher CO and CO_2 concentrations, making it highly compatible with CCS.
> oxyBF-BOF, partial biomass replacement w/ CCS	• Biomass is thermally treated and is injected into an oxyBF as bio-charcoal ('biochar') as an auxiliary reducing agent to reduce coke consumption. Though biochar can fully replace pulverised coal injection (PCI) in the BF, biochar does not undergo softening or deformation during the coking process which is required for coke production. As such, only partial replacement and emissions reduction is feasible in the integrated steel making process.
> BF-BOF, partial H_2 replacement[15]	• Hydrogen is injected into a standard BF as an auxiliary reducing agent to reduce coke consumption. Hydrogen gases cannot fully replace coal, with only partial replacement and emissions reduction feasible in the integrated steel making process. Beyond optimal limits, the flow of reducing gases declines.

[14] In some configurations the recycled off-gas is also used in the sinter plant as a fuel source

[15] This configuration considers pure renewable hydrogen injection; however, as an intermediary solution, the BF-BOF process can be first optimised to accept H_2 enriched gas (i.e., natural gas, coke oven gas, or hot reducing gases).

Greenfield technologies

11 greenfield technology configurations were considered. These configurations fall across 4 technology pathways and are expanded, in detail, in Table 3.

- Direct reduction (pathways 1 and 2): Both direct reduced iron-electric arc furnace (DRI-EAF) and DRI-electric smelting furnace (DRI-ESF)-BOFs are direct reduction pathways. Ironmaking takes place in the DRI furnace,[16] where iron ore pellets are directly reduced using a reducing gas rich in H_2 and CO to obtain DRI. The carbon footprint of pellet production is significantly lower than that of sinter, which forms a large portion of the burden in BF-BOF steelmaking routes.[17] Unlike in a BF, this process only performs the reduction step, producing a solid DRI intermediate, necessitating further processing via an electric arc furnace (EAF) or an electric smelting furnace (ESF).[18]
  - **EAF:** EAFs perform both smelting and refining steps, where the reduced iron is charged, typically together with scrap, carbon-bearing material and lime fluxes, to produce crude steel. EAFs are highly sensitive to impurities, necessitating the use of higher-grade pellets (generally >66% Fe content).[19] Where lower-grade ore (i.e., ≤65% Fe BF-grade ore) is used to generate DRI, power consumption increases significantly, higher slag volumes are produced in the EAF and iron is easily lost.
  - **ESF:** Hot DRI is charged to the ESF which melts and, where carbon is added, carburises the DRI. This is then fed to the BOF where it is converted to crude steel. Comparatively, the ESF can process lower grade ore more efficiently than EAFs, providing an intermediate step between DRI ironmaking and the steelmaking unit. Because the ESF can melt DRI with a wide range of impurities and separate off large volumes of slag, this pathway allows for the continued use of existing steelmaking units and BF-grade ore pellets.
- **Smelting reduction (pathway 3):** Non-coking coal is fired in a melter-gasifier to produce a stream of reducing gases (H_2 and CO). These gases are fed to a reduction chamber which partially reduces the iron ore. The partially reduced ore then passes through to a metal bath where it is fully reduced. Steelmaking occurs in the BOF.
- **Electrolytic (pathway 4):** Electrolytic reduction is a nascent approach to steelmaking. This method uses electrodes to separate iron and oxygen ions by applying a current across an electrolyte which eliminates the need for coke, lime, and processes where CO_2 emissions are an inevitable by-product.

Table 3: Technology category descriptions – Steelmaking (greenfield)

Technology configuration	Explanation
DRI-ESF-BOF[20]	
> Natural gas DRI w/ CCS	• The DRI furnace uses natural gas as the reducing agent, and the process is coupled with CCS. Compared to BF-BOF plants, in which recirculated flue gasses lead to multiple emissions points

[16] The two leading shaft furnace DRI processes are the MIDREX process and the Energiron/HYL ZR process; International Iron Metallics Association (2018) Direct Reduced Iron (DRI) <https://www.metallics.org/dri.html> (accessed 8 November 2023).

[17] Lv W, Sun Z, Su Z (2019) Life cycle energy consumption and greenhouse gas emissions of iron pelletizing process in China, a case study. Journal of Cleaner Production 233, 1314. doi:10.1016/j.jclepro.2019.06.180

[18] IEA GHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology 2024-02.; Gadd A, Tame N, Liu X, Dukino R (2023) Prospect: Pathways to decarbonization episode seven. The Electric Smelting Furnace. BHP.

[19] Shaft furnaces require high grade pelletised ore, however, some variants, such as fluidised beds, allow for the use of lower grade iron ore fines.

[20] Though the DRI-EAF pathway includes a configuration in which H_2-DRI with biomass EAF charge, a similar configuration was not included for the ESF (i.e., H_2-DRI + ESF with biomass carbon input + BOF). This was due to a lack of available data on biomass charging in the Electric Smelting Furnace, as understanding of the quantity and role of biochar continues to be developed. However, research is underway to convert biomass into attractive solid carbon products suitable for industrial applications including ESFs. https://hiltcrc.com.au/projects/biomass-derived-fuels-and-products-for-green-steel-production/

	and require gas separation steps to capture CO_2, DRI plants are less complex and allow for carbon capture systems to be retrofitted to facilities with less modifications. • Coal is used as the solid carbon input to the ESF.
> Hydrogen DRI	• The DRI uses 100% hydrogen[21] as the reducing agent, rather than natural gas, and is preheated (electrically) prior to injection. The hydrogen reaction is endothermic (compared to an exothermic reducing reaction by carbon monoxide, CO), necessitating pre-heating for the reaction to proceed. • Coal is used as the solid carbon input to the ESF.
> Ammonia DRI	• Ammonia is employed as the sole reducing gas in the DRI process, rather than natural gas. • Coal is used as the solid carbon input to the ESF.
DRI-EAF	
> Natural gas DRI w/ CCS	• The DRI furnace uses natural gas as the reducing agent, and the process is coupled with CCS, similar to DRI-ESF-BOF. Compared to BF-BOF plants, in which recirculated flue gasses lead to multiple emissions points and require gas separation steps to capture CO_2, DRI plants are less complex and allow for carbon capture systems to be retrofitted to facilities with less modifications. • Coal is used as the solid carbon input to the EAF.
> Hydrogen DRI	• The DRI uses 100% hydrogen[22] as the reducing agent, rather than natural gas, and is preheated (electrically) prior to injection, similar to the DRI-ESF-BOF. • Coal is used as the solid carbon input to the EAF.
> Hydrogen DRI, w/ biomass EAF	• The DRI uses 100% hydrogen[23] as the reducing agent, rather than natural gas, and is preheated (electrically) prior to injection, similar to the DRI-ESF-BOF. • Charcoal is used as the solid carbon input to the EAF, to replace coal.
> Ammonia DRI	• Ammonia is employed as the sole reducing gas in the DRI process, rather than natural gas, similar to the DRI-ESF-BOF. • Coal is used as the solid carbon input to the EAF.
Smelting reduction	
> Smelting reduction, coal w/ CCS	• The process uses firing coal to reduce the iron oxides and is coupled with CCS.
> Smelting reduction, hydrogen plasma	• Rather than firing coal, the smelting reduction uses hydrogen in a plasma state to reduce iron oxides. This is done by generating a hydrogen plasma arc between a hollow graphite electrode and liquid iron oxide.
Electrolytic steelmaking	
> High temperature molten oxide electrolysis (MOE), >1,500°C	• Iron ore is raised to high temperatures of up to 2000°C and an electrical current is passed through the chamber, causing the high purity molten iron to separate out of a liquid metal electrolyte and accumulate at the bottom of the chamber by the cathode while oxygen bubbles out of the electrolyte and accumulates at the at the bottom of the chamber. • Electrons are the reducing agents, and the products of the reaction are pure metal and oxygen.
> Low temperature electrolysis (or 'electrowinning'), <110°C	• Fine iron oxide particles are suspended in an alkaline electrolyte. When a current is applied across the electrolyte, iron deposits on the cathode forming a solid iron plate at 110°C.

4.3.2 Primary technology filters

For each use case, technology assessment involved evaluating the identified technologies against two performance parameters: 'scalability of production' and 'levelised cost' (Table 4). These performance parameters, were deemed to be core operational requirements that will enable or limit technology uptake, particularly given the energy and cost intensive nature of the subsector. The thresholds for scalability were established based on to the production capacity of incumbent steelmaking processes. Globally, the capacity

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[21] Here assumed to be low emissions hydrogen generated via renewable-powered electrolysis

[22] Here assumed to be low emissions hydrogen generated via renewable-powered electrolysis

[23] Here assumed to be low emissions hydrogen generated via renewable-powered electrolysis

of BF-BOF plants is highly variable,[24] though large plants have typical capacities of 4Mt per year and operate at 80-90% utilisation.[25] The lowest cost mitigation technologies able to meet these filters were progressed for further RD&D opportunity analysis. Further details on the selected parameters are provided in Section 4.4 Technology analysis.

Table 4: Technology filtering criteria – Iron and steelmaking

Subsector	**Iron and steelmaking**	
Use cases	**Brownfield pathway**	**Greenfield pathway**
Preliminary filtering criteria	**Relevance to Australia** Configuration can be reasonably deployed and assist in decarbonisation efforts under Australian conditions. *The criterion identifies constraining factors that may limit or prohibit technology adoption in the Australian context, including geographical constraints, legislation, or incompatibility with key domestic resources.*	
	Technology maturity Configuration has a TRL greater than 3. The TRL index can be found in *Appendix A.2.*	
	Note: Though abatement potential is not assessed for this subsector, estimates have been provided in this analysis.	
Primary technology analysis	**Scalability** Configurations that can technologically meet current production capacities, in terms of plant size and process inputs.	
	Levelised Cost of liquid steel (LCOLS) in 2050 Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in LCOLS relative to other assessed technologies (in $\$/t_L$).	

4.4 Technology analysis

This chapter outlines the process of identifying *Primary technologies* for decarbonising Australia's iron and steelmaking industry. Following the technology analysis framework process, two technology configurations emerged as *Primary technologies* for further RD&D exploration for the brownfield use case**: coal-based oxyBF-BOF w/ CCS and BF-BOF with partial biomass injection**.

Four configurations, across two pathways, emerged as *Primary technologies* for further RD&D exploration for greenfield use case: **DRI-ESF-BOF and DRI-EAF, where the DRI system adopts either natural gas with CCS or 100% hydrogen as the reducing agent**. These technologies were able to service the designated use cases and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in reducing iron and steelmaking emissions, for specific use cases, and over time RD&D can lead to new technologies that can be considered. The results of the technology analysis for iron and steelmaking are provided in Table 5.

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[24] The Global Energy Monitor (n.d.) Summary Tables. <https://globalenergymonitor.org/projects/global-steel-plant-tracker/summary-tables/> (accessed 21 January 2025).

[25] Global Energy monitor (2023) Pedal to the Metal: It's time to shift steel decarbonization into high gear. <https://globalenergymonitor.org/wp-content/uploads/2023/07/GEM_SteelPlants2023.pdf> ; IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02.

Table 5: Technology analysis results – Iron and steelmaking[26]

Meets filter criteria | Meets with caveats | Does not meet | ★ Primary technology | Not assessed further

1. Preliminary filtering				2. Primary technology analysis					
				Brownfield pathway			**Greenfield pathway**		
Technologies	**Relevance to Australia**	**Maturity**	**Abatement potential**	**Plant capacity**	**LCOLS (2050)**		**Plant capacity**	**LCOLS (2050)**	
Pass threshold		*TRL > 3*	*Not assessed. All pathways relevant.*						
Blast furnace-basic oxygen furnace (BF-BOF)									
> oxyBF-BOF, coal w/ CCS + top gas recycling (TGR)	Geo-dependent (CCS)	TRL 5 (chem absorption CCS)	60%	Reliant on successful CCS integration and deployment.	$1087	★			
> oxyBF-BOF, partial biomass w/ CCS		TRL 9	90%	Subject to biomass constraints[2] *222kg of biochar per tonne LS*	$904	★			
> BF-BOF, partial H_2		TRL 7	15%		$1440				
Direct reduced iron (DRI)-electric smelting furnace (ESF)-BOF									
> Natural gas DRI w/ CCS	Geo-dependent (CCS)	TRL 9 (chem absorption CCS)	Data unavailable				Plant capacity uncertain and currently limited.	Inconclusive. Industry investment, comparative cost analysis, and the transitional nature of the pathway indicates economic prospects.[27]	★
> Hydrogen DRI		TRL 6 (DRI)	Data unavailable				Plant capacity uncertain and currently limited.	As above.	★
> Ammonia DRI		TRL 2							
DRI-electric arc furnace (DRI-EAF)									

[26] Details for these figures, including sources/assumptions, are found in Table 6 (maturity), Box 3 (Abatement potential), and under *Levelised cost analysis* / *Technical Appendix: Levelised cost analysis* (LCOLS).

[27] Tata Steel and BlueScope have made commitments towards ESF production routes. Domestically, Fortescue, and BHP, BlueScope and Rio Tinto (jointly) have announced pilot projects. IEAGHG analysis places costs for this pathway more expensive than natural gas DRI-EAF with CCS, but less expensive than H_2 based DRI-EAF, with the pathway attracting producers who wish to incrementally transition their production to the direct reduction route. IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology 2024-02.

> Natural gas DRI w/ CCS	Low tolerance for Pilbara ores (hematite); Geo-dependent (CCS)	TRL 9 (chem absorption CCS)	90%				Smaller average plant size, but capacity can be achieved.	$780	★
> Hydrogen DRI	Low tolerance for Pilbara ores (hematite);	TRL 6 (DRI)	85%				Smaller average plant size, but capacity can be achieved.	$926	★
> Hydrogen DRI, w/ biomass EAF	As above	TRL 6 (DRI)	95%				Subject to biomass constraints[2] *54kg of biochar per tonne LS*	$861	★
> Ammonia DRI	As above	TRL 2 (DRI)							
Smelting reduction									
> Smelting reduction, CCS	Geo-dependent (CCS)	TRL 4-8	80%					*Inconclusive. Established technologies are less economical than DRI-ESF-BOF pathway*	
> Smelting reduction, H_2 plasma		TRL 4	100%				*Inconclusive*	*Inconclusive*	
Electrolysis									
> High temperature electrolysis (>1500°C)		TRL 5	100%					*Inconclusive*	
> Low temperature electrolysis (<110°C)		TRL 4-5	100%					*Inconclusive*	

4.4.1 Preliminary filtering results

Key information – Preliminary filtering

Two criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:

- **Relevance to Australia**: Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.
- **Technology maturity:** Technology has a TRL greater than 3.

Abatement potential was not assessed for Iron and steelmaking. Please see Box 2: Defining low carbon steelmaking.

Relevance to Australia

Most of the technology configurations across the two use cases meet this criterion as they can be reasonably deployed in the Australian context. Both CCS-coupled production routes and DRI-EAF, however, were deemed to meet this criterion with caveats. Explanations are provided below.

CCS-coupled pathways

Pathways reliant on CCS meet the criteria with caveats, as they are dependent on appropriate subsurface formations for permanent geological storage.

CCS-coupled pathways rely on point-source carbon capture along the production route, which is then permanently stored in deep, geological formations. This requires the identification of subsurface structures that possess acceptable injectivity, capacity and sealing characteristics for permanent CO_2 storage. For further detail, please refer to the *Carbon Management* technical appendix.

DRI-EAF

DRI-EAF technology configurations were deemed to meet this criterion with caveats, due to incompatibility with domestic ore extraction activities and challenges in sourcing and producing high-grade iron ore inputs required for this process. A combination of technological and operational solutions will be required to overcome this limitation and continue to meet Australia's export and steel manufacturing commitments.

Hematite-goethite ores are the dominant iron ore type extracted in Australia, for both domestic iron and steel production and export.[28] Hematite ores mined in the Hamerlsey Basin region (Western Australia) possess an average iron content of 56-62%.[29] EAFs, however, require higher iron ore content (>65%) as high levels of impurities (gangue) such as silica, alumina, phosphorus and sulphur limit EAF performance and result in excess electricity consumption, lower yields and increased costs.[30]

Magnetite, while abundant in Australia, constitutes only 4% of iron ore exports; though it is used in steelmaking operations in Whyalla, South Australia. Despite a lower naturally occurring iron content (16-50%), the magnetic properties of magnetite allow it to be more easily processed (or *beneficiated*), resulting in a product with higher iron content (65-69.5%) and fewer impurities than hematite-goethite.[31] This product is suitable for DRI-EAF.

[28] 96% of Australia's iron ore exports constituting high-grade hematite. Summerfield, D (2020) Australian Resource Reviews: Iron Ore 2019. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/9781925848670

[29] Summerfield, D (2020) Australian Resource Reviews: Iron Ore 2019. Geoscience Australia

[30] Nicholas S, Bairat S (2022) Iron Ore Quality a Potential Headwind to Green Steelmaking Technology and Mining Options Are Available to Hit Net-Zero Steel Targets. Institute for Energy Economics and Financial Analysis. <https://ieefa.org/resources/iron-ore-quality-potential-headwind-green-steelmaking-technology-and-mining-options-are> (accessed 20 January 2025)

[31] Geoscience Australia (2023) Australian Magnetite Ore 2023 Factsheet. Department of Industry, Science and Resources. Commonwealth of Australia. https://www.australiaminerals.gov.au/__data/assets/pdf_file/0004/176116/Australian-Magnetite-Ore-2023-Factsheet.pdf (accessed 20 January 2025)

To address this challenge, several strategies could be explored.

1. **Advanced ore processing:** Improved characterisation, sensing, sorting, separation and beneficiation technologies can enable the step towards high-quality iron feedstocks (see *Section 4.6 RD&D opportunity analysis*).
2. **Operational shifts:** Future mining operations could shift focus towards the extraction of higher-grade ores (i.e., magnetite) to meet the demands of DRI steelmakers. It should be noted, however, that the extraction of magnetite is traditionally higher-cost and with different mineralogical complexities compared to hematite, requiring the development of technologies, methods and infrastructure to reduce financial and environmental costs.
3. **Alternative pathways:** The DRI-ESF-BOF pathway is currently being investigated by leading mining and steel manufacturers as a potential avenue to utilise BF-grade ore pellets in a DRI-based process.[32]

Technological maturity

The various pathway and configurations for low carbon iron and steelmaking consist of several integrated technologies of varying maturity. The technology pathways have therefore been assigned a maturity rating based on the least mature technology component (see Table 6).

For DRI processes, it is the DRI shaft furnace that largely dictates the maturity of these pathways. Of the reducing agents considered, the use of ammonia (TRL 2) did not meet the maturity criteria of either DRI pathway (DRI-EAF and DRI-ESF-BOF). Natural gas-based DRI system are commercial and are used in industry today. Though systems have been developed to operate on 100% hydrogen more recently, technology readiness of hydrogen-based DRI is still maturing.

The EAF is a mature technology, designed and optimised for use in secondary steel making. It is therefore more mature than the DRI component of the DRI-EAF configuration.

The ESF is a well-established unit with many applications in metal refining industries, particularly non-ferrous applications where mitigating yield losses from large slag volumes is routine.[33] Despite this, demonstration of the technology in ironmaking has not been achieved at industrial scale, and there are only three operations currently adopting the technology for ironmaking globally. The ores used in these operations do not reflect domestic characteristics and there are still significant challenges to overcome and optimise the ESF for ironmaking; rendering it a lower TRL compared to the DRI component of the DRI-ESF-BOF pathway.

The maturity of CCS in the BF-BOF pathway is less mature than that for DRI-EAF. This is largely due to the routing of flue streams which are channelled through multiple technology units where the calorific component of off-gases is used as internal fuel.[34] This creates many small streams of emissions with varying CO_2 concentrations across the BF-BOF site, making the capturing of emissions challenging (see Box 1: Iron and steelmaking process for more information).

[32] For example, BHP, BlueScope, and Rio Tinto: BHP (2024) BlueScope, BHP and Rio Tinto select WA for Australia's largest ironmaking electric smelting furnace. <https://www.bhp.com/news/media-centre/releases/2024/12/bluescope-bhp-and-rio-tinto-select-wa-for-australias-largest-ironmaking-electric-smelting-furnace> (accessed 20 January 2025); and Fortescue: Fortescue (n.d.) Fortescue starts works on Green Metal Project. < https://www.fortescue.com/en/articles/fortescue-starts-works-on-green-metal-project> (accessed 20 January 2025).

[33] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02; Gadd A, Tame N, Liu X, Dukino R (2023) Prospect: Pathways to decarbonization episode seven. The Electric Smelting Furnace. BHP.

[34] Benavides K, Gurgel A, Morris J, Mignone B, Chapman B, Kheshgi H, Herzog H, Paltsev S (2024) Mitigating emissions in the global steel industry: Representing CCS and hydrogen technologies in integrated assessment modeling. International Journal of Greenhouse Gas Control 131,. doi:10.1016/j.ijggc.2023.103963

Table 6: Technology maturities – Steelmaking

Technology category	TRL
Brownfield pathway	
BF-BOF	
> oxyBF-BOF w/ CCS + TGR *> oxyBF-BOF, partial biomass replacement w/ CCS* *> BF-BOF, partial H_2 replacement*	• **BF/oxyBF:** ○ **oxyBF (coal):** TRL 6 | **CCS:** TRL 5 (Chemical absorption)[35] ○ **oxyBF (partial biomass):** TRL <6[36] | **CCS:** TRL 5 (Chemical absorption) ○ **BF (partial H_2, direct injection):** TRL 7[37]
Greenfield pathway	
DRI-EAF	
> Natural gas DRI w/ CCS *> Hydrogen DRI* *> Hydrogen DRI, w/ biomass EAF* *> Ammonia DRI*	• **DRI:** ○ **NG:** CRI 6 | **CCS:** TRL 9 (Chemical absorption); TRL 5 (Physical absorption) ○ **H_2:** TRL 6-7 (100%, shaft furnace), (TRL 8 for 30% blend)[38] ○ **H_2:** TRL 6-7 (100%, shaft furnace), (TRL 8 for 30% blend) ○ **NH_3:** TRL 2 • **EAF:** CRI 6
DRI-ESF-BOF	
> Natural gas DRI w/ CCS *> Hydrogen DRI* *> Ammonia DRI*	• **DRI:** As for above. ○ **NG:** CRI 6 | **CCS:** TRL 9 (Chemical absorption); TRL 5 (Physical absorption) ○ **H_2:** TRL 6-7 (100%, shaft furnace), (TRL 8 for 30% blend) ○ **NH_3:** TRL 2 • **ESF:** TRL 5-6 (CRI 6 for non-ferrous industries) • **BOF:** CRI 6
Smelting reduction	
> Coal w/ CCS	• **Coal-based smelting reduction**; All TRLs are expected to drop 1-2 levels when considering the integration of CCS due to system complexity and a lack of large scale demonstrations. ○ **HiSmelt/Corex/Finex:** TRL 9 | 7-8 with CCS ○ **Technored:** TRL 7-8 | 6 with CCS ○ **Flash Smelting reduction:** TRL 6 | 4-5 with CCS
> H_2 plasma	• TRL 4
Electrolytic steelmaking	
> High temperature molten oxide electrolysis (MOE), >1500°C	• TRL 5
> Low temperature electrolysis (or 'electrowinning'), <110°C	• TRL 4-5

[35] Though other capture systems are under investigation, chemical absorption technologies are the most progressed

[36] TRL 9 has been achieved by BF operations in Brazil, in which smaller blast furnaces have been designed to operate with biomass. Globally, maturity is considered lower due to the lack of established biochar supply chain and larger blast furnaces. It is further lowered when considering an oxyBF with top gas recycling as opposed to a conventional BF.

[37] H_2-enriched gas injection, such as natural gas or coke oven gas, is higher than direct hydrogen injection at TRL 9, though abatement impact is less (Refer to Box 4)

[38] Shaft-based systems (MIDREX, HYL/ENERGIRON) are most mature for hydrogen DRI, however fluidised bed systems (CIRCORED) are under development and have been pilot tested with 100% hydrogen. Hydrogen-based flash direct reduction (CALIX/ZESTY) is still emerging – TRL 4-5.

Abatement potential – Not assessed

Box 2: Defining low carbon steelmaking

A number of proposed definitions and approaches to defining low- or zero-carbon steelmaking are under development. Efforts are underway to harmonise these definitions and product-level emissions accounting internationally.[39] Notably, the World Steel Association is undertaking a mapping and comparison exercise of steel measurement methodologies to inform discussions including regarding the possibility of a common benchmark threshold.

Definitions for 'near-zero' emissions steel production, including direct and indirect emissions, are converging. The IEA[40] provides the following bounds, with similar thresholds being applied a number of standards and initiatives:[41]

- **100% iron: 400 kgCO_2e/$t_{crude\ steel}$**
- **100% scrap: 50 kgCO_2e/$t_{crude\ steel}$**

For 'low emissions' steel production, a wider range of methodologies are proposed. The IEA secretariat proposes defining technologies where emissions performance is '*substantially lower than the best available technology performance*', but not yet achieving near-zero emissions. This is supported by 5 bands, all varying degrees below the performance of the current dominant production routes.[42]

Other approaches include *'best in class performance'* and *'performance at or below an average global trajectory to net zero'.*

There are also a number of outstanding issues that have been identified by the UN Industrial Deep Decarbonisation Initiative, including the treatment of CCS (i.e., the certainty and duration of storage) and the permissibility, design and application of custody models (i.e., the use of emissions reductions certificates/credits).[43]

Supplementary analysis: Emissions estimates

Box 3: Abatement potential – Steelmaking

Abatement potential was not used as a filter but has been provided for completeness. The exclusion of this criterion was founded on several considerations:

- Incremental transition: While many steelmakers have announced plans to transition away from BF-BOF technology, these plans primarily involve incremental improvements and bridging technologies. This creates a mix of solutions with differing abatement potentials all of which could feature in a future decarbonised sector.
- Uncertainty of future transition pathways: The future mix of technologies in the iron and steel sector is highly uncertain, influenced by a range of factors such as policy settings, technological advances, and market dynamics. This uncertainty makes it challenging to forecast which pathways will ultimately be adopted and at what scale.
- The carbon challenge: Many iron and steelmaking pathways are reliant on hydrocarbons to generate heat or as a process input.[44] While alternative sources, such as biomass or hydrogen, are under development, emissions are likely to persist. This makes it challenging to establish a non-arbitrary abatement benchmark.

Technologies were categorised by their relevant use case to avoid undue comparisons between retrofitted solutions and new-build technologies with inherently lower abatement potential.

Table 7 provides estimated direct emissions from each respective pathway. Associated emissions data has been sourced from the IEAGHG (2024)[45] and POSCO's Port Hedland Green Steel Project Emissions Assessment[46] (pelletising emissions, assumed to emit 42kgCO_2/tonne pellets and occurred upstream at the mining site in the IEAGHG (2024) source material) and are aligned with the carbon costs employed in the levelised cost analysis. These estimates include material and input flows for an integrated plant, including, where relevant, coking ovens, lime production, integrated sinter plant and pathway reactors.

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[39] Industrial Deep Decarbonisation (2024) Driving consistency in the greenhouse gas accounting system for steel, cement and concrete products: GUIDANCE FOR PCR HARMONIZATION. < https://www.cleanenergyministerial.org/content/uploads/2024/12/driving-consistency-in-the-greenhouse-gas-accounting-system.pdf> (accessed 20 January 2025)

[40] International Energy Agency (2024) Definitions for near-zero and lowemissions steel and cement, and underlying emissions measurement methodologies < https://www.iea.org/reports/definitions-for-near-zero-and-low-emissions-steel-and-cement-and-underlying-emissions-measurement-methodologies> (accessed 20 January 2025)

[44] Kim J, Sovacool BK, Bazilian M, Griffiths S, Lee J, Yang M, Lee J (2022) Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. Energy Research & Social Science. 89:102565. https://doi.org/10.1016/j.erss.2022.102565

Indirect emissions were not included due to a lack of available granular data.

Brownfield pathway

Among retrofit options for the BF-BOF configurations, the partial biomass with CCS pathway achieves the highest emissions reductions (90%).

The oxyBF-BOF with CCS pathways also offers significant reductions through direct capture and by reducing coke usage in the oxyBF. However, this currently remains a breakthrough technology with the world's only operational CCS-equipped steel plant capturing 26.6% of emissions in 2023 (for a DR facility).[47] This capture rate also falls short of the 59% determined in this analysis.

Partial hydrogen injection into the BF-BOF process offers more modest abatement potential, primarily stemming from operational constraints which prevent higher injection rates and additional energy demands for hydrogen pre-heating. It can, however, also be coupled with CCS technology, to yield further emission reductions.

Greenfield pathway

Generally, new-build pathways enable greater emissions reductions compared to retrofit options.

The natural gas-based DRI pathway provides significant reductions in direct CO_2 emissions and minimises total energy demand. Coupled with CCS, it achieves up to 90% abatement compared to the BF-BOF reference case.

Employing hydrogen as the reducing agent further reduces direct emissions on the reference case, even when using coal as the carbon source in the EAF. When replaced with charcoal, a 95% reduction is achieved. The difference between the H_2-DRI-EAF process in which a fossil carbon source and where a biomass carbon source is used, suggests that approximately 9% of emissions of direct CO_2 emissions can be avoided when switching to biomass.

A number of pathways also provide the opportunity for minimal emissions when powered by renewable electricity. Assuming the grid is near-decarbonised, reductions would translate to pathways reliant on electrical inputs.

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[42] Similar frameworks are also proposed by ResponsibleSteel; LESS and GCCA.

[43] Industrial Decarbonization Accelerator (2025) FACTSHEET: Aligning global standards to define low and near-zero emissions materials. <https://www.industrialenergyaccelerator.org/general/factsheet-aligning-global-standards-to-define-low-and-near-zero-emissions-materials/> (accessed 20 January 2025)

[44] Kim J, Sovacool BK, Bazilian M, Griffiths S, Lee J, Yang M, Lee J (2022) Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. Energy Research & Social Science. 89:102565. https://doi.org/10.1016/j.erss.2022.102565

[45] IEA (2024) IEAGHG Technical Report 2024-02 Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEA Greenhouse Gas R&D Programme. <https://ieaghg-publications.s3.eu-north-1.amazonaws.com/Technical+Reports/2024-02+Clean+Steel+An+environmental+and+technoeconomic+outlook+of+a+disruptive+technology.pdf> (accessed 17 January 2025).

[46] POSCO (2024) Port Hedland Green Steel Project – Decarbonisation Project Emissions Assessment <https://www.epa.wa.gov.au/sites/default/files/PER_documentation2/Appendix%207%20GHG%20Emissions%20Assessment.pdf> and EPA (Government of Western Australia) (2025) Port Hedland Iron Project – Stage 1, Report 1789 <https://www.epa.wa.gov.au/sites/default/files/EPA_Report/EPA%20report%201789%20Port%20Hedland%20Iron%20Project.pdf>

[47] IEEFA (2024) CCUS for steelmaking rapidly losing its lustre. <https://ieefa.org/articles/ccus-steelmaking-rapidly-losing-its-lustre> (accessed 20 January 2025)

Table 7: Abatement potential – Steelmaking

Technology	Emissions from pellet use	CO_2 produced	CO_2 captured	Total *$kgCO_2$/ton LS*	Abatement potential, *%*	Notes
BF-BOF, coal (Reference case)	23	1837	0	1860		
DRI-EAF, natural gas (NG)	53	524	0	578	**69%**	
Brownfield pathway						
BF-BOF						
> oxyBF-BOF, coal w/ CCS + top gas recycling (TGR)	22	1837	-1102	757	**59%**	94% capture rate.
> BF-BOF, partial H_2	23	1556	0	1579	**15%**	Assumes a maximum hydrogen injection rate of $27.5kgH_2/t_{HM}$, replacing 120kg PCI. This sees a small increase in coke rate.
> BF-BOF, partial biomass w/ CCS	22	1266	-1101	187	**90%**	Assumes 0.899kg PCI to charcoal replacement and carbon-neutral biomass feedstock.
Greenfield pathway						
DRI-ESF-BOF						
> NG w/ CCS	*Data unavailable.*					
> H_2						
DRI-EAF						
> NG w/ CCS	53	524	-369	209	**89%**	95% capture rate.
> H_2	53	223	0	276	**86%**	100% H_2 reduction. Carbon addition to the EAF was assumed to be from coal.
> H_2, w/ biomass EAF	53	47	0	100	**95%**	100% H_2 reduction process. Carbon addition to the EAF was assumed to be from charcoal.
Smelting reduction						
> Coal w/ CCS	*Data unavailable. Industry pilots suggest an 20% reduction using HIsarna smelting reduction compared to a conventional BF-BOF plant, and 80% when coupled with CCS.*[48]				**80%**	Based on a 60,000t/yr melt reduction vessel.
> H_2 plasma	0	0	0	*0*	**100%**	
Electrolysis						
> High temperature electrolysis (>1500°C)	0	0	0	*0*	**100%**	Despite, zero direct emissions, indirect emissions from electricity supply will apply.
> Low temperature electrolysis (<110°C)	0	0	0	*0*	**100%**	

[48] TATA Steel (2020) HISARNA Building a sustainable steel industry. <https://products.tatasteelnederland.com/sites/producttsn/files/tata-steel-europe-factsheet-hisarna.pdf>

4.4.2 Primary technology analysis

Key information – Primary technology analysis

Two criteria were employed to ensure the suitability and feasibility of each technology for the use case applications determined.

- Plant capacity: Configurations that can technologically meet current production capacities, in terms of plant size and process inputs.
- The Levelised Cost of liquid steel (LCOLS): Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive.

Plant capacity

This filter evaluates the operational production capacity of the various steelmaking pathways, to understand solutions that can allow for current and future demands for steel to be met. Configurations that can technologically meet current production capacities, in terms of plant size and process inputs, are deemed to meet the criteria.

Two factors were considered to qualitatively determine the scalability of steelmaking technologies across the two use cases: **typical plant size** and the **scalability of process inputs** such as electricity and hydrogen. Where process inputs are considered, this filter investigates the scale of resources required; it does not consider non-technological considerations such as cost, availability and access. Australia's domestic capacity for compatible ore types, particularly DR-grade pellets, is captured under the *Relevance to Australia* preliminary filtering criteria.

The majority of Australia's steel is produced by two large integrated steel mills: Whyalla, South Australia (1.2Mtpa)[49] and Port Kembla, New South Wales (3.2Mtpa).[50] In 2023, Australia produced about 6 Mt of steel.

Configurations were evaluated, relative to the production capacity of incumbent steelmaking processes. Globally, the capacity of BF-BOF plants is highly variable,[51] though large plants have typical capacities of 4Mt per year and operate at 80-90% utilisation.[52] This is also reflective of Australia's Port Kembla site. Despite high coal usage for reduction and heat generation, BF-BOF production is not constrained by input supply.

Brownfield pathway: BF-BOF configurations

For BF-BOF retrofits, configurations are expected to operate with production capacities comparable to conventional systems (i.e., up to 4Mt of liquid steel). However, input constraints vary by configuration:

oxyBF-BOF with CCS and TGR

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[49] GFG Alliance (n.d.) About the Whyalla Steelworks. <https://www.gfgalliance.com/whyalla-transformation/about-the-steelworks/> (accessed 21 January 2025).

[50] BlueScope (2024) Transforming Port Kembla Steelworks <https://www.bluescope.com/our-steel/case-studies/Transforming-Port-Kembla-Steelworks> (accessed 20 January 2025)

[51] The Global Energy Monitor (n.d.) Summary Tables. <https://globalenergymonitor.org/projects/global-steel-plant-tracker/summary-tables/> (accessed 21 January 2025).

[52] Global Energy monitor (2023) Pedal to the Metal: It's time to shift steel decarbonization into high gear. <https://globalenergymonitor.org/wp-content/uploads/2023/07/GEM_SteelPlants2023.pdf> ; IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02.

This configuration meets the criteria with caveats. The deployment of carbon capture infrastructure and its integration will be the largest constraining factor for meeting scalability. CCS processes demand significant energy demands of ~170kWh/tCO_2.[53] Though this can be supplied by natural gas, if drawing on electricity, this could place significant demand on the grid and may necessitate network upgrades to position this technology as a viable low emissions pathway.

Partial hydrogen

Hydrogen utilisation in the BF-BOF meets the criteria, with caveats. Despite restricted uptake potential in BF configurations kerbing the potential scale of hydrogen adoption, these pathways may be subject to input limitations for large-scale hydrogen production.

Hydrogen injection in BF-BOF is limited to 5-10% due to operational constraints.[54] Beyond this, the exothermic CO reduction shifts to an endothermic hydrogen reduction, necessitating significant redesigns. As such, higher hydrogen shares would require extensive blast furnace redesign to accommodate external heat sources and altered operational chemistry.[55]

For a 4Mt/year production plant, 109kt of hydrogen would be required.[56] Electrolysis pathways (see the *Low Carbon Fuels* technical appendix) require large amounts of electricity to operate, necessitating grid network upgrades and scaled renewable generation capacity to meet hydrogen production demands. Meanwhile, water availability could pose a challenge in arid and water-constrained regions of Australia, whereby regional-specific area studies are required to determine the feasibility of electrolysis developments.

Partial biomass

Biomass-reliant pathways were deemed to meet the criteria, with caveats. Biomass is a supply limited source where cost, availability and access will be a factor in deployment (see the *Low Carbon Fuels* technical appendix for further information).

Biomass can be employed as a complete replacement for coke and coal in several additional BF-BOF processes (see, for example, Table 8). The adoption of biomass at an integrated steelmaking facility depends on its viability as a replacement for PCI as a partial BF reductant. This application offers the highest displacement potential and impetus for shoring up supply chains. Though coal demand for coke production is highest, biomass substitution in the BF potential is capped at 2-10%.[57] At higher concentrations, the biomass degrades the mechanical properties of the coke, thereby reducing furnace stability.[58]

As per the cost analysis (in the subsequent section), approximately 222kg of biochar is required to replace traditional carbon sources, per tonne of liquid steel. Yields for biomass to biochar generally range from 12-

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[53] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02

[54] As a reference case, Yilmaz et al (2017), found an optimal hydrogen injection rate in replacing 120kg/t_{HM} of pulverised coal injection with 27.5kg/t_{HM} of hydrogen. Yilmaz C, Wendelstorf J, Turek T (2017) Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. Journal of Cleaner Production 154, 488. doi:10.1016/j.jclepro.2017.03.162.

[55] Yilmaz C, Wendelstorf J, Turek T (2017) Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. Journal of Cleaner Production 154, 488. doi:10.1016/j.jclepro.2017.03.162

[56] Based on a maximum hydrogen injection rate of 27.5kgH_2/t_{HM}, replacing 120kg PCI.

[57] Please note, the cost analysis only considers biochar as a PCI replacement in the BF, and does not consider alternative methods of biochar adoption as outlines in Table 8. See also, Suopajärvi H, Umeki K, Mousa E, Hedayati A, Romar H, Kemppainen A, Wang C, Phounglamcheik A, Tuomikoski S, Norberg N, Andefors A, Öhman M, Lassi U, Fabritius T (2018) Use of biomass in integrated steelmaking – Status quo, future needs and comparison to other low-CO2 steel production technologies. Appl Energy 213, 384. doi:10.1016/j.apenergy.2018.01.060; Liu Y, Shen Y (2021) Modelling and optimisation of biomass injection in ironmaking blast furnaces. Prog Energy Combust Sci 87,. doi:10.1016/j.pecs.2021.100952

[58] This is caused by the different thermoplastic qualities possessed by biomaterials compared to coal, and lower thermal degradation temperatures. Khasraw D, Martin C, Herbert J, Li Z (2024) A comprehensive literature review of biomass characterisation and application for iron and steelmaking processes. Fuel 368,. doi:10.1016/j.fuel.2024.131459.

50%, depending on feedstock and process; this would therefore require between 440-1850kg of raw biomass feedstock.[59]

Table 8: Biomass BF-BOF displacement potential[60]

Materials	Coal demand (kg/ton HM)	Bio-charcoal replacement ratio
Cokemaking	300	2-10%
BF injection (PCI)	150	Up to 100%
BF nut coke replacement	45	Up to 100%
BF briquette	10	Up to 100%
Sintering solid fuel	76.5	Up to 100%

Greenfield pathway: DRI-EAF configurations

DR plants typically have a smaller capacity than the BF-BOF process, due to the smaller size of the shaft furnace.[61] Typical DRI plants are smaller than blast furnaces (~1.1 Mt/year) but can scale to 4 Mt/year in advanced facilities, with this capacity achieved in several locations worldwide.[62]

Regarding the various DRI-EAF configurations, the scalability of process inputs may introduce constraints*:*

Natural gas DRI with CCS

This configuration meets the criteria with caveats.

The deployment of carbon capture infrastructure and its integration will be the largest constraining factor for meeting scalability. It will also require significant electrical power (124kWh/tCO_2), increasing electricity demands by 60%.[63] This could place significant demand on the grid and may necessitate network upgrades to position this technology as a viable low emissions pathway.

Hydrogen DRI

This configuration meets the criteria with caveats.

Retrofitting natural gas DRI plants for hydrogen requires a volumetric ratio substitution of approximately 3:1 based on the respective energy equivalence of each compound (i.e., 3m³ H_2 replaces 1m³ CH_4).[64]

As per the cost analysis (in the subsequent section), approximately 240m³ of natural gas is consumed per tonne of liquid steel produced via the gas-based DRI-EAF pathway. When replaced and optimised for

[59] Safarian S (2023) Performance analysis of sustainable technologies for biochar production: A comprehensive review. Energy Reports 9, 4574. doi:10.1016/j.egyr.2023.03.111

[60] Mathieson J, Rogers H, Somerville M, Jahanshahi S and Ridgeway P (2011) Potential for the use of biomass in the iron and steel industry. In: Chemeca 2011. Conference Material, September 2011. http://hdl.handle.net/102.100.100/103072?index=1; Fan Z, Friedmann SJ (2021) Low-carbon production of iron and steel: Technology options, economic assessment, and policy. Joule 5, 829. doi:10.1016/j.joule.2021.02.018; Pandit J, Watson M, Qader A (2020) Reduction of Greenhouse Gas Emissions in Steel Production. CO2 CRC. <https://www.resources.nsw.gov.au/sites/default/files/2022-11/report-reduction-of-ghg-emissions-in-steel-industries.pdf>

[61] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02

[62] Global Energy Monitor (2024) Global Steel Plant Tracker. Summary Tables, April 2024. Count of Iron & Steel Plants by Production Method in Each Country/Area & Operating Iron Capacity (TTPA) by Production Method in Each Country/Area. <https://globalenergymonitor.org/projects/global-steel-plant-tracker/summary-tables/> (accessed 22 November 2024); Midrex Technologies Inc. (2024) 2023 WORLD DIRECT REDUCTION STATISTICS. Englewood Cliffs, New Jersey, USA. <https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2023.Final_-2.pdf > ; IEAGHG (2024)

[63] Cost analysis, based on IEA GHG (2024) sees the natural gas DRI-EAF pathway require 433kWh/tonne of liquid steel. This increases to 705kWh per tonne of liquid steel when coupled with CCS. IEA GHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology 2024-02.

[64] Based on the Higher Heating Value, where hydrogen is taken to be 12.7MJ/m³ and natural gas (methane) is taken to be 39.8MJ/m³

hydrogen production, approximately 580m^3 of hydrogen is required per tonne of liquid steel.[65] To meet this requirement, an increase in gas delivery and storage is required, depending on buffering requirements, alongside greater renewable electricity capacity to support electrolytic hydrogen production (see the *Low Carbon Fuels* technical appendix) and for additional process steps, like hydrogen preheating.[66]

For a 4Mt/year production plant, 209kt of hydrogen would be required. This figure is substantially higher than the BF-BOF, partial hydrogen replacement. To overcome hydrogen constraints in the near-term, shaft furnaces may be run on natural gas and transitioned to hydrogen feedstock over time as Australia's capacity to produce fully low carbon fuels grows.

Hydrogen DRI, w/ biomass EAF

Biomass-reliant pathways were deemed to meet the criteria, with caveats. Biomass is a supply limited source where cost, availability and access will be a factor in deployment (see the *Low Carbon Fuels* technical appendix for further information).

As per the cost analysis, the biomass input totals 54kg per tonne of liquid steel. Yields for biomass to biochar generally range from 12-50%, depending on feedstock and process; therefore, this would require between 108-450kg or raw biomass feedstock.[67] Similar to the BF-BOF pathway, biomass pathways are subject to resource limitations with the sustainable supply of biomass will ultimately shaping the scale and role that biofuels will play in a future energy mix.

In addition, the same limitations for hydrogen DR ironmaking apply as per the above pathway.

Greenfield pathway: DRI-ESF-BOF configurations

For this analysis, ESFs are assumed to operate at smaller scales at ~1.5 Mt/year given their nascency in processing DRI into hot metal.[68] Scalability is also dependent on the availability of reducing agent, which were assigned ratings by interpolating the DRI-EAF and BF-BOF pathway results.

- **Natural gas with CCS:** Meets the criteria with caveats, owing to reliance on CCS infrastructure deployments and high low-carbon electricity demand.
- **Hydrogen:** Meets the criteria with caveats, owing to increased hydrogen and electricity requirements (three times the amount of natural gas delivery/storage capacity would be required alongside sufficient electrolyser capacity).
- **Biomass:** Meets the criteria, with caveats. Biomass is a supply limited source where cost, availability and access will be a factor in deployment.

[65] Once also accounting for up to 30% hydrogen can be blended into an existing system without process changes; 100% replacement of natural gas to hydrogen requires minor retrofit. ~0.23MWh of electricity is required for hydrogen pre-heating per ton DRI.

[66] Fan Z, Friedmann SJ (2021) Low-carbon production of iron and steel: Technology options, economic assessment, and policy. Joule 5, 829. doi:10.1016/j.joule.2021.02.018

[67] Safarian S (2023) Performance analysis of sustainable technologies for biochar production: A comprehensive review. Energy Reports 9, 4574. doi:10.1016/j.egyr.2023.03.111

[68] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology 2024-02. <https://ieaghg.org/news/clean-steel-environmental-and-technoeconomic-outlook-of-a-disruptive-technology/ >

Greenfield pathway: Smelting reduction

A number of smelting reduction pilot plants have been established in past decades, however historically, smelting reduction technologies have proven to be unpopular due to unfavourable economics (see Levelised cost analysis) and have therefore not reached a scale comparable to BF-BOF.

Smelting reduction, coal with CCS

This configuration meets the criteria with caveats.

An active HIsarna technology pilot plant was established by Tata Steel in Ijmuiden, Netherlands in 2010. Since its test installation the plant has been adapted to enable continuous operation and has a maximum production capacity of 60,000t of hot metal annually.[69] This is substantially lower than BF capacity, and further industrial-scale demonstration is yet to be achieved. However, conceptual engineering for the first industrial scale plant, targeting 0.5 to 1Mt per year is underway.

HiSmelt technology has also been adopted in Molong, China, producing 0.6Mt of hot metal per year.[70]

Smelting reduction, hydrogen plasma

This configuration does not meet criteria.

SuSteel is a research project in Australia, led by project partners voestalpine, K1-MET, Primetals, and MUL. The project has scaled up from 1990s capacity (a small-scale test of 100g) to a small pilot-scale of 90 kg in 2020.[71] This scale falls far short of the established threshold and due to the uncertainty around the potential system capacity, smelting reduction using hydrogen plasma was unable to be assessed.

Greenfield pathway: Electrolytic steelmaking

Molten oxide (high-temperature) and low-temperature electrolysis

These configurations meets the criteria.

Electrolytic steelmaking faces no ore-type constraints and is flexible to varying ore qualities. However, it is currently limited to small production scales and faces significant developmental challenges before commercial deployment.[72]

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Liquid Steel (LCOLS) was estimated to determine the viability of each technology pathway. The LCOLS is defined as the cost per tonne of product, i.e., liquid steel, generated ($/tL) over the lifetime of the system.

Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis*.

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[69] TATA Steel (2020) HISARNA Building a sustainable steel industry. <https://products.tatasteelnederland.com/sites/producttsn/files/tata-steel-europe-factsheet-hisarna.pdf>

[70] Smelt Tech Consulting (n.d.) Molong HIsmelt plant. <https://smelttech.com/molong/> (accessed 28 March 2025)

[71] K1 MET (n.d) Project SuSteel Sustanable steel productions utilising hydrogen. <https://www.k1-met.com/en/non_comet/susteel> (accessed 20 January 2025); IEAGHG (2024)

[72] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02

For reference:

- Some technologies that did not meet earlier filtering criteria have been included for completeness, where information was available – however, these were not assessed.
- Costs are estimated using the projected fuel, operational, capital and integration costs in 2025 and 2050 to understand the potential for shorter-term and longer-term solutions.
- A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, contributing to the levelised cost of that technology in the long-term. No CO_2 emission cost has been assumed for 2025.

Results from levelised cost analysis are outlined in Figure 9 (Brownfield assessment) and Figure 10 (Greenfield assessment). The following technologies were projected to be the most cost competitive technologies, distinguished by a cost differential in LCOLS relative to other assessed technologies, suggesting areas of promise for further RD&D activity.

- **Brownfield assessment**: oxyBF-BOF with CCS and oxyBF-BOF coupled with partial biomass and CCS exhibited lower levelised costs. BF-BOF with partial hydrogen injection is modelled to have the highest levelised cost due to lower levels of abatement achieved, therefore attracting a higher CO_2 cost.
- **Greenfield assessment:** DRI-EAF configurations (natural gas DRI with CCS, hydrogen DRI, hydrogen DRI with biochar in the EAF) exhibited lower levelised costs. DRI-ESF-BOF configurations were also identified despite a lack of available data as industry investment, comparative cost analysis, and the transitional nature of the pathway indicates economic prospects. Smelting reduction and electrolytic steelmaking technologies remain inconclusive due to insufficient data for LCOE modelling.

This economic assessment focuses on the future production cost for an integrated BF-BOF steel mill nearing the end of a BF campaign. This creates a technology breakpoint whereby the steel mill operator may choose to reline the BF and continue operations with retrofitted mitigation solutions, or switch to an alternative pathway. This represents the two use cases that have been adopted throughout this analysis.

As per the adapted methodology from the IEAGHG (2024),[73] the boundary limit for this analysis captures processes up to, and including, the generation of liquid steel. Downstream processes, such as casting, rolling, and the reheating of furnaces, were not included. The analysis includes material and input flows from the coke oven, integrated sinter plant, lime production and pathway reactors. Pellets were purchased, and so purchase costs were accounted for, but not emissions as this was assumed to occur upstream at the mine site. Connection costs to utilities such as hydrogen or electricity have not been included in this analysis. Refer to the *Technical Appendix: Levelised cost analysis* for detailed cost assumptions.

With the steelmaking pathways consuming and producing electricity at different stages of production, some of the produced electricity is assumed to be re-circulated to other process units. Across all direct reduction pathways there is a deficit of electricity within the system. Therefore, an external source of electricity is required and is assumed to be satisfied by the grid.[74]

[73] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02

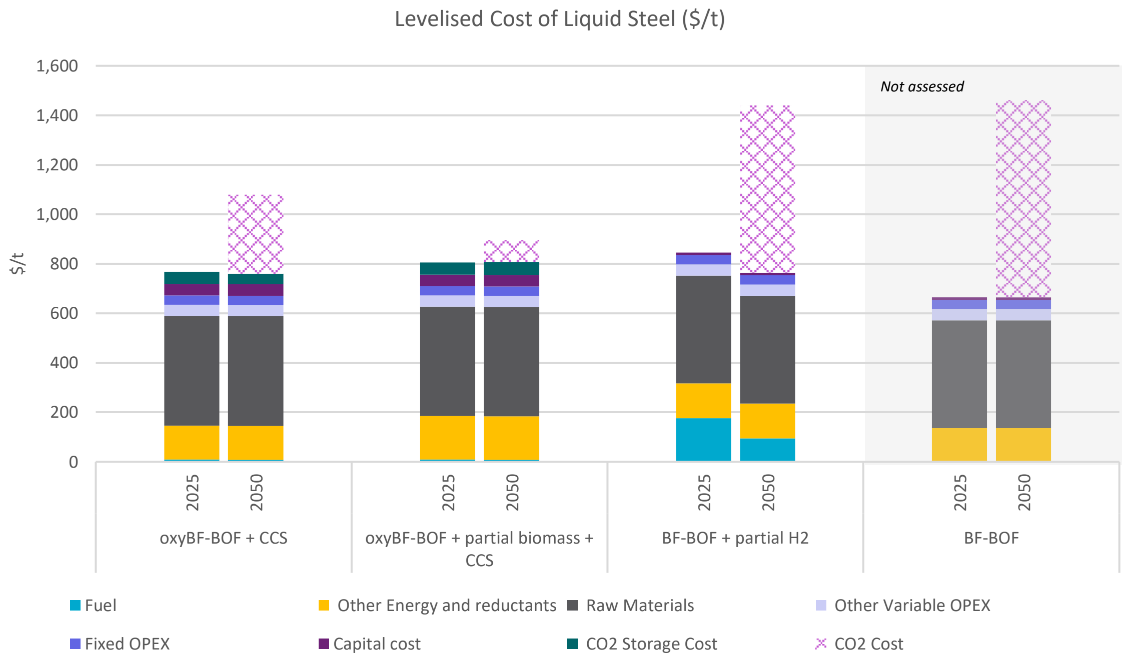
[74] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02

Brownfield pathway

Cost analysis was conducted to determine the levelised cost of liquid steel (LCOLS) across brownfield technology pathways, where the BF of the integrated steel mill is relined and the facility is retrofitted with various low emissions technologies. The reference size of the BF-BOF facility is $2Mt_{LS}$ per year.

In reality, input costs such as raw materials, fuels, electricity, biomass and the cost of CO_2 transport and storage are likely to vary significantly by site location. This variation will influence the preferred pathway for a given site.

Figure 9: Levelised Cost of Liquid Steel ($/t) – Brownfield pathway



The conventional BF-BOF configuration is included as a technology benchmark, though it is not assessed. This pathway is modelled to have the lowest levelised cost of steel in 2025, but the highest in 2050 when accounting for a CO_2 emission cost.

oxyBF-BOF with CCS (incl. with partial biomass injection)

These configurations are estimated to have the lowest LCOLS in 2050 of all assessed technologies.

Despite higher capital costs, the CCS-coupled pathway leads to sizeable reductions in CO_2 emissions. This results in a lower modelled levelised cost in 2050 when compared to the BF-BOF configuration.

Cost are further reduced when the partial biomass is employed as a partial reducing agent. The oxyBF-BOF + partial biomass + CCS configuration has higher CAPEX and fuel costs, driven by biomass feedstock prices. The cost assumptions for biochar equate to $464/t in both 2025 and 2050. However, it also leads to the greatest reduction in CO_2 emissions and is modelled to have the lowest levelised cost in 2050 when accounting for a CO_2 emission cost.

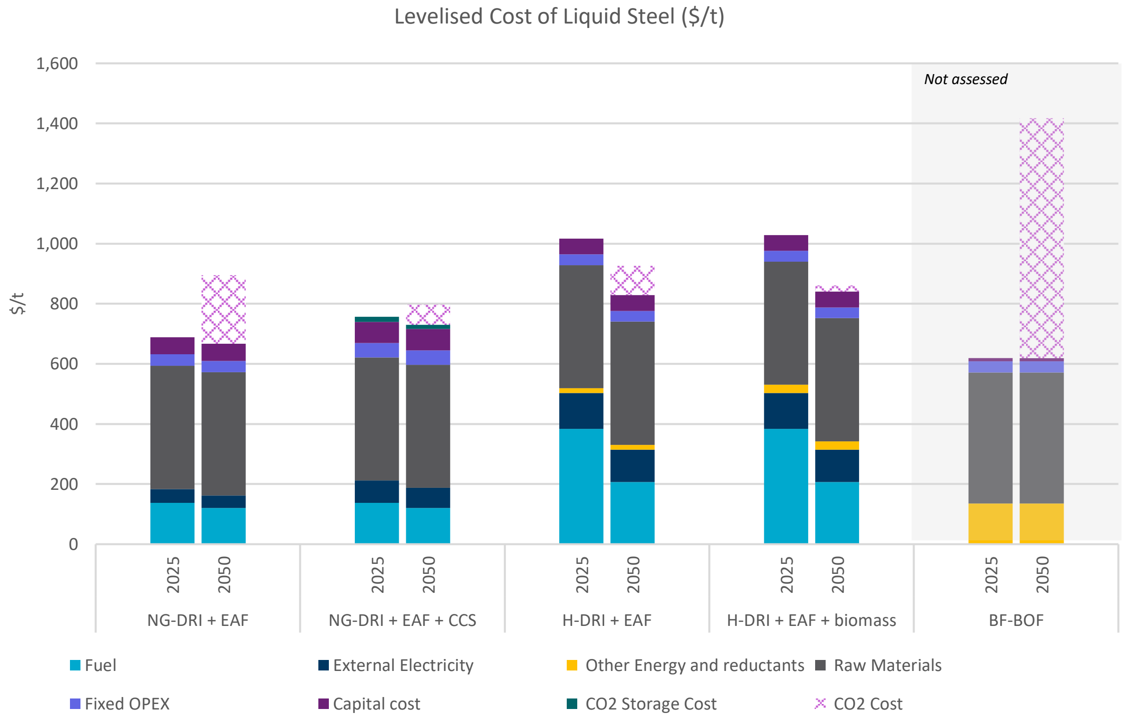
BF-BOF with partial hydrogen

There is a cost differential between BF-BOF with partial hydrogen and the CCS-coupled pathways. This configuration is modelled to have the highest levelised cost in 2025 due to the high cost of hydrogen. Due to assumed cost reductions for hydrogen production, from $7.32 (2025) to $3.95 (2050), this configuration becomes more competitive in 2050. However, as it does not lead to significant emissions reduction, it attracts a high CO_2 cost.

Greenfield pathway

Cost analysis was conducted to determine the LCOLS across greenfield technology pathways. The reference size of each facility is $2Mt_{LS}$ per year (see also the *Technical Appendix: Levelised cost analysis*).

Figure 10: Levelised Cost of Liquid Steel ($/t) – Greenfield pathway



The conventional BF-BOF configuration is included as a technology benchmark, though it is not assessed. This pathway is modelled to have the lowest levelised cost of steel in 2025, but the highest in 2050 when accounting for a CO_2 emission cost.

Natural gas DRI-EAF (incl. with CCS)

These configurations present significant long term cost reductions compared to conventional production processes, when accounting for a CO_2 emission cost. When coupled with CCS, the pathway has higher capital and electricity costs but drives further reductions in CO_2 emissions. This leads to the lowest modelled levelised cost in 2050 relative to other assessed technologies.

The natural gas DRI-EAF configuration is modelled to have a moderately higher levelised cost than BF-BOF in 2025, but significantly reduces CO_2 emissions in the long term. Higher costs in 2025 are driven primarily by capital costs and external electricity costs.

Hydrogen DRI-EAF (incl. with biomass in the EAF)

These configurations also present significant long term cost reductions compared to conventional production processes, when accounting for a CO_2 emission cost.

The hydrogen DRI-EAF pathway is modelled to have significantly higher levelised costs in 2025 compared to other technologies due to the high cost of hydrogen. Costs are modelled to reduce in 2050 in line with other cost pathways, particularly when accounting for a CO_2 emission cost. This pathway still generates CO_2 emissions as thermal coal is added to the EAF to provide chemical energy, reduce non-metallic iron and reach the desired steel carbon content. When biochar is used as a thermal coal replacement, the modelled levelised cost is further reduced in 2050 – rendering it the next most cost competitive configuration after natural gas DRI-EAF with CCS.

DRI-ESF-BOF configurations

For these pathways, sufficient data was not able to be obtained for robust cost analysis; however, they were deemed to meet this filter with caveats, based on indicative information.

There has been significant industry investment and interest towards this pathway in recent years. Globally, Tata Steel and BlueScope have made commitments towards ESF production routes. Domestically, Fortescue, and the NeoSmelt consortium (BHP, BlueScope and Rio Tinto) have announced pilot projects in Western Australia, seen as a potential avenue to utilise BF-grade ore pellets in a DRI-based process.

Though cost analysis was unable to be conducted in this project, IEAGHG analysis places costs for this pathway as more expensive than natural gas DRI-EAF with CCS, but less expensive than hydrogen based DRI-EAF, with the pathway attracting producers who wish to incrementally transition their production to the direct reduction route while retaining existing steel mill equipment.[75]

Smelting reduction

For these pathways, sufficient data was not able to be obtained for robust cost analysis and results remain inconclusive. Though an established and commercial operation, smelting reduction pathways have been unpopular due to poor economic performance.[76] The IEAGHG suggests that even for economies with abundant, cheap coal, it is more economical to feed DRI to a smelting furnace (i.e., DRI-ESF-BOF) rather than to a melter-gasifier. For example:

- In Australia, the HIsmelt Kwinana Plant operated from 2005 until Rio Tinto's exit in 2008, achieving production rates capable of producing 800,000t/y of pig iron using low grade iron ore. Though the process was technically proven, it was deemed financially unviable;[77] noting the economical context of the global financial crisis at the time.
- Tata Steel established a pilot plant to test the Hisarna smelting reduction process in 2016.[78] In September 2021, Tata Steel announced that it would instead pursue hydrogen direct reduced iron at the Ijmuiden plant, indicating a pivot away from pursuing Hisarna in its European operations.[79]

Electrolytic steelmaking

For these pathways, sufficient data was not able to be obtained for robust cost analysis and so results remain inconclusive.

Electrolytic steelmaking costs will be heavily dependent on the cost of renewable energy. This technology is at an early stage of research and development and its financial viability is currently uncertain.

[75] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02

[76] IEAGHG (2024) Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology. IEAGHG Technical Report 2024-02

[77] Klinger P (2011) Tio terminates Kwinana HIsmelt plant. The West Australian. https://thewest.com.au/business/finance/rio-terminates-kwinana-hismelt-plant-ng-ya-184032 (accessed 20 January 2025)

[78] A test plant was established earlier in 2010, but was scaled to a pilot facility in 2016

[79] Please note: Plans are still underway to develop a second large-scale pilot plant (0.5 Mt) employing the Hisarna smelting reduction technology in India, which could open in the 2025-2030 period. TATA Steel (2020) HISARNA Building a sustainable steel industry. <https://products.tatasteelnederland.com/sites/producttsn/files/tata-steel-europe-factsheet-hisarna.pdf>; Hatch (n.d) Tata Steel hydrogen-based steel manufacturing <https://www.hatch.com/Projects/Metals-And-Minerals/Tata-Steel-hydrogen-based-steel-manufacturing> (accessed 20 January 2025)

4.5 Technology landscape

Key information – Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the RD&D opportunity analysis and capture the complexity of the energy system networks and their interdependencies with other technological systems. This was informed by literature review and stakeholder input, and comprised of:

Use case

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

The technology analysis framework identified two technology configurations as *Primary technologies* for the brownfield case**: coal-based oxyBF-BOF w/ CCS and BF-BOF with partial biomass injection**, and four configurations, across two pathways, as *Primary technologies* for greenfield use case: **DRI-ESF-BOF and DRI-EAF, where the DRI systems adopts either natural gas with CCS or 100% hydrogen as the reducing agent and where biochar is used as a replacement for EAF coal inputs** (Figure 11).

Although not explored further, the other low emissions technologies evaluated in this report (Tables 2 and 3) could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the iron and steelmaking subsector. Further RD&D could unlock breakthrough innovations in these technologies, highlighting the need for ongoing assessments to maintain Australia's understanding of the current state of low emissions technologies and future opportunities for RD&D.

Figure 11: Technology landscape identification – Industry, Iron and steel

Brownfield pathway technologies

OxyBF with coal, OxyBF with partial biomass injection

- Agglomeration
- HBI/DRI handling and transport mechanisms
- Biomass feedstock processing

BOF

- Control systems for slag optimisation

Greenfield pathway technologies

NG – DRI , H_2 – DRI

- Renewable hydrogen production, storage and distribution infrastructure
- HBI/DRI handling and transporting mechanisms
- Component modelling
- Agglomeration

ESF, EAF

- Beneficiation
- Renewable electricity generation, storage and transmission infrastructure
- HBI/DRI handling and transporting mechanisms
- Slag utilisation techniques

Carbon capture and storage (CCS) – *See Carbon Management technical appendx*

Energy efficiency solutions

- Carbon capture and utilisation
- Slag and material utilisation
- Waste heat recovery
- Beneficiation
- Sensing and analytics
- Advanced digital modelling

The associated *Auxiliary technologies* and *Energy efficiency solutions* identified for analysis are outlined in Table 9 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Auxiliary technologies

The *Primary technologies* cannot exist in isolation and their successful use and deployment is dependent on a range of *Auxiliary technologies*, summarised in Table 9.

Table 9: Auxiliary technologies – Iron and steelmaking

Primary Technology	Auxiliary Technology	Description
Brownfield pathway		
Blast furnace	**Agglomeration**	Technologies that enhance and improve the metallurgical properties of fine iron ores and steelmaking byproducts by processing them into sinter or pellets for use in the blast furnace.
	HBI/DRI handling and transport mechanisms	Technologies that prevent reoxidation, degradation and material losses by enabling the safe handling and transport of hot briquetted iron (HBI) and direct reduced iron (DRI).
	Biomass feedstock processing	Conversion technologies and processing systems that refine biomass feedstocks into intermediates suitable for partial replacement for coal in blast furnace injection.
Basic oxygen furnace	**Control systems for slag optimisation**	Technologies that allow for enhanced slag composition control and process efficiency by integrating sensing, modelling and process automation.
Greenfield pathway		
Direct reduced iron **Electric arc furnace** **Electric smelting furnace**	**Hydrogen production**	Technologies that enable the large scale, low emissions production of hydrogen (see the *Low Carbon Fuels* technical appendix).
	Hydrogen storage and distribution	Infrastructure and technologies required to store hydrogen and distribute it to refuelling stations.
	HBI/DRI handling and transport mechanisms	Technologies that prevent reoxidation, degradation and material losses by enabling the safe handling and transport of hot briquetted iron (HBI) and direct reduced iron (DRI).
	Technology assessment methodologies	Tools that enable the evaluation of emerging DRI-based pathways by integrating component modelling, process simulation and comparative analysis frameworks, including techno-economic performance.
	Beneficiation	Technologies that upgrade lower-grade iron ores for use in DRI production by removing impurities and improving iron content.
	Agglomeration	Technologies that improve the physical and metallurgical properties of iron ore fines by processing them into high-quality DR-grade pellets suitable for direct reduction.
Crosscutting		
Carbon capture, utilisation and storage	**Carbon capture, utilisation and storage**	Technologies that capture CO_2 from process gases and permanently store it in geological formations or utilise it in industrial applications (see the *Carbon Management* technical appendix).

Energy and material efficiency solutions

For iron and steelmaking, there are a range of *Energy efficiency solutions* that will also support emissions mitigation efforts. The solutions outlined in Table 10.

Table 10: Energy and material efficiency solutions – Iron and steelmaking

Energy and material efficiency solutions	Description
Carbon capture and utilisation (CCU)	Involves the capture of CO_2 from iron and steel making flue gas stream and its chemical conversion into chemicals (TRL 7) or fuels (TRL 8) or other products.

Slag and material utilisation	Involves the recovery, reuse, or recycling of slag streams, or its various constituents, in order to improve the circularity of the iron and steelmaking process.
Process optimisation and scaleup through advanced digital modelling	Involves the application of advanced computational tools and digital technologies to optimise steelmaking processes, reduce energy consumption, and scale up systems.
Sensing and analytics	Involves the development of advanced sensors and data analytics for real-time monitoring and optimisation of material processes in iron and steelmaking.
Waste heat recovery	Involves the recovery of heat from high-temperature off-gases, slag and other steelmaking processes to improve overall process energy efficiency.

4.6 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the identified technology landscape, spanning primary, auxiliary and energy efficiency technologies.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include non-technical RD&D opportunities. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

A summary of RD&D opportunities can be seen in Table 11. For some technologies, these opportunities are associated with specific technology subcomponents. Technologies typically consist of different system components, that are integrated or work in tandem, which may have specific RD&D needs or be at different stages of technology maturity. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9).

Current technologies deployed in iron and steelmaking utilise inexpensive feedstocks and have benefitted from incremental technology and efficiency improvements over past decades to drive down production costs. Accordingly, there is significant RD&D opportunity to reduce costs across all pathways, striving to bring down the cost of alternative configurations as close as reasonably possible to conventional BF-BOF systems. It will also require the industry to improve energy efficiency, both via technology improvements like optimisation and incremental energy intensity reductions, as well as efficiency gains by switching to inherently more efficient production pathways, like DRI-EAF.[80]

Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

[80] IEA (2020) Iron and Steel Technology Roadmap: Towards more sustainable steelmaking. Part of the Energy Technology Perspectives series.

Table 11: Summary of RD&D opportunities – Iron and steelmaking[81]

		BF (oxy/BF) (NG and biomass injection)		BOF
		BF reactor	TGR system	Reactor
Primary technologies	**Commercial**	Shaft BF/oxyBF (NG)	-	Standard basic oxygen furnace
	Mature	-	oxyBF with partial TGR	-
	Emerging	Shaft BF/oxyBF (H_2-enriched)	oxyBF with full TGR	-
Primary RD&D		• Optimise charging by enabling the use of lower energy and emissions intensive ores, novel charging materials like hot briquetted iron (HBI), and increasing scrap utilisation. • Investigate the use of biomass as a partial reducing agent through: - E.g. Further demonstration of biomass injection using Australian biochar supplies - E.g. Characterising biochar properties and impacts on BF operation - E.g. Refining injection strategies, such as by using kinetic and thermodynamic modelling • Demonstrate and optimise the integration and performance of the oxyBF with TGR and CCS through: - E.g. Optimising oxygen enrichments levels, shaft conditions, and gas compositions - E.g. Stabilising operations at high production levels and lowering TGR feedback		• Improve operational flexibility: - E.g. Optimise preheating and charge sequencing activities for the use of lower-carbon feedstocks (DRI, scrap), through: - E.g. Tailor process control mechanisms (i.e., gas management systems) for enhanced carbon capture
Auxiliary RD&D		• Support the use of alternative charging materials through: - E.g. Improving agglomeration processes - E.g. Devising safe and cost-effective means of DRI/HBI handling and transport - E.g. Managing scrap impurities • Develop sustainable and scalable feedstock supply chains for biochar production • Improve circularity by investigating novel slag utilisation techniques (see *Section 4.6.7 Crosscutting – Energy efficiency technologies)*		• Improve circularity by investigating novel slag utilisation techniques (see *Section 4.6.7 Crosscutting – Energy efficiency technologies)*

cf. – Compare

[81] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6; Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

Primary technologies

	DRI (NG and H_2 injection)		EAF		ESF
	Reactor	Beneficiation	Reactor	Beneficiation	Reactor
Commercial	NG shaft furnace (MIDREX; HYL/ENERGIRON); NG fluidised bed (Finored/Finmet)	See *Section 4.6.3*	Conventional electric arc furnace (EAF)	See *Section 4.6.3*	Submerged arc furnace Open slag bath furnace
Mature	H_2 shaft furnace		-		-
Emerging	H_2 fluidised bed (HYFOR, HYREX and Circored); Flash reduction (Calix ZESTY)		-		-

Primary RD&D

DRI (NG and H_2 injection)	EAF	ESF
• Reduce production costs through: - E.g. Reducing cost of hydrogen production **(LCOH$_2$ forecast: \$3.95/kg, cf. \$7.32)** - E.g. Improving operational performance via advanced reactor designs and efficiency gains • Demonstrate Australian lump and agglomerated ores in DR processes, for both NG- and H_2-based reactors. • Optimise H_2 injection and operation at high concentrations for shaft-based reactors through: - E.g. Physics-based modelling and engineering optimisation to support reactor design improvements. • Overcome and minimise particle sticking in fluidised bed reactors, specifically for Australian ores, through: - E.g. Determining baseline operating protocols - E.g. Investigating pre-processing techniques	• Reduce production costs by improving reactor energetics through: - E.g. Improving energy efficiency - E.g. Establishing thermal integration and energy recovery strategies • Enhance carbon utilisation and explore sustainable carbon inputs through: - E.g. Investigating alternatives to coal for carbon supply - E.g. Establishing carbon pick-up and reaction rates under varied operational conditions • Expand understanding of reactor performance using Australian DRI, through: - E.g. Developing further understanding of how performance is impacted by DRI characteristics.	• Establish and reduce costs: - E.g. Building capacity for technoeconomic assessment, tailored to Australian ore characteristics • Demonstrate and optimise the ESF route for Australian ores through: - E.g. Developing further understanding of how performance is impacted by DRI characteristics. • Scale the capacity of ESF reactors **(Target: >2Mt per year, cf. 30,000-40,000t)** • Address reactor-specific challenges

Auxiliary RD&D

DRI (NG and H_2 injection)	EAF and ESF
• Scale-up and improve performance of pelletising for shaft-based reactors • Establish sufficient renewable hydrogen production, storage and distribution infrastructure (Refer to the *Low Carbon Fuels* technical appendix) • Devise safe and cost-effective means of DRI/HBI handling and transport for downstream utilisation • Technically evaluate prospective process configurations for Australian operations through: - E.g. site-based techno-economic or component modelling	• Beneficiation of Australian hematite(-goethite) and magnetite ores to suitable quality for the respective electric melters (EAF or ESF) • Establish sufficient low emissions electricity generation, storage and transmission infrastructure (Refer to the *Electricity* technical appendix) and support integration of variable renewable energy into steelmaking activities (see *Section 4.6.7 Crosscutting – Energy efficiency technologies)* • Devise safe and cost-effective means of handling and transporting DRI/HBI inputs • Improve circularity by investigating novel slag utilisation techniques (see *Section 4.6.7 Crosscutting – Energy efficiency technologies*)

Carbon capture and storage (CCS, refer to Carbon Management technical appendix for further detail)		
Primary technologies	CO_2 capture	CO_2 storage
Commercial	Refer to the *Carbon Management* technical appendix	
Mature		
Emerging		

Primary RD&D

Research opportunities specific to iron and steelmaking pathways include:

- Designing retrofittable CCS systems that minimise disruptions to brownfield operations
- Improving system performance and efficiency
- Validating CCS integration into steelmaking facilities

Auxiliary RD&D

- For broader discussion regarding CO_2 capture and storage technologies, please refer to the *Carbon Management* technical appendix

Industry terminology (see glossary for further detail)

- **Charging:** The controlled introduction of raw materials, including coke, iron ore, and flux into iron and steelmaking equipment.
- **Burden:** The total mass of raw materials (iron-bearing materials like sinter, pellets, lump ore, and coke) loaded into iron and steelmaking equipment.
- **Flux:** A material, such as limestone or dolomite, added to iron and steelmaking equipment to remove impurities by forming slag.

4.6.1 Blast furnace (BF) / oxygen blast furnace (oxyBF)

This section outlines research needs for:

1. BFs with partial biomass injection, and
2. oxyBFs using coal with top-gas-recycling (TGR) and coupled with CCS.

RD&D opportunities for CCS technologies are discussed in the *Carbon Management* technical appendix as they are relevant to other sectors and applications discussed in *The State of Energy Transition Technologies* reports.

Primary technologies

Productivity gains and emissions reductions can be realised through the optimisation of BF feedstocks.

Efforts to reduce the energy and emissions intensity of BF are targeting the optimisation of BF burden. In Australia, sinter, an energy-intensive iron agglomerate, is the predominant iron ore input into BF production routes, supplemented by lump iron ore and pellets. Industry leaders, such as BHP[82] and Rio Tinto,[83] are improving systems to allow a higher usage of lump ore. Other strategies under investigation include the thermal pre-treatment of pre-reduction ore to condition the ores for the BF environment; magnetic separators to ensure better permeability and reduce slag formation; TGR systems to improve reduction efficiencies for less reactive lump ores; or using more reactive reducing agents like hydrogen or plasma. Research opportunities to reduce the emissions intensity of sintering are captured under *Auxiliary technologies*.

Trials are also underway to introduce hot briquetted iron (HBI) as a novel charging material,[84] which has been found to demonstrate reductions in coke consumption rates (~7%) and CO_2 emissions, alongside productivity gains (~8%) for each 10% increase in burden metallisation.[85] Research can help build understanding of the technoeconomic feasibility of HBI in the Australian context, including impacts on reducing agent consumption, productivity, equipment compatibility and product quality.[86] HBI has been utilised in several BF operations (AK

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[82] For instance, BHP, in collaboration with HBIS (China), is installing a lump ore screening plant and has begun constructing a commercial-scale drying system to clean and separate suitable size lump ores for further BF-processing. BHP (2024) Climate Transition Action Plan 2024. <https://www.bhp.com/-/media/documents/investors/annual-reports/2024/240827_bhpclimatetransitionactionplan2024.pdf> (accessed 20 January 2025)

[83] Farry S (2024) How will we decarbonise our steelmaking processes? Rio Tinto. <https://www.riotinto.com/en/news/stories/how-will-we-decarbonise-our-steelmaking-processes> (accessed 20 January 2025)

[84] Other novel charging materials, such as Carbon Containing Agglomerates (CCAs) and Ferro-coke are under investigation, but face limitations due to their high-carbon content, typically from fossil-derived sources. Abatement potential is unlikely to be low unless biomass-based sources are considered, bringing forth challenges related to supply. Zulli P, Dong XF, Mcmahon C, Mcclure A (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.<https://arena.gov.au/knowledge-bank/bluescope-steel-port-kembla-steelworks-renewables-emissions-reduction-study-phase-3-report/>

[85] Di Cecca C, Barella S, Mapelli C, Ciuffini AF, Gruttadauria A, Mombelli D, Bondi E (2016) Use of DRI/HBI in ironmaking and steelmaking Furnaces. La Metallurgia Italiana. 108(4):33-8.

[86] Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

Steel, Voestalpine Linz, and Kobe Steel), but domestic feasibility studies are needed to assess the effect of HBI charging using Australian ores. Notably, an AK Steel plant in Ohio (US) has charged their facility with 30% HBI since the 1980s, seeing substantial reductions in total fuel consumption. Further, Kobe Steel (Japan) has verified a 25% reduction in process emissions, including upstream DRI production.[87]

Partial biomass injection offers abatement potential, but RD&D is needed across the biochar value chain including supply, processing and utilisation.

Research is advancing the use of biomass-derived carbon materials, particularly biochar, as a partial reducing replacement for PCI in the BF raceway. Though biochar can be adopted in several BF-BOF applications, this application offers the highest displacement potential and impetus for shoring up supply chains (Table 8).[88]

In steel applications, slow or low temperature pyrolysis (torrefaction) processes are a preferred method of biochar production to maximise yields, but performance depends on the chemical and physical properties of the biomass used. RD&D presents opportunities to investigate the impacts that the characteristics of biochar can have on operations including combustion behaviour, effects on raceway adiabatic flame temperature (RAFT) and gas compositions, and trace metal content on steelmaking recycling streams. [89]

Though optimisation has been theoretically determined, further piloting and demonstration of partial biomass injection is required using Australian biomass supplies.[90] While some mechanical property limitations can be overcome via tuyere injection, biomass consistency, supply and infrastructure compatibility remain challenges. Overcoming knowledge gaps on the grinding behaviour of biochar can improve production across the biomass-value chain from processing (i.e., pyrolysis), pretreatment (i.e., milling and pulverisation) and usage (i.e., injection).[91]

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[87] Kobe Steel, Ltd (2023) Kobelco Group's CO_2 Reduction Solution for Blast Furnace Ironmaking Enhanced. <https://www.kobelco.co.jp/english/releases/1214021_15581.html> (accessed 20 January 2025)

[88] Several trials are underway to replace coal and coke in the BF route with biomass-derived carbon materials, both as a solid fuel and as a partial reducing agent. Examples include ArcelorMittal's Torero Project (Gent, Belgium) [commissioning stage], and pilot trials by BlueScope and University of Wollongong completed pilot testing 30% biochar blend for 24 hours

[89] Suopajärvi H, Umeki K, Mousa E, Hedayati A, Romar H, Kemppainen A, Wang C, Phounglamcheik A, Tuomikoski S, Norberg N, Andefors A (2018) Use of biomass in integrated steelmaking–Status quo, future needs and comparison to other low-CO2 steel production technologies. Applied Energy. 213:384-407. https://doi.org/10.1016/j.apenergy.2018.01.060

[90] For example, Thyssenkrupp have been demonstrating injection of hydrogen in the blast furnace in their Duisburg plant, with a pure feeding rate of $1000m^3H_2$/hour, however the share of H_2 is undisclosed. A. Bhaskar, M. Assadi, H. Nikpey Somehsaraei (2020) Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen

[91] Suopajärvi H et al. (2018) Use of biomass in integrated steelmaking–Status quo, future needs and comparison to other low-CO2 steel production technologies.

Box 4: Partial H_2-based reduction in the blast furnace

The utilisation of additional hydrogen as a reducing agent for iron-bearing materials is being explored due to its strong diffusion which can enhance reaction kinetics and efficiency, possess high reduction ability, and allow for zero emission by-products (i.e., H_2O). Though partial hydrogen injection was not projected to be a cost competitive solution during assessment, further research could improve its economic prospects.

A large barrier to adoption is cost, creating opportunity to reduce the cost of hydrogen inputs (LCOH$_2$ forecast: $3.95/kg, cf. $7.32) and achieve broader BF efficiency improvements. This may be enabled through kinetic and thermodynamic modelling, to refine injection strategies.

Other H_2-based partial reducing agents, like coke oven gas (COG), can also provide emissions reductions, though smaller than for pure hydrogen and at disproportionally higher costs.

- COG, primarily consists of H_2 and CO, and can be injected to partially substitute the coke from the blast furnace to reduce CO_2 emissions.[92] International trial results suggest that approximately 3% of emissions could be reduced through COG and reformed COG.[93] The injection of COG faces technical challenges, including the development of gas film at the BF wall (which is detrimental to the refractory and lining) and the accumulation of water (which reduces the temperature of the hot blast). There are also costs associated with purifying tar, naphthalene, and organic sulphur from the COG gas.
- Natural gas also faces economical and technical challenges. Natural gas was previously employed as a partial reducing agent at Bluescope's Port Kimbla Steel Works plant but was replaced with PCI in 2002 for productivity gains and cost reductions. Injection faces limitations, with higher concentrations lowering the Raceway Adiabatic Flame Temperature (RAFT) and creating operational challenges that require additional heat to overcome.[94]

Top-gas recycling and oxygen enrichment in oxyBFs can reduce coke use and enable integration with CCS, however further demonstration and optimisation of integrated carbon capture is required.[95]

The oxygen blast furnace (oxyBF) recirculates top gas and operates on enriched air or pure oxygen, reducing coke consumption, improving energy efficiency, and producing a top gas with low nitrogen content that is more suitable for point source carbon capture. In this process, a TGR system recirculates part of the top gas, but as the reintroduction of CO_2 and H_2O directly can disrupt the chemical equilibrium, a carbon capture system is often incorporated before recycling the top gas to remove CO_2.[96]

However, this process presents control challenges, especially at high productivity levels, due to the complicated and nonlinear feedback mechanisms induced by the TGR.[97] Advanced modelling (numerical,[98] thermodynamic) and experimental validations could be leveraged to optimise injection levels, shaft conditions, and top gas compositions. Further research can help to stabilise oxyBF operation, enabling it to match or exceed the performance of conventional BF system.[99]

Auxiliary technologies

Improving agglomeration processing can reduce emissions from sintering while maintain BF performance.

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[92] Liu et al (2021) The production and application of hydrogen in steel industry. 10.1016/j.ijhydene.2020.12.123

[93]Nishioka K, Ujisawa Y, Tonomura S, Ishiwata N, Sikstrom P (2016) Sustainable aspects of CO 2 ultimate reduction in the steelmaking process (COURSE50 Project), part 1: Hydrogen reduction in the blast furnace. Journal of sustainable metallurgy. 2:200-8

[94] If the RAFT is lowered unfavourably, this can mean there is insufficient heat for coke gasification (and reducing gas generation), potential chilling of the lower furnace (risking slag solidification), impacts on burn descent (risking unburnt char accumulation) and lower melting efficiencies.

[95] Pandit J et al. (2020) Reduction of Greenhouse Gas Emission in Steel Production Final Report.

[96] Perpiñán J, Peña B, Bailera M, Eveloy V, Kannan P, Raj A, Lisbona P, Romeo LM. (2023) Integration of carbon capture technologies in blast furnace based steel making: A comprehensive and systematic review. Fuel. 336:127074. https://doi.org/10.1016/j.fuel.2022.127074

[97] Perpiñán J et al. (2023) Integration of carbon capture technologies in blast furnace based steel making: A comprehensive and systematic review.

[98] Pandit J et al. (2020) Reduction of Greenhouse Gas Emissions in Steel Production.

[99]Zhang W, Dai J, Li C, Yu X, Xue Z, Saxén H. (2021) A review on explorations of the oxygen blast furnace process. steel research international. 92(1):2000326.

Sintering is an energy-intensive key agglomeration process for iron ores, representing up to 10% of energy consumption of a steel plant.[100] As such, methods to improve energy efficiency and reduce energy demands continue to be a cornerstone of research in this field, alongside transitioning to lower carbon fuel alternatives to replace coke.

While sinter provides essential stability for BF operation, it can be partially substituted be by pellets or DRI/HBI, which offer emissions advantages. Both are discussed under the *Auxiliary technologies* heading of *Section 4.6.3 Direct reduced iron (natural gas-DRI and* H_2-DRI).

Enhancing DRI/ HBI transport and storage safety will underpin its use in downstream operations, such as BF optimisation.

DRI and HBI are susceptible to reoxidation, which can lead to spontaneous heating or fire hazards during transport and storage. Though inert atmosphere transport techniques are available, there are opportunities to reduce risks by developing safe handling equipment, corrosion-resistant materials, real-time monitoring systems/sensors (e.g., to detect changes to temperature and gas composition).

Additionally, as production scales and shifts towards lower grade ores or low carbon DRI, RD&D can support the development of appropriate safety standards and procedures for different operational contexts.[101]

Integrating scrap can lower emissions and material costs but requires impurity management and control systems.

While iron-rich scrap presents a cost-effective emissions reduction opportunity, variability in chemical composition and quality can disrupt furnace operation. RD&D can support the development of pre-treatment strategies such as sorting, cleaning and pre-heating scrap to remove impurities. Simulation tools and digital twin tools could be developed to model scrap blending impacts on BF productivity, slag chemistry and energy use, enabling more dynamic operation when scrap is introduced.

Slag utilisation presents a multi-pronged opportunity for emissions reduction, resource efficiency and material recovery.

Slag offers potential value for steelmakers if leveraged efficiently, allowing for improved energy conservation and waste recycling.[102] It is discussed broadly in *Section 4.6.7 Crosscutting - Energy efficiency technologies.*

For the BF, dry slag granulation (DSG) technology with integrated heat recovery has been developed by CSIRO, with support from BlueScope and Arrium, and demonstrates how molten slag can be granulated while recovering heat. This technology produces granulated slag suitable for cement manufacturing and generates heated air that can be used within the steel plant (i.e., drying, preheating or steam generation), resulting in improved energy usage and presenting significant water savings.[103] RD&D can further improve heat recovery efficiencies, integration strategies, and adaptability of DSG systems to different BF and slag chemistries,

The development of sustainable and scalable feedstock supply chains will underpin the production of biochar.

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[100] Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

[101] Unpublished pre-feasibility study for a Low-Emissions Ironmaking R&D facility in WA. CSIRO (2023) Pre-feasibility study on common user pilot facility for low emissions ironmaking. <https://research.csiro.au/tnz/pre-feasibility-study-on-common-user-pilot-facility-for-low-emissions-ironmaking/> (accessed 20 January 2025).

[102] Farry S (2024) How will we decarbonise our steelmaking processes?

[103] CSIRO (2015) Forging a guture in green steelmaking. News release. <https://www.csiro.au/en/news/all/news/2015/march/dry-slag-granulation> (accessed 20 January 2025); Pandit J et al. (2020) Reduction of Greenhouse Gas Emissions in Steel Production.

Please refer to the *Low Carbon Fuels* technical appendix.

4.6.2 Basic oxygen furnace (BOF)

The BOF process involves charging hot metal. A lance is inserted into the top of the converter and oxygen (>99.5% purity) is blown into the liquid to oxidise the carbon and silicon in the hot metal. This exothermic reaction generates sufficient heat to melt the scrap.[104] Unlike other steelmaking processes, the BOF is self-sufficient in energy (autogenous).

Typically, the charge consists of 70-80% hot metal, with the remainder being steel scrap, which serves as a cooling agent and contributes to the final steel composition.

Primary technologies

Improving operational flexibility can enable the use of lower-carbon feedstocks and integration with evolving upstream processes.

As a commercially mature process, RD&D opportunities focus on enhancing material and process flexibility to maintain performance while adapting to changes in feedstock availability and gas composition.[105]

Increasing low carbon alloying materials, such as scrap and DRI, requires solutions to manage heat balance and bath chemistry. Scrap is used in the BOF vessel both as an iron source and as a coolant to control the BOF steelmaking temperature. Scrap is limited to 25-30%, and further consideration needs to be given to maintaining the required temperature if exceeding these limits.[106] This may include preheating strategies, charge sequencing or process control, among others.

Tailoring gas management systems allows BOFs to integrate with upstream processes that produce variable gas compositions (e.g., H_2-based DRI or top-gas recycling). This involves tailoring BOF systems to modulate and control evolving gas streams, while enabling integration with carbon capture. Broader carbon capture systems are discussed under the *Carbon Management* technical appendix.

Auxiliary technologies

Slag utilisation presents a multi-pronged opportunity for emissions reduction, resource efficiency and material recovery.

Slag offers potential value for steelmakers if leveraged efficiently, allowing for improved energy conservation and waste recycling.[107] It is discussed broadly in *Section 4.6.7 Crosscutting - Energy efficiency technologies.*

[104] Wright RN. Relevant aspects of carbon and low-alloy steel metallurgy (2016) Wire Technology: Process Engineering and Metallurgy.199-228. https://doi.org/10.1016/B978-0-12-802650-2.00014-5

[105] Hoffman C, Van Hoey M, Zeumer B (n.d) Decarbonization challenge for steel. McKinsey & Company. <https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel#/> (accessed 20 January 2025)

[106] Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

[107] Farry S (2024) How will we decarbonise our steelmaking processes?

4.6.3 Direct reduced iron (natural gas-DRI and H_2-DRI)

The two major technology providers of gas-based direct reduction, Midrex[108] and HYL[109], have developed shaft-based systems that can operate on pure hydrogen, as well as those that operate on natural gas-hydrogen blends. Several projects in Europe and Asia are already adopting or have announced the adoption of DRI as an input for steelmaking.[110] Some projects aim to use a hydrogen reductant, while others have indicated plans to adopt natural gas and later transition. The HYBRIT project, using HYL technology, is the only system currently in operation with 100% electrolytic hydrogen in operation at pilot scale.[111] The Stegra Boden plant, using Midrex technology, is targeting a 2026 commission to become the first commercial scale H_2-DRI plant with a 2.1 Mtpa capacity supported by 700MW electrolyser capacity.[112]

Of the various direct reduction reactor types (Table 12), 70% of global production produced via shaft furnace processes in 2023.[113] Each reactor type has its own technical challenges and present RD&D opportunities. Of these systems, this discussion will centre on gas-based systems; offering lower emissions, reduced reliance on coal, and aligning with movements by industry proponents toward gas-based DRI routes.

Table 12: DRI reactor vessels – Steelmaking[114]

Reactor	Iron oxide feedstock	Reducing gas	Energy consumption (GJ/tonne)	Production capacity (Mt/year)	Metallisation[115]
Shaft furnace	Pellet ore	Natural gas/H_2	10	1.8	≥90%
Fluidised bed	Powder ore	Natural gas/H_2	13	1.5	≥91%
Rotary kiln	Pellet ore	Coal	20	0.15	≥90%
Rotary hearth furnace	Pellet ore	Coal	12	0.14	≥93%
Tunnel kiln	Lump ore	Coal	25	0.04	≥98%

Primary technologies

Reducing hydrogen and reactor costs is central to improving economic viability of DRI steelmaking routes.

The cost of steelmaking is highly sensitive to the cost of the reducing gas – influenced by fluctuations in market price and, especially in the case of hydrogen, the cost of production, storage and distribution. For hydrogen-based reduction to scale, high capital costs associated with the DR reactor system and hydrogen supply must be addressed. RD&D could reduce reactor costs through improved operational performance, reactor design,

[108] Midrex Technologies, Inc (n.d) Midrex flex <https://www.midrex.com/technology/midrex-process/midrex-flex/> (accessed 20 January 2025)

[109] ENERGIRON (n.d.) A technology for flexible solutions. <https://www.energiron.com/solutions> (accessed 20 January 2024). Association for Iron & Steel (n.d) Japanese DRI Demonstration Project Selects ENERGIRON Technology. <https://www.aist.org/japanese-dri-demonstration-project-selects-energiron-technology> (accessed 20 January 2025)

[110] Basirat S (2024) Hydrogen unleashed: Opportunities and challenges in the evolving H2-DRI-EAF pathway beyond 2024. Institute for Energy Economics and Financial Analysis. <https://ieefa.org/resources/hydrogen-unleashed-opportunities-and-challenges-evolving-h2-dri-eaf-pathway-beyond-2024> (accessed 20 Janaury 2025)

[111] HyBrit (n.d.) Demonstration of hydrogen-based direct reduction. <https://www.hybritdevelopment.se/en/demonstration-of-hydrogen-based-direct-reduction/> (accessed March 2025)

[112] Stegra (n.d.) Our Boden Plant. <https://stegra.com/the-boden-plant> (accessed March 2025)

[113] MIDREX (2023) World Direct Reduction Statistics <https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2023.Final_.pdf> (accessed March 2025)

[114] Recreated from Ling J et al (2024) Direct reduction of iron to facilitate net zero emissions in the steel industry: A review of research progress at different scales.

[115] Based on natural gas reduction for gas-based DRI

and TGR, as well as lower the cost of hydrogen production and delivery ($LCOH_2$ forecast: \$3.95/kg, cf. \$7.32).[116] (refer to *Low Carbon Fuels* technical appendix).

Higher costs also present the opportunity for efficiency improvements, both energy and material efficiency, to reduce operating costs.

Demonstrating Australian ores in DR reactors is critical to enabling the domestic production of natural gas and hydrogen-based direct reduction routes.

Although DR processes have been demonstrated at pilot scale, there is a distinct need to demonstrate Australian lump and agglomerated ores in direct reduction processes (both natural gas and hydrogen) to assess performance and compatibility.[117] Shaft furnace and fluidised bed technologies respond differently to ore properties, and much less is known about how Australian lump ores, magnetite concentrates, and hematite-goethite fines behave in these settings. In particular, their post-reduction handling, metallurgical performance, and suitability for top gas recycling remain under-explored. Transitioning from natural gas to pure hydrogen reduction is also expected to come with technical challenges.[118]

Demonstrating ore performance is particularly important as Australian feedstocks differ mineralogically from those used in international pilots. Additional RD&D is required to test these ores under hydrogen conditions, assess material degradation and handling, and evaluate their impact on furnace control, productivity, and emissions.

Shaft furnaces may benefit from RD&D to maintain efficiency and stability under 100% hydrogen reduction.

Shaft furnaces are the most mature DR reactor technology, and are already used at scale with natural gas. Transitioning these systems to use 100% hydrogen introduces specific technical and operational challenges, though these systems have been piloted. The endothermic nature of hydrogen reduction necessitates higher inlet temperatures; without sufficient preheating, furnace materials cool rapidly, lowering reduction efficiency and productivity while increasing costs. There are opportunities to optimise hydrogen preheating strategies to maintain reduction efficiency and productivity at reduced cost.

Moreover, hydrogen's lower density increases total gas volumes in the shaft furnace, leading to higher gas velocity, pressure loss, and more complex gas-solid contact behaviour.[119] These effects could be overcome with RD&D into shaft furnace design, including optimised gas distribution and gas-solid contact, top gas recycling, and reheating systems.[120] Physics-based modelling and engineering optimisation will be crucial to support design improvements, and development of operating references specific to Australian ironworks can accelerate safe and stable implementation.[121]

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[116] Note: $LCOH_2$ forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. For further detail, please see the $LCOH_2$ model in the *Low Carbon Fuels* technical appendix.

[117] Unpublished pre-feasibility study for a Low-Emissions Ironmaking R&D facility in WA. CSIRO (2023) Pre-feasibility study on common user pilot facility for low emissions ironmaking. <https://research.csiro.au/tnz/pre-feasibility-study-on-common-user-pilot-facility-for-low-emissions-ironmaking/> (accessed 20 January 2025).

[118] Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

[119] Rechberger K, Spanlang A, Sasiain Conde A, Wolfmeir H, Harris C (2020) Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. Steel Research International 91,. doi:10.1002/srin.20200011; Fei Y, Guan X, Kuang S, Yu A, Yang N (2024) A Review on the Modeling and Simulation of Shaft Furnace Hydrogen Metallurgy: A Chemical Engineering Perspective.

[120] Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS; Wang RR, Zhao YQ, Babich A, Senk D, Fan XY (2021) Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. J Clean Prod 329,. doi:10.1016/j.jclepro.2021.129797

[121] https://steel.gov.in/sites/default/files/GSI Report.pdfMinistry of Steel, Government of India. (2024) Greening the steel sector in India: Roadmap and action plan. <<https://steel.gov.in/sites/default/files/GSI%20Report.pdf>; Fei Y, Guan X, Kuang S, Yu A, Yang N (2024) A Review on the Modeling and Simulation of Shaft Furnace Hydrogen Metallurgy: A Chemical Engineering Perspective. ACS Engineering Au 4, 145. doi:10.1021/acsengineeringau.3c00033

Fluidised bed systems offer fines flexibility but require sticking mitigation for viability.

Fluidised bed systems allow for the direct use of iron ore fines,[122] offering costs and emissions advantages by eliminating the high-temperature firing step of pelletising (1200-1350°C) which is typically reliant on coke combustion and gas burners.[123] Fluidised bed reactors face particular challenges,[124] and the risk of particle sticking limits the maximum operating temperature (i.e., <850-950°C), resulting in poor metallisation and undermining efficiency by affecting the fluidisation behaviour and particle transport of the ores.[125]

Optimisation research can allow for operating parameters to be adjusted to prevent particle sticking behaviour. This could be addressed by determining appropriate baseline temperatures, gas compositions, flow rates, reduction times, and ore characteristics that prevent the likelihood of sticking. Australian fines, including magnetite concentrates and Pilbara hematite-goethite fines, also need to be demonstrated in fluidised bed systems to adequately determine the feasibility of this technology in domestic operations.[126] These ore types may exhibit different fluidisation behaviour under operating conditions, compared to internationally demonstrated ore types.[127] While preprocessing (e.g., classification, sizing, or coating) could improve performance, this may increase capital and operating costs.

Flash reduction technologies offer new pathways but require further demonstration.

Emerging flash reduction-based systems, such as Calix's ZESTY process, offer the potential to use fines without pelletising, while improving energy efficiency and reducing emissions. Zesty has achieved a 30,000t per annum demonstration capacity.[128] RD&D can enable the evaluation Australian ores in these systems and to assess scalability under local energy, ore, and infrastructure conditions.

Auxiliary technologies

The scaleup and improved performance (i.e., energy reductions) of agglomeration processes will be a key enabler for the use of Australian pellet- and lump-based DR steelmaking.

As steelmaking techniques are adopted that favour pellets and lump ore over sinter, RD&D that centres on scaling up and enhancing methods of pelletising ores will be increasingly important. In particular, cold agglomeration techniques and the use of novel binders or additives that improve strength can allow for reduced energy consumption and improved reaction efficiency.[129] Cold agglomeration plants are being

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[122] This eliminates the firing/induration and cooling steps during pelletising

[123] Parvathaneni S, Kodukula B, Andrade MW (2024a) Iron-Ore Reduction in Fluidized Beds: Review of Commercial Technologies, Status, and Challenges. Ind Eng Chem Res. doi:10.1021/acs.iecr.4c02282

[124] Various processes have been commercialised since the 1960s with limited success; some failing to achieve desired metallisation rates (i.e., Nu-Iron at 70%) and others citing closures due to unfavourable market conditions (i.e., H-IRON and Iron-Carbide). Currently, the FINEX process is the only commercialised system available, achieving annual production rates up to 2Mt of DRI per year. Emerging hydrogen-based technologies like HyREX, Circored, and HYFOR aim to produce DRI with a lower metallisation degree (around 75-80% instead of >90%), suitable for lower-grade ores when integrated with electric smelters.

[125] Elmquist, S. A.; Kipfstuhl, L. A.; Dowling, E. C. Cliffs and Associates' Circored Iron Plant. Min. Eng. 2003, 55 (11), 40−44.

[126] Unpublished pre-feasibility study for a Low-Emissions Ironmaking R&D facility in WA. CSIRO (2023) Pre-feasibility study on common user pilot facility for low emissions ironmaking. <https://research.csiro.au/tnz/pre-feasibility-study-on-common-user-pilot-facility-for-low-emissions-ironmaking/> (accessed 20 January 2025).

[127] For example, HYFOR is capable of processing fines <150 microns, and Circored can process fines up to 2mm and ultra-fines if they are micro granulated. Parvathaneni S, Karmakar S, Buwa V (2024b) Effect of Bubbling/ Spouting Behavior on Dynamics of Segregation of Particles with Different Size and Density Ratios. Ind. Eng. Chem. Res. 63 (8), 3695−3710; Parvathaneni S, Karmakar S, Buwa, V. (2023) Effect of Local Hydrodynamics on the Performance of a Fluidized-Bed Gasifier. Ind. Eng. Chem. Res. 62 (30), 11814−11830.; Parvathaneni S, Buwa V, (2021) Eulerian Simulations of Mixing and Segregation of Binary Gas-Solid Flow of Particles with Different Densities. Chem. Eng. Sci, 245, 116901.

[128] CSIRO (2024) HyResource: Calix Zero Emissions Steel Technology-pre-FEED and FEED Study. <https://research.csiro.au/hyresource/calix-zero-emissions-steel-technology-pre-feed-and-feed-study/> (accessed March 2025)

[129] Unpublished pre-feasibility study for a Low-Emissions Ironmaking R&D facility in WA. CSIRO (2023) Pre-feasibility study on common user pilot facility for low emissions ironmaking. <https://research.csiro.au/tnz/pre-feasibility-study-on-common-user-pilot-facility-for-low-emissions-ironmaking/> (accessed 20 January 2025).

constructed abroad[130] and novel low temperature agglomeration techniques are being developed in Australia,[131] while Mineral Resources (MinRes) is licencing Binding Solutions Limited (BSL) technology to manufacture cold-bonded pellets on Australian ores.[132]

Alternatively, hybrid heating solutions for induration are also under investigation, including electric and hydrogen-based solutions. Hydrogen burners are an emerging area of research which could provide high temperature heat for pelletising and material preparation.[133]

Renewable hydrogen infrastructure will require dedicated RD&D to support sector and flexible DR operation, presenting further opportunities for development.

Stoichiometrically, hydrogen-based DRI requires 54kg of hydrogen per tonne of pure iron for complete metallisation; but higher amounts (70-140kg of H_2 per tonne of DRI) are typically required to shift the equilibrium in the reactor in favour of the final reduction step.[134] Some industry proponents have announced plans to establish electrolyser capacity capable of meeting their steelmaking needs (i.e., Stegra, 700MW electrolyser capacity);[135] others are planning to outsource hydrogen supply (i.e., ThyssenKrupp).[136]

For details regarding hydrogen production, storage and distribution technologies and associated RD&D opportunities, please refer to the *Low Carbon Fuels* technical appendix.

Enhancing DRI/ HBI transport and storage safety will underpin its use in downstream operations or for export.

Refer to the *Section 4.6.1 BF / oxyBF Auxiliary technologies.*

Standardised assessment tools can accelerate the evaluation of emerging DR pathways.

Advanced modelling and process assessment methodologies, including techno-economic performance and component modelling, can support the comparison and evaluation of emerging process configurations in the Australian context.

4.6.4 Electric smelting furnace (ESF)

The ESF is a well-established technology widely employed in non-ferrous and ferro-alloy industries. The DRI-ESF-BOF route is emerging as an alternative direct reduction route, particularly for lower-grade Pilbara ores that cannot be efficiently or economically upgraded. This approach pairs the ESF with DR systems capable of

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130 For example, US DOE (n.d.) Industrial Demonstrations Program Selections for Award Negotiations: Iron and Steel. <https://www.energy.gov/oced/industrial-demonstrations-program-selections-award-negotiations-iron-and-steel> (accessed March 2025).

131 CSIRO is developing the Lime Magnetite Pellet (LMP) process, a novel, low-temperature iron ore agglomeration method designed to maintain desired physical and metallurgical agglomerate properties <https://arena.gov.au/projects/csiro-low-temperature-agglomeration-process-for-australian-iron-ores/>

132 Mineral Resources (2023) MinRes Invests in Low-Carbon Iron Ore Pellet Technology. <https://www.mineralresources.com.au/news/minres-invests-in-low-carbon-iron-ore-pellet-technology/> (accessed March 2025).

133 Sourced from: IEA (2024) Plasma torches for iron ore pelletisation. ETP Clean Technology Guide [Database] <https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?layout=trl&selectedTechID=3a587dba> (accessed 21 January 2025)

134 Shahabuddin M, Rahbari A, Sabah S, Brooks G, Pye J, Rhamdhani MA (2024) Process modelling for the production of hydrogen-based direct reduced iron in shaft furnaces using different ore grades. *Ironmaking & Steelmaking*. doi:10.1177/03019233241254666

135 Martin P (2023) World's first commercial-scale green steel plant on track for FID after ordering 700MW of hydrogen electrolysers. Hydrogen Insight. <https://www.hydrogeninsight.com/industrial/worlds-first-commercial-scale-green-steel-plant-on-track-for-fid-after-ordering-700mw-of-hydrogen-electrolysers/2-1-1454069> (accessed 21 January 2025)

136 ThyssenKrupp has announced a call for tenders to outsource hydrogen supply for its Duisburg plant (Germany). Thyssenkrupp (2024) thyssenkrupp Steel is intensively pushing ahead with developing the hydrogen economy: Call for tenders for supplying hydrogen to the first direct reduction plant at the Duisburg location. <https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/thyssenkrupp-steel-is-intensively-pushing-ahead-with-developing-the-hydrogen-economy:-call-for-tenders-for-supplying-hydrogen-to-the-first-direct-reduction-plant-at-the-duisburg-location-251160> (accessed 21 January 2025)

processing lower-grade ore inputs. The ESF system removes impurities and gangue as slag, producing hot metal that can be converted to steel in a BOF or exported as pig iron.

Three commercial plants in operation globally: BlueScope Zealand Steel (NZ), Steel Dynamics Inc. (USA), and Highveld Robusteel (South Africa). Additionally, major steelmakers, such as ThyssenKrupp,[137] POSCO,[138] Baowu (in partnership with Rio Tinto),[139] have selected ESF technology for further development. In Australia, the NeoSmelt consortium (BHP, Rio Tinto and BlueScope), are working with Hatch to design an ESF pilot plant, designed to evaluate the use of Australian hematite-goethite ores and optimise ironmaking activities.[140]

Primary technologies

Targeted RD&D is needed to establish ESF cost profiles and to validate economics in the context of Australian ores.

Given the nascency of this technology for processing DRI, there is a high degree of uncertainty around the technology cost. Detailed analysis in the Australian context remains limited, reflected in the inability to conduct levelised cost analysis for this pathway in this report using existing data. Building capacity for technoeconomic assessment of ESF pathways can overcome this existing gap and inform cost reduction targets. Specifically, these assessments can help account for ore processing, plant design, and scalability in Australia.

While the ESF can utilise lower-grade ores and maintain the use of existing plant equipment (i.e., BOFs), there may be hidden costs associated with reactor metallurgy, slag formation, and equipment wear , especially for Pilbara-type ores.[141] Characterising these requirements is required to accurately inform current costs and the potential for cost decreases in alignment with technology advancements and optimisation with Australian ores.

Reactor design and process optimisation must be tailored to Australian ore types and DR characteristics for domestic use.

The performance of ESF is highly dependent of the quality and form of the DR feedstock. RD&D can assist in assessing the viability of the DRI-ESF ironmaking route for Australian ores, with a focus on developing fundamental understanding on how the ESF performance is impacted by DRI characteristics.[142] More specifically, it can help to determine optimal metallisation levels and to evaluate how ore characteristics impact reduction load, slag chemistry, corrosion behaviour, and iron yield.[143] Specific areas of investigation may include: [144]

- Slag formation practices optimised for furnace melting, reduction, carburisation, and/or iron yield;

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137 Thyssenkrupp (2024) Cooperation for low-carbon steel production: Thyssenkrupp Steel is working with international partners on carbon-neutral steel production with a focus on smelter technologies. (Trade press) <https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/cooperation-for-low-carbon-steel-production-thyssenkrupp-steel-is-working-with-international-partners-on-carbon-neutral-steel-production-with-a-focus-on-smelter-technologies.html> (accessed 21 January 2025)

138 POSCO (n.d) HyREX? Hydrogen Reduction Ironmaking. <https://www.posco.co.kr/homepage/docs/eng7/jsp/hyrex/> (accessed 21 Janaury 2025)

139 Farry S (2024) How will we decarbonise our steelmaking processes?

140 Gadd A, Tame N, Liu X, Dukino R (2023) Prospect: Pathways to decarbonization episode seven. The Electric Smelting Furnace. BHP.

141 Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

142 Unpublished pre-feasibility study for a Low-Emissions Ironmaking R&D facility in WA. CSIRO (2023) Pre-feasibility study on common user pilot facility for low emissions ironmaking. <https://research.csiro.au/tnz/pre-feasibility-study-on-common-user-pilot-facility-for-low-emissions-ironmaking/> (accessed 20 January 2025).

143 Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

144 Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

- Electrical resistivity of slag composition ranges *likely to result from Australian ores; and*
- Melting behaviours under higher melting temperatures associated with low carbon or carbo free iron inputs.

Though the TRL for BlueScope's NZ Steel Plant is high (TRL 9), its maturity for the use with Pilbara ores is likely much lower.[145] Therefore, demonstration projects are needed to de-risk ESF use in Australian contexts.

Scale-up of ESF capacity would be required to match current integrated steel production capacities.

Currently, most ESF demonstrations operate at modest scales (c.f., 30,000-40,000t per annum).[146] Scaling ESFs to capacities exceeding 2 million tonnes per year can assist in these aligning production capacities with the capacities of upstream DRI and downstream BOF pathway equipment.[147] This may require new design approaches and management to ensure furnace stability, material throughput and energy efficiency at commercial scale.

Both submerged arc and open slag bath furnace variants require targeted RD&D to address reactor-specific considerations.

Submerged arc furnaces operate via resistance heating where electrodes approach or are submerged in the slag melt, providing energy required for melting.[148] Research opportunities for improved performance include optimising the refractory design and durability; investigating strategies to reduce electrode consumption, whether through new materials or operational practices to minimise erosion; and enhancing thermal efficiency to reduce operational costs.[149]

Open slag bath furnaces (OSBF) differ from the submerged arc furnace in the electrode positioning. These reactors use brush arcs positioned above the raw materials, providing energy for melting.[150] These systems are well suited to lower grade ores and may offer improved feedstock flexibility, but are generally less energy efficient. RD&D can improve their viability by optimising heat recovery systems and identifying slag management strategies that enhance their process stability.

Auxiliary technologies

Electric melters will be heavily influenced by the availability of low-cost electricity (including, generation, transmission and storage)

Electricity costs make up a significant portion of electrified steelmaking pathways, and as such, innovations that reduce electricity costs will also contribute to lower steel costs. For detailed targets and RD&D opportunities related to the electricity system, refer to the *Electricity* technical appendix.

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[145] Unpublished pre-feasibility study for a Low-Emissions Ironmaking R&D facility in WA. CSIRO (2023) Pre-feasibility study on common user pilot facility for low emissions ironmaking. <https://research.csiro.au/tnz/pre-feasibility-study-on-common-user-pilot-facility-for-low-emissions-ironmaking/> (accessed 20 January 2025).

[146] Based on the target capacity of the NeoSmelt collaboration in WA, announced December 2024. Rio Tinto (2024) Bluescope, BHP and Rio Tinto select WA for Australia's largest ironmaking electric smelting furnace pilot plant study. [News release] <https://www.riotinto.com/en/news/releases/2024/bluescope-bhp-rio-tinto-wa-electric-smelting-furnace-study>

[147] CSIRO (2025) India-CSIRO Partnerships as part of the India Economic Strategy (IES) <https://www.csiro.au/en/work-with-us/international/asia/south-asia/india> (accessed 21 January 2025)

[148] Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

[149] RHI Magnesita GmHB (2023) The Journal of Refractory Innovations bulletin – 2023. <https://www.rhimagnesita.com/wp-content/uploads/2024/01/bulletin-2023-1-231220-2-mon-compressed.pdf> (accessed 21 January 2025)

[150] Nicholas S, Basirat S (2022) Solving Iron Ore Quality Issues for Low-Carbon Steel: Technology Solutions are Under Development. Institute for Energy Economics and Financial Analysis <https://ieefa.org/sites/default/files/2022-08/Solving%20Iron%20Ore%20Quality%20Issues%20for%20Low-Carbon%20Steel_0.pdf>

In order to effectively integration variable renewable energy (VRE) electricity generation, additional RD&D may be required. See *Section 4.6.7 Crosscutting – Energy efficiency technologies* for further detail.

Enhancing DRI/ HBI transport and storage safety will underpin its use in ESF operations, domestically or abroad.

Refer to *Section 4.6.1 BF / oxyBF Auxiliary technologies.*

Slag utilisation presents a multi-pronged opportunity for emissions reduction, resource efficiency and material recovery.

Slag offers potential value for steelmakers if leveraged efficiently, allowing for improved energy conservation and waste recycling.[151] It is discussed broadly in *Section 4.6.7 Crosscutting – Energy efficiency technologies*.

4.6.5 Electric arc furnace (EAF)

The EAF is a widely used metallurgical reactor which melts and heats metallic materials. Research opportunities for the EAF largely relate to optimising operations, particularly adaptations to enable DRI as the material input, alongside scrap metal.

BlueScope Steel is constructing an EAF at New Zealand Steel that is expected to reduce the site's Scope 1 and 2 emissions by ~55%, subject to securing additional renewable energy power purchase agreements and recycling more domestic scrap steel.[152]

Primary technologies

Improving reactor energetics can reduce operational costs and enhance EAF performance, including efficiency, thermal integration and energy recovery.

EAF are energy intensive, requiring ~430kWh/tLS.[153] Therefore, efforts to improve electricity efficiency can assist in immediate emissions reductions where electricity is supplied by the grid and reduce long-term demands on renewable generation systems.

US-based research programs have established goals to improve energy efficiency by 33.3% and reduce energy consumption by 20-60kWh/tLS, largely via process optimisation.[154] Optimisation of the EAF is challenging for a number of reasons. For example, the destructive environment of the reactor makes it challenging to deploy sensing equipment, resulting in high-cost and/or single use measurements where available; variability in feedstock chemistry and quality (especially for scrap); and limited capabilities to turn process data into actionable operator guidance.[155] Overcoming these challenges will require the development of novel instrumentation, process models that collect and interpret process data, and fundamental research into slag properties at various points in the reactor and under different heat and operational conditions in the heat and various conditions.

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151 Farry S (2024) How will we decarbonise our steelmaking processes?

152 Bluescope Steel Limited (2024) Climate Action Report 2024. <https://www.bluescope.com/content/dam/bluescope/corporate/bluescope-com/sustainability/documents/FY2024-Climate_Action_Reportv2.pdf>

153 As per the cost model established in *Levelised cost analysis*

154 Forrest D (2023) Iron and Steel Programmatic Summary. Office of Energy Efficiency & Renewable Energy. US Department of Energy <https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Forrest_IEDO_EEII%20Iron%20and%20Steel%20Programmatic%20Summary.pdf> (accessed 21 January 2025)

155 Voss Z, Jones J, O'Malley R, Seetharaman S, Evenson E (n.d) IDEAS: Intelligent Dynamic EAF Advisory System <https://www.eases.rwth-aachen.de/dl/EASES-2021/Voss_IDEAS%20Intelligent%20Dynamic%20EAF%20Advisory%20System%20for%20Improving%20Operating%20Efficiency.pdf> (accessed 21 Janaury 2025)

There is also potential to fully electrify EAF energy processes by removing the carbon-based chemical energy component used to assist with melting and slag foaming. Operational practices that minimise or eliminate the need for combustion-based inputs, particularly when paired with renewable electricity, can reduce emissions and enhance process efficiency.[156]

Thermal integration strategies, particularly for DRI-based operations, also allow for performance gains through improved heat/energy utilisation. Hot charging to the EAF, where DRI is charged from the DRI furnace at temperatures above 600°C, allows the system to capture and use sensible heat, increasing productivity and lowering power demands. Where hot charging is not feasible, optimising DRI storage and preheating practices can allow for plants with alternative set-ups to reap these benefits.[157]

Understanding metallisation behaviour is central to effective furnace control and slag formation.

The metallisation level of the DRI feedstock significantly influences EAF performance. A higher degree of metallisation in the DRI reduces in-furnace reduction requirements, lowering carbon consumption and slag formation.[158] However, limited understanding exists regarding the melting behaviour of DRI, both hydrogen- and natural gas-based, and its impacts on slag formation and EAF operation.[159] Key areas of research to overcome this may include characterising melting profiles of different DRI feedstocks, establishing an optimal baseline for slag basicity and viscosity, and investigating impacts of DRI variability on process stability and energy consumption.[160]

Improving carbon utilisation and exploring sustainable carbon inputs can further reduce emissions impacts.

Carbon remains a critical input for alloying in the EAF, with carbon utilisation an important factor in carbon efficiency and supporting reduction and slag formation. When using hydrogen-DRI, additional carbon must be added for carburisation. RD&D can assist in establishing a rate of carbon pick-up by the metal and reaction rates with slag and metal under varied metallisation conditions and optimum carbon input strategies.

Additionally, evaluating biochar and other non-fossil carbon sources will be critical for enabling the EAF as a low to no carbon steelmaking pathway. Though biochar is seen as a potential solution, this will be dependent on feedstock availability and sustainability factors (see Box 5). Note that iron containing carbon, such as natural gas-based DRI or blast furnace hot metal, is more efficiently utilised in an EAF (>95%), rather than charging or injecting carbon (24-76%).[161]

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156 Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

157 Technical trials conducted by Air Products, indicate that the adaptation of existing conveyer feed systems can be aligned with preheating furnaces, and have found no to minimal oxidation occurring due to direct flame impingement; however, scale-up and piloting has not been conducted. Sane A, Buragino G, Makwana A, He X (2020) Enhancing Direct Reduced Iron (DRI) for Use in Electric Steelmaking. Air Products and Chemicals, Inc., Allentown, PA, USA.

158 Hornby S, Brooks G (2021) Impact of Hydrogren DRI on EAF Steelmaking <https://www.midrex.com/tech-article/impact-of-hydrogen-dri-on-eaf-steelmaking/> (accessed 21 January 2025)

159 Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

160 Zulli P et al (2023) PHASE 3 REPORT PORT KEMBLA STEELWORKS RENEWABLES AND EMISSIONS REDUCTION STUDY ASSESSMENT OF PRIORITISED OPTIONS AND POTENTIAL DECARBONISATION PATHWAYS FOR THE PORT KEMBLA STEELWORKS.

161 Hornby S, Brooks G (2021) Impact of Hydrogren DRI on EAF Steelmaking

Box 5: Bio-based carbon supply in EAF

Biochar could offer an incremental reduction of steelmaking carbon intensity in EAF operations.[162] The DRI-EAF production route requires 1.5-3% carbon in the EAF to metallise the iron, provide extra energy for smelting, and enable slag formation.[163] To minimise emissions, such carbon will need to be sourced sustainably.

Carbon is more efficiently used when in-situ (i.e., carbon-containing DRI) compared to the charging or injection of carbon-based material. This can be achieved by using natural gas-DRI or by using carbonaceo**us** material in the cooling zone during H_2-DRI production. Emissions associated with the carbon containing materials would be released in the EAF phase, producing approximately 50kgCO2/t_{LS}.[164]

The addition of carbon from renewable sources in the EAF furnace can also be used to achieve incremental reduction of carbon intensity,[165] assuming the biomass feedstock is considered carbon neutral.

There are non-technical challenges related to biomass availability, the establishment of supply chains and processing infrastructure for biochar production. It should be noted that while biomass feedstocks could allow for incremental emissions reductions for some enterprises, it is unlikely to be a scalable strategy for Australian ironmaking due to supply limitations. Especially of biomass that is sustainably certified and would qualify as a zero or low emissions CO_2 source.

Refer to the *Low Carbon Fuels* technical appendix for further detail.

Auxiliary technologies

Identifying and advancing effective, cost-efficient strategies for the beneficiation of domestic iron ore to DRI-EAF quality, will be a key enabler of establishing the EAF as a viable steelmaking process in the Australian context. Though these processing steps increase Scope 1 emissions, larger scale Scope 3 emissions can be reduced, whether by domestic or international steelmakers.

The beneficiation and dephosphorisation of hematite(-goethite) is essential for unlocking DR-grade feedstocks from Pilbara deposits.

As low-phosphorus hematite-dominant reserves become depleted, Pilbara producers are increasingly reliant on alternative ore types, such as high-phosphorus Brockman ores, Marra Mamba and Channel Iron Deposits. These with differing textural components. These ores tend to contain higher proportions of goethite, which has diverse textural forms that significantly influence processing performance. However, most analysis to date has focused on the chemical rather than textural composition, with limited understanding of how texture influences beneficiation outcomes.

There are RD&D opportunities to improve the characterisation of textural features within goethite-dominant ores and optimising processing performance.[166] Achieving DR-grade quality will necessitate more effective gangue removal, particularly for alumina, silica, and phosphorus.

Phosphorus[167] is especially problematic because it is often present in a structurally bound form within the goethite matrix, making conventional physical separation techniques largely ineffective, oftentimes, with high iron losses.[168] As such, RD&D is needed to advance combined ore processing and dephosphorisation pathways,

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[162] CSIRO (2025) India-CSIRO Partnerships as part of the India Economic Strategy (IES)

[163] Wang RR, Zhao YQ, Babich A, Senk D, Fan XY (2021) Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. J Clean Prod 329,. doi:10.1016/j.jclepro.2021.129797

[164] Duarte P (2019) Hydrogen-based steelmaking. Millennium Steel: Botany, Australia

[165] CSIRO (2025) India-CSIRO Partnerships as part of the India Economic Strategy (IES)

[166] CSIRO (2017) Understanding the effects of goethitic iron ore. <https://research.csiro.au/resourcesandsustainability/goethitic-ore-classification/> (accessed March 2025)

[167] High phosphorus level (>0.1 wt%) invokes a price penalty arising from adverse quality effects on the steel product (i.e., embrittlement)

[168] HILT CRC (n.d) Green pyromet/hydromet beneficiation pathways. <https://hiltcrc.com.au/projects/green-pyromet-hydromet-beneficiation-pathways/> (accessed 21 January 2025)

such as those that combine thermal treatment to dehydroxylate the goethite (i.e. convert it to hematite), followed by chemical separation.[169] The HILT CRC have established a number of projects related to novel beneficiation techniques across these areas of interest.[170] Developing a deeper understanding of impurity bonding mechanisms can also support the identification and optimisation techniques for their removal.[171] Complementary technoeconomic analysis of these beneficiation pathways will be essential for understanding their wide-scale deployment on lower-grade Pilbara ores.[172]

Water intensity is another key concern for future ore processing. To this end, new dry beneficiation technologies are being investigated, such as CSIRO's semi-inverted hydrocyclone technology.[173]

Improving magnetite beneficiation performance can improve the economic viability associated with magnetite deposits, which are well positioned for nearer-term DRI production in Australia.

Magnetite ores offer high iron content once processed and are well suited to DR-grade applications, but require more intensive beneficiation processes than hematite ores. This raises both capital and operational costs, creating a strong case for RD&D that can reduce these costs, improve efficiency and improve yields. Opportunities include optimising various processing steps (i.e., comminution and separation) to increase yield and quality, developing new reagents or flow sheets to reduce energy demand, and improving water and tailing managements to minimise environmental impacts.

Further cost-benefit analysis of various magnetite processing pathways can indicate areas through which routes can be further developed, optimised and trailed.[174]

Electric melters will be heavily influenced by the availability of low-cost electricity (including, generation, transmission and storage)

Electricity costs make up a significant portion of electrified steelmaking pathways, and as such, innovations that reduce electricity costs will also contribute to lower steel costs. For detailed targets and RD&D opportunities related to the electricity system, refer to the *Electricity* technical appendix.

In order to effectively integration variable renewable energy (VRE) electricity generation, additional RD&D may be required. See *Section 4.6.7 Crosscutting – Energy efficiency technologies* for further detail.

Enhancing DRI/ HBI transport and storage safety will underpin its use in EAF operations, domestically or abroad.

Refer to *Section 4.6.1 BF / oxyBF Auxiliary technologies.*

Slag utilisation presents a multi-pronged opportunity for emissions reduction, resource efficiency and material recovery.

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169 Suggestion also from Pownceby et al.

170 The HILT CRC also has a number of research programs, including a scoping study investigating high flux thermal pre-treatment of low-grade iron ores (https://hiltcrc.com.au/projects/program01-rp1006/) & pyrometallurgical-hydrometallurgical processes (https://hiltcrc.com.au/projects/green-pyromet-hydromet-beneficiation-pathways/)

171 Pownceby MI, Hapugoda S, Manuel J, Webster NAS, MacRae CM (2019) Characterisation of phosphorus and other impurities in goethite-rich iron ores – Possible P incorporation mechanisms. Minerals Engineering 143,. doi:10.1016/j.mineng.2019.106022; Ofoegbu SU (2019) Technological challenges of phosphorus removal in high-phosphorus ores: Sustainability implications and possibilities for greener ore processing. Sustainability (Switzerland) 11,. doi:10.3390/su11236787

172HILT CRC (n.d.) Scoping study of the viability of high flux thermal pre-treatment of low-grade iron ores for improved liberation, beneficiation and quality. <https://hiltcrc.com.au/projects/program01-rp1006/> (accessed 21 January 2025)

173 CSIRO (2023) The race for copper. <https://www.csiro.au/en/news/all/articles/2023/november/copper-capability> (accessed March 2025)

174 Metso (nd) Eco-efficient and cost-effective process design for magnetite iron ore <https://www.metso.com/insights/blog/mining-and-metals/eco-efficient-and-cost-effective-process-design-for-magnetite-iron-ore/> (accessed 21 January 2025)

Slag offers potential value for steelmakers if leveraged efficiently, allowing for improved energy conservation and waste recycling.[175] It is discussed broadly in *Section 4.6.7 Crosscutting - Energy efficiency technologies.*

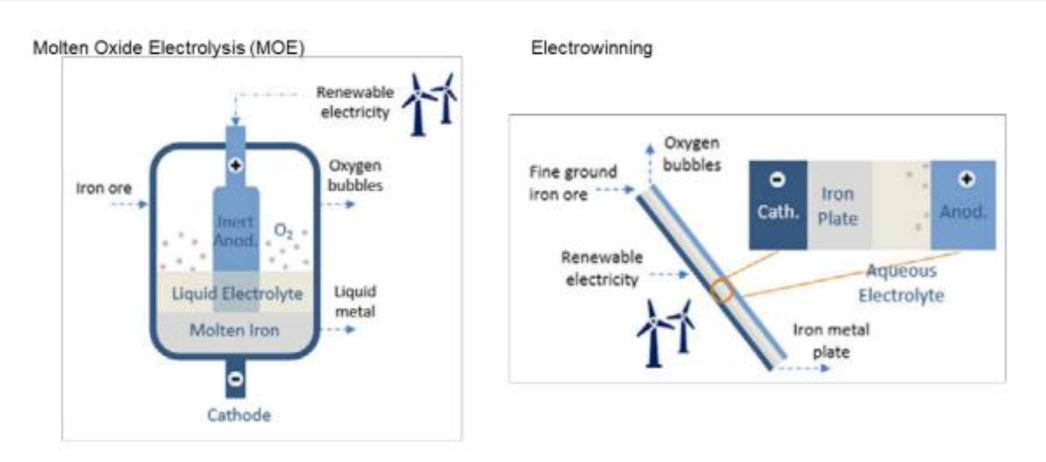
Case study: Electrolytic steelmaking

Box 6: Electrolysis case study

Electrolytic steel production was not identified as a primary technology as there is a lack of publicly available cost data to perform robust levelised cost analysis. However, there has been significant industry interest in this field, with several start-ups targeting pilot-scale plants in the coming decade. This is a breakthrough technology that could enable efficient, near-zero emissions iron production, with low operating costs.

The scalable and modular nature of these production routes presents a potential opportunity to increase scale and reduce costs, which may be more challenging for more bespoke production routes. The two main pathways under investigation for electrolytic steel production, as described in Table 3, are outlined in Figure 12 below.

Figure 12: Electrolytic steelmaking process diagram



For the high-temperature MOE process, Boston Metal group is a leading industry mover. The current phase of research for MOE involves further technological development, process optimisation, scaleup and addressing the handling the of slag and metals.[176]

Boston Metal

- Boston Metal, a US-based start-up, has piloted an inert anode that successfully splits the iron oxide bond in the iron ore. The inert anode is reported to have a long lifetime that can withstand the corrosive conditions of the electrolysis cells at high temperatures.[177] The company claims that uninterrupted cell lines mean that no downtime associated with replacing anodes is removed.
- Boston Metal is currently addressing challenges related to the scale-up from laboratory to industrial scale, with a full-scale industrial cell prototype anticipated as early as 2026. This is supported by the construction of a development and manufacturing facility for raw materials though to the final technology system, focusing on achieving high production efficiencies to maintain commodity prices and adoption.[178]
- BHP has an equity investment in Boston Metal and is a strategic partner through knowledge sharing and by supplying ores for testing. BHP commenced a larger scale, longer testing campaign in May 2024 to better understand the performance of Australian iron ores in the commercial-scale cell.[179]

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[175] Farry S (2024) How will we decarbonise our steelmaking processes?

[176] Shahabuddin M, Brooks G, Rhamdhani MA (2023) Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis. Journal of Cleaner Production. 395:136391.

[177] Boston Metal (2023) Cutting-Edge Materials Science is Key to Decarbonizing Steelmaking <https://www.bostonmetal.com/news/cutting-edge-materials-science-is-key-to-descarbonizing-steelmaking/> (accessed 21 Janaury 2025)

[178] Forrest D (2023) Iron and Steel Programmatic Summary.

[179] BHP (2024) Climate Transition Action Plan 2024.

For low-temperature electrolysis (LTE), also referred to as electrowinning, key proponents include Electra and ArcelorMittal. The current phase of research for LTE involves further technology development, process optimisation, scale-up and safety.[180]

Electra

- Electra uses a low temperature hydrometallurgical and electrochemical process to produce a highly pure metal plate, whereby ore is dissolved in a water-based acidic solution near room temperature. Electricity is used to extract pure iron from the solution while regenerating all chemicals and water used in the process.[181]
- Electra produced its first 1m^2 plate of iron in December 2023 and is now planning scale up activities.
- BHP has an equity investment in Electra and is strategic partner through knowledge sharing and by supplying ores for testing.

ArcelorMittal (SIDERWIN project)

- The SIDERWIN project has completed a targeted trial in an industrial-size production, producing iron plates with an average metallic iron content of between 96% to 98.7% under stable working conditions.[182] Investment approval has been secured for an industrial plant.[183]

Fortescue Metals has also developed a low-energy direct electrochemical reduction process (LEDER) to convert Pilbara iron ores into green iron metal, however little has been published.[184]

4.6.6 Crosscutting – Carbon capture systems

This section discusses the integration of carbon capture systems into iron and steelmaking facilities, with a focus on retrofit potential and operational considerations. Further discussion pertaining to the development of the carbon capture systems is addressed separately in the *Carbon Management* technical appendix.

Piloting integrated carbon capture systems is required to establish technical and economic viability.

Pilot and demonstration projects remain essential to validate integration strategies, quantify capture efficiency, and assess operational impacts. As noted throughout the analysis, the world's only operational CCS-equipped steel plant captured 26.6% of plant emissions in 2023 (for a DR facility), falling far below anticipated capture rates.[185] This underperformance underscores the technical and systems-level challenges of integrating CCS into dynamic industrial operations. In BF-BOF pathways, CO_2 emissions are distributed across multiple sources, including BF top gas, BOF off-gas, and sinter plant emissions - each with distinct flow rates, temperatures, and contaminant profiles.[186] RD&D is required to determine the feasibility of integrating carbon capture into brownfield plants and close the gap between theoretical efficiencies and practical outcomes in the context of steelmaking, and to establish the economics of system integration.

Coupling carbon capture systems with heat recovery can improve performance and efficiency.

Carbon capture processes, particularly solvent-based systems such as amine scrubbing, are highly energy intensive due to solvent regeneration requirements. Integrating CCS with heat recovery systems to harness

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[180] Shahabuddin et al (2023) Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis.

[181] IEA (nd) Steel. <https://www.iea.org/energy-system/industry/steel> (accessed 21 January 2025)

[182] Technalia (2021) Siderwin: Development of new methodologies for Industrial CO2-free steel production by electrowinning. Results. <https://www.siderwin-spire.eu/content/results> (accessed 21 January 2025)

[183] BHP (2024) Climate Transition Action Plan 2024.

[184] Fortescue Metals (n.d) What is green iron metal? <https://metals.fortescue.com/en/green-metals> (accessed 21 January 2025)

[185] Nicholas S, Basirat S (2024) Steel CCUS update: Carbon capture technology looks ever less convincing. Institute for Energy Economics and Financial Analysis. <https://ieefa.org/resources/steel-ccus-update-carbon-capture-technology-looks-ever-less-convincing>

[186] Benavides K, Gurgel A, Morris J, Mignone B, Chapman B, Kheshgi H, Herzog H, Paltsev S (2024) Mitigating emissions in the global steel industry: Representing CCS and hydrogen technologies in integrates assessment modelling. International Journal of Greenhouse Gas Control. <https://www.sciencedirect.com/science/article/pii/S1750583623001330>; Perpiñán J, Peña B, Bailera M, Eveloy V, Kannan P, Raj Abhijeet, Lisbona P, Romeo L.M (2023) Integration of carbon capture technologies in blast furnace based steel making: A comprehensive and systematic review. Fuel <https://www.sciencedirect.com/science/article/pii/S0016236122038984>

waste heat from hot off-gases and process streams can offset these energy demands.[187] Research into integration strategies, including optimal heat exchanger placement, thermal storage solutions, and steam cycle optimisation, could support the development of systems tailored to steelmaking applications.

Retrofittable point-source systems can reduce the operational downtime associated with facility upgrades.

Integrating CCS into BF-BOF steelmaking presents significant technical and operational challenges due to the complexity and distribution of emissions sources across the plant and the high-temperature nature of gas streams.[188] RD&D could assist in the development of carbon capture systems that can be retrofitted to existing plants with minimal disruption to operations. This includes designing modular capture units that integrate with complex steel plant layouts and account for variable gas compositions and flow rates associated with steelmaking off-gases.

4.6.7 Crosscutting – Energy efficiency technologies

Further RD&D in solutions that reduce energy use in iron and steelmaking will also support emissions mitigation efforts. Iron and steelmaking processes are highly energy-intensive and crosscutting *Energy efficiency solution*s are critical for reducing energy consumption, enhancing material efficiency, and enabling the transition to low emissions production pathways. The solutions outlined in Table 13 are technology-agnostic with the ability to improve energy efficiencies for a range of technologies and pathway configurations.

Table 13: Energy efficiency RD&D opportunities – Iron and steelmaking

Energy efficiency technology	RD&D opportunities
Carbon capture and utilisation (CCU) *Involves the capture of CO_2 from iron and steel making flue gas stream and its chemical conversion into chemicals (TRL 7) or fuels (TRL 8) or other products.*	• Develop and refine pathways that allow for the reuse of CO_2, delaying its atmospheric release and allowing for the production of carbon-neutral products.[189] • Reduce the energy intensity of preparing gas streams containing CO/CO_2, including by optimising gas networks of steal plants.[190] • For more detail regarding CO_2 conversion into chemicals and fuels, please refer to the *Carbon Management* technical appendix. • CO_2 can also be combined with iron and steelmaking slag wastes to form mineral carbon aggregates which can be used to manufacture concrete or other building materials (discussed below).[191]
Slag and material utilisation *Involves the recovery, reuse, or recycling of slag streams, or its various constituents, in order to improve the circularity of the iron and steelmaking process.*	• Assess the chemical parameters present in each type of iron and steelmaking slag.[192] • Developing technologies to manage and optimise slag properties, particularly as input and impurity profiles evolve with the adoption of low-carbon feedstocks (i.e., increased basicity control).

[187] Perpiñán J, Peña B, Bailera M, Eveloy V, Kannan P, Raj Abhijeet, Lisbona P, Romeo L.M (2023) Integration of carbon capture technologies in blast furnace based steel making: A comprehensive and systematic review. Fuel <https://www.sciencedirect.com/science/article/pii/S0016236122038984>

[188] Perpiñán J, Peña B, Bailera M, Eveloy V, Kannan P, Raj Abhijeet, Lisbona P, Romeo L.M (2023) Integration of carbon capture technologies in blast furnace based steel making: A comprehensive and systematic review. Fuel <https://www.sciencedirect.com/science/article/pii/S0016236122038984>

[189] Ministry of Steel, Government of India. (2024) Greening the steel sector in India: Roadmap and action plan.; IEA Clean Technology Guide; Draxler M, Sorman A, Kempken T, Hauck T, Pierret J, Borlee J, Di Donato A, De Santis M, Wang C (2021) Green Steel For Europe: Technology Assessment and Roadmapping (deliverable 1.2). Green Steel for Europe Consortium. <https://www.estep.eu/assets/Projects/GreenSteel4Europe/GreenSteel_Publication/210308_D1-2_-Assessment_and_roadmapping_of_technologies_-Publishable-version.pdf>

[190] ESTEP AIBSL (2020) Proposal for CLEAN STEEL PARTNERSHIP under the Horizon Europe Programme.

[191] Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) CO2 Utilisation Roadmap. CSIRO; US DOE (2019) Advance Manufacturing Office. Steel Industry Roundtable. Office of Energy Efficiency and Renewable Energy. <https://www.energy.gov/sites/default/files/2020/02/f71/2019%20AMO%20Steel%20Industry%20Roundtable%20Summary_compliant%20FINAL.PDF

[192] Ryu GU, Kim HJ, Yu HJ, Pyo S (2024) Utilization of steelmaking slag in cement clinker production: A review. Journal of CO2 Utilization.;84:102842.

	• Develop treatments for primary slag streams to effectively optimise metal and mineral recovery or to enable and enhance its use in secondary products.[193] There are opportunities for RD&D to assist in tailoring pretreatments to (1) the various types of steelmaking slags, and (2) use case applications, such as for cement clinker production. For example, a US-based project is targeting to:[194] o Obtain 90% pure $CaCO_3$ o Remove undesired metal constituents in flue dust and sludge with a separation efficiency of ≥90% o Recover >85% iron oxide from sludge and dust.
Process optimisation and scaleup through advanced digital modelling *Involves the application of advanced computational tools and digital technologies to optimise steelmaking processes, reduce energy consumption, and scale up systems.*	• Develop advanced tools for digital modelling of steelmaking processes, including digital twins, for process optimisation.[195] These require the use of visualisation tools as well as computational fluid dynamic modelling and failure analysis models, combined with high performance computing. • For example, in the US, Purdue University's Northwest Steel Manufacturing Simulation and Visualisation Consortium are targeting a 4.5% reduction in BF energy consumption using virtual plants for real-time energy improvements.[196] • Use high-performance modelling, simulation and visualisation capabilities to analyse gas flows, combustion, and chemical reactions in order to scale up steelmaking operations.
Sensing, analytics and digitalised process controls *Involves the development of advanced sensors and data analytics for real-time monitoring and optimisation of material processes in iron and steelmaking.*	• Develop advanced sensors capable of operating under harsh steelmaking conditions to provide real-time data on critical parameters such as temperature, pressure, and chemical composition.[197] • Enhance data analytics tools for interpreting sensor data, enabling real-time decision-making and process optimisation, including by integrating sensing technologies with digital twins and advanced simulation models. • Develop sensing technologies to enable rapid and accurate ore identification and sorting and beneficiation.
Waste heat recovery *Involves the recovery of heat from high-temperature off-gases, slag and other steelmaking processes to improve overall process energy efficiency.*	• Develop advanced waste heat recovery systems capable of operating under harsh steelmaking conditions, including those suitable for heat recovery from slag, off gases, and melting and heating systems.[198] • Solutions suitable for high-temperature iron and steelmaking processes include solid-state waste recovery technologies, heat exchangers and thermal energy storage systems. For lower-grade waste heat, solutions such as Mechanical Vapour Recompression may be applied. Please refer to *Section 5 Medium-temperature steam* for more detail.
Variable renewable energy (VRE) integration *Involves the technologies, infrastructure, and process adaptations to enable the stable and efficient integration of variable renewable electricity into steelmaking operations. Including solutions for energy storage, grid interaction, and process flexibility to mitigate the impact of intermittent power supply.*	• Develop demand-responsive and batch-based operational strategies to align steelmaking activities with renewable energy availability. • Sensing, analytics and digitalised process controls can also serve to adapt steelmaking operations dynamically in response to VRE fluctuations. • Develop smart-grid integration, power management and energy storage solutions for stable electricity supply. For more detail, please refer to the *Electricity* technical appendix.

[193] ESTEP AIBSL (2020) Proposal for CLEAN STEEL PARTNERSHIP under the Horizon Europe Programme.

[194] Forrest D (2023) Iron and Steel Programmatic Summary.

[195] Digital twins are a multi-dimensional digital representation of a plant or system.

[196] Forrest D (2023) Iron and Steel Programmatic Summary.

[197] Horizon Europe Programme (2020) Proposal for a European Partnership under Horizon Europe Clean Steel - Low Carbon Steelmaking. Version 15 July 2020. <https://research-and-innovation.ec.europa.eu/system/files/2020-07/ec_rtd_he-partnerships-for-clean-steel-low-carbon-steelmaking.pdf>

[198] IEA (2020) Iron and Steel Technology Roadmap: Towards more sustainable steelmaking. Part of the Energy Technology Perspectives series.; US DOE (2019) Advanced Manufacturing Office. Steel Industry Roundtable. Office of Energy Efficiency and Renewable Energy. <https://www.energy.gov/sites/default/files/2020/02/f71/2019%20AMO%20Steel%20Industry%20Roundtable%20Summary_compliant%20FINAL.PDF>

5 Medium-temperature process steam

5.1 Executive summary

As energy is typically the largest component of operating costs for alumina refineries, low emissions boilers, thermal energy storage with electricity input and heat output (eTESh) systems and biomass combustion will benefit from RD&D to improve process energy efficiency.

Technology Landscape: Alumina digestion, 100 t/hr, using steam produced at 210°C (8 bar)

A variety of boiler technologies using low emissions fuels can play a role in supporting the transition.

Electric boiler	eTESh system
• Co-located generation infrastructure • Off-grid generation infrastructure • Integrated storage systems	

Hydrogen boiler	Biomass combustion
• Hydrogen production, storage and distribution systems • Co-located infrastructure	• Feedstock pre-treatments

Energy efficiency solutions

- Heat exchanges and flash vessels
- Tube digestion
- Double digestion
- Thermal energy storage
- Mechanical vapour recompression

RD&D Opportunities

Electric boiler	• Trials and integration testing are needed to support the upper temperature range of medium-temperature (and pressure) electric boilers. • Auxiliary technologies such as integrated energy storage, and the co-location or off-grid support of electricity generation infrastructure may help to reduce electricity input costs, as a key driver for potential system cost reductions.
eTESh system	• Although TES systems have been deployed for other applications, applying TES systems for large-scale industrial steam requires further RD&D and commercial trials. • Improving thermal insulation and thermal management will lower the amount of heat lost, and therefore fuel used, by the process.
Hydrogen boiler	• Hydrogen flames have poor radiative properties, and to improve efficiency there are RD&D opportunities in exploring non-greenhouse gas additives to enhance flame glow.
Biomass combustion	• Minimising and managing the occurrence of fouling, ash and agglomeration will help to preserve reactor performance and efficiency. • RD&D efforts will advance resistive materials, preserving reactor integrity and extending their lifespan.

Auxiliary

See Electricity – Electricity generation and Electricity storage and
Low Carbon Fuels – Hydrogen production and Hydrogen storage

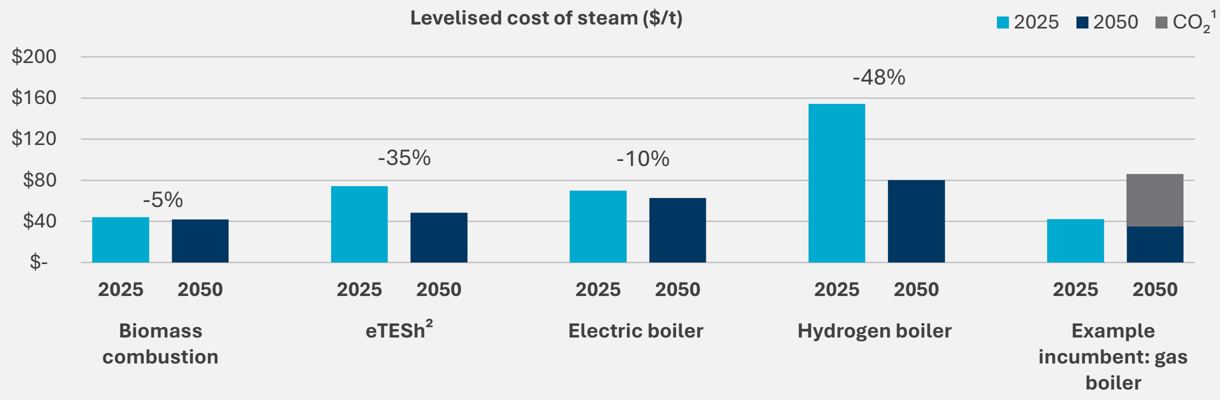
Energy efficiency solutions

- Demonstrations at scale to integrate solutions that minimise heat loss, such as thermal energy storage (TES) and tube digestion, can work to lower fuel consumption and decrease fuel costs per unit of alumina produced.
- The more efficient use of fuel can be encouraged through solutions such as digestion and mechanical vapour recompression (MVR), which require increased development and demonstration to be applied at scale for medium-temperature process steam applications.

Levelised Cost Analysis

Alumina digestion (100 tonnes per hour at 210°C and 8 bar)

Focus on improving the economic viability of auxiliary technologies will be crucial to the deployment of electric and hydrogen boilers, as fuel costs are the primary driver influencing the levelised cost of each technology.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

5.2 Introduction

The medium-temperature process steam is commonly defined by industry as steam with temperatures ranging from 100°C to 300°C across a wide variety of pressures. To achieve these temperatures, a heat input is required for effective operation. Medium-temperature process steam is used across a range of industries, including alumina digestion, pulp and paper, and food processing. These sectors together emitted 19.35MtCO_2e in 2022, accounting for 11% of Australian industry scope 1 emissions (including fugitive emissions).[199]

Given the diversity of Australian requirements, this chapter focuses on alumina digestion as a large-scale use case for medium-temperature process steam. Alumina digestion is a process extracting alumina from bauxite ore and accounts for a significant amount of medium-temperature process steam emissions, with a fuel mix that is more than 90% fossil-based.[200] Alumina digestion is also representative of the expanding hydrometallurgical industry. While temperatures range from 80°C to 450°C across applications, general steam supply principles remain consistent, and current alumina plants are significantly larger than other hydrometallurgical plants in the Australian sector.

Australia currently has six alumina digestion plants, four of which require lower digestion temperatures of about 140-150°C and two of which need higher digestion temperatures of about 240-310°C.[201] Steam temperature may need to reach 5-40°C higher than these rangers to account for energy losses, depending on whether heat is provided directly or indirectly by a digester. The Alumina digestion process is described in more detail in Box 7 below.

Conventional methods of generating medium-temperature process steam rely heavily on fossil fuels, resulting in high energy consumption and emissions. Past decades of RD&D have principally focused on improving process energy efficiency, as energy is typically the largest operating cost for alumina refineries.[202] In transitioning to low emissions technologies, the integration of renewable energy sources may lower energy costs while decreasing industrial process emissions. Given the scale of the alumina digestion industry, one or more options may be adopted by industry in tandem.

However, the transition faces challenges such as the high initial costs of deploying new technologies and upgrading existing infrastructure. In remote areas where industries like alumina digestion operate, the development of supporting systems, such as renewable energy grids and efficient heat distribution networks, is crucial for the successful implementation of decarbonisation solutions.

This chapter presents an analysis of low emissions technologies for medium temperature steam production in the context of alumina refining, to identify technically feasible and cost competitive solutions. This informs an exploration of RD&D opportunities that could support the scale-up, de-risking, and deployment of these technologies.

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[199] Emissions estimates have been calculated based on figures adapted from: Energy Transitions Initiative (2021) Australian Industry ETI Phase 1 Technical Report. <https://arena.gov.au/assets/2021/06/australian-industry-energy-transitions-initiative-technical-report.pdf> (accessed 31 March 2025). These reports only capture a select few subsectors and processes, making the emissions estimates a gross underestimate of actual emissions.

[200] ARENA (2019) Renewable energy options for industrial process heat. <https://arena.gov.au/assets/2019/11/renewable-energy-options-for-industrial-process-heat.pdf> (accessed 31 March 2025).

[201] Taylor G, Eggleton RA, Foster LD, Tilley DB, Le Gleuher M, Morgan CM (2008) Nature of the Weipa Bauxite deposit, northern Australia. Australian Journal of Earth Sciences. 55, S45-S70. https://doi.org/10.1080/08120090802438241; ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025).

[202] Henrickson, L. (2016). The Need for Energy Efficiency in Bayer Refining. In: Donaldson, D., Raahauge, B.E. (eds) Essential Readings in Light Metals. Springer, Cham. https://doi.org/10.1007/978-3-319-48176-0_96

5.2.1 Medium-temperature steam use case(s)

To explore low emissions technologies in the medium-temperature steam subsector, a single use case has been defined, reflecting alumina digestion process (see Box 7). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with this use case.

The alumina digestion process is representative of steam produced at 210°C (8 bar) at a rate of 100 tonnes per hour (see Table 14). Medium-temperature process steam (100-300°C) is used in various industries, including alumina digestion, pulp and paper, and food processing. Alumina digestion, as the largest emissions source for medium-temperature process steam, has been selected as a use case to compare low emissions technologies for this type of process steam. The alumina digestion process is described in Box 7. This use case is illustrative and presents requirements that technologies must be able to meet to service Australia's medium-temperature steam subsector. In reality, operations in Australia are diverse and will differ in their operating temperatures and pressures.

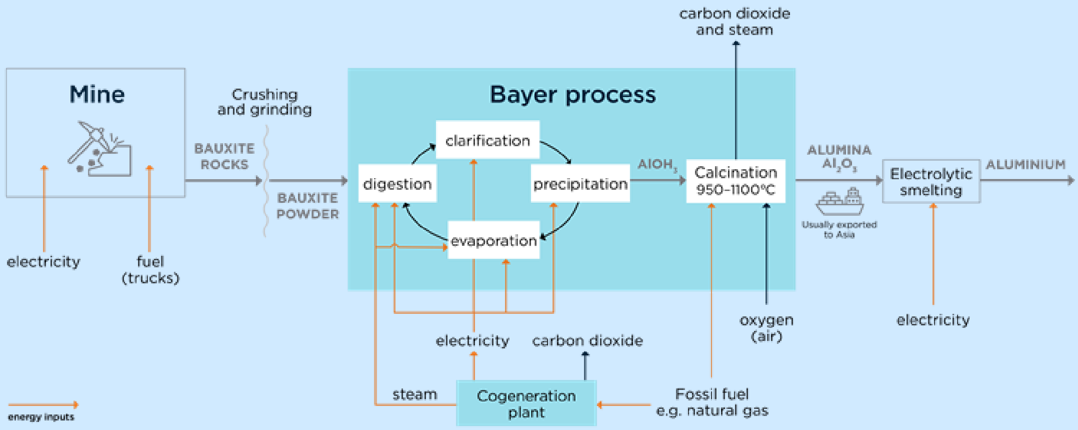
Table 14: Use case(s) – Medium-temperature steam

Use case(s)	Alumina digestion
Description:	The use case specifies steam being produced at a temperature of 210°C with a pressure of 8 bar, at a rate of 100 tonnes per hour.

Box 7: Summary of the alumina digestion process

Digestion, the first chemical step of refining bauxite to alumina through the Bayer process, is where steam is utilised (see Figure 13) This step involves mixing bauxite ore with a hot, concentrated solution of sodium hydroxide. The solution dissolves the alumina present in the ore, resulting in the formation of sodium aluminate. The equipment configuration varies among refineries, including using indirect heating of the slurry through a heat exchanger or direct injection of steam into the slurry.

Figure 13: Simplified schematic diagram of the current primary aluminium production chain[203]



Steam is used to maintain the required temperature and pressure conditions that facilitate the dissolution of alumina. Higher digestion temperatures speed up digestion but increase the risk of impure oxides dissolving in the Bayer liquid. Pressure does not directly affect digestion but is determined by the steam's saturation pressure.

The steam temperature needed varies with the composition of the bauxite ore used.[204] Gibbsite-rich ores require lower digestion temperatures of about 140-150°C, while boehmite or diaspore-rich ores need higher temperatures of about 240-310°C and pressures of about 35 bar or more for digestion.[205] For indirectly heated digestors, steam is usually provided at temperatures approximately 30°C to 40°C higher than the digestion temperature. For directly heated digestors, the steam temperature differential is typically lower, ranging from 5°C to 15°C.[206]

Digestion boilers usually have the ability to produce higher temperature steam (~450°C) for combined heat and power operations. Australia currently has four lower-temperature alumina digestion plants operating in Western Australia,[207] and two active higher-temperature alumina digestion plants in Queensland.[208]

The theoretical energy requirement for digestion is about 0.5 GJ per tonne of alumina, depending on the ore composition and required digestion process.[209] In practice, energy needed for digestion typically exceeds 3 GJ per tonne of alumina, due to substantial heat losses in a conventional natural gas boiler digestion system. However, energy requirements are highly dependent on equipment configuration.

Digestion usually takes 30-40 minutes, allowing for additional impurities to be removed from the sodium aluminate solution needed for the next step, precipitation.[210] Impurities that do not dissolve, such as iron oxides, form a residue known as ‘red mud’. The Bayer process produces about 1.0-1.5 tonnes of red mud per tonne of alumina.[211]

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[203] CSIRO (2024) How hydrogen can help decarbonise the Australian alumina industry <https://www.csiro.au/en/research/environmental-impacts/fuels/hydrogen/Hydrogen-for-alumina> (accessed 17 January 2024).

[204] Ruys A (2019) refining of alumina: The ayer process. Alumina Ceramics. 49-70. https://doi.org/10.1016/B978-0-08-102442-3.00003-8; Donoghue A, Frisch N, Olney D (2014) Bauxite mining and alumina refining: process description and occupational health risks. Journal of Occupational and Environmental Medicine. 56, S12-S17. https://doi.org/10.1097/jom.0000000000000001

[205] Taylor G, Eggleton RA, Foster LD, Tilley DB, Le Gleuher M, Morgan CM (2008) Nature of the Weipa Bauxite deposit, northern Australia. Australian Journal of Earth Sciences*.* 55**,** S45-S70. https://doi.org/10.1080/08120090802438241; ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025).

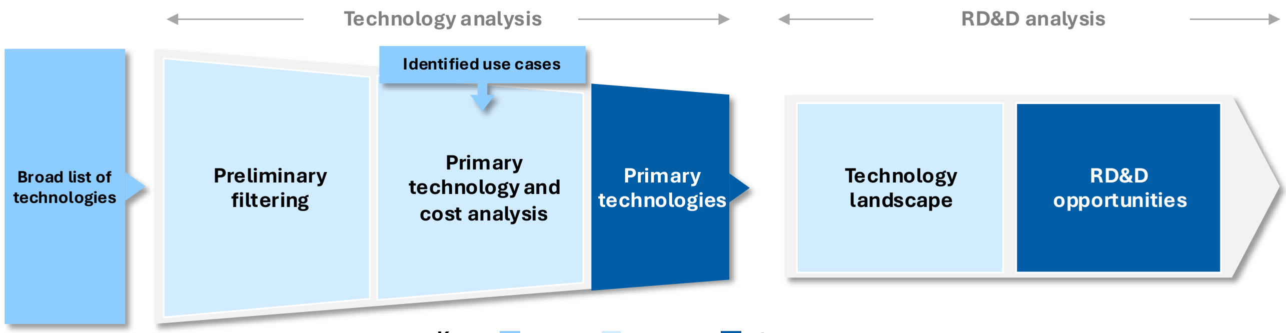
[206] Henrickson L (2016) The need for energy efficiency in Bayer refining. In: Donaldson D, Raahauge BE (eds) *Essential Readings in Light Metals.* The Minerals, Metals and Materials Society.

[207] ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025); ITP Energised Group (2020) Feasibility study of concentrated solar thermal technologies for the low temperature requirements of the Bayer Alumina Process. <https://itpthermal.com/wp-content/uploads/2020/12/itp-

5.3 Methodology: Medium-temperature process steam inputs and criteria

The methodology is comprised of several steps. Technology analysis was performed to first determine prospective technologies with the potential to decarbonise medium-temperature process steam of 100-300°C. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress (Figure 14).

Figure 14: Technology and RD&D analysis framework for medium-temperature process steam



5.3.1 Broad technology list

A broad technology list comprised of five technologies was developed (Table 15). These technologies were passed through three preliminary filters: Relevance to Australia, technological maturity, and abatement potential. The technologies that satisfied the preliminary filters were then assessed against the performance parameters for the relevant use case.

Table 15: Technology category definitions – Medium-temperature process steam

Technology category	Definition
Biomass combustion (100%)	Biomass combustion uses organic materials such as wood chips, agricultural residues, or dedicated energy crops to produce steam and heat.
Electric boiler	Electric boilers use electricity to generate steam and heat.
Thermal energy storage system with electricity input and heat output (eTESh)	Electricity is converted to heat and used to heat up the thermal medium. A heat output is used with a resistance mechanism to create steam.
Hydrogen boiler	Hydrogen boilers use hydrogen as a fuel to produce steam and heat.

alumina-report-public-30112020.pdf> (accessed 17 January 2025). Note the Kwinana refinery will close in late 2025: ABC News (2024) Alcoa Kwinana alumina refinery shutdown to have significant impact on WA economy, costing $650m annually. <https://www.abc.net.au/news/2024-01-10/alcoa-alumina-refinery-shutdown-to-slash-650-m-from-wa-economy/103299516> (accessed 18 June 2025).

[208] ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025).

[209] Scarsella AA, Noack S, Gasafi E, Klett C, Koschnick A (2015) Energy in alumina refining: setting new limits. Hyland M (ed.) Light Metals 2015. Springer.

[210] Ruys A (2019) refining of alumina: The ayer process. Alumina Ceramics. 49-70. https://doi.org/10.1016/B978-0-08-102442-3.00003-8

[211] Climateworks Centre and Climate-KIC Australia (2021) Setting up industry for net zero. Australian Industry Energy Transitions Initiative, Phase 1. <https://www.climateworkscentre.org/resource/australian-industry-energy-transitions-initiative-phase-1-report/> (accessed 16 January 2025); ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025).

Mechanical vapour recompression (MVR)	MVR involves the recycling of energy by compressing and reusing steam. Low-pressure steam is captured and mechanically compressed to a higher pressure and temperature. The compressed steam can then be reused to provide heat reducing the need for fresh steam generation. An initial round of steam must be produced, at which point MVR can become the primary technology for generating medium-temperature steam.

5.3.2 Primary technology filters

Technology assessment involved evaluating the technologies identified through preliminary filtering against two performance parameters for medium-temperature process steam (Table 16). Further details on the selected parameters are provided in *Section 5.4.2 Primary technology analysis*

Table 16: Technology filtering criteria – Medium-temperature process steam

Subsector	Medium-temperature process steam
Use case(s)	**Alumina digestion**
Preliminary filtering criteria	**Relevance to Australia** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions. *The criterion identifies constraining factors that may limit or prohibit technology adoption in the Australian context, including geographical constraints, legislation, or incompatibility with key domestic resources*
	Technology maturity Technology has a TRL greater than 3. The TRL index can be found in *Appendix A.2.*
	Abatement potential Technology options are assessed against an abatement threshold of 90%, relative to a conventional natural gas boiler.
Primary technology analysis	**Scalability** The presence of supply constraints.
	Levelised Cost of Steam (LCOSteam) in 2050 Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in LCOSteam relative to other assessed technologies (in $/t).

5.4 Technology analysis

This chapter outlines the process of identifying *Primary technologies* for medium-temperature steam production, in the context of alumina digestion. Following the technology analysis framework, **electric boilers, thermal energy storage system with electricity input and heat output (eTESh), and hydrogen boilers emerge as *Primary technologies* for further RD&D exploration.** These technologies were able to service the designated use case and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in reducing medium-temperature process steam emissions, for specific use cases, and over time RD&D can lead to new technologies that can be considered. The results of the technology analysis are provided in Table 17.

Table 17: Technology analysis results – Medium-temperature process steam[212]

Legend: Meets filter criteria | Meets with caveats | Does not meet | ★ Primary technology | Not assessed further

1. Preliminary filtering

2. Primary technology analysis

Alumina digestion (Bayer process) steam conditions: 210°C, 8 bar, 100t/hr

Technologies	Maturity *TRL > 3*	Abatement threshold *≥90% decrease in emissions*	Scalability *Presence of supply limits*	2050 LCOSteam *$/t*	
Biomass combustion (100%)	TRL 5-7	97%	Limited supply	$42/t	★
Electric boiler	TRL 7- CRI 6	99.9%		$63/t	★
Thermal energy storage system with electricity input and heat output (eTESh)	TRL 7 - CRI 1	99.9%		$48/t	★
Hydrogen boiler	TRL 8 - CRI 2	100%		$80/t	★
Mechanical vapour recompression (MVR)	TRL 5-7	99.9%		Inconclusive	

[212] Details for these figures, including sources/assumptions, are found in Table 18 (maturities), and under 'Abatement potential', 'Levelised cost analysis' and the *Technical Appendix: Levelised cost analysis* (LCOSteam).

5.4.1 Preliminary filtering results

Key information – Preliminary filtering

Three criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:

- **Relevance to Australia:** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.
- **Technology maturity*:*** Technology has a TRL greater than 3.
- **Abatement potential:** Technology demonstrates the potential to meet a nominated abatement threshold. The threshold for this sector is distinguished in the relevant filtering section, below.

Relevance to Australia

All technologies were found to meet this criterion for the designated use case, as they can be reasonably deployed in the Australian context.

Technological maturity

All technologies were found to meet this criterion, with each production routes possessing a TRL greater than 3 (Table 18). Maturity ratings are informed by desktop research, drawing on the IEA Clean Energy Technology Guide[213] and Mission Possible Partnership publications.[214]

All technologies were assessed in the context of alumina digestion. It is important to note that the scale of mid-temperature steam requirements vary by industry. For example, the identified alumina digestion process represents a large-scale industrial process producing steam at about 210°C with low pressure, which may vary relative to the mid-temperature steam requirements required in other industries. As such, different TRL/CRIs may be assigned by industry based on the maturity of a technology to the specific industrial use, and scale, in question.

Table 18: Technological maturities – Medium-temperature process steam, alumina digestion

Technology category	TRL / CRI
Biomass combustion (100%)	• TRL 5-7
Electric boiler	• Lower temperature heating (<220°C): CRI 5-6 • Higher temperature heating (>240°C): TRL 7
eTESh system	• TRL 7- CRI 1
Hydrogen boiler	• TRL 8- CRI 2
MVR	• TRL 5-7[215]

[213] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[214] Mission Possible Partnership (2023) Making net-zero aluminium possible. <https://www.energy-transitions.org/wp-content/uploads/2023/04/MPP-Aluminium-Full-Report-041223-final-digital.pdf>

[215] Mission Possible Partnership (2023); Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025); Alcoa (2024) Alcoa MVR for Low Carbon Alumina Refining Close-Out Report. <https://arena.gov.au/assets/2024/06/Alcoa-MVR-for-Low-Carbon-Alumina-Refining-Close-Out-Report.pdf> (accessed 16 January 2025).

Abatement potential

Key information – Abatement potential

The abatement potential criterion identifies technologies that meet or exceed a nominated abatement threshold. Emissions estimates reflect full fuel cycle emissions, including:

- Scope 1 (direct) emissions: arising from the direct use of a technology from the combustion or use of its fuel, including fugitives in some instances.
- Scope 2 (indirect) emissions: arising the production of a given energy input.
- Some Scope 3 emissions: For biofuels, indirect land-use change (ILUC) have been included for completeness; however, other Scope 3 emissions, such as embodied emissions have been excluded due to a lack of available data and low likelihood of impacting the relative results of the filtering criteria.

For more details, please refer to the *Appendix A.4.*

The abatement potential was assessed against a conventional natural gas boiler with an emissions factor of 52gCO_2/GJ. A 90% abatement potential threshold was set for medium-temperature steam to reflect the availability of cost competitive low emissions technology solutions by 2050 and the challenges of decarbonising energy-intensive subsectors.

Due to limited information on the emissions of the technologies for this use case, emissions factors are estimated using the Department of Climate Change, Energy, the Environment and Water's (DCCEEW) National Greenhouse Account Factors by fuel type. These emissions factors (in CO_2 equivalents), include methane (CH_4), nitrous oxides (N_2O) and carbon dioxide (CO_2), as reported in Table 19. All assessed technologies meet the set threshold.

Table 19: Abatement potentials (fuel cycle) – Medium-temperature steam[216]

Technology	Emission factor *gCO2e/GJ*	Abatement potential *Threshold: 90%*	Source/assumptions
Conventional natural gas boiler	**52**		**DCCEEW (2024)**
Biomass combustion (100%)	1.4[217]	97%	DCCEEW (2024)
Electric boiler	*0.008*[218]	99.9%	Energy consumption from Feng et al. Grid intensity determined via internal analysis.
eTESh system	*0.008*	99.9%	Per electric boiler above
Hydrogen boiler	*Assumed zero*	100%	Hydrogen production facility is assumed to operate at 60% utilisation, aligning with 100% variable renewable energy generation.
MVR (used in conjunction with electricity)	*0.008*	99.9%	Per electric boiler above

Meets filter criteria Meets with caveats Does not meet

[216] Sources: See the 'Energy: Scope 1' table: DCCEEW (2024) National greenhouse accounts factors 2024. Department of Climate Change, Energy, the Environment and Water. <https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-factors> (accessed 17 January 2025).

[217] This represents an evenly weighted average of the emissions factors for dry wood, green and air-dried wood, bagasse, and primary solid biomass fuels. Excluded are sulphite lyes and municipal and industrial biomass materials due to their impurities, making them unlikely for alumina digestion.

[218] Assumes a grid intensity of 0.0307kgCO_2-e per kWh, based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas, with the remainder generated from renewable resources and assumed to produce no direct emissions. Feng Y, Liu Q, Li Y, Yang Jue, Dong Z (2022) Energy efficiency and CO2 emission comparison of alternative powertrain solutions for mining haul truck using integrated design and control optimization. Journal of Cleaner Production, 370, 133568. https://doi.org/10.1016/j.jclepro.2022.133568

5.4.2 Primary technology analysis

Key information – Primary technology analysis

Two criteria were employed to ensure the suitability and feasibility of each technology for the use case applications determined.

- **Resource scalability:** Technologies that do not face supply constraints.
- **Levelised Cost of Steam (LCOSteam):** Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive.

Resource scalability

The resource scalability of technologies was assessed based on the presence of fuel supply limits. All technologies meet this criterion.

Biomass

Biomass meets this criterion with caveats. Biomass is a supply limited source where cost, availability and access will be a factor in deployment (please refer to the *Low Carbon Fuels* technical appendix for further information).

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Steam (LCOSteam) was estimated to determine the viability of each technology considered. LCOSteam is defined as the cost per unit of steam generated ($/t) over the lifetime of the system.

Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis*.

For reference:

- Some technologies that did not meet earlier filtering criteria have been included for completeness, where information was available – however, these were not assessed.
- Costs of new deployments are estimated using the projected fuel, operational, capital and integration costs in 2025 and 2050 to understand the potential for shorter-term and longer-term solutions.
- A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, contributing to the levelised cost of that technology in the long-term. No CO_2 emission cost has been assumed for 2025.

Results from the levelised cost analysis are outlined in Figure 15. Electric boilers, eTESh and hydrogen boilers were projected to be the most cost competitive technologies, distinguished by a cost differential in LCOE relative to other assessed technologies; suggesting areas of promise for further RD&D activity. MVR remains inconclusive due to insufficient data for LCOE modelling.

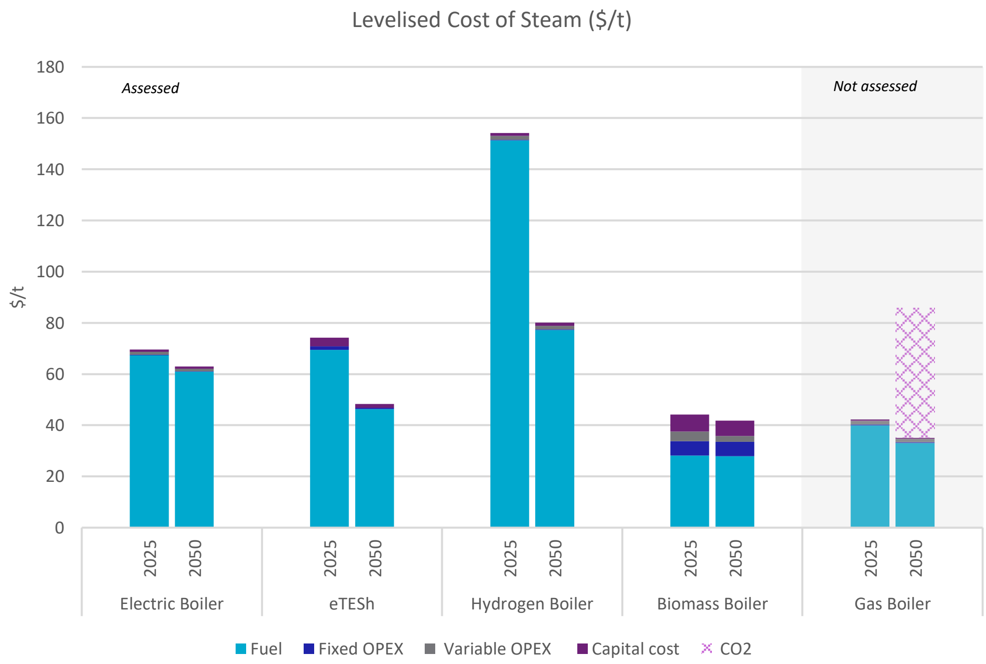
The cost assessment was designed to reflect lower-temperature alumina digestion, at a temperature and pressure that broadly aligns across industries where medium-temperature steam is used. This approach was taken to allow for versatility of the costs across different sectors as needed (e.g., paper and pulp). The key characteristics of the use case include a boiler operating to produce a steam temperature of 210°C at a pressure of 8 bar. Feed water is set at a temperature of 150°C.

The electricity price is derived from the National Electricity Market (NEM), and for WA-based operations, electricity and hydrogen fuel prices will vary. This will result in a different LCOSteam.

The fixed cost component includes operating and maintenance labour costs, and miscellaneous fixed charges.[219] The variable cost component includes scheduled maintenance and spare parts.[220]

Although it does not meet the earlier filtering stages, the LCOSteam for biomass combustion is included for reference only.

Figure 15: Levelised cost of steam ($/t) – Medium-temperature process steam



Electric boilers, eTESh, hydrogen boilers

Electric boilers, eTESh and hydrogen boilers were all estimated to have relatively low levelised costs in 2050, particularly in comparison to conventional gas boilers when accounting for a CO_2 emission cost. Energy is typically the largest operating cost for alumina refineries,[221] and this is expected to persist. Energy costs will be the primary determinant of the financial viability of electrification and fuel switching when replacing old equipment or setting up a new site. Anticipated reductions in the cost of renewable electricity and hydrogen will improve the economic prospects of associated technologies.

Electric boilers are modelled to have lower costs than hydrogen boilers in 2025 and 2050, with a large cost advantage in 2025 due to the high price of hydrogen.

[219] Aurecon (2024) Cost and Technical Parameters Review Report for the AEMO. <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2024/aurecon-2024-cost-and-technical-parameters-review-report.pdf?la=en> (accessed 10 December 2024).

[220] Aurecon (2024) Cost and Technical Parameters Review Report for the AEMO. <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2024/aurecon-2024-cost-and-technical-parameters-review-report.pdf?la=en> (accessed 10 December 2024).

[221] Henrickson, L. (2016). The Need for Energy Efficiency in Bayer Refining. In: Donaldson, D., Raahauge, B.E. (eds) Essential Readings in Light Metals. Springer, Cham. https://doi.org/10.1007/978-3-319-48176-0_96.

Biomass combustion

Biomass combustion was assessed to have the lowest LCOSteam of all assessed technologies in 2025 and 2050.

Biomass boilers have a considerably larger capital cost than other assessed technologies. This reflects the additional equipment required to handle the biomass and remove ash and other residues. The capital costs of alternative technologies are comparable with conventional industrial equipment.[222]

The projected cost competitiveness of biomass boilers is highly subject to the cost of biogenic feedstocks, which is in turn influenced by availability and competition. The above estimates feature an assumption of $200/tonne for biomass feedstock; however, this is highly uncertain and subject to a range of environmental and supply chain considerations.

Gas boilers

While not assessed, the LCOSteam of gas boilers has been modelled for informational purposes. Despite being modelled to have the lowest levelised cost of steam in 2025, the gas boiler technology is also estimated to have the highest cost in 2050 due to the addition of a CO_2 emissions cost.

MVR

For MVR, sufficient data was not able to be obtained for robust cost analysis and so results remain inconclusive.

The technology has seen limited application in pilot projects to date for alumina digestion to date. Despite this, MVR may still contribute to decarbonisation of alumina digestion and is widely used in other industries with medium-temperature steam requirements, including food and beverage, paper and pulp, and chemicals. An RD&D case study on MVR is provided in Box 8.

5.5 Technology landscape

Key information – Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the RD&D opportunity analysis and capture the complexity of the energy system networks and their interdependencies with other technological systems. This was informed by literature review and stakeholder input, and comprised of:

Use case

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

The technology analysis framework identified Electric boilers, hydrogen boilers, eTESh systems and biomass combustion systems as *Primary technologies* for an alumina digestion use case (Figure 16).

[222] This is consistent with qualitative literature: see, e.g., Climateworks Centre and Climate-KIC Australia (2021) Setting up industry for net zero. Australian Industry Energy Transitions Initiative, Phase 1. <https://www.climateworkscentre.org/resource/australian-industry-energy-transitions-initiative-phase-1-report/> (accessed 16 January 2025); Roelofsen, O, Somes, K, Speelman, E, & Witteveen, M (2020) Plugging in: What electrification can do for industry. McKinsey. <https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry> (accessed 17 January 2025).

Although not explored further, the other low emissions technologies evaluated in this report (Table 15) could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the medium-temperature process steam subsector. Further RD&D could unlock breakthrough innovations in these technologies, highlighting the need for ongoing assessments to maintain Australia's understanding of the current state of low emissions technologies and future opportunities for RD&D.

Figure 16: Technology landscape identification – Medium-temperature process steam

Electric boiler

- Co-located generation infrastructure
- Off-grid generation infrastructure
- Integrated storage systems

eTESh system

Hydrogen boiler

- Hydrogen production, storage and distribution systems
- Co-located infrastructure

Biomass combustion

- Feedstock pre-treatments

Energy efficiency solutions

- Heat exchanges and flash vessels
- Tube digestion
- Double digestion
- Thermal energy storage
- Mechanical vapour recompression

The associated *Auxiliary technologies* and *Energy efficiency solutions* identified for analysis are outlined in Table 20 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Auxiliary technologies

Electric boilers, eTESh systems and hydrogen boilers cannot exist in isolation and their successful use and deployment is dependent on a range of *Auxiliary technologies*, summarised in Table 20.

Table 20: Auxiliary technologies – Medium-temperature process steam

Primary Technology	Auxiliary Technology	Description
Electric boiler	**Co-located on-gird electricity generation infrastructure with industrial operations**	Placing on-grid electricity generation infrastructure nearby to industrial operations to decrease transmission distance needs. It may also enhance electricity reliability if combined with load balancing demand response.
	Off-grid electricity generation and/or storage	The provision of additional, dedicated off-grid electricity generation and/or storage for an industrial site, to preserve electricity reliability.
	Integrated storage	Integrated storage into a boiler system allows for demand response support by allowing a site to adjust electricity usage based on grid signals.
eTESh system	**On-grid and off-grid electricity infrastructure**	As for electric boilers above.
Hydrogen boiler	**Hydrogen production, storage, and distribution infrastructure**	Hydrogen production, storage, and distribution infrastructure are needed to ensure a stable and affordable supply of hydrogen.
	Co-located hydrogen hubs of production and storage	Co-locating hydrogen production and storage sites can reduce fuel storage and transport costs.
Biomass combustion	**Feedstocks pre-treatments**	Pre-treatment processes are necessary for favourable processing, and to mitigate risks associated with storage and transportation, including deterioration, fire hazards, and loss of valuable energy.

Energy efficiency technologies

For medium-temperature process steam, there are a range of *Energy efficiency solutions* that will also support emissions mitigation efforts. The solutions outlined in Table 21.

Table 21: Energy efficiency solutions – Medium-temperature process steam

Energy efficiency solutions	Description
Heat exchangers and flash vessels	Facilitates the transfer heat and steam from higher-temperature processes within the Bayer circuit (i.e. calcination) to lower-temperature processes (i.e. digestion).
Tube digestion	Digestion conducted using jacketed pipe heaters (rather than conventional shell-and-tube heat exchangers) to improve preservation of heat.
Double digestion	Involves the processing bauxite twice: first at lower temperatures first, dissolving 80% of the alumina, and then at higher temperatures for the remaining 20%.
MVR	Involves the recycling and reuse of steam using a mechanical compressor to increase energy efficiency across the digestion process.
Thermal energy storage	The integration of TES such as to catch residue heat.

5.6 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the identified technology landscape, spanning primary, auxiliary and energy efficiency technologies.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include non-technical RD&D opportunities. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

A summary of RD&D opportunities can be seen in Table 22. For some technologies, these opportunities are associated with specific technology subcomponents. Technologies typically consist of different system components, that are integrated or work in tandem, which may have specific RD&D needs or be at different stages of technology maturity. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9).

Please note, levelised cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

Given the scale of the alumina digestion industry, one or more options may be simultaneously used by industry.

Table 22: Summary of RD&D opportunities – Medium-temperature steam[223]

		Electric boilers	eTESh system	Hydrogen boilers	Biomass combustion
Primary technologies		Boiler technology	Boiler technology	Boiler technology	Boiler technology
	Commercial	Lower temperatures (<220°C)	-	-	-
	Mature	Higher temperatures (>240°C)	eTESh system	Hydrogen	Biomass combustion
	Emerging	-	-	-	-
Primary RD&D		• Reduce system costs **(LCOSteam forecast: $63/t cf. $70),** through: - E.g. Integration of Thermal Energy Storage (TES) to collect waste heat • Expand operational pressure and temperature conditions to broaden potential applications, through: - E.g. Developing advanced systems, such as three-phase power balancing	• Reduce system costs **(LCOSteam forecast: $48/t cf. $74)**, through: - E.g. Improving the efficiency of the convective transfer from heat to electricity - E.g. Improving thermal cycle stability of TESe media - E.g. Identifying materials and techniques with increased durability - E.g. Integrating advanced control systems • Enhance safety measure and demonstrate safe integration of electrical inputs into steam generation equipment at industrial scale.	• Reduce system costs **(LCOSteam forecast: $80/t cf. $154)**, through: - E.g. Integration of thermal energy storage (TES) to collect waste heat - E.g. Exploring non-GHG addititives to enhance flame properties	• Optimise system performance, including efficiency and durability, through: - E.g. Minimising the occurrence of fouling and ash - E.g. Managing agglomeration in fluidised bed biomass combustion - E.g. Developing reactor materials that are resistive to thermal and mechanical stesses • Avoid heavy metal production during biomass combustion to mitigate environmental detriments
Auxiliary RD&D		• Reduced electricity costs through: - E.g. Co-location of renewable electricity infrastructure for industrial operations - E.g. Integrating energy storage to reduce power price volatility, lengthen load bearing capabilities and support demand response - E.g. Investigating potential for hybrid generation systems (i.e., CST)		• Reduced hydrogen costs **($LCOH_2$ forecast: $3.95/kg cf. $7.32)**, through: - E.g. Co-location of hydrogen hubs of production and storage - E.g. Enhancing the hydrogen combustion process to reduce NO_x emissions	• Establish sustainable supply of cost-effective biomass, through: - E.g. Improving feedstock pre-treatments • For biofuel production, distribution and storage RD&D opportunities, *see the Low Carbon Fuels* technical appendix

cf. – Compare

[223] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6; Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

5.6.1 Electric boiler

Electric boilers operate by converting electrical energy into heat to produce steam from water. These boilers include components such as heating elements, a water tank, a steam chamber, and control systems to manage the heating process. Most boilers involve an electric current being passed through heating elements that act as resistors, generating heat. This heat is transferred to the water in the tank, converting it into steam which can then be transported and used for the digestion process. For larger and high temperature electric boilers, current is directly passed through the water to generate steam.

Electric boilers are commercially available for medium-pressure and temperature applications (350-7,500 kg/h steam at up to about 220°C and 24 bar).[224] These commercially available options offer high electricity-to-steam conversion efficiency (at 99-100%), precise steam pressure control, and straightforward integration with existing plant infrastructure.[225]

Primary technologies

Competitiveness is largely determined by electricity feed costs; however, improved boiler performance could also lead to incremental operational cost reductions.

Levelised costs are forecasted to reach $63/t by 2050 (compared to $70/t in 2025). Though largely driven by reductions in electricity inputs, efficiency improvements could also improve cost prospects. There are opportunities to increase efficiency of these systems using MRV and TES systems (see *Section 5.6.6 Energy efficiency solutions).*

Higher-pressure, higher-temperature electric boilers could expand technology uses, with RD&D serving to address performance and safety challenges.

Steam systems operating above 240°C and 50-100 bar are in trial and integration phases.[226] Though not yet at commercial scale for digestion process,[227] these technologies are expected to be ready within the next decade. These systems pass current directly through water, necessitating advanced designs (i.e., three-phase power balancing or pressure vessel reinforcement) to ensure safe and efficient operation under extreme conditions.[228]

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[224] Hydro (2025) Alunorte Starts Two New Electric Boilers, Reducing Carbon Emissions. <https://www.hydro.com/en/global/media/news/2025/alunorte-starts-two-new-electric-boilers-reducing-carbon-emissions/> (accessed 17 January 2025).

[225] Energy Transitions Commission (2023) MPP Aluminium: Full Report. <https://www.energy-transitions.org/wp-content/uploads/2023/04/MPP-Aluminium-Full-Report-041223-final-digital.pdf> (accessed 16 January 2025). See, e.g., examples of general industrial scale electric boilers: Babcock Wanson (n.d.) Industrial Electric Boilers. <https://www.babcock-wanson.com/product-category/industrial-electric-boilers/> (accessed 16 January 2025); Bosch Industrial (n.d.) Electric Steam Boiler ELSB. <https://www.bosch-industrial.com/global/en/ocs/commercial-industrial/electric-steam-boiler-elsb-19175285-p/> (accessed 16 January 2025).

[226] Aluminium Association (2024) Fact Sheet 03: Alumina. <https://aluminium.org.au/wp-content/uploads/2024/10/241023-FACT-SHEET-03-ALUMINA.pdf> (accessed 16 January 2025); ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025); Rio Tinto (2024) Decarbonising Rio Tinto's Australian Alumina Refineries: Proceedings of the 12th International AQW Conference and Exhibition. <https://aqw.com.au/component/zoo/?task=callelement&format=raw&item_id=601&element=7a9fb9aa-c8cf-4e64-8a22-71d6f4c3ca3b&method=download> (accessed 16 January 2025).

[227] Rio Tinto (2024) Decarbonising Rio Tinto's Australian Alumina Refineries: Proceedings of the 12th International AQW Conference and Exhibition. <https://aqw.com.au/component/zoo/?task=callelement&format=raw&item_id=601&element=7a9fb9aa-c8cf-4e64-8a22-71d6f4c3ca3b&method=download> (accessed 16 January 2025).

[228] Three-phase power is an electrical power distribution method that uses three alternating currents, each set 120 degrees apart, to provide a continuous and balanced power supply for industrial and commercial applications.

RD&D can be leveraged to address design limitations imposed by alloy strength and system geometry, and to implement high-efficiency process configurations (i.e., double digestion, see *Section 5.6.6 Energy efficiency solutions)*, that reduce energy demand while improving output.[229]

Auxiliary technologies

The cost competitiveness of electrified steam generation will be heavily dependent on electricity input prices.

The decarbonisation of steam generation in sectors like alumina refining, where fully electrified refineries could consume approximately 1,000MW of dedicated power, will rely upon affordable and reliable supply of renewable electricity.[230] Electrification of alumina digestion will significantly raise site electricity demand, compared to sites traditionally fuelled by natural gas or coal. Co-location of generation infrastructure and grid demand-response integration can reduce costs by decreasing transmission distances[231] and improve electricity reliability.[232] The growth in electricity demand required by electric boilers may require off-grid electricity generation and/or storage where the grid does not have the capacity to rapidly accommodate for demand uplift at this scale.[233] Off-grid electricity generation and storage infrastructure built to support process infrastructure can mitigate against unreliable electricity supply and associated price hikes. Refer to the *Electricity* technical appendix for further detail on VRE supply.

Thermal and electrical storage integration could the improve operational flexibility of electric boiler systems and lower electricity costs.

Electric boilers can be paired with TES or electrical storage to decouple steam production from electricity usage, enabling cost-optimised operation during off-peak or renewable-rich periods.[234] The use of integrated storage can support demand response by adjusting electricity usage based on grid signals.

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[229] ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025).

[230] Aluminium Association (2024) Fact Sheet 03: Alumina. <https://aluminium.org.au/wp-content/uploads/2024/10/241023-FACT-SHEET-03-ALUMINA.pdf> (accessed 16 January 2025); Climateworks Centre and Climate-KIC Australia (2023) Pathways to industrial decarbonisation: Positioning Australian industry to prosper in a net zero global economy', Australian Industry Energy Transitions Initiative, Phase 3. <https://www.climateworkscentre.org/wp-content/uploads/2023/12/Pathways-to-Industrial-Decarbonisation-report-Updated-August-2023-Australian-Industry-ETI.pdf> (accessed 16 January 2025).

[231] The AEMO 2022 Integrated Systems Plan (ISP) includes proposed renewable energy zones, some of which are located near aluminium smelters: Climateworks Centre and Climate-KIC Australia (2023) Pathways to industrial decarbonisation: Positioning Australian industry to prosper in a net zero global economy', Australian Industry Energy Transitions Initiative, Phase 3. <https://www.climateworkscentre.org/wp-content/uploads/2023/12/Pathways-to-Industrial-Decarbonisation-report-Updated-August-2023-Australian-Industry-ETI.pdf> (accessed 16 January 2025).

[232] Aluminium Council of Australia (2024) Fact Sheet 05: Electricity. <https://aluminium.org.au/wp-content/uploads/2024/10/241023-FACT-SHEET-05-ELECTRICITY.pdf> (accessed 16 January 2025); Aluminium Council of Australia (2020) Aluminium Response Technology Roadmap. <https://aluminium.org.au/wp-content/uploads/2020/07/200619-Aluminium-Response-Technology-Roadmap.pdf> (accessed 16 January 2025).

[233] Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025).

[234] Rio Tinto (2024) Decarbonising Rio Tinto's Australian Alumina Refineries: Proceedings of the 12th International AQW Conference and Exhibition. <https://aqw.com.au/component/zoo/?task=callelement&format=raw&item_id=601&element=7a9fb9aa-c8cf-4e64-8a22-71d6f4c3ca3b&method=download> (accessed 16 January 2025).

Current refineries can adjust electricity loads when supply is low for periods of up to 3 hours without risking plant equipment damage and production losses.[235] Refineries with storage could collaborate with grid operators to reduce peak demand and allow rapid load response during periods of instability.[236]

Research is exploring alternative technologies like compressed air energy storage (CAES), given the scale limitations and round-trip inefficiencies of batteries at refinery-scale. Given these inherent inefficiencies, considering a mix of energy and steam generation systems would be beneficial and could enable greater flexibility.

RD&D of hybrid generation systems, such as CST, could serve to diversify energy inputs but economic viability has not yet been established.

CST systems may serve as a complementary or backup energy source for electric boilers, particularly where land, solar resource, and transmission capacity allow.[237] All Australian refineries are in suitable solar resource areas (about 2,100-2,500 kWh/m^2/year), but may face land requirement challenges for CST uptake.[238] Similar to other VRE sources, transmission line limits and costs may restrict the capacity of CST to transfer the necessary heat. RD&D can help determine whether, as suggested by literature, CST is not cost-effective for continuous digestion production without the use of boilers as back-up fuel sources.[239] Refer to the *Electricity* technical appendix for additional commentary on CST RD&D.

5.6.2 Thermal energy storage system with electricity input and heat output (eTESh system)

Electricity is converted to heat, often using electric resistance, radiation or induction elements, and stored as heat in a thermal energy storage (TES) system until required. When heat is needed, air is pushed through the TES system and heated at the exact temperature and pressure necessary (with the ability to reach temperatures over 1000°C). The heat delivery rate is adjustable by varying the air flow, and use of a heat exchanger allows for the delivery of steam as an output.

Primary technologies

Cost reductions will primarily be driven by lower electricity fuel input costs; however, improved eTESh performance could also offer opportunities for savings.

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[235] Judd B (2016) Portland smelter to operate at just 27pc capacity after unexplained power failure. ABC News. <https://www.abc.net.au/news/2016-12-05/portland-smelter-to-operate-at-one-third-capacity/8092256> (accessed 16 January 2025); Butler C (2020) Why Aluminium Smelters Are a Critical Component in Australian Decarbonisation. Institute for Energy Economics and Financial Analysis. <https://ieefa.org/sites/default/files/2022-05/IEEFA_Why-Aluminium-Smelters-are-a-Critical-Component-in-Australian-Decarbonisation_June-2020.pdf> (accessed 16 January 2025); Climateworks Centre and Climate-KIC Australia (2023).

[236] Aluminium Association (2024) Fact Sheet 03: Alumina. <https://aluminium.org.au/wp-content/uploads/2024/10/241023-FACT-SHEET-03-ALUMINA.pdf> (accessed 16 January 2025).

[237] The IEA notes the use of boilers with concentrated solar thermal energy generation as at TRL 3: International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024); European Commission (2015) Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry. Joint Research Centre. <https://publications.jrc.ec.europa.eu/repository/bitstream/JRC96680/ldna27335enn.pdf> (accessed 16 January 2025); ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. <https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf> (accessed 16 January 2025).

[238] Climateworks Centre and Climate-KIC Australia (2021); University of Adelaide (2024) Integrating Concentrating Solar Thermal Energy into the Bayer Alumina Process: Final Report. <https://arena.gov.au/assets/2024/07/Univeristy-of-Adelaide-Integrating-Concentrating-Solar-Thermal-Energy-into-the-Bayer-Alumina-Process-Final-report.pdf> (accessed 16 January 2025); Australian Renewable Energy Agency (2024) Integrating Concentrating Solar Thermal Energy into the Bayer Alumina Process. <https://arena.gov.au/projects/integrating-concentrating-solar-thermal-energy-into-the-bayer-alumina-process/> (accessed 16 January 2025).

[239] University of Adelaide (2024) Integrating Concentrating Solar Thermal Energy into the Bayer Alumina Process: Final Report. <https://arena.gov.au/assets/2024/07/Univeristy-of-Adelaide-Integrating-Concentrating-Solar-Thermal-Energy-into-the-Bayer-Alumina-Process-Final-report.pdf> (accessed 16 January 2025).

The levelised cost of an eTESh system is forecasted to reach $48/t by 2050 (compared to $74/t in 2025), primarily driven by lower electricity fuel input costs. However, incorporating energy efficiency technologies (see *Section 5.6.6 Energy efficiency solutions*), in addition to improved thermal insulation and thermal management, could reduce heat loss in eTESh systems. This would lower fuel consumption and lower fuel costs on a unit basis.

Technologies that improve the efficiency of converting stored thermal energy into electricity, is another performance improvement that could help reduce system costs. Conventional processes to convert heat to electricity are notably ineffective, with efficiencies of below 40%.[240] For more detail on RD&D opportunities to improve this efficiency, see the *Electricity* technical appendix.

Other examples of performance improvements include improving the thermal cycle stability of TESe media, identifying materials and techniques with increased durability e.g. protective coatings, and integrating advanced control systems. Realising the resulting cost benefits from these performance improvements, will hinge on specific RD&D, some of which is highlighted in the *Electricity* technical appendix.

Improving safety measures and facilitating large scale testing and demonstration of eTESh systems in industrial settings, could improve the technical feasibility of this technology.

For example, RD&D to enable the use of induction heating in large facilities could address wiring challenges posed by resistive heating. Safety improvements such as this, make it possible to integrate electricity into steam generation systems, which could in turn reduce fossil fuel use. However, the application of eTESh systems to meet the large-scale industrial steam requirements, such as those in the alumina industry, is currently uncertain. Despite being commercially available for other applications,[241] RD&D is needed to determine and prove their feasibility in this context and to explore opportunities for modular and scalable deployment.

Auxiliary technologies

Refer to the *Auxiliary technologies* RD&D discussion in *Section 5.6.1 Electric boiler*.

5.6.3 Hydrogen boiler

Hydrogen boilers operate by combusting hydrogen fuel with air, using the resulting heat to generate steam with a byproduct of flue gas. The primary components of a hydrogen boiler include a burner, combustion chamber, heat exchanger, and control systems to regulate the combustion process. When hydrogen gas is fed into the burner, it mixes with oxygen, ignites, and produces a high-temperature flame. The heat generated is transferred to water in the boiler, converting it into steam.

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[240] Reaching best efficiencies of 37-42%. See, e.g., Dunham MT, Iverson BD (2014) High-efficiency thermodynamic power cycles for concentrated solar power systems. Renewable and Sustainable Energy Reviews 30, 758–770. https://doi.org/10.1016/j.rser.2013.11.010.; Gamisch S, Kick M, Klünder F, Weiss J, Laurenz E, Haussmann T (2023) Thermal storage: From low-to-high-temperature systems. Energy Technology 11(6), 2300544. https://doi.org/10.1002/ente.202300544; LaPotin A, Schulte KL, Steiner MA, Buznitsky K, Kelsall CC, Friedman DJ, Tervo EJ, France RM, Young MR, Rohskopf A, Verma S, Wang EN, Henry A (2022) Thermophotovoltaic efficiency of 40%. Nature 604, 287–291. https://doi.org/10.1038/s41586-022-04473-y; Helman U, Kaun B, Stekli J (2020) Development of long-duration energy storage projects in electric power systems in the United States: A survey of factors shaping the market. Frontiers in Energy Research 8. https://doi.org/10.3389/fenrg.2020.00008; O'Connor P et al. (2020) Hydropower Vision: A new chapter for America's first renewable electricity source. https://doi.org/10.2172/1502612; Augustine C, Blair N (2020) Storage technology modeling input data report; Albertus P, Manser J, Litzelman S (2020) Long-duration electricity storage: Applications, economics, and technologies. Joule 4, 21–32. https://doi.org/10.1016/j.joule.2019.11.009; Denholm P, Cole W, Blair N (2023) Moving beyond 4-hour Li-ion batteries: Challenges and opportunities for long(er)-duration energy storage. NREL. https://www.nrel.gov/docs/fy23osti/85878.pdf (accessed 13 December 2024).

[241] See, e.g., Graphite Energy (n.d.) Green steam: Zero carbon heat. <https://www.graphiteenergy.com/> (accessed 17 January 2025); Rondo Energy (n.d.) The Rondo Heat Battery. <https://rondo.com/> (accessed 17 January 2025).

Primary technologies

The cost competitiveness of hydrogen boilers will be heavily dependent on the cost of hydrogen as an input; however, improving their energy efficiency could also support cost reductions.

The levelised cost of hydrogen boilers are forecasted to reach $80/t by 2050 (compared to $154/t in 2025), primarily driven by lower hydrogen fuel input costs rather than the boiler system itself. While commercial boilers capable of operating with a blend of natural gas and hydrogen (typically up to 20%) are available, RD&D is needed to resolve uncertainties around fuel cost and supply (see *Auxiliary technologies*).[242]

As with electric boilers, incorporating energy efficiency technologies (see *Section 5.6.6 Energy efficiency solutions*), could also improve cost prospects. For example, incorporating TES to capture and reuse waste heat or exploring the addition of non-greenhouse gas additives to enhance flame glow. With RD&D, the latter could address the poor radiative properties of hydrogen flames and improving boiler efficiency during initial operation.

Auxiliary technologies

The economic viability of hydrogen-based steam generation will hinge on Australia's ability to reduce hydrogen fuel prices.

RD&D for hydrogen production, storage, and distribution systems could support the reduction of hydrogen fuel costs to $3.95/kg by 2050 (compared to $7.32/kg in 2025). Adopting hydrogen boilers will be highly dependent on the cost trajectory for hydrogen fuel, given that fuel costs are forecasted to account for over 95% of the levelised cost of hydrogen boilers in 2025 and 2050.

Key RD&D opportunities include co-locating hydrogen production and storage hubs near refineries to reduce fuel storage and transport costs,[243] or improving hydrogen combustion technologies to reduce greenhouse emissions. While hydrogen itself is carbon free, hydrogen and air combustion can produce nitrogen oxides (NO_x). To address this, CSIRO is developing industrial hydrogen burners that safely control the combustion process for use in a range of processing plants.[244] For an in-depth discussion of RD&D opportunities relating to hydrogen production, storage and distribution, see the *Low Carbon Fuels* technical appendix.

5.6.4 Biomass combustion

Biomass combustion harnesses organic feedstocks such as wood chips, pellets, and agricultural residues to directly heat air to produce steam.[245] Often, these reactors will incorporate fluidised bed designs for larger scale production. Although they are a well-established technology for heat and power production,[246] 100% biomass combustion that delivers the sustained pressures and temperatures necessary for alumina digestion

[242] Aluminium Association (2024) Fact Sheet 03: Alumina. <https://aluminium.org.au/wp-content/uploads/2024/10/241023-FACT-SHEET-03-ALUMINA.pdf> (accessed 16 January 2025).

[243] Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025); IEA (2019) The Future of Hydrogen. <https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf> (accessed 17 January 2025).

[244] CSIRO (n.d.) How hydrogen can help decarbonise the Australian alumina industry. <https://www.csiro.au/en/research/environmental-impacts/fuels/hydrogen/Hydrogen-for-alumina> (accessed 16 January 2025).

[245] Globally, there is growing interest in unconventional, region-specific feedstocks; for instance, acai stones in Brazil: https://www.hydro.com/en/global/media/news/2022/alunorte-alumina-plant-fires-up-first-electric-boiler/

[246] Motola V, Scarlat N, Hurtig O, Buffi M, Georgakaki A, Letout S, Mountraki A, Salvucci R, Schmitz A (2023) *Clean Energy Technology Observatory: Bioenergy in the European Union – 2023 Status Report on Technology Development, Trends, Value Chains and Markets*. Publications Office of the European Union, Luxembourg. <https://publications.jrc.ec.europa.eu/repository/handle/JRC135079> (accessed 12 June 2025).

has not yet been commercially scaled. Biomass co-generation has been piloted with feedstocks containing up to 30% organic material.[247]

Primary technologies

RD&D can assist in minimising the occurrence of fouling and ash, for optimal biomass combustion system performance.

Fouling occurs when ash deposits accumulate on heat transfer tubes. Biomass contains elements such as sulphur, chlorine, and silicon that can increase the volatility of metals like sodium and potassium. These volatile compounds condense and form sticky ash deposits on surfaces. Interactions between flue gas species and elements like magnesium, calcium, and silicon can further contribute to deposit formation. Fouling reduces boiler efficiency and heat transfer, and increases operating costs and emissions of carbon monoxide and nitrogen oxide.[248] Pre-treating biomass with water can lower ash content, enhancing combustion efficiency. Using warmer water during pre-treatment raises the melting point of ash, eventually improving the efficiency of the combustion process. Fouling in wooden biomass can also be reduced by optimising airflow and temperature. Monitoring systems designed with tools such as neural networks can simulate, predict, and control of soot blowing cycles to reduce fouling while potentially achieving up to 3.5% in energy savings.[249]

Effective management of agglomeration in fluidised bed biomass combustion is critical for maintaining reactor performance and reducing operational failures.

Agglomeration occurs when alkali metals in biomass ash react with silicate materials to form sticky liquid phases, leading to adhesion and clumping of bed particles.[250] This process, influenced by chemical reactions, liquid-phase presence, and solid-state sintering,[251] disrupts reactor performance and increases maintenance costs by causing defluidisation, temperature imbalances, and operational failures. Agglomeration severity is affected by operating variables such as fuel, bed material, additives, fluidising gas velocity and temperature.[252] Continued RD&D efforts focused on exploring alternate bed materials, the use of dual-fuel biomass blends, and the optimisation of additives can improve management techniques. Design improvements like stirrers, high-velocity gas streams, or hydro-beam floors may also help reduce agglomeration by breaking clumps and removing coarse particles.[253]

Crosscutting RD&D, such as materials engineering innovations, can improve technical performance characteristics and durability of biomass reactors.

Biomass feedstocks rich in alkali metals, ash, and moisture create a highly corrosive environment within biomass reactors. This chemical stress compounds the thermal and mechanical stresses endured by the reactor during alumina digestion, especially given the continuous demand for steam production. Continuing to

[247] South32 (2018) Worsley Alumina biomass trial. <https://www.south32.net/news-media/latest-news/worsley-alumina-biomass-trial> (accessed 12 June 2025).

[248] Niu Y, Tan H, Hui S (2016) Ash-related issues during biomass combustion: Alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion, ash utilization, and related countermeasures. Progress in Energy and Combustion Science 52:1-61. https://doi.org/10.1016/j.pecs.2015.09.003

[249] Sharma S, Sharma M, Mudgal D, Bhowmick H (2021) Adoption of strategies for clean combustion of biomass in boilers. Reviews on Corrosion 39:275-288. https://doi.org/10.1515/corrrev-2020-0095

[250] Morris JD, Daood SS, Chilton S, Nimmo W (2018) Mechanisms and mitigation of agglomeration during fluidized bed combustion of biomass: A review. Fuel 230:452-473. https://doi.org/10.1016/j.fuel.2018.04.098

[251] Sharma S et al. (2021) Adoption of strategies for clean combustion of biomass in boilers. Reviews on Corrosion 39:275-288. https://doi.org/10.1515/corrrev-2020-0095

[252] Morris JD et al. (2018) Mechanisms and mitigation of agglomeration during fluidized bed combustion of biomass: A review. Fuel 230:452-473. https://doi.org/10.1016/j.fuel.2018.04.098

[253] Sharma S et al. (2021) Adoption of strategies for clean combustion of biomass in boilers. Reviews on Corrosion 39:275-288. https://doi.org/10.1515/corrrev-2020-0095

investigate resistive materials to incorporate into reactors, including superalloys, high chromium steel, and the application of thermal coatings can assist these endeavours.[254] As noted in the discussion for *Biomass and waste conversion* for Hydrogen production in the *Low Carbon Fuels* technical appendix, favourable properties for resistive materials include high thermal stability, oxidation resistance, and creep resistance to prevent deformations from mechanical stress.[255]

Demonstration of techniques avoiding heavy metal production during biomass combustion are needed at scale to avoid environmental harm like soil and water contamination.

Heavy metals such as arsenic, cadmium, and lead are released during the burning of biomass and are highly toxic to the environment. The concentration of these heavy metals depends on the source of biomass and its proximity to pollution sources. Experimental and industrial research indicates that silicates and aluminosilicate absorption can effectively reduce heavy metal emissions, although they may raise ash content.[256] Further studies are required to determine optimal dosage and application paths that minimise ash occurrence while enhancing emissions reduction.[257] Additionally, RD&D is investigating the use of activated carbon adsorption, and post-precipitation techniques to further minimise heavy metal emissions.[258]

Auxiliary technologies

The sustainable supply of cost-effective biomass sources will be a crucial factor in driving the adoption biomass boilers.

Australian industry has raised concerns about the availability of large quantities of sustainably sourced and competitively priced biomass.[259] The cost and accessibility of biomass feedstock directly impacts the feasibility and scalability of biomass combustion for alumina digestion. Robust supply of sustainably sourced and competitively priced biomass is necessary to meet and maintain the large energy demands of alumina digestion processing.

While feedstock costs are impacted by market availability and competition, improvements in feedstock pre-treatments and smart sorting technologies can enhance feedstock quality and process reliability, and may help to reduce costs. Pre-treatment processes are necessary for favourable processing, and to mitigate risks associated with storage and transportation, including deterioration, fire hazards, and loss of valuable energy, given the high moisture content and low energy density of these feedstocks. Please see additional discussion in the *Biofuels* chapter of the *Low Carbon Fuels* technical appendix.

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[254] Sharma S et al. (2021) Adoption of strategies for clean combustion of biomass in boilers. Reviews on Corrosion 39:275-288. https://doi.org/10.1515/corrrev-2020-0095

[255] Morris JD et al. (2018) Mechanisms and mitigation of agglomeration during fluidized bed combustion of biomass: A review. Fuel 230:452-473. https://doi.org/10.1016/j.fuel.2018.04.098

[256] Sharma S et al. (2021) Adoption of strategies for clean combustion of biomass in boilers. Reviews on Corrosion 39:275-288. https://doi.org/10.1515/corrrev-2020-0095

[257] Maj I, Matus K (2023) Aluminosilicate Clay Minerals: Kaolin, Bentonite, and Halloysite as Fuel Additives for Thermal Conversion of Biomass and Waste. Energies 16(11):4359. https://doi.org/10.3390/en16114359

[258] Sharma S et al. (2021) Adoption of strategies for clean combustion of biomass in boilers. Reviews on Corrosion 39:275-288. https://doi.org/10.1515/corrrev-2020-0095

[259] See, e.g., https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf

ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 12 June 2025).

5.6.5 Case study: Mechanical vapour compression

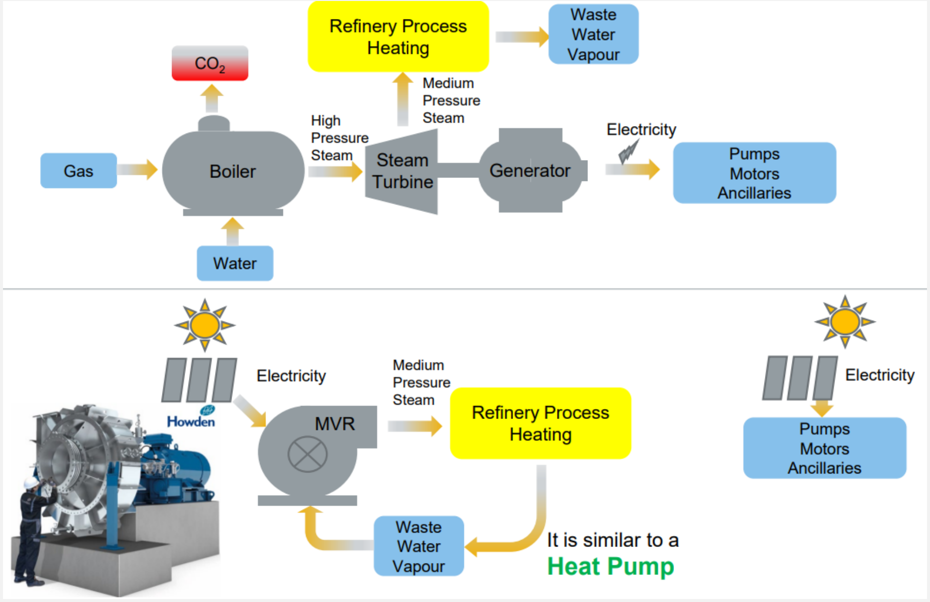
Box 8: Mechanical vapour compression (MVR) RD&D case study

MVR systems operate in a manner akin to heat pumps, substituting the evaporator used in a heat pump with the low-pressure vapour that is released during digestion.[260] This vapour is compressed to elevate its pressure and temperature, enabling it to resupply heat within the same process. The reuse of vapour can reduce or eliminate steam demand from the boiler, increasing the process's energy efficiency and minimising water use, given the elimination of continuous boiler feed water (Figure 17).[261]

The MVR system is often driven by electricity, running a compressor and reduce the heating load. If renewable energy is used to supply the initial steam required at digestion start-up, CO_2 emissions can be entirely eliminated (Figure 17).[262] The technology can be applied to new and existing assets, provided space requirements are met.

While MVR is widely used in other industries such as food processing and paper and pulp,[263] its use in the alumina industry is still in early stages (TRL 5-7).[264] Despite this, MVR is regarded in industry as a leading option for providing low emission Bayer process heating for lower temperature digestion.[265]

Figure 17: Alumina boiler digestion set up (top diagram), and potential digestion set up incorporating MVR as primary digestion driver (bottom diagram)[266]



Continued on next page.

[260] Bantle M, Schlemminger C, Tolstorebrov I, Ahrens M, Evenmo K (2018) Performance evaluation of two-stage mechanical vapour recompression with turbo-compressors. Proceedings of the 13th IIR Gustav Lorentzen Conference on Natural Refrigerants, Valencia. https://doi.org/10.18462/IIR.GL.2018.1157

[261] See, e.g., Thermal Kinetics (n.d.) Why mechanical vapour recompression. <https://thermalkinetics.net/why-mechanical-vaporrecompression/> (accessed 17 January 2025); Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025); Chatfield R (2020) Renewables and Electrification in Alumina Refining: 2020 Energy and Mines conference. Alcoa. <https://cdn-api.swapcard.com/public/files/91a1f0fca8f24f12bd694e51a0e9976b.pdf> (accessed 16 January 2025). Regarding minimised water use, please see, e.g., Alcoa (2024) Alcoa MVR for Low Carbon Alumina Refining Close-Out Report. <https://arena.gov.au/assets/2024/06/Alcoa-MVR-for-Low-Carbon-Alumina-Refining-Close-Out-Report.pdf> (accessed 16 January 2025); ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. <https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf> (accessed 16 January 2025); Climateworks Centre and Climate-KIC Australia (2021); MVR could save about 5.2 GL of water annually if adopted by all Australian refineries: ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. <https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf> (accessed 16 January 2025); ARENA (2022) MVR retrofit commercialisation study. <https://arena.gov.au/assets/2022/11/mvr-retrofit-commercialisation-study.pdf> (accessed 17 January 2025).

[262] Climateworks Centre and Climate-KIC Australia (2021).

Primary technologies

RD&D is required to reduce MVR integration costs.[267]

Some researchers have argued that initial capital costs must target $162-324/kW to be cost competitive. The economic feasibility of a refinery will strongly depend on its scale, with larger refineries more likely to achieve these cost targets.[268] In addition to high capital expenditure, integration costs may grow due to the technology's technical complexity, and space constraints.[269]

Demonstrations must be conducted across new and existing assets to clarify and reduce MVR's integration costs for alumina refineries.

For example, retrofitting is plausible but economically challenging, as shown by the development project at scale conducted by ARENA and Alcoa in WA between 2021 and 2023.[270] The project aimed to demonstrate a low capital, low operating cost MVR system retrofit to the Wagerup refinery. A range of safety considerations were considered in initial project cost estimates, including prevention of recovery condensate, flash condensate, and caustic washing. However, design changes, equipment price increases and an increased construction schedule led to the project being found to be financially unviable, and it was stopped in its pre-execution phase.[271]

Researchers are exploring methods to improve MVR's ability to manage the higher temperatures and lower pressures required in alumina digestion.

Digestion temperatures are higher than those commonly dealt with by MVR, increasing energy demands and mechanical stress on the compressors used to process the vapour. These are typically single-stage compressors that can elevate vapour temperature by up to 20°C,[272] and are designed for gas-phase operations. For lower temperature alumina refining, steam at 175-230°C is needed. The steam has a saturation point around 170°C, below which it transitions into a liquid state.[273] MVR becomes unsuitable for the digestion system where steam falls below the saturation point. The use of multiple recompression stages may contribute to

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[263] ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. <https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf> (accessed 16 January 2025); Aluminium Association (2024) Fact Sheet 03: Alumina. <https://aluminium.org.au/wp-content/uploads/2024/10/241023-FACT-SHEET-03-ALUMINA.pdf> (accessed 16 January 2025); Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025). See e.g., in food (Gen Less (n.d.) Mechanical vapour recompression for evaporation, distillation, and drying. <https://www.genless.govt.nz/assets/Business-Resources/Mechanical-vapour-recompression-for-evaporation-distillation-drying.pdf> (accessed 17 January 2025), and wastewater (Paras Hydrotech (n.d.) Mechanical vapor recompression: a proven energy-saving technology for wastewater. <https://parashydrotech.com/blog-post/mechanical-vapor-recompression-mvr-a-proven-energy-saving-technology/> (accessed 17 January 2025)).

[264] Mission Possible Partnership (2023) Making net-zero aluminium possible. <https://www.energy-transitions.org/wp-content/uploads/2023/04/MPP-Aluminium-Full-Report-041223-final-digital.pdf> (accessed 16 January 2025); Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025); Alcoa (2024) Alcoa MVR for Low Carbon Alumina Refining Close-Out Report. <https://arena.gov.au/assets/2024/06/Alcoa-MVR-for-Low-Carbon-Alumina-Refining-Close-Out-Report.pdf> (accessed 16 January 2025).

[265] See, e.g., ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. <https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf> (accessed 16 January 2025).

[266] Chatfield R (2020) Renewables and Electrification in Alumina Refining: 2020 Energy and Mines conference. Alcoa. <https://cdn-api.swapcard.com/public/files/91a1f0fca8f24f12bd694e51a0e9976b.pdf> (accessed 16 January 2025).

[267] Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025).

[268] For example, smaller scale systems are expected to have initial capital costs of above $1620/kW. Cost conversions from EUR to AUD on 28/11/24. Bantle M, Schlemminger C, Tolstorebrov I, Ahrens M, Evenmo K (2018) Performance evaluation of two-stage mechanical vapour recompression with turbo-compressors. Proceedings of the 13th IIR Gustav Lorentzen Conference on Natural Refrigerants, Valencia. https://doi.org/10.18462/IIR.GL.2018.1157

[269] In 2020, it was noted that retrofitting costs may be in the range of $2-5 billion: Chatfield R (2020) Renewables and Electrification in Alumina Refining: 2020 Energy and Mines conference. Alcoa. <https://cdn-api.swapcard.com/public/files/91a1f0fca8f24f12bd694e51a0e9976b.pdf> (accessed 16 January 2025).

[270] Chatfield R (2020) Renewables and Electrification in Alumina Refining: 2020 Energy and Mines conference. Alcoa. <https://cdn-api.swapcard.com/public/files/91a1f0fca8f24f12bd694e51a0e9976b.pdf> (accessed 16 January 2025).

[271] https://arena.gov.au/assets/2024/06/Alcoa-MVR-for-Low-Carbon-Alumina-Refining-Close-Out-Report.pdfThe compressor had a compression ratio of 2 (i.e. a possible temperature increase in the vapour of 19°C). Alcoa (2024) Alcoa MVR for Low Carbon Alumina Refining Close-Out Report. <https://arena.gov.au/assets/2024/06/Alcoa-MVR-for-Low-Carbon-Alumina-Refining-Close-Out-Report.pdf> (accessed 16 January 2025).

[272] Economic viability is tied to compression ratios of about 2: Minton PE (1986) Handbook of Evaporation Technology. Noyes Publications, United States. Typically, these compressors sit at a compression ratio of 1.2 to 1.4 (i.e. 6-12°C uplift): AIChE (2018) Essentials of continuous evaporation. Chemical Engineering Progress Magazine. May 2018. <https://www.aiche.org/resources/publications/cep/2018/may/essentials-continuous-evaporation> (accessed 17 January 2025).

[273] **Saturated steam** is steam that contains the maximum amount of energy without additional heat turning it into superheated steam.

maintaining the higher temperatures required. Researchers are also exploring the ability to use sub-atmospheric vapour pressure as the MVR feed. This may require 6 to 7 stages of recompression, and the potential use of parallel compressors in the low pressure end due to the large size of equipment. Exploring MVR optimisation by using multiple recompression stages may raise costs and complexity, affecting MVR's efficiency and economic viability.

Auxiliary technologies

Renewable electricity infrastructure is essential for providing reliable and affordable power supply for MVR in alumina digestion.[274]

Current alumina refineries do not often have a high electricity demand as they rely on the combustion of natural gas or coal to produce thermal energy. The electricity demand required by MVR, while 33% of the power needed for an electric boiler and 25% of the power required for equivalent hydrogen generation,[275] will significantly increase electricity demand at alumina refineries that are traditionally powered by natural gas or coal. The introduction of MVR would mandate a several-fold increase in electricity demand by a refinery. These sites will require increased access to reliable renewable electricity. Where the grid does not have the capacity to rapidly accommodate for this uplift in electricity demand at this scale, this growth may rely on off-grid electricity generation and/or storage.[276]

The use of MVR in combination with double digestion, an energy efficiency technique, could enable further reduction in total energy requirements.[277]

5.6.6 Energy efficiency solutions

As energy is typically the largest operating cost for alumina refineries, ongoing R&D has focused on improving Bayer process energy efficiency.[278] The most energy efficient refineries to date achieve energy intensities of around 7 GJ per tonne of alumina, and under 0.54 GJ of electrical energy per tonne of alumina.[279]

Further RD&D in solutions that reduce energy use in medium-temperature steam is required. The solutions outlined in Table 23 are technology-agnostic with the ability to improve energy efficiencies for a range of technology types and systems. The suitability of these solutions will vary across brownfield and greenfield plants and will need to be assessed on a case-by-case basis considering site specific characteristics and requirements. Please note that individual plants may optimise for factors other than energy use. For instance, buffering capabilities may reduce the need for energy imports during periods of low availability, optimising performance by leveraging cost-effective energy sources.

Table 23: Energy efficiency solutions – Medium-temperature process steam

Energy efficiency solutions	RD&D opportunities
Heat exchangers and flash vessels *Can be used to transfer heat and steam from higher-temperature processes within the Bayer circuit (i.e.*	• More project-specific demonstrations of these conjoined structures are sought. In addition to improving energy efficiency, the recycling of steam can reduce overall consumption of fresh boiler steam. • This can only be used in conjunction with a shift to cleaner fuels (e.g. electricity, hydrogen) across the circuit. Maintenance issues like caustic corrosion and sodalite

[274] Climateworks Centre and Climate-KIC Australia (2023)

[275] Similarly to waste heat optimisation and heat pumps: Martin F (2005) Spent liquor evaporation using mechanical vapour recompression: A means of boosting evaporation capacity. <http://www.aqw.com.au/papers/item/spent-liquor-evaporation-using-mechanical-vapour-recompression-a-means-of-boosting-evaporation-capacity.html> (accessed 16 January 2025); Climateworks Centre and Climate-KIC Australia (2021) ; Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025).

[276] Mission Possible Partnership (2021) Closing the Gap for Aluminium Emissions. <https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Closing-the-Gap-for-Aluminium-Emissions.pdf> (accessed 16 January 2025).

[277] ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. <https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf> (accessed 16 January 2025).

[278] Henrickson, L. (2016). The Need for Energy Efficiency in Bayer Refining. In: Donaldson, D., Raahauge, B.E. (eds) Essential Readings in Light Metals. Springer, Cham. https://doi.org/10.1007/978-3-319-48176-0_96

[279] Unreleased CSIRO analysis.

calcination) to lower-temperature processes (i.e. digestion)	scaling can impede heat recovery for conventional fuels but are of less concern with cleaner fuels.[280]
Tube digestion *Replacement of the conventional shell-and-tube heat exchangers with jacketed pipe heaters*	• Additional demonstrations of tube digestion at scale are being undertaken. o Tube digestion can reduce the energy required for digestion by up to 15% through improved thermal efficiency.[281] The jacketed pipe heaters allow for maximised digestion temperature, and eliminate temperature dilution to limit energy consumption on the boiler.[282] o They can also operate at higher temperatures by using a molten salt heat transfer medium.[283] • Tube digestion simplifies equipment and lowers maintenance costs, as it can be constructed from standard piping materials that facilitate easier chemical and mechanical cleaning.[284] Its implementation simplifies plant design and allows a single-stream flow sheet to be employed. • Due to cost and space constraints, this technology is likely primarily suitable for greenfield sites. Conversion from most existing digester designs would necessitate a complete plant redesign.[285]
Double digestion *Lowers energy use by processing bauxite at lower temperatures first, dissolving 80% of the alumina. The remaining 20% is then processed at higher temperatures*	• 'Double digestion' is being trialled to minimise overall energy use where needed for higher temperature digestion. It can cut energy use by up to 30%.[286] It may be particularly useful while trials and integration testing are underway for higher temperature and pressure (i.e. 50-100 bar) electric boiler systems.[287]
MVR *The recycling and reuse of steam using a mechanical compressor*	• MVR needs to be further developed and demonstrated in the context of alumina digestion. It can be used to increase energy efficiency across the digestion process by supporting a primary technology. For additional detail, see Box 8.
Thermal energy storage (TES) *The integration of TES to catch residue heat*	• Researchers are determining which thermal media may be optimal for the durations and temperature ranges required by alumina refineries.[288] o They can also operate at higher temperatures by using a molten salt heat transfer medium.[289] TES can be a useful mechanism to harness residue heat from digestion or different parts of a process (e.g. calcination) to improve the

[280] Unreleased CSIRO analysis; Thomas, D. (2016). Heat Transfer in the Bayer Process. Donaldson, D., Raahauge, B.E. (eds) Essential Readings in Light Metals. Springer, Cham. https://doi.org/10.1007/978-3-319-48176-0_98. See also: CSIRO (n.d.) Hydrogen for Alumina. <https://www.csiro.au/en/research/environmental-impacts/fuels/hydrogen/Hydrogen-for-alumina> (accessed 17 January 2025). See Climateworks Centre and Climate-KIC Australia (2023)

[281] Climateworks Centre and Climate-KIC Australia (2021); Hatch (2020) Alumina tube digestion: Tubular heating for digestion of boehmitic bauxite. <https://www.hatch.com/Expertise/Services-and-Technologies/Alumina-Tube-Digestion> (accessed 17 January 2025).

[282] Haneman B (2016) Evolution of tube digestion for alumina refining. Hatch Associates. <https://icsoba.org/assets/files/publications/2016/AA01S.pdf> (accessed 17 January 2025).

[283] European Commission (2015) Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry. Joint Research Centre. <https://publications.jrc.ec.europa.eu/repository/bitstream/JRC96680/ldna27335enn.pdf> (accessed 16 January 2025).

[284] Haneman B (2016) Evolution of tube digestion for alumina refining. Hatch Associates. <https://icsoba.org/assets/files/publications/2016/AA01S.pdf> (accessed 17 January 2025).

[285] Australian Renewable Energy Agency (ARENA) (2021) Australian Industry Energy Transitions Initiative: Phase 1 Technical Report. <https://arena.gov.au/assets/2021/06/australian-industry-energy-transitions-initiative-technical-report.pdf> (accessed 16 January 2025); Chan Y, Petithuguenin L, Fleiter T, Herbst A, Arens M & Stevenson P (2019) Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis. <https://climate.ec.europa.eu/document/download/92ce3722-bd35-4508-87cf-1b02d7b1e72d_en> (accessed 17 January 2025); European Commission (2015) Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry. Joint Research Centre. <https://publications.jrc.ec.europa.eu/repository/bitstream/JRC96680/ldna27335enn.pdf> (accessed 16 January 2025).

[286] Rio Tinto (2024) Decarbonising Rio Tinto's Australian Alumina Refineries: Proceedings of the 12th International AQW Conference and Exhibition. <https://aqw.com.au/component/zoo/?task=callelement&format=raw&item_id=601&element=7a9fb9aa-c8cf-4e64-8a22-71d6f4c3ca3b&method=download> (accessed 16 January 2025).

[287] ARENA (2022) Roadmap for Decarbonising Australian Alumina Refining. https://arena.gov.au/assets/2022/11/roadmap-for-decarbonising-australian-alumina-refining-report.pdf (accessed 16 January 2025).

[288] Heavy Industry Low-carbon Transition Cooperative Research Centre (HILT CRC) (2024) Final project outcomes: Evaluation of Thermal Storage and MVR use to allow variable renewable input for steam in alumina production. Beath, A. (CSIRO) <https://hiltcrc.com.au/projects/program01-rp1002/> (accessed 31 March 2025).

[289] European Commission (2015) Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry. Joint Research Centre. <https://publications.jrc.ec.europa.eu/repository/bitstream/JRC96680/ldna27335enn.pdf> (accessed 16 January 2025).

	efficiency of digestion.[290] See the TES RD&D discussion in the *Electricity* technical appendix for additional information. o The presence of TES also provides improved thermal insulation, enhancing thermal management and decreasing energy losses.

[290] Climateworks Centre and Climate-KIC Australia (2023)

6 Mining heavy haulage

6.1 Executive summary

To meet performance requirements, low emissions technologies for mining heavy haulage require RD&D to achieve the necessary energy density improvements for on-board hydrogen or batteries.

Technology Landscape: Open-pit heavy haulage truck (299t carrying capacity)

Battery electric haul trucks (BEHTs) and fuel cell electric haul trucks (FCEHTs) are long-term decarbonisation options for Australia's mining sector, but the transition will also benefit from a focus on energy efficiency solutions.

Battery electric haul truck

- Charging infrastructure
- Off-grid production and storage infrastructure

Hydrogen fuel cell electric haul truck

- Hydrogen refuelling infrastructure
- On-grid hydrogen storage and distribution networks
- Off-grid production and storage infrastructure

Energy efficiency solutions

- Trolley assist
- In-pit crushing conveying
- Autonomous trucks
- Electro-mechanical flywheels
- Regenerative braking
- Digital fleet management tools/software

RD&D Opportunities

Battery electric haul truck	• As the battery pack is the primary cost driver and performance constraint for battery electric haul trucks (BEHTs), there are RD&D opportunities to help realise the energy dense, durable and cost-effective mobile battery systems needed for BEHTs to become widely adopted. • Improvements to the energy density of lithium-ion based batteries could support the cost-competitiveness of BEHTs by reducing the number of battery cells needed for a given capacity. • Exploring alternative battery chemistries that use earth abundant materials, or fewer critical minerals, could lower BEHT costs while maintaining their performance. • Optimising battery pack design and cell integration to maximise payload, alongside improvements to battery cycle life, could reduce total cost of ownership and improve BEHT utilisation. • Understanding how temperature, depth-of discharge and duty cycle characteristics such as haul road grade, length and terrain, impact batteries could extend their lifespan and lower replacement costs.
Fuel cell electric haul truck	• For fuel cells, the primary challenge for RD&D is to progress the technology and manufacturing economies of scale of Proton Exchange Membrane (PEM) fuel cells to be cost-competitive with diesel haulage engines. Research opportunities are focused on developing new catalyst materials or structures to improve fuel cell durability and minimise reliance on expensive materials, such as platinum. • For on-board hydrogen storage, improvements to the energy density of on-board hydrogen storage could improve the commercialisation and large-scale prospects of the technology. Current research directions include compression, cryo-compression and liquid storage prototypes, but RD&D is required to ensure safety due to the volatility of hydrogen gas at high pressures.

Auxiliary

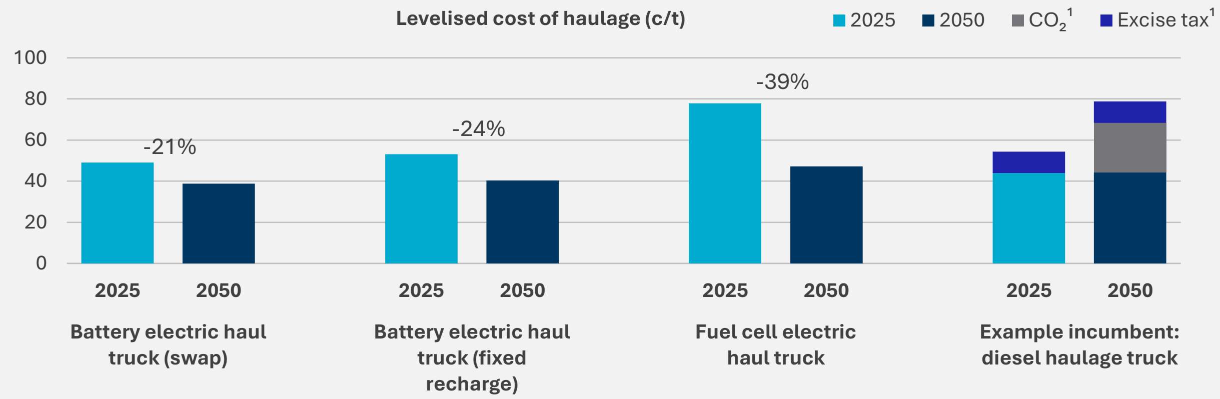
- RD&D is required to develop the necessary supporting infrastructure for the on-site deployment of BEHTs and FCEHTs. Developing advanced charging systems, improving hydrogen refuelling networks and expanding on-site renewable power cost-effectively will enable these technologies to support the subsector's transition.
- The development of advanced compression systems with lower energy consumption and operational costs is also required to improve the economics of on-board hydrogen storage.

Energy efficiency solutions
• In the near term, the high upfront costs of these technologies, combined with the need for extensive supporting infrastructure, are major barriers to initial investment and widespread adoption. A mix of energy efficiency solutions could support the subsector as it transitions, offering near-term cost and emission reductions that are technology-agnostic.

Levelised Cost Analysis

Open-pit heavy haulage truck (299t carrying capacity)

For heavy-duty haulage trucks, which demand significant energy consumption and high utilisation rates, large-scale fleet electrification or the integration of hydrogen fuel cells provide the most cost-competitive options in 2050.



1. Fuel excise: Is typically claimed back via a fuel tax credit for this use case. The perceived cost of diesel and renewable diesel haulage trucks would therefore not include this component, reducing their levelised cost.

2. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

6.2 Introduction

Mining heavy haulage is a key contributor to the mining sector's emissions. Global estimates suggest that heavy-duty diesel trucks are responsible for 68 million tons of CO_2 emissions annually.[291] A 2022 analysis revealed that, in Australia, heavy mining haulage in iron, bauxite, coal and other metal (copper, lithium, nickel and zinc) mines released 12.57 $MtCO_2e$, however this is considered an underestimate of actual emissions.[292]

Mining heavy haulage typically refers to the transport of large volumes (100 to 400 tonnes) of mined materials in open-pit or underground mining operations. It generally involves the use of specialised heavy-duty diesel trucks that have been engineered to navigate challenging conditions, including steep inclines (±10% grade). Trucks operate for long hours, typically accumulating around 6000 hours of use per year.

In practice, heavy haulage requirements vary considerably based on commodity, mining method, and individual mining operational characteristics. For example, heavy haulage trucks are more common in open-pit mining due to the lack of spatial constraints like tunnels or shafts. In contrast, underground mines extract smaller quantities of ore and use alternative low emission haulage methods, such as conveyor belts or load-haul-dump machines, better suited to confined spaces and short distances.

Due to their significant energy consumption, high emissions intensity, and demanding operational requirements, heavy-duty diesel trucks present as a decarbonisation challenge for the mining industry. While emerging solutions exist, decarbonising heavy haulage in mining remains challenging due to its critical operational role, the long lifespan of haul trucks, the cost of purchasing zero-emission alternatives, and the need to develop supporting infrastructure in remote mining regions – such as charging stations, hydrogen refuelling networks, and grid upgrades. RD&D can play a pivotal role in reducing the challenges associated with low emissions heavy haulage vehicles and their broader adoption.

This chapter presents an analysis of low emissions technologies for mining heavy haulage to identify technically feasible and cost competitive solutions. This informs an exploration of RD&D opportunities that could support the scale-up, de-risking, and deployment of these technologies.

6.2.1 Mining heavy haulage use case(s)

To explore low emissions technologies in the mining heavy haulage subsector, a single use case has been defined, reflecting an open-pit heavy haulage truck (see Table 24) Through the technology analysis framework, the technologies explored by this study meet select criteria associated with this use case.

This use case is representative of a heavy haulage truck with ≥200t payload capacity, operating in an open-pit mine with an incline of ±10%. Underground haulage has been excluded as an end use case from this report as these mines pose more complex challenges for electrification, such as ventilation for battery-operated equipment, limited space for charging stations, and stricter safety regulations. Decarbonising open-pit haulage is likely to yield more immediate and larger-scale emissions reductions.

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[291] Muralidharan R, Kirk T, Blank T (2019) Pulling the Weight of Heavy Truck Decarbonization: Exploring Pathways to Decarbonize Bulk Material Hauling in Mining. Rocky Mountain Institute. <https://rmi.org/insight/pulling-theweight-of-heavy-truck-decarbonization>

[292] Emissions estimates have been calculated based on figures adapted from the Australian Industry Energy Transitions Initiative Phase 1 report found here; Setting up industry for net zero – Australian Industry Energy Transitions Initiative Phase 1 report - Climateworks Centre and a University of Adelaide Mobile Mine report found here; FBICRC_Mobile-Mine-Report-VFINAL.pdf. These reports only capture a select few subsectors and processes, making the emissions estimates an underestimate of actual emissions.

This use case is illustrative and presents requirements that technologies must be able to meet to service Australia's mining heavy haulage subsector. In reality, operations in Australia are diverse and mining heavy haulage vehicles will differ in their required payload capacity and the design of the mine in which they operate.

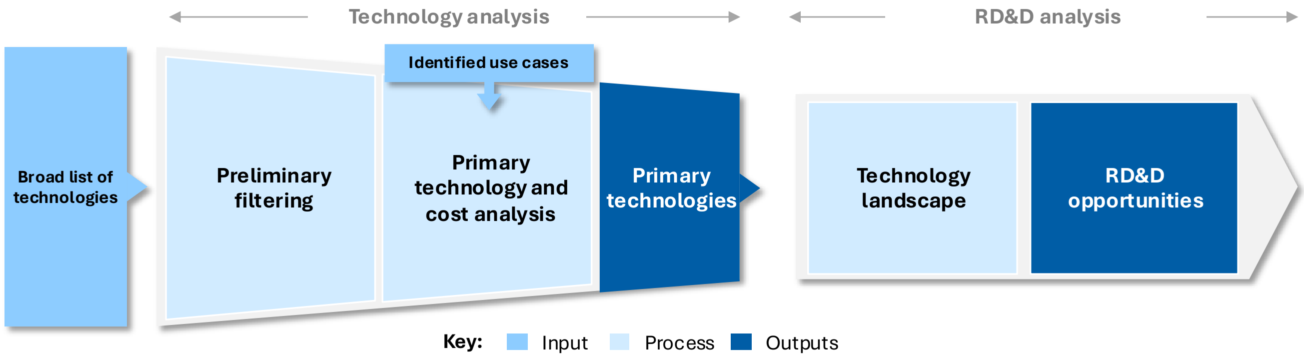
Table 24: Use case(s) – Mining heavy haulage

Use case(s)	Open-pit heavy haulage truck (299t carrying capacity)
Description:	Involves the use of highly specialised trucks to transport extracted ore, remove waste and build infrastructure. Trucks typically have ≥200t payload capacity, operate in open – pit mines and operate on an incline (±10%).

6.3 Methodology: Mining heavy haulage inputs and criteria

The methodology is comprised of several steps. Technology analysis was performed to first determine prospective technologies with the potential to contribute to decarbonisation across various heavy haulage vehicle types. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress (Figure 18).

Figure 18: Technology and RD&D framework for mining heavy haulage



6.3.1 Broad technology list

A broad technology list comprised of four technologies was developed (Table 25). These technologies were passed through three preliminary filters: Relevance to Australia, technological maturity, and abatement potential. The technologies that satisfied the preliminary filters were then assessed against the performance parameters for the relevant use case.

Table 25: Technology category definitions – Mining heavy haulage

Technology category	Definition
Diesel	Haulage trucks that employ a diesel internal combustion engine to produce electrical power.[293]

[293] Ahluwalia RK, Wang X, Papadias, DD, Star, AG (2023) Performance and Total Cost of Ownership of a Fuel Cell Hybrid Mining Truck. Energies, 16, 286. <https://doi.org/10.3390/en16010286>

Renewable diesel	Haulage trucks that employ a drop-in fuel, fully interchangeable with conventional hydrocarbon fuels and compatible with existing haulage trucks and their fuel infrastructure. Renewable diesel is typically derived from the hydrotreatment of oils and fats, or through Fischer Tropsch synthesis.[294]
Battery electric haul truck (BEHT)	Haulage trucks that that employ batteries to convert electrical energy into mechanical energy. An electric storage system can be used during idle periods to store recaptured braking energy.[295] Using a battery swap system, when the battery is depleted, the depleted battery is exchanged with a fully charged one at a dedicated battery swapping station. With fixed recharging, when the battery is depleted, the haul truck is replenished by connecting the vehicle to a charging station to restore energy to the battery.
Fuel cell electric haul truck (FCEHT)	Haulage trucks that employ a hydrogen fuel cell system to generate electric power and drive an electric traction system. The electric power generated can also be stored in an energy storage system and accessed during idle periods to preserve fuel or to store recaptured braking energy.[296]

6.3.2 Primary technology filters

The performance requirements and characteristics of mining heavy haulage trucks in open-pit mines are highly variable and dependant on the profile of the mine. Two performance parameters were selected to compare the suitability of identified technologies to an open-pit heavy haulage truck: **Truck utilisation (%)** and **Levelised Cost of Haulage (LCOH)** (Table 26). These are core operating requirements that will enable or limit technology uptake, particularly in mining applications that require high truck utilisation rates.

The thresholds for these parameters were ascertained based on the characteristics of a conventional diesel truck with a diesel electric drive system, a 1295 gallon fuel tank (4900L) and a 299 tonne payload capacity. The truck has an average duty cycle[297] of 0.24hr, a duty cycle distance of 3km and encompasses the following stages: loading; driving loaded up an incline on a flat road (maximum +10%); unloading on a flat road; and returning unloaded down the incline (-10%) on a flat road. It has an expected lifetime of 15 years.

The threshold for truck utilisation (85%) was determined by considering the utilisation of a diesel haulage truck and balancing it with an appropriate level of downtime in a high utilisation sector, while avoiding unrealistic targets that could prohibit this sectors progress towards adopting low emissions technologies and achieving net zero. The lowest cost low emissions technologies able to meet the truck utilisation threshold (85%) were progressed for further RD&D opportunity analysis. Further details on the selected parameters are provided in *Section 6.4.2 Primary technology analysis.*

Table 26: Technology filtering criteria – Mining heavy haulage

Subsector	Mining heavy haulage
Use case(s)	**Open-pit heavy haulage truck (299t carrying capacity)**
Preliminary filtering criteria	**Relevance to Australia**

[294] Brown A, Ebadian M, Saddler J, Nylund N, Aakko-Saska P, Waldheim L (2020) The Role of Renewable Transport Fuels in Decarbonizing Road Transport Production Technologies and Costs. Advanced Motor Fuels TCP and IEA Bioenergy TCP. AMF Annex <https://www.ieabioenergy.com/wp-content/uploads/2020/11/Production-Technologies-and-Costs.pdf>

[295] Climateworks Centre and Climate-KIC Australia (2023)

[296] Ahluwalia RK et al. (2023); Climateworks Centre and Climate-KIC Australia (2023)

[297] One operational cycle of a mining haulage truck, including the time and distance required to load, transport, unload material, and return to the loading site.

	Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions. *The criterion identifies constraining factors that may limit or prohibit technology adoption in the Australian context, including geographical constraints, legislation, or incompatibility with key domestic resources.*
	Technology maturity Technology has a TRL greater than 3. The TRL index can be found in *Appendix A.2.*
	Abatement potential Technology options are assessed against an abatement threshold of 90%, relative to a conventional diesel haulage truck.
Primary technology parameters	**Truck utilisation** Technologies that meet an acceptable rate of truck utilisation (%), compared to the typical utilisation of a conventional diesel haulage truck. It is defined as the ratio of truck operating time to truck operating time plus time taken to refuel/recharge/battery swap. It does not include downtime related to scheduled or unscheduled maintenance activities.
	Levelised Cost of Haulage (LCOH) Technologies projected to be cost competitive, distinguished by a cost differential in LCOH relative to other assessed technologies (in c/t).

6.4 Technology analysis

This chapter outlines the process of identifying *Primary technologies* for Australia's mining heavy haulage subsector. Following the technology analysis framework, **battery electric haul trucks (BEHT)** and **fuel cell electric haul trucks (FCEHT)** emerged as *Primary technologies* for further RD&D exploration. These technologies were able to service the designated use cases and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in mining heavy haulage decarbonisation, for specific use cases, and over time RD&D can lead to new technologies that can be considered. The results of the technology analysis for the mining heavy haulage subsector are provided in Table 27.

Meets filter criteria | Meets with caveats | Does not meet | ★ Primary technology | Not assessed further

Table 27: Technology analysis results – Mining heavy haulage

2. Primary technology analysis

Technologies	Maturity[298]	Abatement potential[298]	Open pit heavy haulage truck: Truck utilisation[299]	Open pit heavy haulage truck: LCOT 2050	
	TRL > 3	*≥90% decrease in emissions*	*>90%*	*c/t*	
Renewable diesel	TRL 9	44-78%			
Battery electric haul truck (BEHT)	TRL 7-9	97%	88-94% (battery swap) 76-88% (fixed recharge)	39c/t (battery swap) 40c/t (fixed recharge)	★
Fuel cell electric haul truck (FCEHT)	TRL 6-7	100%	92-95%	47c/t	★

[298] Details for these figures, including sources and assumptions, are found in Table 28 (Maturities), Table 37 (Abatement potentials) and in the levelised cost analysis found in *Section 6.4.2 Primary technology analysis* and *Technical Appendix: Levelised cost analysis*.

[299] This performance parameter defines an acceptable rate of truck utilisation (%), compared to the typical utilisation of a conventional diesel haulage truck operating within a 19-hour workday. Details for these figures, including sources and assumptions can be found in *Section 6.4.2 'Truck Utilisation'*.

6.4.1 Preliminary filtering

Key information – Preliminary filtering

Three criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:

- Relevance to Australia: Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.
- Technology maturity*:* Technology has a TRL greater than 3.
- Abatement potential: Technology demonstrates the potential to meet a nominated abatement threshold. The threshold for this sector is distinguished in the relevant filtering section, below.

Relevance to Australia

All of the technologies listed in Table 25 have met this criterion as they can be reasonably deployed to assist with the decarbonisation of Australian mines.

Technological maturity

All technologies assessed have a TRL greater than three, meeting the criteria (Table 28). The technologies needed to produce renewable diesel are at TRL 9. The fuel itself is fully commercialised and used in various industries, including mining. BHET and FCEHT technologies are currently being demonstrated and piloted in mining environments and are nearing operational readiness. For instance, Fortescue in collaboration with Liebherr has deployed a hydrogen-powered prototype haul truck for testing in the Pilbara region of Western Australia.[300] Refer to *Appendix A.2* for details on the Technology Maturity Rating Index.

Table 28: Technology maturities – Mining heavy haulage

Technology category	TRL
Diesel	• CRI 6
Renewable diesel	• TRL 9[301]
BEHT [302]	• Battery swap: TRL 7-9, fixed recharge: TRL 7-9
FCEHT[303]	• TRL 6-7

Abatement potential

Key information – Abatement potential

[300] Parkinson G (2024) Fortescue operates giant haul truck on hydrogen fuel cells for first time. The Driven. <https://thedriven.io/2024/05/23/fortescue-operates-giant-haul-truck-on-hydrogen-fuel-cells-for-first-time/>

[301] IEA Bioenergy (2023) Transport biofuels - Bioenergy Review 2023. <https://www.ieabioenergyreview.org/transport-biofuels/>

[302] Carrol D (2023) Fortescue powers ahead with battery electric truck testing. PV Magazine. <https://www.pv-magazine-australia.com/2023/08/24/fortescue-powers-ahead-with-battery-electric-truck-testing/>; IM International mining (2021a) XEMC's retrofitted 120 t all battery electric truck gets to work at Huolinhe coal mine. <https://im-mining.com/2021/07/26/xemcs-retrofitted-120-t-battery-electric-truck-gets-work-huolinhe-coal-mine/>; IM International mining (2021b) BELAZ all electric 90 t 7558E prototype mining truck starts testing in Zhodino. <https://im-mining.com/2021/05/06/belaz-electric-90-t-7558e-prototype-mining-truck-starts-testing-zhodino/>

[303] Liebherr (2024) Hydrogen-powered Liebherr T 264 truck arrives on site. <https://www.liebherr.com/en-sg/n/hydrogen-powered-liebherr-t-264-truck-arrives-on-site-55296-6060538>; Anglo American (2022) Press release - 2022: Anglo American unveils a prototype of the world's largest hydrogen-powered mine haul truck – a vital step towards reducing carbon emissions over time.

The abatement potential criterion identifies technologies that are meet or exceed a nominated abatement threshold. Emissions estimates reflect full fuel cycle emissions, including:

- Scope 1 (direct) emissions: arising from the direct use of a technology from the combustion or use of its fuel, including fugitives in some instances.
- Scope 2 (indirect) emissions: arising the production of a given energy input.
- Some Scope 3 emissions: For biofuels, indirect land-use change (ILUC) have been included for completeness; however, other Scope 3 emissions, such as embodied emissions have been excluded due to a lack of available data and low likelihood of impacting the relative results of the filtering criteria.

For more details, please refer to th*e Appendix A.4.*

The abatement potential was assessed against a conventional diesel truck with a diesel electric drive system, producing 299kgCO_2 per operational cycle. The operational cycle encompasses a waiting/loading period; driving, loaded, up an incline on a flat road (maximum +10%); unloading on the flat road; and returning, unloaded, down the incline (-10%) on the flat road. The conventional diesel truck assumes a 236-tonne payload capacity and has a 2098 second operational cycle that covers a total distance of approximately 12km.[304]

Emissions estimates (Table 29) reflect the full fuel-cycle, encompassing both well-to-tank (WTT) emissions from fuel production, and tank-to-wheel emissions (TTW) from fuel use. These estimates are based on models from international academic literature. The diesel, FCEHT, BEHT (swap) and BEHT (fixed) emissions estimates were extracted from a model by Feng et al. [305] The emissions estimates for renewable diesel were taken from secondary analysis of results from the US Argonne National Laboratory's GREET Model.[306] Please note, these models were not designed in reference to domestic mining and energy sectors. Therefore, they may not directly reflect exact emissions reductions in the Australian setting.

A 90% abatement potential threshold was set for mining haulage to reflect the availability of cost competitive low emissions technology solutions by 2050 and the challenges of decarbonising energy-intensive modes of transportation. This threshold also takes into account residual emissions in the grid, recognising that some fossil fuel capacity is likely to remain in the long-term. See the *Appendix A.4* for further detail.

[304] Ahluwalia RK, Wang X, Papadias, DD, Star, AG (2023) Performance and Total Cost of Ownership of a Fuel Cell Hybrid Mining Truck. Energies, 16, 286. <https://doi.org/10.3390/en16010286>

[305] Feng Y, Liu Q, Li Y, Yang Jue, Dong Z (2022) Energy efficiency and CO2 emission comparison of alternative powertrain solutions for mining haul truck using integrated design and control optimization. Journal of Cleaner Production, 370, 133568.

[306] GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. Secondary analysis obtained from: Xu H, Ou L, Li Y, Hawkins TR, Wang M (2022) Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. Environmental Science & Technology. 2022 May 16;56(12):7512-21.

Table 29: Abatement potentials – Mining heavy haulage

	ASSUMPTIONS		RESULTS				
Technology	**Total energy consumption** *kg or kWh*	**Fuel emissions intensity** *$kgCO_2/kg$ (or kWh) fuel*	**Well-to-tank** *kg of CO_2*	**Tank-to-wheel** *kg of CO_2*	**Well-to-wheel** *kg of CO_2*	**Abatement potential** *Threshold: 90%*	**Sources/ assumptions**
Conventional diesel	**76kg**	**3.96**	**50**	**249**	**299**		
Renewable diesel	78kg[307]	0.85-2.12	*Breakdown unavailable*		70-174	44-78%[308]	Emissions intensities derived from Xu et al. (2022) and Cai et al. (2022).[309] Includes ILUC. Lower bound reflects a diesel from Canola; upper bound reflects used cooking oil.
FCEHT	21kg	zero	-	-	-	100%	Hydrogen production facility is assumed to operate at 60% utilisation, aligning with 100% VRE generation.
BEHT (swap)	323 kWh	0.03	10	-	10	97%	Energy consumption from Feng et al.[310] Grid intensity determined via internal analysis.
BEHT (fixed)	323 kWh	0.03	10	-	10	97%	Energy consumption from Feng et al. Grid intensity determined via internal analysis.

Meets filter criteria | Meets with caveats | Does not meet

307 Assumes the renewable diesel has approximately 96% of the energy of diesel. U.S. Department of Energy's Vehicle Technologies Office (n.d.) Fuel Properties Comparison. <https://afdc.energy.gov/fuels/properties>

308 Xu H et al. (2022).

309 Emissions intensities from these sources were converted from kgCO2/MJ to kgCO2/kg fuel using an energy density of 39.36 MJ/kg. Xu H et al. (2022); Cai H, Prussi M, Ou L, Wang M, Yugo M, Lonza L, Scarlat N (2022) Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy and Fuels 6, 4398. <https://doi:10.1039/d2se00411a>

310 Assumes a grid intensity of 0.0307kgCO_2-e per kWh, based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas, with the remainder generated from renewable resources and assumed to produce no direct emissions. Feng Y, et al. (2022)

FCEHTs

Hydrogen FCEHTs meet the filter, owing to the potential for zero emissions hydrogen production via electrolysis.

Hydrogen electrolysis facilities are assumed to operate with a 60% utilisation factor in 2050: aligning with electricity generation from variable renewable energy (VRE). Only operating electrolysers when renewable generation assets are online can enable zero emissions hydrogen production and allow for cost savings compared to higher utilisation rates (see *Low Carbon Fuels* technical appendix).

BEHT

BEHTs (swap and fixed) meet the filter, on the basis that electricity-based systems will draw on a heavily decarbonised grid with low emissions intensity. These figures assume a grid intensity of 0.0307kgCO_2-e per kWh, based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas and the remainder is generated from renewable resources and assumed to produce no direct emissions.[311]

The modelled results by Feng et al. leverage an integrated design and control optimisation method to compare the energy efficiency and CO_2 emissions of these alternative powertrain solutions across the operational profile described above. Based on the energy consumed over this operational cycle, and the total emissions factors determined, BEHTs (swap and fixed) satisfy the abatement threshold criteria.

Renewable diesel

Renewable diesel does not meet the filter when accounting for the impacts of direct and indirect emissions. Despite being a viable short-term solution to decarbonise the mining haulage subsector due to its drop-in nature (see Box 9), the emission abatement potential of renewable diesel does not meet the 90% threshold.

The WTT emissions includes emissions from land use change, feedstock production, oilseed crushing, fat rendering, conversion processes, transportation and combustion. An emissions range is provided, reflecting various feedstocks and pathways for renewable diesel production. Total emissions vary significantly, depending on the lifecycle analysis of the feedstocks and the production methods used. Due to the indirect impacts of land use change, first-generation feedstocks (canola, soybean) have a lower abatement potential (40-55%) compared to second-generation sources (used cooking oil, ~75%).[312]

Other literature suggests that switching to renewable diesel can decrease the carbon emissions of a 400t mining haulage truck by 55-85% depending on the carbon intensity of the electricity source used in production.[313] In each case, TTW emissions are assumed to be zero, where the CO_2 emissions from combusting renewable diesel is offset by the CO_2 absorbed during plant growth.

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[311] Internal analysis. Emissions factors of new entrants obtained from ACIL Allen Consulting (2016) AEMO Emissions Factors. Australian Energy Market Operator (AEMO). <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/ntndp/2016/data_sources/acil-allen---aemo-emissions-factors-20160511-pdf-document.pdf?la=en&hash=AB233ACCECC78768D7C236E307433C10>

[312] Xu H et al (2022); Cai H, Prussi M, Ou L, Wang M, Yugo M, Lonza L, Scarlat N (2022) Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy and Fuels 6, 4398.

[313] McKinsey & Company (2021) Creating a the zero-carbon mine. <https://netzerohub.id/wp-content/uploads/2022/02/creating-the-zero-carbon mine-vf.pdf>

Box 9: The impact of renewable diesel on the short-term decarbonisation of mining haulage fleets

Renewable diesel could significantly aid the short-term decarbonisation of existing Australian fleets, as longer-term solutions continue to be developed. Although electric and hydrogen-powered vehicles are emerging as alternatives to diesel for light passenger and commercial vehicles (see the *Transport* technical appendix), their commercial viability for mining haulage trucks remains limited. Renewable diesel could function as a practical 'drop in' option to service existing haulage fleets until retirement, as replacing these vehicles before their end of life is not economically viable.

Interest in renewable diesel as a short-term decarbonisation strategy for mining haulage fleets has been growing.[314]

6.4.2 Primary technology analysis

Key information – Primary technology analysis

Two criteria were employed to ensure the suitability and feasibility of each technology for the use case applications determined.

- Truck utilisation: Technologies that meet an acceptable rate of truck utilisation (%), compared to the typical utilisation of a conventional diesel haulage truck operating within a 19-hour workday. It is defined as the ratio of truck operating time to truck operating time plus time taken to refuel/recharge/battery swap. It does not include downtime related to scheduled or unscheduled maintenance activities.
- Levelised Cost of Haulage (LCOH): Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive.

Truck utilisation

Truck utilisation has been used as the performance filter for mining heavy haulage trucks, given the importance of minimising truck downtime for production efficiency and reducing total operating costs. Here, truck utilisation is defined as the ratio of truck operating time to truck operating time plus time taken to refuel/recharge/battery swap.

The threshold for truck utilisation (85%) was determined as an appropriate level of downtime in a high utilisation sector, while avoiding unrealistic targets that could prohibit this sectors progress towards adopting low emissions technologies and achieving net zero.

This calculation of truck utilisation is for comparative purposes only. It assumes that the trucks are operating continuously with no down time between duty cycles, and no down time pre- and post-refuel/recharge/battery swap. It is based on a duty cycle that takes 14.4 minutes (0.24 hours) to complete, covering approximately 3km. All trucks have an assumed carrying capacity of 299 tonnes and the weights of the battery and fuel cell have been modelled to not impact payload capacity. It does not consider fluctuations in energy consumption along the operational profile of the mine, such as higher energy use during more demanding sections like inclines. These assumptions are based on those used to model the levelised cost of haulage across all technology types (see *Technical Appendix: Levelised cost analysis*). [315]

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[314] DCCEW (2023) Enabling supply of renewable diesel in Australia: a consultation paper on establishing a paraffinic diesel fuel standard for Australia. Department of Climate Change, Energy, the Environment and Water, Commonwealth of Australia. Canberra. CC BY 4.0. <https://consult.dcceew.gov.au/supply-of-renewable-diesel-australian-paraffinic-diesel-fuel-quality-standard>

For example, Rio Tinto has transitioned all heavy mining equipment at its Kennecott copper mine in Utah from conventional to renewable diesel. Renewable diesel is 90% soybean and 10% animal fat and used cooking oil. In total, 97 haul trucks are fuelled by renewable diesel, expected to reduce the mine's Scope 1 emissions by 450,000 tonnes. Rio Tinto (2024) Rio Tinto transitions to renewable diesel at Kennecott. <https://www.riotinto.com/en/news/releases/2024/rio-tinto-transitions-renewable-diesel-at-kennecott>

[315] The levelised cost model was based on data from two sources: Bao Hm Knights P, Kizil M, Nehring M (2024) Energy Consumption and Battery Size of Battery Trolley Electric Trucks in Surface Mines. <https://doi.org/10.3390/en17061494>; Ahluwalia R.K, Wang X, Papadias D.D., Star A.G (2023) Performance and Total Cost of Ownership of a Fuel Cell Hybrid Mining Truck. Energies 2023, 16, 286 <https://doi.org/10.3390/en16010286>.

The utilisation rates calculated, and results of this filter for all technology types, are presented in Table 30, with additional detail on methodology and assumptions found in *Appendix A.3.3.*

Table 30: Truck utilisation rates by technology – Mining heavy haulage

	Unit	Diesel	Battery swap	Battery fixed	Fuel cell
Fuel volume	-	4145kg	2546 kWh	2546 kWh	777kg
Fuel density	kWh/kg	11.83	-	-	33.33
Energy capacity	kWh	49,054	-	-	25,900
Efficiency	%	20	-	-	36
Usable energy	kWh	9810.78	-	-	9324
Energy consumption per duty cycle	kWh/cycle	126	202	202	126
Duty cycles per refuel/recharge/battery swap	-	77	6	6	74
Total operating hours per refuel/recharge/battery swap	hr	18.94	1.46	1.46	18.01
Lower bound					
Refuelling time	hr	0.9	0.33	0.75	0.98
Utilisation	%	**95%**	**82%**	**66%**	**95%**
Upper bound					
Refuelling time	hr	0.2	0.167	0.33	0.55
Utilisation	%	**99%**	**90%**	**82%**	**97%**

Meets performance parameter   Meets with caveats   Does not meet

BEHTs

BEHTs with a battery swap configuration meet this performance parameter at the upper bound but fall short at the lower bound. In contrast, BEHTs dependent on a fixed charging configuration do not currently meet this performance filter. These results suggest that BEHTs using a swap model could become competitive with incumbent diesel technology due to their ability to match operational demand. However, BEHTs dependent on a fixed charging configuration do not currently match the required operational efficiency.

Improvements in charging technology and supporting infrastructure, such as increased charging capacity, increased charging speeds and high voltage grid upgrades, could improve the speed and efficiency of fixed charging systems. This could, in turn improve the utilisation of BEHTs that rely on fixed charging. Both battery swap and fixed charging configurations will also benefit from improved battery technology, such as increased energy density. Ongoing RD&D efforts are focused on these improvements to further increase BEHT utilisation. *Section 2.3.1* outlines RD&D opportunities that aim to achieve these advancements.

Given the current utilisation range of 66-90% and the potential to improve lower end performance, BEHTs meet this performance parameter with caveats.

FCEHTs

FCEHTs meet this performance parameter. While their refuelling time is slightly longer than the time taken to refuel incumbent diesel technology, the improved efficiency of FCEHTs make their utilisation (%) just as competitive.

Similar to diesel, the refuelling rate for FCEHTs is likely to vary depending on the refuelling protocols and systems used at each mine. Moreover, the refuelling rate is also impacted by the form of hydrogen storage (gaseous or liquid), tank pressure, temperature control, dispenser flow rate, boil off and transfer efficiency.

Shorter refuelling durations, improved hydrogen storage and enhanced fuel cell characteristics, are expected to improve the utilisation rate of FCEHTs. *Section 2.3.1* outlines RD&D opportunities that aim to achieve these advancements.

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Haulage (LCOH) was estimated to determine the viability of each technology considered. LCOH is defined as the average net present cost per unit of output (in cents/tonne), over a mining haulage truck's lifetime.

Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis.*

For reference:

- Some technologies that did not meet earlier filtering criteria have been included for completeness, where information was available – however, these were not assessed.
- Costs of new deployments are estimated using the projected fuel, operational, capital and integration costs in 2025 and 2050 to understand the potential for shorter-term and longer-term solutions.
- A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, contributing to the levelised cost of that technology in the long-term. No CO_2 emission cost has been assumed for 2025.

Results from the levelised cost analysis are outlined in Figure 19. **BEHTs and FCEHTs were projected to be competitive technologies,** distinguished by a cost differential in LCOT relative to other assessed technologies; suggesting areas of promise for further RD&D activity.

Levelised cost analysis was conducted for mining haulage to determine which low emissions technology solutions could be viable in the future. This measure reflects the average net present cost per unit of output (in cents/tonne), over a mining haulage truck's lifetime. The levelised costs are estimated in 2025 and 2050, to understand the potential for shorter-term and longer-term solutions.

The assessment is based on a mining haulage truck operating on a deep surface level mine.[316] Drawing on a simulation study by Terblanche et al.,[317] the truck is assumed to shift 7,380,464 tonnes per year across 6000 hours of annual usage. Operational conditions include a duty cycle time of 876 seconds, a duty cycle distance of 3482 metres, an ascent distance of 1005 metres, an ascent grade of 10% at 12 km/h and a utilisation rate of 19 hours per day.[318] Results are presented in Figure 19.

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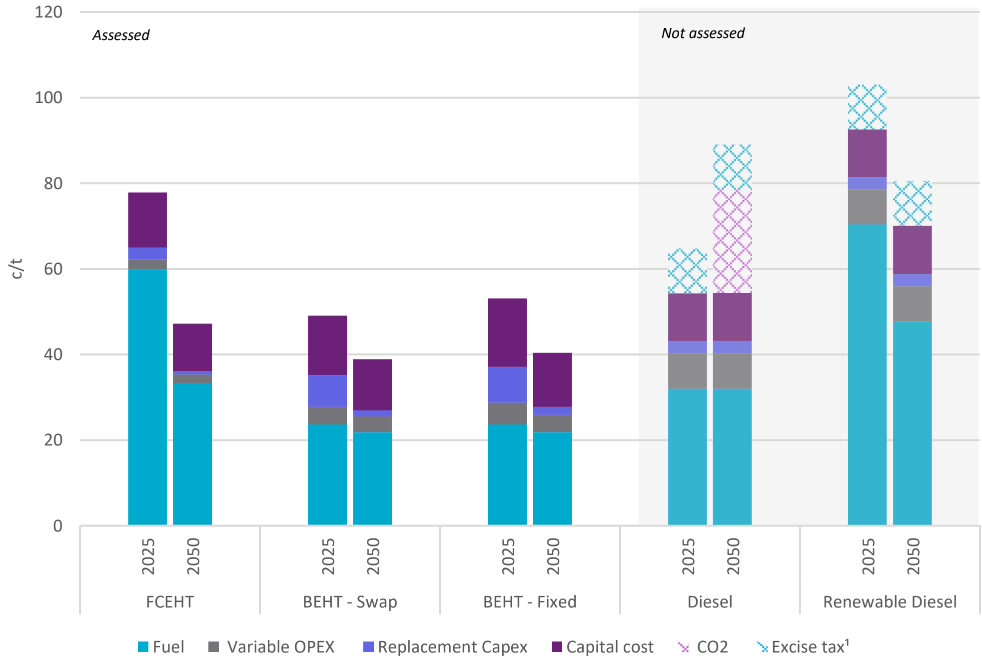
[316] A deep surface level mine is a mine that is considered surface mining but has relatively deep ore bodies, requiring significant excavation or overburden removal to reach the desired material. These mines are usually considered open-pit mines.

[317] Terblanche PJ, Kearney, MP, Nehring M, Knights PF (2018) Potential of on-board energy recovery systems to reduce haulage costs over the life of a deep surface mine. Mining Technology, 128(1), 51–64. https://doi.org/10.1080/25726668.2018.1554933

[318] Ahluwalia RK et al. (2023)

Figure 19: Levelised cost of mining haulage (c/t) – Mining heavy haulage



The replacement capex is modelled higher than diesel for BEHTs (swap and fixed) and FCEHTs in 2025, reflecting the shorter lifetimes of their batteries and their fuel cells. Diesel haulage trucks are modelled to have higher variable opex, reflecting the additional maintenance required for their diesel generators.

Conventional diesel trucks are the only technology considered for this use case that produce CO_2 emissions, impacting their cost viability by 2050. Renewable diesel trucks emit tailpipe emissions, however the CO_2 released is considered biogenic, which helps offset total emissions over the fuel's lifecycle. Therefore, these trucks are not subject to CO_2 emissions costs.

The potential for a fuel tax credit is shown in both 2025 and 2050 as a separate cost component to fuel cost. This reflects the ability per current legislation for businesses to claim a tax credit on excise tax paid on fuel used in machinery such as haulage trucks.[319] This excise tax and tax credit applies to both diesel and renewable diesel. This is significant in 2025, as the tax credit improves the cost competitiveness of fossil fuels. Despite this, LCOH analysis for 2025 indicates that BEHT are cost-competitive even at this early stage of the transition.

BEHTs

BEHTs (swap and fixed) are modelled to be relatively competitive with diesel haulage trucks in 2025 and achieve the lowest levelised cost of haulage in 2050, regardless of carbon pricing effects. This is driven by a decrease in electricity and battery costs, and an increase in battery lifetimes. The levelised cost of recharging infrastructure has been included in the electricity price. The higher capex of the battery swap technology is modelled to be outweighed by the higher utilisation it can achieve through reduced recharging time. This results in a slightly lower levelised cost relative to the fixed battery BEHT.

[319] See: Australian Taxation Office (2024) Fuel tax credits – business. Commonwealth of Australia. <https://www.ato.gov.au/businesses-and-organisations/income-deductions-and-concessions/incentives-and-concessions/fuel-schemes/fuel-tax-credits-business>

FCEHTs

FCEHTs are modelled to have the second highest levelised costs in 2025, primarily due to the high cost of hydrogen. This technology is modelled to become competitive with diesel trucks in 2050, regardless of carbon pricing effects, primarily due to an assumed reduction in hydrogen price.

Renewable diesel

While not explored in this report due to the presence of emissions, renewable diesel may be an intermediary solution in the near-term, for infrequent, long distance freight routes that lack sufficient charging infrastructure, supported by its 'drop-in' nature. Cost analysis has been conducted for reference; however, further analysis was not performed.

As a drop-in fuel, renewable diesel haul trucks incur similar capex and opex costs to a diesel mining haulage truck, where the overall cost competitiveness remains dictated by fuel price. Feedstock costs, production processes and a lack of infrastructure increase the overall cost of renewable diesel. Feedstock prices are heavily susceptible to price fluctuations and face competition for other uses (e.g., food, recycling, animal feed, export) and other biofuel production (i.e., sustainable aviation fuels), further constraining large-scale production and adoption.

Though renewable diesel is estimated to be less costly that conventional diesel haulage in 2050 when accounting for a CO_2 emission cost, it is more costly than other technology solutions.

6.5 Technology landscape

Key information – Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the RD&D opportunity analysis and capture the complexity of the energy system networks and their interdependencies with other technological systems. This was informed by literature review and stakeholder input, and comprised of:

Use case

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

The technology analysis framework identified BEHTS and FCEHTs as *Primary technologies* for an open-pit heavy haulage truck use case (Figure 20).

Although not explored further, the other low emissions technologies evaluated in this report (Table 25) could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the mining heavy haulage subsector. Further RD&D could unlock breakthrough innovations in these technologies, highlighting the need for ongoing assessments to maintain Australia's understanding of the current state of low emissions technologies and future opportunities for RD&D.

Figure 20: Technology landscape – Mining heavy haulage

Battery electric haul truck

- Charging infrastructure
- Off-grid production and storage infrastructure

Fuel cell electric haul truck
• Hydrogen refuelling infrastructure • On-grid hydrogen storage and distribution networks • Off-grid production and storage infrastructure

Energy efficiency solutions

- Trolley assist
- In-pit crushing conveying
- Autonomous trucks
- Electro-mechanical flywheels
- Regenerative braking

The associated *Auxiliary technologies* and *Energy efficiency solutions* identified for analysis are outlined in Table 31 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Auxiliary technologies

BEHTs and FCEHTs cannot exist in isolation and their successful use and deployment is dependent on a range of *Auxiliary technologies*, summarised in Table 31.

Table 31: Auxiliary technologies – Mining heavy haulage

Primary Technology	Auxiliary Technology	Description
BEHTs	Charging infrastructure	Charging systems that transfer electricity via physical connection (conductive) or wireless (inductive) and are capable of providing charging power outputs across various levels, including: • Level 3, fast-charging: 250-350kW • Level 3, fast-charging: 350kW-1MW Level 4 ultra-fast charging: >1MW
	Off grid production and storage infrastructure	Technologies that enable the generation (wind, solar PV, hydro) and storage of electrical energy (battery storage, thermal energy storage) independent of centralised power grids.
FCEHTs	Hydrogen refuelling technologies	Technologies that enable the safe transfer (compression systems, dispensers, nozzles) of hydrogen from storage to FCEHTs at an appropriate pressure and temperature.
	On-grid hydrogen production, storage and distribution.	Technologies that enable the production of hydrogen using power from the centralised grid, store this power and distribute this power to various end use applications.
	Off-grid hydrogen production, storage and distribution.	Technologies that enable the production (electrolysers) storage (compressed H2 tanks, cryogenic storage) and distribution (pipelines, mobile storage units) of hydrogen within a mining site.

Energy efficiency solutions

For mining heavy haulage transport, there are a range of *Energy efficiency solutions* that will also support emissions mitigation efforts. The solutions outlined in Table 32.

Table 32: Energy efficiency solutions – Mining heavy haulage

Energy efficiency solution	Description
Trolley assist system	A trolley assist system in open-pit mining uses electric energy from the mine's grid to propel haul trucks along designated segments of the haul road, reducing fuel consumption and

	emissions. It also has the potential to increase the speed of the trucks.[320] Rectifier substations are required to provide AC power to trolley assist systems at intermittent intervals.[321]
In-pit crushing conveying (IPCC) system[322]	A system that breaks down mined material into smaller pieces and transports this material via conveyor belts to the processing plant or waste dump outside of the pit.
Electro-mechanical flywheels[323]	A system that stores kinetic energy by spinning a rotor at high speeds and converting it back into electrical energy to assist with acceleration and energy recovery.
Regenerative braking	The process where kinetic energy is recovered during braking and converted into electrical energy which is then stored in a battery or energy storage system.
Autonomous trucks	Autonomous haulage trucks are self-driving vehicles used in mining operations to transport materials without the need for a human driver.

6.6 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D specific opportunities for the identified technology landscape, spanning primary, auxiliary and energy efficiency technologies.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include non-technical RD&D opportunities. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

A summary of RD&D opportunities can be seen in Table 33. For some technologies, these opportunities are associated with specific technology subcomponents. Technologies typically consist of different system components, that are integrated or work in tandem, which may have specific RD&D needs or be at different stages of technology maturity. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9).

Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

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[320] For example, a pilot trolley assist system reduced diesel use and emissions by up to 30%. The trolley assisted haulage trucks demonstrated speeds over twice that of diesel haulage trucks and completed haul ramp climbs at 1/12th of the cost. Rolfe K (2022) All in on trolley assist, CIM Magazine. <https://magazine.cim.org/en/environment/all-in-on-trolley-assist-en/> (accessed 15 January 2025)

[321] Cruzat JV, Valenzuela MA. Modeling and evaluation of benefits of trolley assist system for mining trucks. IEEE Transactions on Industry Applications. 2018 Apr 4;54(4):3971-81. DOI: 10.1109/TIA.2018.2823261.;

[322] Osanloo M, Paricheh M (2019) In-pit crushing and conveying technology in open-pit mining operations: a literature review and research agenda. International Journal of Mining, Reclamation and Environment, 34(6), 430–457. https://doi.org/10.1080/17480930.2019.1565054

[323] Terblanche PJ, Kearney MP, Nehring M, Knights PF. (2019) Potential of on-board energy recovery systems to reduce haulage costs over the life of a deep surface mine. Mining Technology.;128(1):51-64. https://doi.org/10.1080/25726668.2018.1554933

Table 33: Summary of RD&D opportunities – Mining heavy haulage[324]

Primary technologies

	Battery electric haul truck			Hydrogen fuel cell electric haul truck	
	Battery chemistries				
	Metal-ion	Metal-S	Solid state	Fuel cell	On board storage
Commercial	Li-ion	-	-	-	-
Mature	Na-ion	-	-	PEM	Physical storage (Compressed, cryo-compressed, liquid H_2)
Emerging	Mn-ion	Li-S	Li-sulphide, Li-oxide	-	-

Primary RD&D

Battery electric haul truck	Hydrogen fuel cell electric haul truck: Fuel cell	Hydrogen fuel cell electric haul truck: On board storage
• Reduce battery cell costs **(Target: $117/kWh, cf. $229/kWh)** through: - E.g. Improving energy densities **(Target: Li-ion, 320-500Wh/kg, cf. 220-260Wh/kg)**[325] - E.g. Increasing battery lifetime - E.g. Exploring alternative battery chemistries that reduce reliance on critical minerals while maintaining performance - E.g. Optimising battery cell integration through cell-to-pack or cell-to-chassis designs	• Reduce fuel cell costs **(Target: $240/kWh, cf. $681/kWh)** through: - E.g. Designing alternative fuel cells with novel, lower cost catalysts or electrode materials - E.g. Enhancing performance including by improving fuel cell designs (i.e., hybridisation, cell architecture etc.)	• Improve the efficiency and safety of onboard storage systems through: - E.g. Developing advanced materials that prevent leakage and degradation - E.g. Developing advanced compression systems with lower energy consumption

Auxiliary RD&D

Battery electric haul truck	Hydrogen fuel cell electric haul truck
• Develop electric vehicle supply equipment through: - E.g. Developing ultra-fast, static wireless, dynamic wireless and contact charging systems (for additional RD&D opportunities see the *Transport* technical appendix) • Improve the scalability and interoperability of battery swapping systems • Establish of off-grid/on-grid energy production and storage infrastructure	• Support adoption through the development of hydrogen refuelling infrastructure (on grid and off grid) • For Hydrogen production, distribution and storage RD&D opportunities, see *Low Carbon Fuels* technical appendix.

[324] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6; Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

[325]Fraunhofer Institute for Systems and Innovation Research ISI (2023) Alternative Battery Technologies Roadmap 2030+. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf>

6.6.1 Battery electric haul truck (BEHT)

BEHTs use large-format rechargeable batteries to power electric motors for traction. The battery pack stores electrical energy, which is delivered to one or more traction motors via a power control system. These vehicles include regenerative braking systems that recover energy during deceleration, improving overall efficiency. Current battery systems are typically Li-ion chemistries optimised for high energy density and thermal stability, with integrated battery management systems to ensure safe operation and performance.

BEHTs are commercially demonstrated in mining and heavy-duty haulage applications. They operate high torque at low speeds making them suitable for extreme duty cycles and terrain.

Primary technologies

RD&D will be essential to help realise the energy dense, durable and cost-effective mobile battery systems ($/kWh) needed for BEHTs to become widely adopted in open pit mines.

To date the size, quantity and cost of battery systems for mining haulage trucks is significant, making it difficult for BEHTs to achieve operational outcomes. The battery pack is the primary cost driver and technical constraint, with energy and volumetric densities not yet competitive with diesel engines.[326] This section highlights RD&D opportunities that could help achieve cell level targets of $117/kWh (cf. $229/kWh)[327], without compromising truck utilisation (>19hrs/day) and performance.

Improving the energy density of Li-based batteries could help reach BEHT cell-level cost forecasts.

Increasing energy density reduces the number of battery cells needed to power a vehicle. This reduces initial material and manufacturing costs, as well as total on-board storage weight. As a result, researchers are exploring alternate Li-ion battery chemistries with improved densities, such as solid-state Li-S (TRL 4-5) and Li-NMC (TRL 4-5) batteries. These battery chemistries have improved volumetric density and increased range and compared to conventional Li-ion batteries, offer a safer alternative to liquid-electrolytes. They are estimated to have energy densities of 410Wh/kg and 350Wh/kg and volumetric densities of up to 770Wh/L and 1000Wh/L, respectively.[328]

Increasing battery lifetimes could lower the total cost of ownership and improve utilisation of BEHTs.

High utilisation rates, heavy load duty cycles and deep discharge patterns accelerate battery cell degradation and shorten overall battery life in mining haulage applications.[329] Researchers are therefore exploring battery chemistries with higher cycle life, such as Lithium Titanate Oxide (LTO) batteries.[330] LTO batteries have higher cycle life than $LiFePO_4$ and Li-NMC types, however significantly lower energy density.[331] RD&D is needed to

[326] Assuming a 20% engine efficiency, the usable energy of a 4900L tank is 9810 kWh as sourced from; Ahluwalia R.K, Wang X, Papadias D.D, Star A.G (2023) Performance and Total Cost of Ownership of a Fuel Cell Hybrid Mining Truck. <https://doi.org/10.3390/en16010286>

[327] Levelised cost forecasts per CSIRO levelised cost analysis. On a vehicle level, this would translate to about $8.6 million per vehicle by 2050 (compared to $9.3 million in 2025).

[328] Schmaltz T, Wicke T, Weymann L, Voß P, Neef C, Thielmann A (2022) Solid-State Battery Roadmap 2035+. Fraunhofer Institute for Systems and Innovation Research ISI. NMC = nickel manganese cobalt.

[329] Voeltzel N, Shirazy M, Frechette L, Fillion S (2021) Extending Battery Lifetime of Electric Mining Vehicles through Thermal and Duty Cycle Management. SAE Technical Paper 2021-01-0223, SAE International, Warrendale, PA.

[330] Mehta N, Patel P R (2024) Innovations in Lithium-Titanium Oxide (LTO) Battery Technology Coupled with Advanced Battery Management System Strategies for Electric Vehicles. Journal of East-West Thought 14(4), 1398–1417; RK Consulting (2024) TCO equation stacks up for 150-t payload battery-electric trucks, SRK report shows. International Mining, 25 October. <https://im-mining.com/2024/10/25/tco-equation-stacks-up-for-150-t-payload-battery-electric-trucks-srk-report-shows/>

[331] SIKE Battery (n.d.) Comprehensive comparison : NMC vs LFP vs LTO batteries. SIKE Battery, <https://www.sikebattery.com/comprehensive-comparison-nmc-vs-lfp-vs-lto-batteries/#elementor-toc__heading-anchor-3>

improve battery lifetime and optimise battery pack design and cell integration in a way that balances energy density, cycle life and cost. Further research into the impact of temperature, depth-of discharge and duty cycle characteristics such as haul road grade, length and terrain, could also help maximise battery lifetime. [332]

Exploring alternative battery chemistries could reduce a BEHTs reliance on costly critical minerals.

Best available batteries for BEHTs include $LiFePO_4$ and Li-NMC types, with energy densities reaching up to 260 and 220Wh/kg respectively.[333] Both battery types have been demonstrated in mining haulage applications.[334] However, as a result of high lithium demand and supply shortages, the price of typical Li-ion batteries used in electric vehicles increased from $100USD/kWh in 2020/21 to $120USD/kWh in 2022.[335] There is a clear RD&D opportunity to explore battery chemistries that minimise the use of critical minerals such as lithium, or harness more abundant resources to reduce cell level costs.

Optimising battery cell design and integration could improve the utilisation, payload capacity and operational suitability of BEHTs in Australian mines.

There is an opportunity to improve cell-to-pack technology, where cells are integrated into the battery pack, or cell-to-chassis technology, where cells are integrated directly into the vehicle's chassis. Optimising battery cell integration could enable more energy storage per unit of volume or mass, increasing truck utilisation without compromising total payload capacity. Simultaneously, RD&D is needed to mitigate against thermal, structural and maintenance risks induce by this type of battery integration. For example, cooling systems embedded in cell-to-chassis designs could propagate thermal runway, particularly in the extreme temperatures experienced by Australian mining operations. Careful design and monitoring systems may be needed to mitigate this risk.

Auxiliary technologies

RD&D to advance electric vehicle supply equipment, in particular charging systems, could play a significant role in supporting successful fleet electrification.

Given the high utilisation (>19 hours per day) and substantial energy demands of BEHTs, their widespread adoption will likely depend on the development of fast and ultra-fast charging systems (See the Road Transport chapter of the *Transport* technical appendix). Wireless charging is being developed for heavy duty vehicles to facilitate automated static charging within the operational haulage path.[336] However, RD&D is needed to facilitate automation in mining heavy haulage applications, enhance system durability in harsh environments and improve the efficiency of wireless charging.

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[332] Bao, H., Knights, P., Kizil, M., & Nehring, M. (2024) Energy Consumption and Battery Size of Battery Trolley Electric Trucks in Surface Mines. *Energies*, *17*(6), 1494. <https://doi.org/10.3390/en17061494>; Voeltzel N, Shirazy M, Frechette L, Fillion S (2021) Extending Battery Lifetime of Electric Mining Vehicles through Thermal and Duty Cycle Management. SAE Technical Paper 2021-01-0223, SAE International, Warrendale, PA.

[333] International Energy Agency (2023) Global EV Outlook 2023. Trends in Batteries: Battery demand for EVs continues to rise. <https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries>

[334] For example, the XEMC SF31904 electric haul truck, with a 120-ton carrying capacity, uses CATL LiFePO4 batteries, while the BelAZ 7558E prototype haulage truck features fifteen modules of Li-NMC batteries. Although out of scope, Mn-ion batteries (TRL 3) offer a potential cost-effective solution, with energy densities expected to exceed 300-600Wh/kg by 2035. Mn, being more abundant than Li, could also reduce costs to about one-third of Li-based batteries. Further research is needed to improve electrolyte efficiency and extend cycle life (currently 100-1000 cycles).

[335] BloombergNEF (2022) Lithium-ion Battery Pack Prices Rise for First Time to an Average of $151/kWh. <https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/>

[336] Wireless charging systems are those that transfer energy through an electromagnetic wave travelling from a transmitter (current source) to a receiver (battery). For example, InductEV has developed and demonstrated static wireless charging systems for heavy duty transport, port and industrial equipment (115 vehicles in operation), Hardware (Induct EV). <https://www.inductev.com/hardware>

In a similar vein, dynamic wireless charging technology could reduce operational downtimes for BEHTs.[337] While it has yet to be demonstrated in the mining industry, there has been industry movement in developing dynamic wireless charging systems for electric heavy-duty on-road vehicles.[338] Further research is required to understand the durability, flexibility and appropriateness of the system within a mining environment.

Lastly, contact charging systems (line or rail) require improved infrastructure integration to ensure economic viability and compatibility across different mining haulage trucks. Contact charging systems work by connecting BEHTs to an electrified rail system or roadway to provide a steady power supply to the trucks whilst they are in motion. Contact charging can reduce a trucks reliance on large on-board battery storage, extend battery life and improve truck utilisation rates.[339]

RD&D to improve the scalability and interoperability of battery swapping systems could improve their viability as a BEHT charging solution.

Despite mature development, battery swapping systems require RD&D to improve their scalability in a mining-specific context and ensure their interoperability across various vehicle types and charging systems. Battery swapping is a static charging solution that could reduce the total downtime of a mining haulage fleet.[340] While it is already well developed (TRL 5-7), its application has primarily been demonstrated outside the mining industry.[341]

Establishing off-grid/on-grid renewable energy production and storage infrastructure could support the deployment of BEHTs in open pit mines.

A large proportion of Australian mines are often located in isolated areas with limited or no access to centralised power grids. Moreover, the electrification of BEHTs requires significant amounts of energy to meet operational demands. As a result, RD&D focused on building onsite renewable-power infrastructure may be needed to support fleet electrification in remote locations. In contrast and for mines co-located near centralised power grids, RD&D to optimise grid integration could help deploy BEHTs at a reduced cost. For detailed RD&D opportunities related to electricity generation, see the *Electricity* technical appendix.

6.6.2 Fuel cell electric haul truck (FCEHT)

FCEHTs are a type of heavy-duty mining truck that employ a hydrogen fuel cell system to generate electric power and drive an electric traction system. These trucks feature a fuel cell stack where hydrogen reacts electrochemically to produce electricity, water, and heat. The system includes high-pressure hydrogen storage tanks and a battery pack. The latter provides additional power during peak loads and enhances the overall efficiency and longevity of the system. Despite significant potential, the primary challenge for FCEHTs is cost and meeting the significant energy demands of heavy mining haulage.

[337] Dynamic charging systems allow mining haulage trucks to operate continuously while moving. Dynamic wireless charging systems use embedded coils in the in-pit mine road to transmit energy via magnetic resonance to a receiver in the truck.

[338] Alcomendas A (2024) Australia to trial wireless charging for heavy-duty vehicles, AfMA. <https://afma.org.au/australia-to-trial-wireless-charging-for-heavy-duty-vehicles/>

[339] For example, Cat Dynamic Energy Transfer (DET) is a Caterpillar-developed system designed to transfer energy to diesel-electric and battery-electric mining trucks at steep segments of the haulage route: Caterpillar (2024) Caterpillar introduces groundbreaking dynamic energy transfer solution for battery and diesel-electric mining equipment. Caterpillar Public Release 17 September 2024. <https://www.cat.com/en_US/by-industry/mining/minexpo2024/news/press-releases/caterpillar-introduces-groundbreaking-dynamic-energy-transfer-solution-for-battery-and-diesel-electric-mining-equipment.html#multimedia-g8r7oUMbM8mGCaD-poster>

[340] Static charging systems deliver electrical energy to stationary mining haulage trucks through direct contact or inductive methods.

[341] For example, SANY heavy industry cooperation has developed and evaluated an intelligent battery swap system that stores eight batteries and completes 168 swaps a day: *Sany's first Intelligent Battery Swapping Station debuts*. <https://www.sanyglobal.com/press_releases/729/>

Primary technologies

Reducing reliance on critical materials can lower upfront technology costs and supply chain exposure.

Ongoing technological progress and manufacturing economies of scale suggest that proton exchange membrane (PEM) fuel cells could become competitive with diesel haulage engines as the hydrogen economy grows. PEM fuel cells are well-suited to mining haulage due to their high power density, rapid start-up times, and efficient operation at relatively low temperatures (60–80°C). However, RD&D is needed to reduce costs while maintaining efficiency and durability. Innovations in catalyst design - such as alloy catalysts, nanomaterials, or non-precious metal alternatives - could reduce platinum loading and enable long-term cost competitiveness (LCOH forecast: $240/kWh in 2050, c.f., $681/kWh today).[84]

Catalysts in state-of-the-art PEM hydrogen fuel cells are made from carbon supported platinum. To date, it is estimated that these catalysts account for up to 40% of the total fuel cell cost, largely due to the material costs of platinum.[342] Improving catalyst activity by using improved materials such as nanomaterials, alloy catalysts or non-precious metals can enhance PEM fuel cell efficiency and significantly reduce fuel cell costs.[343] Improved system assembly and component integration are also key to scaling production and achieving economies of scale.

Improving fuel cell efficiency and durability can support reductions in operational system costs, achieved through advancements in fuel cell architecture and design.

Efficiency gains could be enabled through improvements to fuel cell architecture and component performance. State-of-the-art PEM fuel cells feature a membrane electrode assembly (MEA) with a polymer membrane, catalyst layer, microporous layer, and gas diffusion layer. New membrane materials, like sulfonated hydrocarbon polymers could enhance high-temperature properties.[344] Nanoparticle additives like carbon nanotubes or silica are being pursued to enhance electrolyte conductivity and advanced gas diffusion layers, like metallic or 3D printed structures, are being explored to enhance the rate of diffusion.

Research into alternative fuel cell types, such as alkaline fuel cells (AFCs), may also unlock performance benefits. These fuel cells present high efficiency, long operational life and ability to run using non-precious metal catalysts that are lower cost. This can be beneficial in reducing overall operational costs for mining haulage trucks.[345]

Hybridisation, the use of an energy storage system alongside the fuel cell, can reduce peak loads on the stack, improving efficiency and lifetime. The hybridisation factor is the ratio of the maximum power output from the energy storage system to the total maximum power output of the vehicle.[346] Optimising the hybridisation factor could improve energy efficiency, durability, and cost-effectiveness. Research indicates that a high

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[342] Mancino AN, Menale C, Vellucci F, Pasquali M, Bubbico R (2023) PEM Fuel Cell Applications in Road Transport. Energies. 16(17):6129. <https://doi.org/10.3390/en16176129>

[343] **Regarding nanomaterials:** Wang Y, Diaz DFR, Chen KS, Wang Z, Adroher XC (2020). Materials, technological status, and fundamentals of PEM fuel cells–a review. Materials today, 32, 178-203. <https://doi.org/10.1016/j.mattod.2019.06.005>; **Regarding alloy catalysts**: Zhang L, Liu H, Liu S, Norouzi Banis M, Song Z, Li J, Yang L, Markiewicz M, Zhao Y, Li R, Zheng M. (2019). Pt/Pd single-atom alloys as highly active electrochemical catalysts and the origin of enhanced activity. ACS Catalysis, 9(10), 9350-9358. <https://doi.org/10.1021/acscatal.9b01677> **Regarding non-precious metals:** Du L, Zhang G, Liu X, Hassanpour A, Dubois M, Tavares AC, Sun S (2020) Biomass-derived nonprecious metal catalysts for oxygen reduction reaction: the demand-oriented engineering of active sites and structures. Carbon Energy. (4):561-81. <https://doi.org/10.1002/cey2.73>

[344] Mo S, Du L, Huang Z, Chen J, Zhou Y, Wu P, Meng L, Wang N, Xing L, Zhao M, Yang Y (2023) Recent advances on PEM fuel cells: from key materials to membrane electrode assembly. Electrochemical energy reviews. <https://doi.org/10.1007/s41918-023-00190-w>

[345] Ferriday TB, Middleton PH. Alkaline fuel cell technology-A review (2021) International journal of hydrogen energy. 46(35):18489-510. <https://doi.org/10.1016/j.ijhydene.2021.02.203>

[346] For instance, a hybridization factor of 0% indicates that energy is fully supplied by the fuel cell, whereas a hybridisation factor of 100% indicates that energy is fully supplied by the battery.

hybridisation factor of about 70% may reduce the cost of a fuel cell electric vehicle by 25% compared to its original design.[347]

Innovation in hydrogen storage technologies is critical to improve viability for FCEHTs, including financial prospects and operational safety.

The primary challenge limiting the commercialisation and large-scale promotion of hydrogen storage systems for FCEHTs is energy density. Utilising hydrogen as a fuel is challenged by its low density, which makes huge volumes difficult to store. Physical hydrogen storage systems such as compressed gas, cyro-compressed gas and liquid storage are being prototyped in FCEHTs.[348] However, these systems face efficiency challenges due to hydrogen boil off and safety challenges due to hydrogen volatility at high pressures. Moreover, meeting on-board energy density requirements to power FCEHTs demands significant energy inputs at a significant cost to compress/liquify and store hydrogen.

Developing robust and insulating materials that minimise leaks could improve safety for on-board storage systems. Novel materials and methods could enhance storage capacity, while decreasing tank weight – for example carbon nanotubes.[349] For greater detail on RD&D opportunities, see the *Low Carbon Fuels* technical appendix.

Auxiliary technologies

Off-grid hydrogen systems are critical to enable FCEHT deployment at remote mining sites.

Off-grid systems will be needed to support the use of FCEHTs in mines located in isolated areas with limited or no access to centralised power grids. For example, an iron ore mine in the Pilbara region of Western Australia is utilising renewables-based hydrogen production infrastructure from the Christmas Creek Green Energy Hub.[350] This hub produces, stores and dispenses both gaseous and liquid hydrogen and has been supporting the replacement of Fortescue's fleet of diesel coaches and the onsite testing of their hydrogen-powered haul truck prototype.[351]

On-grid hydrogen systems could offer more stable and lower-cost supply for FCEHTs at connected sites.

Improvements to grid-connected systems could enable FCEHTs to access stable, reliable and more affordable hydrogen compared to off-grid systems that depend on independent power sources. For greater detail on hydrogen production, distribution and storage infrastructure technologies, please refer to the *Low Carbon Fuels* and *Transport* technical appendices.

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[347] De Almeida SC, Kruczan R (2021) Effects of drivetrain hybridization on fuel economy, performance and costs of a fuel cell hybrid electric vehicle. International Journal of Hydrogen Energy. 46(79):39404-14. <https://doi.org/10.1016/j.ijhydene.2021.09.144>

[348] Alta Battery Technology (nd) Project Spotlight: NTH150: Hydrogen Fuel Cell Haul Truck. <https://altatechnology.com.au/projects/fuel-cell-haul-truck>

[349] Le TT, Sharma P, Bora BJ, Tran VD, Truong TH, Le HC, Nguyen PQ (2024) Fueling the future: A comprehensive review of hydrogen energy systems and their challenges. International Journal of Hydrogen Energy. 54:791-816. <https://doi.org/10.1016/j.ijhydene.2023.08.044>

[350] CSIRO (2024) Christmas Creek Renewable Hydrogen Mobility Project. Commonwealth of Australia. <https://research.csiro.au/hyresource/christmas-creek-renewable-hydrogen-mobility-project/>

[351] Fortescue (2024) Fortescue's hydrogen-powered haul truck prototype arrives in the Pilbara. < https://www.fortescue.com/en/articles/fortescue-s-hydrogen-powered-haul-truck-prototype-arrives-in-the-pilbara>; As of July 2024, Fortescue has announced a scale back in its involvement in hydrogen projects, refocusing resources towards renewable electricity. For more see; Ker P, Macdonald-Smith A (2024) Labor's hydrogen dream stalls as Fortescue slims down H2 vision. <https://www.afr.com/companies/mining/fortescue-puts-hydrogen-on-backburner-with-700-jobs-cut-20240717-p5jufj>

6.6.3 Energy efficiency solutions

Further RD&D in solutions that reduce energy use in heavy-duty mining haulage will also support emissions mitigation efforts. The solutions outlined in Table 34 are technology-agnostic and reflect energy efficiency solutions that could reduce emissions, independent of shifts in technology.

Table 34: Energy efficiency solutions – Heavy mining haulage

Energy efficiency solutions	RD&D opportunities
Trolley assist	• Determine economic feasibility (considering electricity and infrastructure development, mine planning, site characteristics and constraints, etc). • Determine integration feasibility of trolley assist system with current mining fleets. • Improve power transmission from system to truck.
In-pit crushing conveying (IPCC)[352]	• Optimise mine planning to ensure positive financial outcomes (e.g. understanding where IPCC systems should be applied, how can mines adapt, the transition time from existing systems to an IPCC system, the feasibility of semi mobile/fully mobile IPCC systems, etc). [353]
Electro-mechanical flywheels[354]	• Improve storage capacity. • Reduce integration and retrofit costs. • Reduce weight and size (magnetic gears, combined radial and axial magnetic bearings).[355] • Develop higher spinning speed and raise the shape factor of the flywheel. [356]
Regenerative braking	• Improve energy recovery rate. • Assess the impact of braking on truck durability and road surface conditions.
Autonomous trucks	• Improve sensor systems, GPS integration and collision avoidance mechanisms.[357] • Develop digital fleet management tools.

[352] Osanloo M, Paricheh M (2019) In-pit crushing and conveying technology in open-pit mining operations: a literature review and research agenda. International Journal of Mining, Reclamation and Environment, 34(6), 430–457. <https://doi.org/10.1080/17480930.2019.1565054>

[353] Osanloo M, Paricheh M (2019)

[354] Terblanche PJ, Kearney MP, Nehring M, Knights PF (2019) Potential of on-board energy recovery systems to reduce haulage costs over the life of a deep surface mine. Mining Technology.;128(1):51-64. <https://doi.org/10.1080/25726668.2018.1554933>

[355] Li X, Palazzolo A (2022) A review of flywheel energy storage systems: state of the art and opportunities. Journal of Energy Storage. 46:103576.

[356] Li X, Palazzolo A (2022)

[357] Some autonomous truck systems have reduced operational costs by 20%, and improved productivity by 30%. Mining Technology (2021) Autonomous haulage systems for mining industry: Leading manufacturers. < https://www.mining-technology.com/features/autonomous-haulage-systems/?cf-view> (accessed 15 January 2025)

Part 3: Appendix

A.1 Glossary

TERM	DESCRIPTION
Agglomeration	Technologies that enhance and improve the metallurgical properties of fine iron ores and steelmaking byproducts by processing them into sinter or pellets for use in the blast furnace.
Artificial intelligence / machine learning (AI/ML)	Commonly referred to by its acronym AI/ML, artificial intelligence refers to the stimulation of human intelligence in machines that programmed to think and learn like humans and machine learning is a subset of AI that involves the development of algorithms and statistical models that enable computers to learn from and make predictions or decisions based on data.
Basic oxygen furnace (BOF)	Commonly referred to by its acronym BOF, a basic oxygen furnace is a large industrial vessel used in the steelmaking process to convert molten iron into steel.
Batteries: Flow	Rechargeable batteries, where two chemical components are dissolved in liquids and pumped through the system on either side of a membrane. They store and release energy through reversible oxidation and reduction reactions.
Batteries: Metal-ion	Rechargeable batteries that utilise the movement of ions (such as lithium or sodium) between electrodes through an electrolyte to store and release electrical energy. Examples include Li-ion and Na-ion.
Battery swap	A technology that is used in electric vehicles and allows for the quick exchange of a depleted battery pack with a fully charged one.
Bayer process	The Bayer process is the principal industrial method for refining bauxite to produce alumina (aluminium oxide) needed for aluminium production.
Battery electric haul truck (BEHT)	Commonly referred to by its acronym BEHT, a battery electric haul truck employs batteries to convert electrical energy into mechanical energy. An electric storage system can be used during idle periods to store recaptured braking energy.
Biochar	Biochar is a carbon-rich material produced by heating organic biomass (such as wood chips, plant residues, or manure) in an oxygen-limited environment through a process called pyrolysis.
Biomass	Biomass refers to organic material that comes from plants and animals, and it is a renewable source of energy. Biomass can be used directly for heating or power generation, or it can be converted into biofuels.
Biomass combustion	Biomass combustion uses organic materials such as wood chips, agricultural residues, or dedicated energy crops to produce steam and heat.
Blast furnace (BF)	Commonly referred to by its acronym BF, a blast furnace is a large industrial structure used primarily in the production of iron from iron ore.
Brownfield pathway	The development or deployment of technologies or infrastructure by repurposing or upgrading existing assets.
Burden (Iron and steelmaking)	The total mass of raw materials (iron-bearing materials like sinter, pellets, lump ore, and coke) loaded into iron and steelmaking equipment.
Carbon capture and storage (CCS)	Commonly referred to by its acronym CCS, carbon capture and storage is the practice of capturing atmospheric carbon dioxide emissions (typically produced from the use of fossil fuels and industrial processes) for long term secure storage.
Carbon containing agglomerates (CCA)	Commonly referred to by its acronym CCA, carbon containing agglomerates are pellets or briquettes comprised of a mixture of carbonaceous (coal, coke fine or carbon-rich materials) and iron oxide materials.
Charging (iron and steelmaking)	The controlled introduction of raw materials, including coke, iron ore, and flux into iron and steelmaking equipment.

Coke	A coking oven decomposes coal into a coke residue under high temperatures in the absence of air in a pyrolysis process. The 'coking coal' or 'coke' is porous residue with a higher purity and carbon content than thermal coal.
Coke oven gas (COG)	Commonly referred to by its acronym COG, coke oven gas is a byproduct of the coking process, where bituminous coal is heated to high temperatures (900°C to 1000°C) in the absence of air to produce metallurgical coke
Combined heat and power (CHP)	Commonly referred to by its acronym CHP, combined heat and power, also known as cogeneration, is a highly efficient technology that simultaneously generates electricity and useful thermal energy (heat) from a single fuel source. For example, an engine generates electricity and the waste heat it produces is captured and used for heating purposes.
Concentrated solar thermal (CST)	Commonly referred to by its acronym CST, concentrated solar thermal specifically refers to the initial generation and storage of thermal energy in concentrated solar power technology.
Dephosphorisation	The process of removing phosphorus from molten iron or steel.
Digestion	A process used in various industrial applications where steam at moderate temperatures (typically between 100°C and 200°C) is used to break down materials.
Direct reduced Iron (DRI)	Commonly referred to by its acronym DRI, direct reduced iron is iron that is produced by reducing iron ore in its solid state, without melting it. This process involves the use of reducing gases, such as hydrogen or carbon monoxide, to remove oxygen from the iron ore at temperatures below the melting point of iron (typically between 800°C and 1,200°C).
Distributed energy resources (DER)	Commonly referred to by its acronym DER, distributed energy resources are small scale units of local generation connected to the grid at the distribution level. These resources can include solar panels, wind turbines, energy storage systems etc.
Double digestion	Involves the processing bauxite twice: first at lower temperatures first, dissolving 80% of the alumina, and then at higher temperatures for the remaining 20%.
Drop-in fuel	Drop-in fuels are a synthetic and completely interchangeable substitute for conventional petroleum-derived hydrocarbons, meaning they do not require adaptations to existing engines, fuel systems or networks.
Duty cycle	One operational cycle of a mining haulage truck, including the time and distance required to load, transport, unload material, and return to the loading site.
Electric arc furnace (EAF)	Commonly referred to by its acronym EAF, an electric arc furnace uses high-voltage electric arcs to melt scrap steel or direct reduced iron. The electric arc is generated between graphite electrodes and the metal charge.
Electric boiler	Electric boilers use electricity to generate steam and heat.
Electric smelting furnace (ESF)	Commonly referred to by its acronym ESF, an electric smelting furnace uses electric currents to produce the heat necessary for smelting. This process involves melting the ore and reducing it to its base metal.
Electro-mechanical flywheels	A device used to store and release energy through rotational motion. They are used in transportation systems to provide a quick burst of energy.
Energy recovery system (ERS)	Commonly referred to by its acronym ERS, an energy recovery system is a technology designed to capture and reuse energy that would otherwise be wasted.
Ferro-coke	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.
First generation feedstock	First-generation feedstocks are types of biomasses that are often used for food, such as corn, soy, and sugarcane. Biofuels are made through fermentation or chemical processes that convert the oils, sugars, and starches in the biomass into liquid fuels.[5]
Fixed recharging	When a battery is depleted in an electric vehicle, the battery is replenished by connecting the vehicle to a charging station to restore energy to the battery.

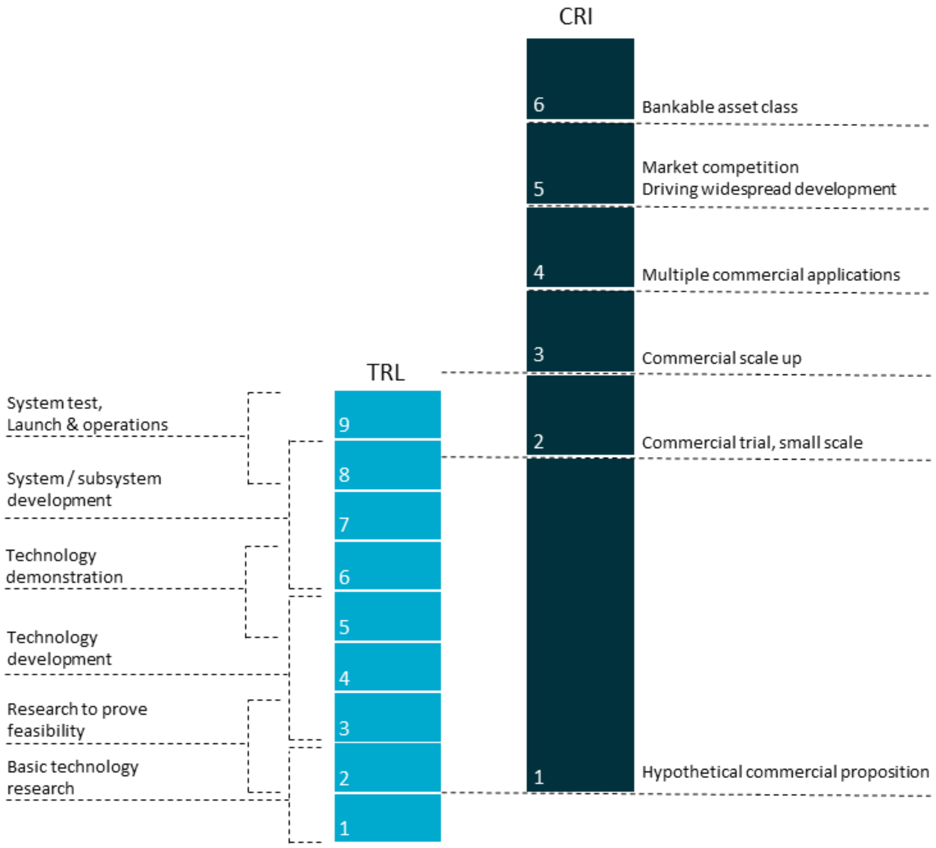
Flue gas (exhaust gas or stack gas)	Exhaust gases produced from combustion processes, such as burning fuel in a boiler, furnace or power plant. Gas streams typically contain combustion productions like carbon dioxide, water vapour and potentially pollutants like nitrogen and sulphur oxides
Fluidised bed	A technology used to process fine iron ore particles by suspending them in an upward flow of gas, creating a fluid-like state.
Flux	A material, such as limestone or dolomite, added to iron and steelmaking equipment to remove impurities by forming slag.
Fuel cell electric haul truck (FCEHT)	Commonly referred to by its acronym FCEHT, a fuel cell electric haul truck is a type of haulage truck that employs a hydrogen fuel cell system to generate electric power and drive an electric traction system. The electric power generated can also be stored in an energy storage system and accessed during idle periods to preserve fuel or to store recaptured braking energy.
Greenfield pathway	A greenfield pathway typically refers to the development of new projects.
Hematite	A common iron oxide mineral with the chemical formula Fe_2O_3.
Hot briquetted iron (HBI)	Commonly referred to by its acronym HBI, hot briquetted iron is produced by reducing iron ore with natural gas, resulting in a product that can be used in both blast furnaces and electric arc furnaces as a substitute for scrap metal or pig iron.
Hybridisation factor	The hybridisation factor is the ratio of the maximum power output from the energy storage system to the total maximum power output of the vehicle (in the context of heavy haulage mining trucks).
Hydrogen boiler	Hydrogen boilers use hydrogen as a fuel to produce steam and heat.
Hydrogen compressed tanks	Hydrogen is compressed at high pressure (up to 800 bar) in steel or carbon fibre tanks.
Hydrogen storage	Energy is stored by producing hydrogen, that can then be stored in different forms and later converted back into electricity using fuel cells or steam turbines. Hydrogen can be stored using a variety of mechanisms, including tanks and underground storage.
In-pit crushing conveying (IPCC)	Commonly referred to by its acronym IPCC, in-pit crushing and conveying refers to a system that breaks down mined material into smaller pieces and transports this material via conveyor belts to the processing plant or waste dump outside of the pit.
Lightweighting	The process of reducing the weight of a component or assembly, often to improve efficiency, performance, and sustainability. This concept is widely used in industries such as automotive, aerospace, and manufacturing.
Liquid natural gas (LNG) vehicles	Commonly referred to by its acronym LNG, liquified natural gas vehicles are vehicles that employ an internal combustion engine fuelled by liquefied natural gas (LNG).
Lithium ion (Li-ion) batteries	Commonly referred to by its acronym Li-ion, lithium ion batteries are a type of rechargeable battery that relies on lithium ions moving between the anode and cathode to store and release energy.
Lithium iron phosphate ($LiFePO_4$) batteries	Commonly referred to by its acronym $LiFePO_4$, lithium ion phosphate batteries are a type of lithium-ion battery that uses lithium iron phosphate as the cathode material
Mechanical vapour recompression (MVR)	Commonly referred to by its acronym MVR, mechanical vapour recompression involves the recycling of energy by compressing and reusing steam. Low-pressure steam is captured and mechanically compressed to a higher pressure and temperature. The compressed steam can then be reused to provide heat reducing the need for fresh steam generation.
Membrane electrode assembly (MEA)	Commonly referred to by its acronym MEA, a membrane electrode assembly consists of several layers that work together to facilitate the electrochemical reactions necessary for energy conversion and fuel cell function. Consists of a proton exchange membrane, catalyst layers and gas diffusion layers.
Municipal solid waste (MSW)	Commonly referred to by its acronym MSW, municipal solid waste includes a wide range of materials such as product packaging, food scraps, yard waste, furniture, clothing, bottles, and appliances.

Natural gas (NG)	Commonly referred to by its acronym NG, natural gas is a fossil fuel composed primarily of methane (CH_4), along with smaller amounts of other hydrocarbons such as ethane, propane, and butane.
Off gas	A general term to refer to any gas released as a byproduct of a process, including chemical reactions and metallurgical operations. It can encompass a wide range of gases, including flue gas, but also gases from other industrial applications.
Oxygen blast furnace (oxyBF)	Commonly referred to by its acronym oxyBF, an oxygen blast furnace is a type of furnace used in the steelmaking process. The blast oxygen furnace process involves blowing oxygen through molten iron to reduce the carbon content and convert it into steel.
Pelletising	Similar to sintering (see glossary definition below), pelletising is a widely used process to agglomerate iron ore. Ore is crushed, ground and concentrated in several steps to obtain a small grain size (over 75% less than 45 µm). The grains are combined with additives and binders and rolled into pellets. The pellets are screened to obtain those 9-11mm in diameter and heated to 1290-1400°C in an oxidising atmosphere to harden them.
Plant capacity	Plant configurations in iron and steel making that can technologically meet current production capacities, in terms of plant size and process inputs.
Proton exchange membrane (PEM) fuel cells	Commonly referred to by its acronym PEM, proton exchange membrane fuel cells are a type of fuel cell that converts chemical energy from hydrogen and oxygen into electrical energy through electrochemical reactions.
Pulverised coal injection (PCI)	Commonly referred to by its acronym PCI, pulverised coal injection is a process used in blast furnaces to improve the efficiency and cost-effectiveness of iron production.
Reduction	Iron oxide compounds in iron ore undergo chemical reactions with reducing agents (typically CO and H_2 gas) at high temperatures to strip them of oxygen and convert them into metallic, or 'reduced', iron.
Refining	Excess reduced elements that are dissolved in the molten iron (i.e., carbon, phosphorus, sulphur) are removed.
Regenerative braking	The process where kinetic energy is recovered during braking and converted into electrical energy which is then stored in a battery or energy storage system.
Rotary hearth furnace	A type of industrial furnace used in the direct reduction of iron ore, annealing, calcination and heat treatment of various metals.
Rotary kiln	A type of industrial furnace used for high-temperature processes such as calcination, sintering, and pyroprocessing. Materials are fed into the upper end of the kiln. As the kiln rotates, the materials gradually move down towards the lower end, undergoing various chemical and physical changes due to the high temperatures.
Scrap	Recycled steel or iron materials that are re-melted and reused in the production of new steel.
Second generation feedstock	Second-generation feedstocks are produced from non-food biomass, such as perennial grass and fast-growing trees. The processes to make biofuels are more complex and less developed than for first-generation feedstocks, often involve converting fibrous non-edible material (cellulose) into fuel.
Shaft furnace reactor	A type of industrial furnace used primarily for the direct reduction of iron ore to produce direct reduced iron (DRI).
Sintering	A process used to agglomerate iron-containing fine-grained materials, whereby the ore materials are heated to 1400°C where they start to melt and stick together. After the materials pass the combustion zone, the material solidifies to form 'sinter'. Typical sinter suitable for blast furnace process is from 15 to 25 mm.
Slag	A by-product formed during the smelting or refining of metals.
Smelting	Metallic iron is heated until melted, and any impurities that resisted reduction (typically silica and alumina) form a floating molten slag which can easily be separated.
Sodium ion (Na-ion)	Commonly referred to by its acronym Na-ion, a sodium ion is a positively charged ion formed when a sodium atom loses one electron.

Submerged arc furnace (SAF)	Commonly referred to by its acronym SAF, a submerged arc furnace is an electric furnace used primarily for smelting ores and reducing metals. The furnace operates under submerged conditions, meaning the electric arc is buried under the raw materials, minimizing air exposure and enhancing efficiency.
Tailpipe emissions	The gases and particles that are expelled from the exhaust system of a vehicle as a result of fuel combustion.
Tank-to-wheel (TTW)	Commonly referred to by its acronym TTW, tank-to-wheel refers to the analysis of emissions and energy consumption that occur during the operation of a vehicle, from the point when fuel is added to the tank until it is used to power the vehicle.
Thermal energy storage (TESe)	Commonly referred to by its acronym TESe, thermal energy storage is an energy input stored in the form of thermal energy in a medium. The energy input can be in the form of electricity or heat for use at a later period to generate electricity using heat engines or turbines (eTESe and hTESe respectively). There are three categories of TES media: sensible, latent and thermochemical heat storage.
Thermal energy storage (eTESe) (electricity input, electricity output)	Commonly referred to by its acronym eTESe, thermal energy storage is an energy input stored in the form of thermal energy in a medium. The energy input is in the form of electricity and is used at a later period to generate electricity using turbines.
Thermal energy storage (eTESh) (electricity input, heat output)	Commonly referred to by its acronym eTESh, thermal energy storage is an energy input stored in the form of thermal energy in a medium. Electricity is converted to heat and used to heat up the thermal medium. A heat output is used with a resistance mechanism to create steam.
Top gas recycling (TGR)	Commonly referred to by its acronym TGR, top gas recycling is a process used in blast furnaces to improve efficiency and reduce emissions. The top gas, which is the exhaust gas from the blast furnace is collected. The collected gas is then cleaned to remove dust and other impurities. The cleaned gas, rich in CO_2 and H_2 is then re-injected back into the blast furnace.
Tube digestion	Digestion conducted using jacketed pipe heaters (rather than conventional shell-and-tube heat exchangers) to improve preservation of heat.
Tunnel kiln	A type of continuous kiln used for high-volume production of ceramics, bricks, and other materials. As the kiln cars move through the tunnel, the materials are gradually heated to the desired temperature, held at that temperature for a specific period, and then cooled down.
Underground hydrogen storage (UHS)	Commonly referred to by its acronym UHS, underground hydrogen storage is where hydrogen is compressed and injected into geological or engineered subsurface structures including salt caverns, depleted gas fields, aquifers or excavated caverns.
Variable renewable energy (VRE)	Commonly referred to by its acronym VRE, variable renewable energy refers to renewable energy sources that produce electricity intermittently, depending on environmental conditions. This includes sources like wind power and solar power, which are not continuously available due to their dependence on weather and time of day.
Well-to-tank (WTT)	Commonly referred to by its acronym WTT, well-to-tank is the lifecycle emissions and energy consumption associated with the production, processing, and transportation of fuels before they are used in vehicles or other applications.

A.2 Technology maturity rating index

Figure 21: Technology Readiness Levels and Commercial Readiness Index[358]



[358] Adapted from ARENA (2014) Commercial Readiness Index. <https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf>

A.3 Technology analysis framework supplementary information

A.3.1 Broad list of technologies

Over 500 technologies were identified from most recent literature and existing global databases, such as the IEA Clean Energy Technology Guide,[359] publications from domestic[360] and international[361] government bodies, and prominent literature from Australian research centres (e.g., ClimateWorks Australia,[362] Net Zero Australia,[363] and the CSIRO[364]).

These technologies were assigned to key (sub)sectors. As the level of detail varied across sources only technologies that directly contribute to emissions reduction efforts were considered as inputs to the prioritisation framework. This ensured a structured and objective filtering process to prioritise technologies.

A.3.2 Primary technology analysis criteria, by subsector

To technically evaluate technologies, criteria were identified for each (sub)sector to assess each technology's ability to meet the functional requirements of its use case. For example, for Transport, use cases require a minimum travel distance between refuelling/recharging, therefore a 'range' performance parameter was included. For energy applications in which a scale of production or storage is required by the use case, a performance parameter that assessed the capacity of a technology was used.

The threshold for each criterion was established based on the performance of conventional technologies used for the same application, using values sourced from literature.

Table 35: Primary technology analysis criteria used, by (sub)sector

		Subsector	Criteria
Energy supply	Electricity	Electricity generation	Levelised cost
		Electricity storage	Discharge duration Levelised cost

[359] IEA (2023) ETP Clean Energy Technology Guide, <https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide>

[360] Australian Government (2021) Low Emissions Technology Statement 2021. Department of Industry, Science, Energy and Resources. <dcceew.gov.au/sites/default/files/documents/low-emissions-technology-statement-2021.pdf; Australian Government (2020) Technology Investment Roadmap. Department of Industry, Science, Energy and Resources. <Technology Investment Roadmap Discussion Paper (storage.googleapis.com)>

[361] U.S. Department of Energy (2022) ARPA-E Strategic Vision Roadmap, August 2022. Report to Congress. <arpa-e.energy.gov/sites/default/files/2022 ARPA-E Strategic Vision Roadmap.pdf> (accessed 15 November 2023).

[362] Climateworks (2020), Decarbonisation Futures: Solutions, actions and benchmarks for a net zero emissions Australia <https://www.climateworkscentre.org/wp-content/uploads/2020/04/Decarbonisation-Futures-March-2020-full-report-.pdf> (accessed 6 September 2023); Jointly with Climate-KIC Australia, Australian Industry Energy Transition Initiative (2023) Pathways to industrial decarbonisation. <https://energytransitionsinitiative.org/wp-content/uploads/2023/08/Pathways-to-Industrial-Decarbonisation-report-Updated-August-2023-Australian-Industry-ETI.pdf> (accessed 14 July 2023).

[363] Net Zero Australia (2023) Modelling Summary Report. <https://www.netzeroaustralia.net.au/wp-content/uploads/2023/04/Net-Zero-Australia-Modelling-Summary-Report.pdf> (accessed 14 July 2023); Net Zero Australia (2023) Downscaling reports (series). <https://www.netzeroaustralia.net.au/final-modelling-results/> (accessed 19 February 2024).

[364] CSIRO (2023) Renewable energy storage roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy-and-Resources/Renewable-Energy-Storage-Roadmap>; CSIRO (2021) CO2 Utilisation Roadmap - CSIRO. <https://www.csiro.au/-/media/Services/Futures/21-00285_SER-FUT_REPORT_CO2UtilisationRoadmap_WEB_210810.pdf>; CSIRO (2023) Sustainable Aviation Roadmap <https://www.csiro.au/en/research/technology-space/energy/sustainable-aviation-fuel>; CSIRO (2023) Hydrogen vehicle refuelling infrastructure <https://www.csiro.au/en/about/challenges-missions/hydrogen/hydrogen-vehicle-refuelling-infrastructure>; CSIRO (2023) Pathways to Net Zero Emissions – An Australian Perspective on Rapid Decarbonisation. <https://www.csiro.au/en/research/environmental-impacts/decarbonisation/pathways-for-australia-report>

	Low carbon fuels	Hydrogen production	Scalability Levelised cost
	Low carbon fuels	Hydrogen storage	Storage capacity Discharge frequency Levelised cost
Energy demand	Transport	Road Aviation Rail	Refuelling duration Minimum range requirement Levelised cost
Energy demand	Transport	Shipping	Safety Minimum range requirement Levelised cost
Energy demand	Industry	Iron and steelmaking	Plant capacity Levelised cost
Energy demand	Industry	Medium temperature steam	Resource scalability Levelised cost
Energy demand	Industry	Mining heavy haulage	Truck utilisation Levelised cost

A.3.3 Truck utilisation methodology and assumptions

The energy capacity was standardised to kWh across haulage truck types. As an example, for the diesel haulage truck, this analysis assumes a 4145kg tank (4900 L) and an energy density of 11.83 kWh/kg. For the FCEHT, this analysis assumes a 777kg tank and an energy density of hydrogen at 33.33 kWh/kg.[365] The energy capacity for the BEHTs (swap and fixed recharge) is 2546 kWh.

The usable energy for the Diesel and FCEHT was calculated by multiplying the energy capacity of each haulage technology by their efficiency. Fuel volumes and truck efficiencies were derived from the LCOH model (see *Technical Appendix: Levelised cost analysis*).[315]

$$Usable\ energy\ (kWh) = Fuel\ volume\ \times Energy\ density\ \times Efficiency$$

The total operating time per refuel is a product of the number of duty cycles completed with a full tank and the duty cycle time (0.24 hours). For consistency with the LCOH model, it was assumed that FCEHT and Diesel haulage trucks consume 126 kWh of energy per duty cycle, and that BEHTs can complete 6 duty cycles before requiring a swap or recharge.

$$Duty\ cycles\ per\ full\ tank = \frac{Usable\ energy}{Energy\ per\ duty\ cycle}$$

$$Operating\ time, per\ refuel\ (hr) = Duty\ cycles\ per\ full\ tank \times Time\ per\ duty\ cycle\ (hr)$$

Utilisation was calculated by considering the total operating hours divided by the sum of total operating hours and downtime created by refuelling or recharging. To consider two refuelling rates, both a lower and upper bound utilisation was calculated. In the case of diesel, a 95L/min (0.9L/hr) and a 380L/min (0.2L/hr)

[365] Energy densities are standard values taken from literature.

refuelling rate from Pirtek has been used.[366] In the case of the BEHT, the values for the battery swap refuel duration (the time required to physically replace a 2546 kWh lithium-ion battery) and the battery fixed refuel duration (the time needed to fully charge the battery) were directly extrapolated from the literature used to model the LCOH.[315]

The values for the two hydrogen refuelling rates were identified from the National Renewable Energy Laboratory (NREL).[367] The lower bound is an average flow rate of 13.2kg/min and accounts for the controlled pressurisation of the tank through a cascading flow. The upper bound is 23.6kg/min and is a peak rate that has been demonstrated at a lab scale to refuel a heavy-duty vehicle system.

$$Utilisation\ (\%) = \frac{Operating\ time\ (hr)}{Operating\ time\ (hr) + Refuel\ duration\ (hr)} \times 100$$

The utilisation rates calculated, and results of this filter for all technology types, are presented in Table 36.

Table 36: Truck utilisation rates by technology – Mining heavy haulage

	Unit	Diesel	Battery swap	Battery fixed	Fuel cell
Fuel volume	-	4145kg	2546 kWh	2546 kWh	777kg
Fuel density	kWh/kg	11.83	-	-	33.33
Energy capacity	kWh	49,054	-	-	25,900
Efficiency	%	20	-	-	36
Usable energy	kWh	9810.78	-	-	9324
Energy consumption per duty cycle	kWh/cycle	126	-	-	126
Duty cycles per refuel/recharge/battery swap	-	77	6	6	74
Total operating hours per refuel/recharge/battery swap	hr	18.94	1.46	1.46	18.01
Lower bound					
Refuelling time	hr	0.9	0.33	0.75	0.98
Utilisation	%	**95%**	**82%**	**66%**	**95%**
Upper bound					
Refuelling time	hr	0.2	0.167	0.33	0.55
Utilisation	%	**99%**	**90%**	**82%**	**97%**

Meets performance parameter Meets with caveats Does not meet

[366] Pirtek Fast Fill Systems Product Catalogue < https://www.pirtek.com.au/-/media/feature/products/fast-fill-small-v18-2024_cmpr.pdf>

[367] NREL (2022) Fast Flow Future for Heavy-Duty Hydrogen Trucks Expanded Capabilities at NREL Demonstrate High-Flow-Rate Hydrogen Fueling for Heavy-Duty Applications. <https://www.nrel.gov/news/program/2022/fast-flow-future-heavy-duty-hydrogen-trucks.html> (accessed March 2025)

A.4 Abatement potential data repository

Table 37: Abatement potential sources and assumptions – Industry

Subsector	Abatement threshold		Emissions data		Source
	Threshold	**Explanation**	**Direct emissions**	**Indirect emissions**	
Iron and steelmaking	*Not applicable. Abatement potential excluded as a filtering criteria due to (1) the expected uptake of bridging technologies; (2) the uncertainty of future transition pathways and (3) the sectoral reliance on carbon as a process input.*				
Medium temperature steam	90%	Technologies are compared against a *relative abatement threshold*, compared to a conventional natural gas boiler, producing 52gCO_2/GJ. Threshold reflects the availability of low emissions technology solutions by 2050, accounting for residual emissions in the grid and the challenges of decarbonising energy-intensive modes of transportation.	Scope 1 emissions associated with combustion, including fugitives	No	DCCEEW (2024)[368]
Mining heavy haulage	90%	Technologies are compared against a *relative abatement threshold*, compared to a conventional diesel truck with a diesel electric drive system, producing 299kgCO_2 per operational cycle.[369] Threshold reflects the availability of low emissions technology solutions by 2050, accounting for residual emissions in the grid and the challenges of decarbonising energy-intensive modes of transportation.	Full fuel cycle	Includes ILUC for biofuels	Biofuels derived from Xu et al. (2022) and Cai et al. (2022). Energy consumption of vehicle trains obtained from Feng et al.[370]

[368] DCCEEW (2024) National greenhouse accounts factors 2024. Department of Climate Change, Energy, the Environment and Water. <https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-factors> (accessed 17 January 2025).

[369] The operational profile encompasses a waiting/loading period; driving, loaded, up an incline on a flat road (maximum +10%); unloading on the flat road; and returning, unloaded, down the incline (-10%) on the flat road. The conventional diesel truck assumes a 236-tonne payload capacity and has a 2098 second operational cycle that covers a total distance of 11.7km.

[370] Assumes a grid intensity of 0.0307kgCO_2-e per kWh, based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas, with the remainder generated from renewable resources and assumed to produce no direct emissions. Feng Y, et al. (2022)

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