MANDALA

CME
CHAMBER OF MINERALS AND ENERGY WA

Realising WA’s green iron potential

Report

DECEMBER 2024

Contents

MANDALA

This document is intended for general informational purposes only. The analysis in this report was commissioned by the Chamber of Minerals and Energy of Western Australia and prepared by Mandala.

Mandala is an economics research and advisory firm. Mandala specialises in combining cutting-edge data and advanced analytical techniques to generate new insights and fresh perspectives on the challenges facing businesses and governments.

Note: All dollar figures are Australian dollars unless indicated otherwise.

Executive summary

Steelmaking is highly carbon-intensive, accounting for 6% to 9% of global emissions each year. Ironmaking generates up to 90% of steel emissions under the most common process.

Current decarbonisation options for ironmaking use higher-grade iron ore feedstocks, including magnetite, or increasing production via the Direct Reduced Iron (DRI) pathway. While DRI offers substantial emissions reduction potential, less than 5% of global iron ore meets the required purity level.

Transformational reductions in ironmaking emissions will require the development and commercialisation of new processes capable of producing green iron using lower-grade ore feedstocks. As the world's largest iron ore exporter, Western Australia's (WA) iron ore industry is actively exploring pathways to support global decarbonisation of the steel industry and generate local economic value.

If these technologies are commercialised and supported with the right policy settings, WA could produce at least 4.5Mt of green iron by 2030, with industry feedback indicating this nearer term opportunity could be larger. Over the longer term, WA could supply in excess of 14% of global green iron by 2050, leveraging established industrial capability and renewable energy generation potential.

This could reduce global emissions by 1.2% (456Mt of CO_2), nearly equivalent to Australia's current domestic emissions (465Mt of CO_2), generate $74 billion in economic value in addition to iron ore exports, and support 19,600 additional ongoing direct jobs by 2050 (excluding construction jobs).

However, WA's future position as a globally competitive green iron producer is not guaranteed. Other regions are moving quickly to develop green iron capabilities and lower the cost of low emissions energy generation – the main cost factor in green iron production.

Meeting WA's 2030 green iron potential could require $37.5 billion in investment from private and public sources:

- $23 billion (62%) in energy infrastructure, including renewable energy generation, storage, and transmission;
- At least $2.2 billion in upgrading or expanding enabling infrastructure like ports, roads, and water facilities; and
- $12.2 billion in production facilities for green iron and low carbon hydrogen.

Long development timeframes mean investment is needed now, but WA's fragmented electricity networks, complex State and Federal approval processes, and the high-cost environment are slowing investment.

Government and industry need to work together to realise WA's potential and create value-adding opportunities for one of Australia's largest exports.

This can be done by developing a green iron industry strategy for WA, outlining the coordinated actions needed between State and Federal Government to encourage investment in first mover projects and reach WA's 2030 potential green iron potential.

This includes accelerating the construction of low emissions energy generation in WA, growing WA's enabling infrastructure network and fast-tracking the scale-up of new green iron technologies.

Priority policy actions for 2030 include:

- Expanding state and federal measures to ensure access to reliable and cost-competitive low emissions energy;
- Developing common-user infrastructure for electricity transmission, hydrogen transport, and water pipelines to help unlock economies of scale;
- Expanding research and development (R&D) support, incentives and grants to fast-track Australian green iron technology development and commercialisation;
- Streamlining environmental and planning approvals across jurisdictions and establishing priority pathways for activities supporting global decarbonisation;
- Facilitating offtake agreements with potential green iron importer countries; and
- Supporting international efforts to develop standards for green iron measurement.

With coordinated action, WA could become a global leader in green iron production, increasing the economic contribution of its iron ore resources and contributing to global emissions reduction.

Steel underpins global growth and is essential to the energy transition

Steel is a core building block of modern economies. Steel demand increases with economic development and growth. It is an essential input for the production of cars, ships, trains, electrical appliances and buildings.

In 2023, global crude steel production reached nearly 1.9 billion tonnes (1,855Mt).[1] Annual steel production is projected to increase by 35% from 2020 to 2050.

Supporting the energy transition alone will require an annual average of 170 million tonnes of steel from 2022 to 2050 – equivalent to 8% of projected steel production in 2030.[2] Steel is critical to enabling transition technologies, including wind turbines, electric vehicles, and advanced manufacturing processes.[3]

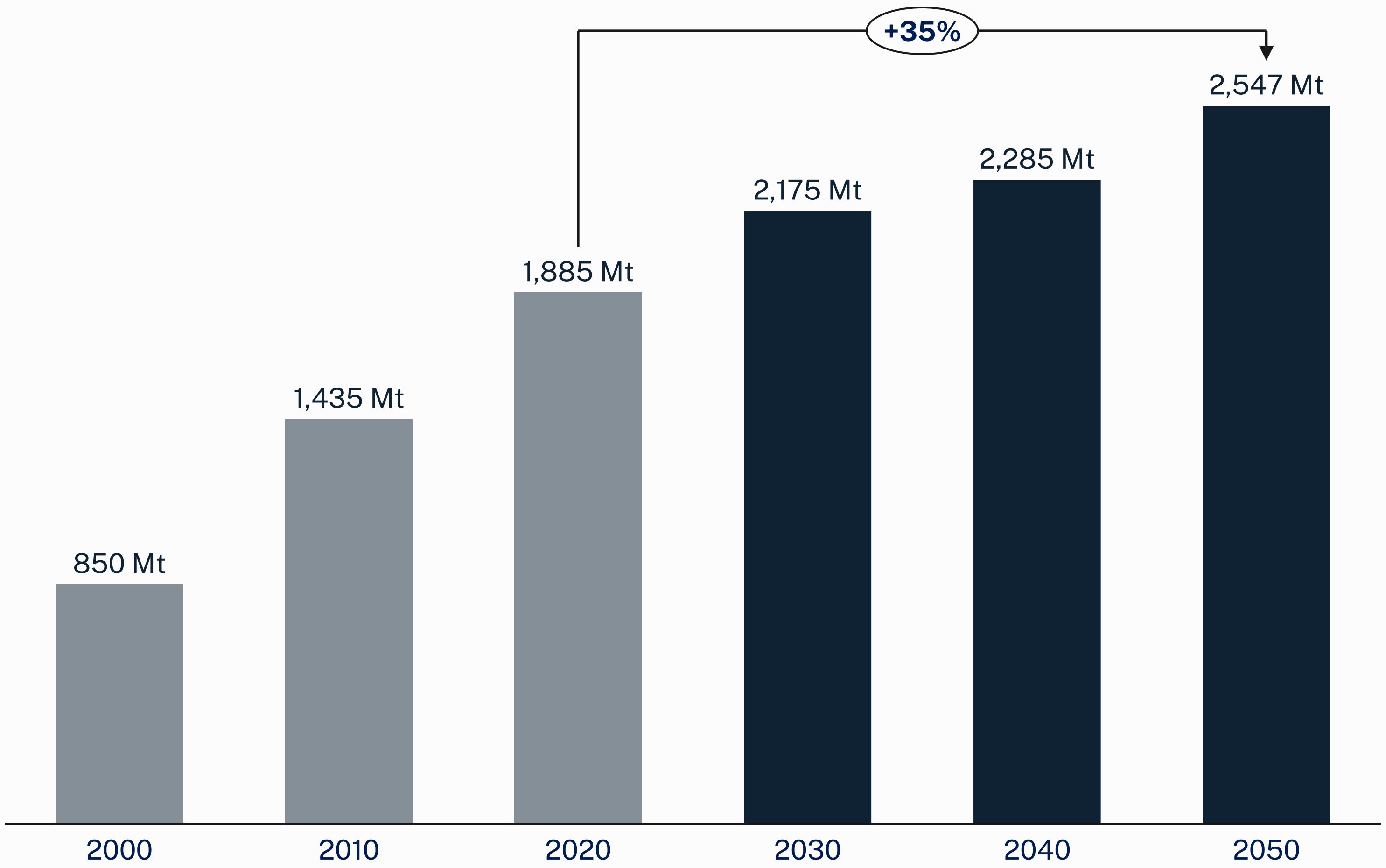
Steel is produced globally using iron ore feedstocks in two dominant pathways:

1. Blast Furnace – Basic Oxygen Furnace (BF-BOF): The primary method responsible for about 73% of global steel production.
2. Direct Reduced Iron – Electric Arc Furnace (DRI-EAF): This process requires very high-grade iron ore feedstocks, which are in short supply (only 5% of global seaborne ore). It is also the primary pathway for recycling scrap steel.

1 2 Energy Transitions Commission (2023) *Material and Resource Requirements for the Energy Transition.* 3 Energy Transitions Commission (2022) *Making Net-Zero Steel Possible.*
Source: World Steel Association (2021) *Energy use in the steel industry*; Mandala analysis.

Global crude steel production by year[1]

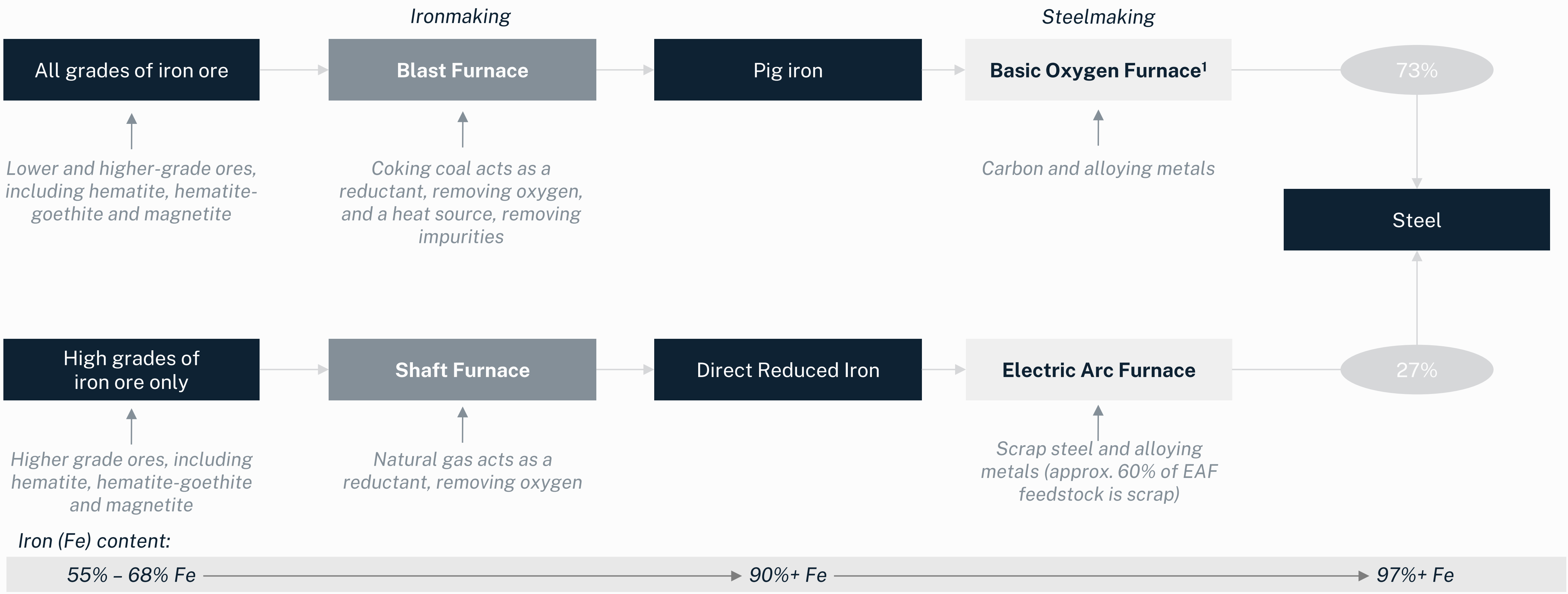
Million tonnes (Mt), annual production 2000 – 2020, forecast production 2020 – 2050



1 Forecasts are informed by IEA (2023) *Steel and Aluminium;* Mission Possible Partnership (2022) *Steel: Pathways to Net Zero*, Net Zero Industry (2024) *Net Zero Steel Pathways;* and Wood Mackenzie (2023) *Steel decarbonisation to redefine supply chains by 2050.*

There are two dominant steelmaking pathways from iron ore feedstocks with the BF-BOF pathway the most common (73% of production)

Overview of current iron and steelmaking processes using iron ore feedstock



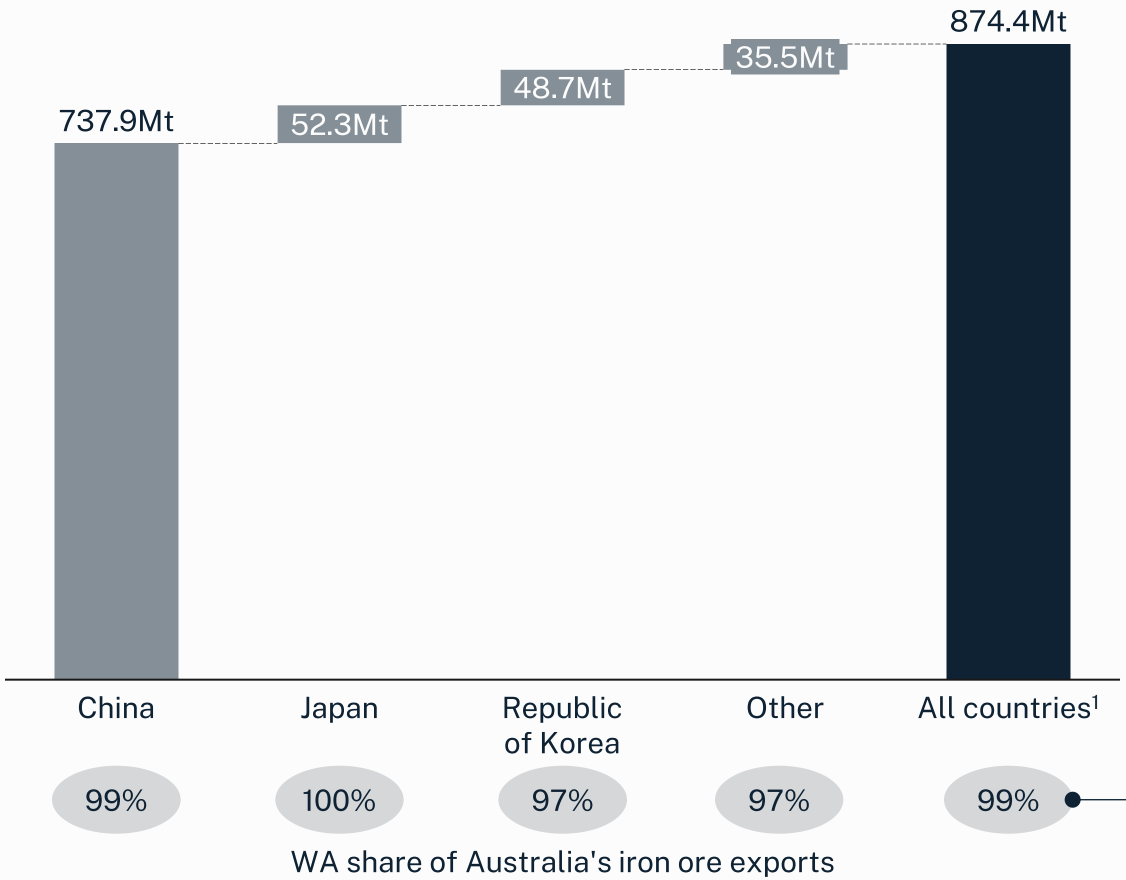
1. Basic oxygen furnaces can also include scrap steel in production.

Source: Benavides et al. (2024) *Mitigating emissions in the global steel industry*; Center on Global Energy Policy (2021) *Low-Carbon Production of Iron & Steel*; Geosciences Australia (2018) *Iron Ore*; MRIWA (2023) *Western Australia's Green Steel Opportunity;* SMS Group (2021) *Decarbonization of iron production*; World Steel Association (2021) *Fact sheet: Energy use in the steel industry;* Mandala analysis.

Australia, particularly Western Australia, is a major source of iron ore globally, supplying 58% of global iron ore import demand

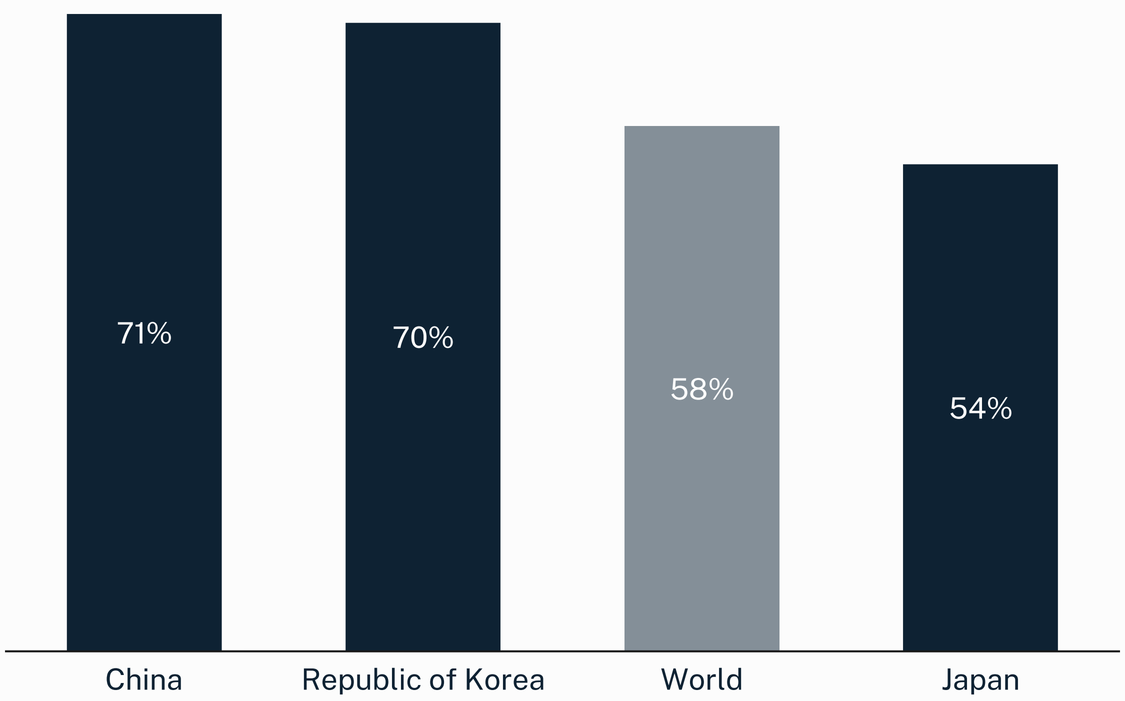
Volume of Australian iron ore exports by destination

Million tonnes (Mt) of iron ore and WA share by trade partner, FY 2024



Australia's share of iron ore imports

% of iron ore imports supplied by Australia, 2023



- 99% of Australia's iron ore exports were produced in WA (865Mt in FY24)[2,3]
- 96% of exports are hematite and hematite-goethite, with <4% magnetite[4]

1 Exports only include 'iron ore and concentrates.' 2 DFAT (2024) *Trade Statistical Pivot Table, State by country and SITC pivot table.* 3 WA Dept of Energy, Mines, Industry Regulation and Safety (2024) *Major Commodities Resource Data.* 4 WWF Australia (2024) *Australia's Green Iron Key.*

Source: Department of Industry, Science and Resources (2024) *Resources and energy quarterly: September 2024;* DFAT (2024) *Trade Statistical Pivot Table, State by country and SITC pivot table;* Department of Energy, Mines, Industry Regulation and Safety (2024) *Latest statistics release;* UN (2024) *UN Comtrade Database;* Mandala analysis.

Iron ore, produced primarily in the Pilbara, makes a large contribution to the economy

WA's iron ore industry is an important contributor to the state economy. For example, iron ore accounted for half of the total value of WA's resource production, half of onsite minerals employment, and 22% of the WA Government's general revenue in 2022-23 (equivalent to $9 billion paid in royalties, payroll taxes and transfer duties to the WA Government).

WA's iron ore industry also contributed 5% of Australia's economic add (as measured by gross value add), and provided $72 billion in direct spending to employees, businesses, community organisations, and governments. The industry directly employed approximately 51,100 Australians (full-time equivalent) and delivered $21 billion in federal corporate and fringe benefit taxes.

Approximately $57 billion in indirect economic value was generated by WA's iron ore industry in 2022-23, and the industry supported 357,000 jobs indirectly across the economy.

The industry is globally competitive – driven by its low-cost position on the global cost curve. This has been achieved through decades of investments in mine, rail, and port infrastructure and constant innovation in mining technologies.

Source: CMEWA (2024) *2022-23 Economic Contribution: WA Iron Ore*; Mandala analysis.

Economic contribution of the WA iron ore industry

FY2023

$72 billion
Direct spending by the WA iron ore sector in the Australian economy

$57 billion
Indirect spending supported by the WA iron ore sector

51,500 jobs
In the WA iron ore sector on a full-time equivalent basis

357,000 jobs
Supported from spending by the WA iron ore sector

$165,000
Average annual salary of WA iron ore employees

$9 billion
Royalties, payroll taxes and transfer duties paid to the WA Government

99% of Australia's iron ore exports are from WA, and 96% are from the Pilbara region[1]

1 DFAT (2024) *Trade Statistical Pivot Table, State by country and SITC pivot table;* WWF Australia (2024) *Australia's Green Iron Key;* Mandala analysis.
Source: CMEWA (2024) *2022-23 Economic Contribution: WA Iron Ore;* Geosciences Australia (2018) *Iron;* Australia Minerals (2023) *Australian Magnetite Ore Factsheet;* Mandala analysis.

Steelmaking is emissions intensive particularly during the ironmaking phase

Nearly all (98%) iron ore is used in steelmaking.[1] Steelmaking is emissions-intensive and generates around 6-9% of global emissions each year, and 7% of global emissions in 2023.[2] This is more than the total CO_2 emissions generated by the European Union in 2023.[3] This will drive increasing demand for green steel in the short term.

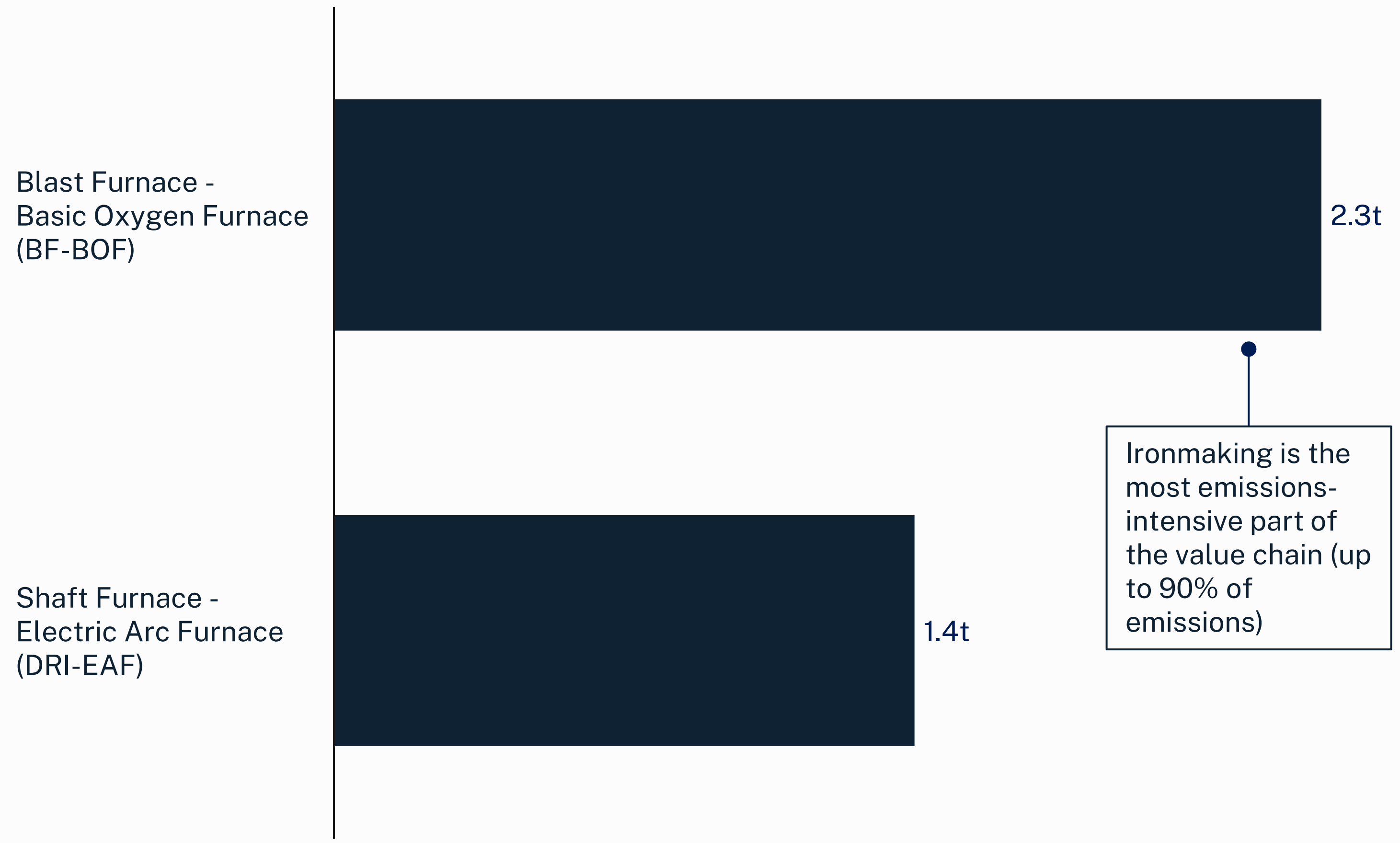
Ironmaking is the most emissions-intensive part of the value chain (up to 90% of emissions), particularly if using a Blast Furnace.[4] This reflects the use of coking coal in the Blast Furnace to generate the high temperatures required to melt away ore impurities, compared to the natural gas used in a Shaft Furnace. However, the Shaft Furnace does not reach temperatures required to remove impurities.

Decarbonising ironmaking has the potential to substantially contribute to global emissions reduction. Under current production pathways, there are two ways to reduce ironmaking emissions:

1. Using higher-grade ores, such as magnetite or high-grade hematite, reduces the amount of coking coal or gas required. For example, some magnetite products can deliver around a 10% reduction in net lifecycle emissions.[5] Additionally, assuming a 1% increase in average iron ore content in the BF-BOF process will result in a 1.6% reduction in CO_2 emissions.[6]
2. Increasing the proportion of iron produced via the existing DRI (Shaft Furnace) pathway could have a material emissions reduction impact; however, it is not currently applicable to the majority of global and WA iron ore supplies.

Emissions intensity by steelmaking process

Tonnes (t) of CO_2 per tonne of crude steel[7]



1 Government of Canada (2024) *Iron ore facts.* 2 IEA (2023) *CO2 emissions in 2023;* IEA (2023) *Steel;* World Steel Association (2024) *World Steel in Figures 2024;* Mandala analysis. 3 Our World in Data (2020), *CO2 emissions.* 4 MRIWA (2023) *Western Australia's Green Steel Opportunity Report.* 5 CITIC/The Crucible Group (2022) *Greenhouse emissions and magnetite iron ore "from pit to product."* 6 Government of Western Australia (2023) *Western Australia iron ore profile;* World Steel Association (2022) *Steel Facts;* World Steel Association (2023) *Fact sheet: Steel and raw materials*; Mandala analysis. 7 Emissions intensity varies based on iron ore grade. Minerals Research Institute of Western Australia (2023) *Western Australia's Green Steel Opportunity*. Mandala analysis.

A major reduction in ironmaking emissions requires development of new processes

The vast majority of global iron ore supply (97%) is not suitable feedstock for the existing lower-emission DRI-EAF pathway, given its high impurity levels and lower iron content.[1] Over recent years, the average purity of iron ore has been in decline globally. For example, in 2006, the average iron content mined by major producers was above 62% with 5% impurities, compared to 61% with 6.5% impurities by 2016.[1]

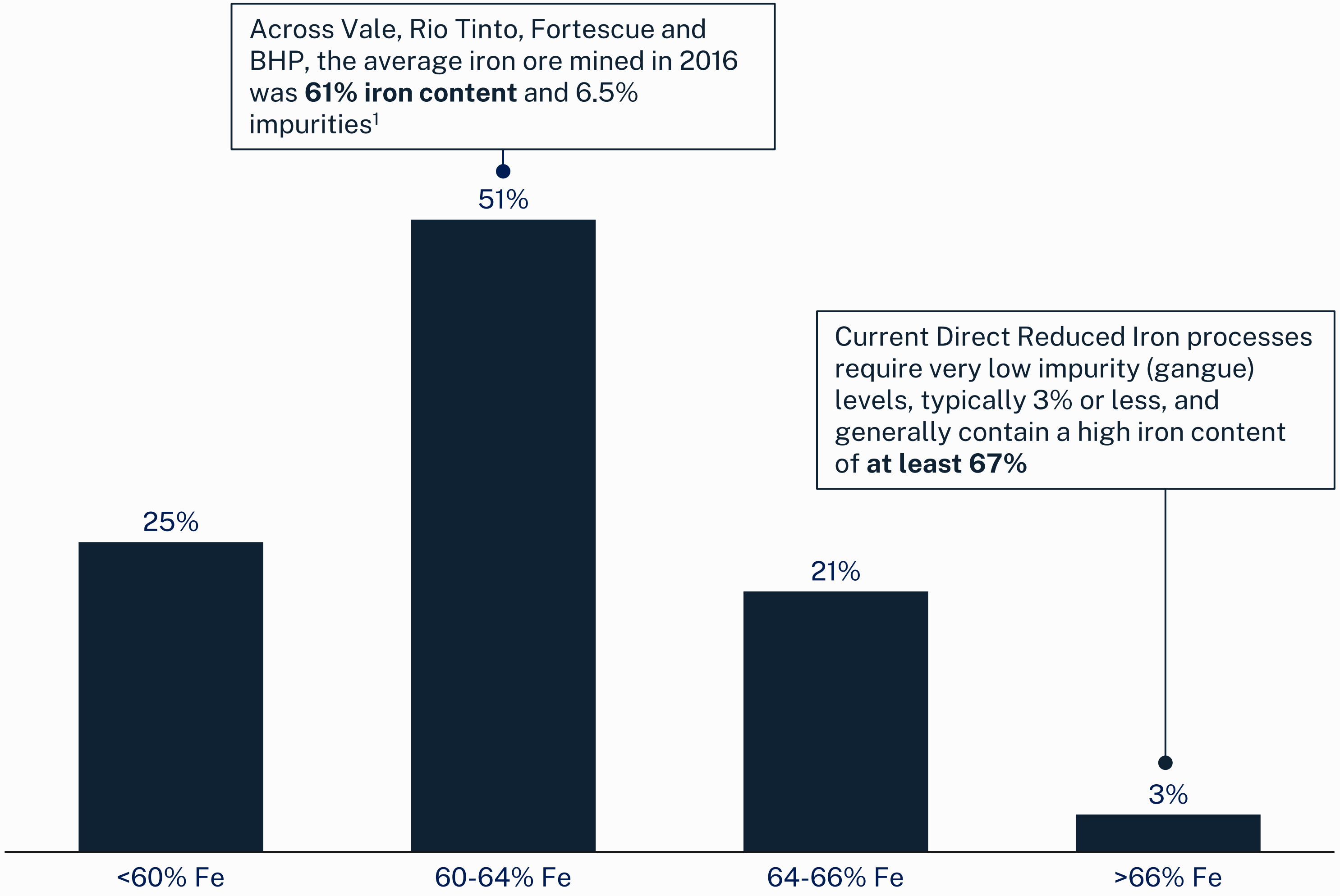
Most (96%) of WA's iron ore exports are considered low to mid-grade hematite and goethite, with the balance (<4%) comprising higher-grade (but not DRI-grade) magnetite concentrate products. Australia's average iron content in exported ore was 62% in 2023-24, with only 3% of exported Pilbara ore exceeding 65% iron.[2]

While the higher impurity levels in lower-grade iron ore are manageable in conventional steelmaking, decarbonisation pathways are not yet commercially viable for lower-grade feedstocks.[3] The industry is taking two key approaches to address this challenge. First, there is an effort to develop high-grade deposits, although the potential for growth here is limited.[4] Second, technologies are being developed to use lower-grade feedstocks. These efforts are ongoing, and no new processes are commercially viable or cost-competitive at scale. Government support is needed to scale and ensure the commercial feasibility of these technologies.

1 Minerals Council of Australia (2021) *Best in Class: Australia's Bulk Commodity Giants.* 2 Department of Industry, Science and Resources (2024) *Resources and energy quarterly: September 2024;* Minerals Council of Australia (2022) *Best in Class.* 3 MRIWA (2023) *Western Australia's Green Steel Opportunity Report.* 4 Geoscience Australia (2023) *Iron ore.*

Global iron ore supply based on iron (Fe) content

% of seaborne iron ore by % iron content



1 Minerals Council of Australia (2023) *Best in Class: Australia's Bulk Commodity Giants.*
Source: Geoscience Australia (2019) *Iron Ore 2019*; BHP (2023) *Pathways to decarbonisation;* Mission Possible Partnership (2022) *Making net-zero steel possible;* CME (2024) *Green metal statecraft.* Mandala analysis.

Australian industry is developing new green iron processes for WA iron ore

There is no internationally agreed definition for 'green iron'. For the purposes of this report, and in line with the proposed definition for green steel under the International Energy Agency's Breakthrough Agenda, green iron refers to iron produced in a near-zero emissions manner.[1]

CME members and other research and industry bodies are exploring pathways to decarbonise ironmaking using WA iron ore. These processes are at various stages of technological readiness, and none are commercially viable at an industrial scale or cost-competitive with established production pathways.

Most of the prospective pathways will require a two-step process to use WA iron ore feedstocks, as opposed to the current one-step processes. The most prospective pathway involves modifying Shaft Furnace technologies to replace natural gas with low carbon hydrogen, though natural gas could be used as a transition pathway towards green ironmaking.[2] However, to make this process compatible with lower-grade ore, the reduced iron must also be put through an Electric Smelting Furnace (ESF) to remove impurities.

A one-step electrolysis pathway is in the early stages of development. Here, an electric current generated by low-emissions energy is used to reduce ore to iron. However, it is expected to take a decade to advance this research to a TRL of 9.[3]

1 IEA (2024) *Breakthrough Agenda Report.* 2 MRIWA (2023) *Western Australia's green steel opportunity;* Calix (2024) *KS5 Pilot Plant Study Report.* 3 Mission Possible Partnership (2022) *Making net-zero steel possible.*

Potential green iron pathways

Technology readiness level (TRL) range - 1: basic concept to 9: fully operational[1]

	Overview	Reductant	TRL[1]	Key enablers
Shaft Furnace	Low carbon hydrogen replaces natural gas in the shaft furnace	Hydrogen[2]	6-8	▪ Reliable, low cost, low emissions energy ▪ Low carbon hydrogen availability ▪ Electric smelting furnace[3]
Fluidised Bed	Low carbon hydrogen reduces iron in a steady stream (adapting existing technology)	Hydrogen	5-6	▪ Reliable, low cost, low emissions energy ▪ Low carbon hydrogen availability ▪ Electric smelting furnace
Electrolysis	An electric current is used to remove oxygen from iron oxide ore	Electricity	3-6	▪ Reliable, low cost, low emissions energy
Microwave Furnace	Biomass is blended with iron ore and heated by gases released from biomass and microwaves	Biomass	4	▪ Reliable, low cost, low emissions energy ▪ Biomass feedstock availability ▪ Electric smelting furnace

1 Technology readiness levels (TRLs) are a benchmarking metric for technologies ranging from basic concept (TRL 1) to a working system that has performed successfully across the full range of expected operating conditions (TRL 9). 2 Hydrogen is assumed to be produced through electrolysis using low emissions energy. Until low carbon hydrogen is readily available, shaft furnaces using natural gas may be a transition pathway. 3 Shaft furnaces need pellets, and processing hematite into pellets would add a carbon-intensive step to production.
Source: Calix (2024) *KS5 Pilot Plant Study Report;* Fortescue (2024) *Low temperature electrochemical reduction*; BHP (2024) *Climate transition action plan;* Rio Tinto (2024) *Decarbonising steelmaking*; Mandala analysis.

Australian industry is developing new green ironmaking technologies suitable for WA iron ores, with most involving a two-step process

Potential green iron pathways

CURRENT PATHWAYS	**BF-BOF**	Coking coal acts as a reductant and heat source to remove impurities in the blast furnace	Iron ore → **Blast Furnace** *+ Coal* → Pig iron
CURRENT PATHWAYS	**DRI-EAF**	Natural gas is used as a reductant in the shaft furnace	Iron ore → **Shaft Furnace** *+ Natural gas* → DRI
POTENTIAL PATHWAYS	**Shaft Furnace (hydrogen)**	Low carbon hydrogen replaces natural gas as a reductant (iron ore must be pelletised) *Most prospective*	Iron ore → ① *Oxygen reduction*: **Shaft Furnace** *+ Hydrogen* → DRI → ② *Impurity removal*: **Electric Smelting Furnace** → Pig iron
POTENTIAL PATHWAYS	**Fluidised Bed**	Low carbon hydrogen reduces iron in a steady stream (adapting existing technology)	Iron ore → **Fluidised Bed** *+ Hydrogen* → DRI → **Electric Smelting Furnace** → Pig iron
POTENTIAL PATHWAYS	**Microwave Furnace**	Biomass is blended with iron ore and heated by gases released from biomass and microwaves	Iron ore → **Microwave Furnace** *+ Biomass* → DRI → **Electric Smelting Furnace** → Pig iron
POTENTIAL PATHWAYS	**Electrolysis**	A single-step process where an electric current is used to remove oxygen from iron oxide ore at low temperature	Iron ore → **Electrolyser** *+ Electricity* → Pig iron / DRI

2-step ironmaking process (Shaft Furnace (hydrogen), Fluidised Bed, Microwave Furnace)

1. Hydrogen is assumed to be produced through electrolysis using low emissions energy. Until low carbon hydrogen is readily available, shaft furnaces using natural gas are a suitable transition pathway as they use less emissions than a blast furnace. 2. Shaft furnaces need pellets, and processing hematite into pellets would add a carbon-intensive step to production.
Source: Calix (2024) *KS5 Pilot Plant Study Report;* Fortescue (2024) *Low temperature electrochemical reduction*; BHP (2024) *Climate transition action plan;* Rio Tinto (2024) *Decarbonising steelmaking*; Mandala analysis.

WA has several natural advantages which underpin its potential green iron competitiveness

Drivers of competitive advantage for conventional and green iron production

Product	Conventional	Green
Key inputs	Reliable access to iron ore	
	Low-cost coal	Reliable, low cost, low emissions energy
Location driver	Co-location with steel production (and low cost labour)	Co-location with low emissions energy and green hydrogen production (for H2 pathways)

WA's natural advantages

Iron ore

World's largest exporter

Wind

12,000 kms of coastline and Perth is one of the windiest capital cities in the world

Solar

Amongst the highest irradiance levels in the world

Land

One-third of the Australian continent with low intensity land use and low population density

Source: WA Government (2024) *Western Australia Iron Ore Profile May 2024;* WA Govt (2022) *Wind energy generation fact sheet;* WA Government (2024) *Western Australia's Renewable Hydrogen Strategy 2024-30;* WA Government (2021) *Western Australian Renewable Hydrogen Strategy;* RMI (2024) *Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future;* Mandala analysis.

WA could export at least $4bn of green iron by 2030 and $170bn by 2050

As countries search for low carbon alternatives to steelmaking, demand for cost-competitive green iron will rapidly increase. WA's iron ore reserves, mature mining operations and renewable energy potential are strong foundations for a competitive green iron industry.

Assuming supportive policy settings, it is estimated that WA has the potential to produce at least 4.5Mt of green iron in 2030, ramping up to 218Mt in 2050 (14% of global supply). This could generate $4 billion and $170 billion of export revenue in 2030 and 2050 respectively.

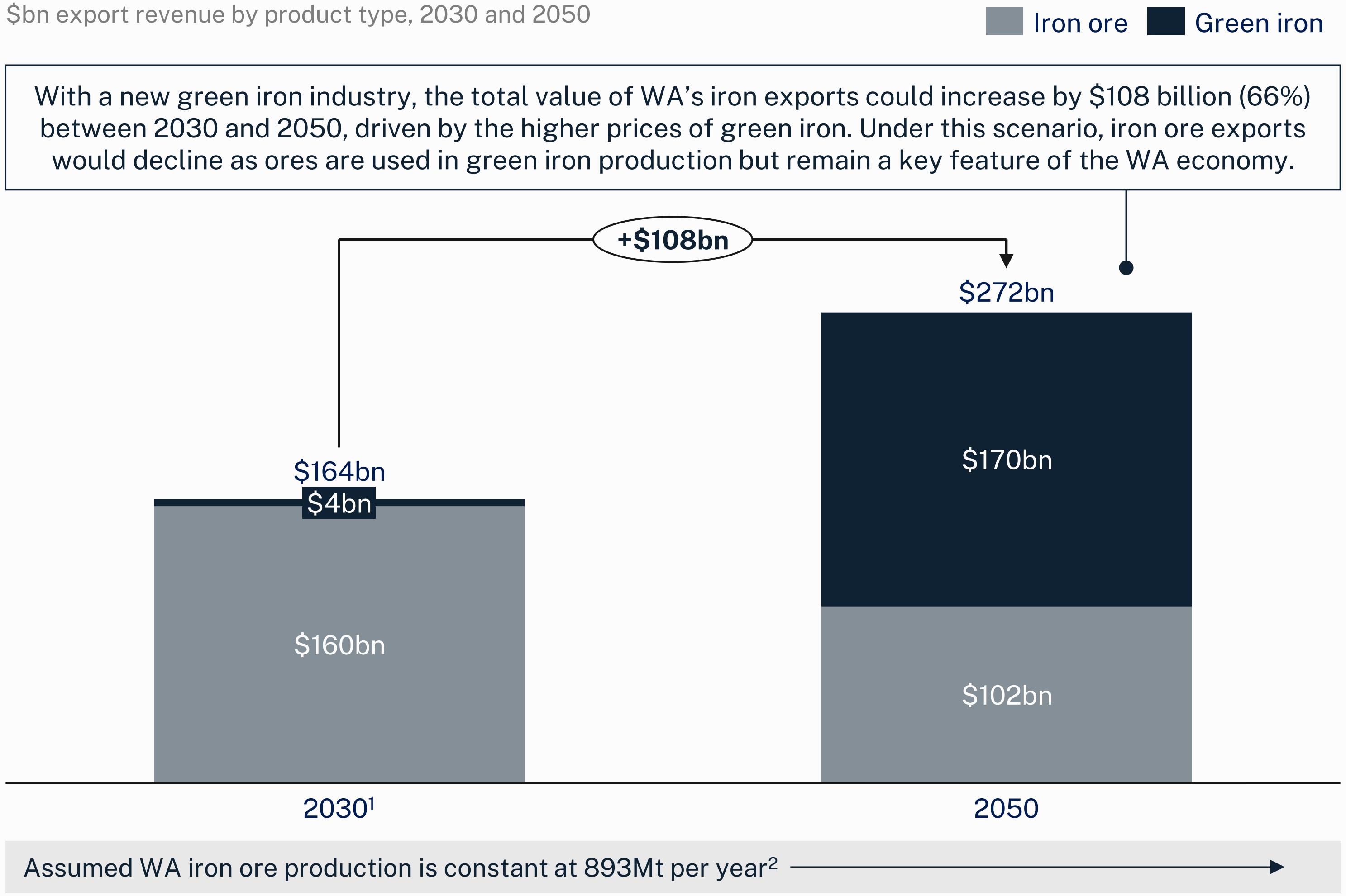
WA is expected to continue to export the iron ore that it does not use in green iron production. This ore may be used to support the green iron production in other jurisdictions.

Assuming constant iron ore production in the state (893Mt per year), the value of iron ore exports is expected to decline between 2030 to 2050 (from $160 billion to $102 billion), as WA iron ore is used as an input in domestic industry instead of being sold offshore. This estimate would change with changes in global demand for iron ore.

Developing a commercial green iron industry has the potential to not only drive substantial growth in export value but also safeguard the economic contribution of the iron ore sector by guaranteeing demand. Assuming iron ore production stays constant to 2050, a WA green iron industry would use approximately 37% of WA iron ore supply.

Indicative value of potential WA iron exports

$bn export revenue by product type, 2030 and 2050



Note: See appendix for methodology. Export value measures the total revenue generated (quantity of product sold multiplied by price). 1 Assumes constant price of iron ore ($180 per tonne); Estimated price of green iron is $934 per tonne in 2030, falling to $779 per tonne in 2050. 2 Assumes iron ore sales volumes are constant from FY28 to 2050, using FY28 forecast from Department of Jobs, Tourism, Science and Innovation (2024) *Western Australia Iron Ore Profile – August 2024.*

WA green iron production could offset Australia's entire domestic emissions

Steelmaking generated approximately 7% of global emissions in 2023.[1] This equates to almost 20% of the remaining global CO_2 budget, in a scenario where the world has a 50% chance of limiting global warming to less than 1.5°C.[2] However, the steel sector is not on track to achieving net zero, with total emissions still rising.[3]

In 2023, around 58% of steel production emissions were generated from the overseas processing of Australian iron ore into steel, equivalent to 4% of global emissions.[4]

As the world's largest iron ore exporter, Australia is at the forefront of global supply chains. Local production of green iron would allow WA to contribute to global emissions reduction efforts in a significant way.

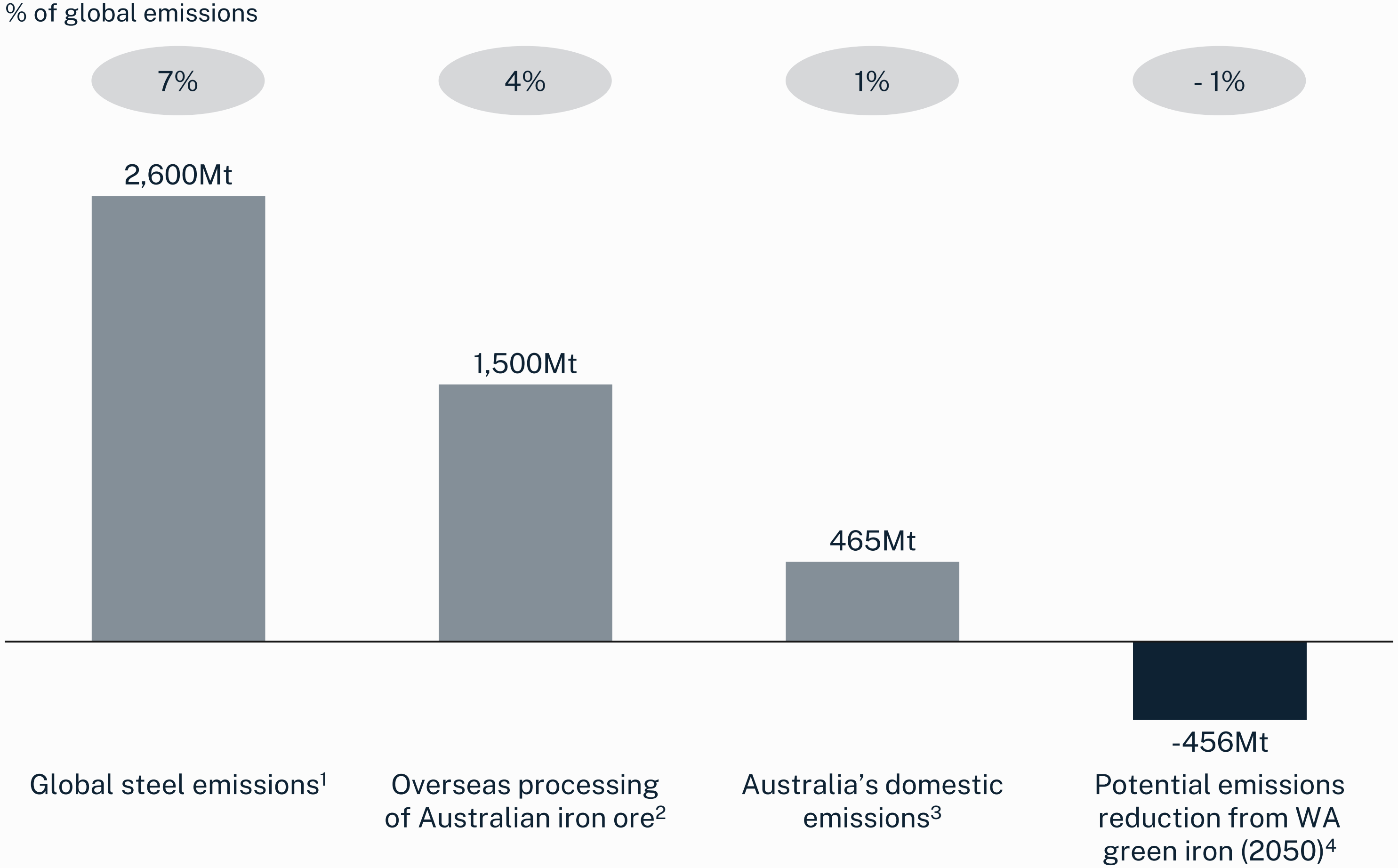
If WA supplied 218Mt of green iron in 2050, it would be equivalent to reducing global emissions by 1.2% - equal to Australia's current domestic emissions, or nearly 20% of steel value chain emissions.[5]

The urgent commercialisation of green iron technologies that use WA's lower-grade ores will help capture early demand for green iron products and support WA producers to contribute to the decarbonisation of overseas ironmaking.

1 IEA (2023) *CO2 emissions in 2023;* IEA (2023) *Steel;* World Steel Association (2024) *World Steel in Figures 2024;* Mandala analysis. 2 Mission Possible Partnership (2021) *Net-Zero Steel: Sector transition strategy.* 3 IEA (2023) *Steel: Overview.* 4 ARENA (2024) *Strategic priorities: support the transition to low emissions metals.* 5 World Steel Association (2023) *Sustainability indicators 2023;* Mandala analysis.

Comparison of annual emissions by source

Mt CO_2 emissions in 2023 and potential reduction from a WA green iron industry in 2050



Note: Potential emissions reduction assumes WA green iron production replaces blast furnace iron production. Source: IEA (2023) *Steel;* World Steel Association (2024) *World Steel in Figures 2024;* Mandala analysis. 2 ARENA (2024) *Strategic priorities: support the transition to low emissions metals.* 3 Department of Climate Change, Energy, the Environment and Water (2023) *Australia's emissions projections 2023.* 4 World Steel Association (2023) *Sustainability indicators 2023;* Mandala analysis.

A WA green iron industry could generate $74bn in economic value by 2050

A green iron industry in WA has the potential to generate $74 billion in additional economic activity by 2050, measured in gross value add (GVA), averaging nearly $18 billion per annum from 2030 to 2050. This is nearly four times larger than WA's current manufacturing industry, and nearly the size of Australia's existing iron ore industry ($97 billion in GVA in FY24).[1]

While global demand for WA's iron ore will continue, green iron presents an opportunity for Australia to capture additional economic benefits by moving up the value chain.

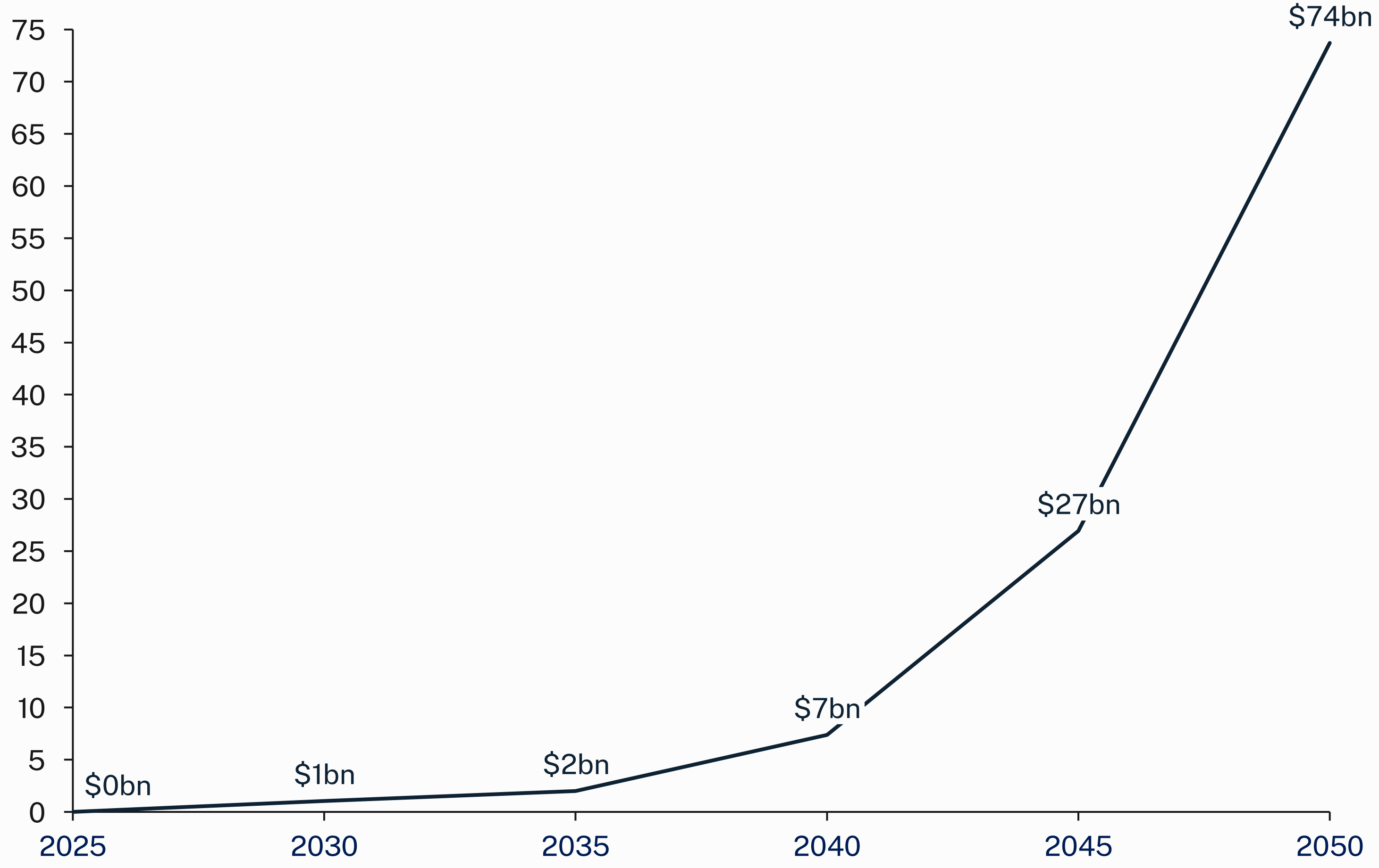
A WA green iron industry is forecast to support an additional 19,600 ongoing direct jobs by 2050,[2] equivalent to 25% of WA's current manufacturing workforce.[3] During the development and building of green iron facilities and enabling infrastructure, such as low emissions energy generation, the green iron industry will also create significant employment opportunities in construction and related industries.

New industry development presents long-term opportunities for WA communities, particularly in regional and remote areas. For example, low emissions energy infrastructure development can create new income streams, employment, and equity and social infrastructure opportunities for Traditional Owners.

1 WA Government (2024) *Western Australia Economic Profile: June 2024*; ABS (2024) *Gross Value Add (GVA) by Industry.* 2 Employment forecasts based on Net Zero Australia (2023) *Downscaling – Employment impacts.* 3 ABS (2024) *Labour Force – Employed persons.*

Economic activity (GVA) of a potential WA green iron industry

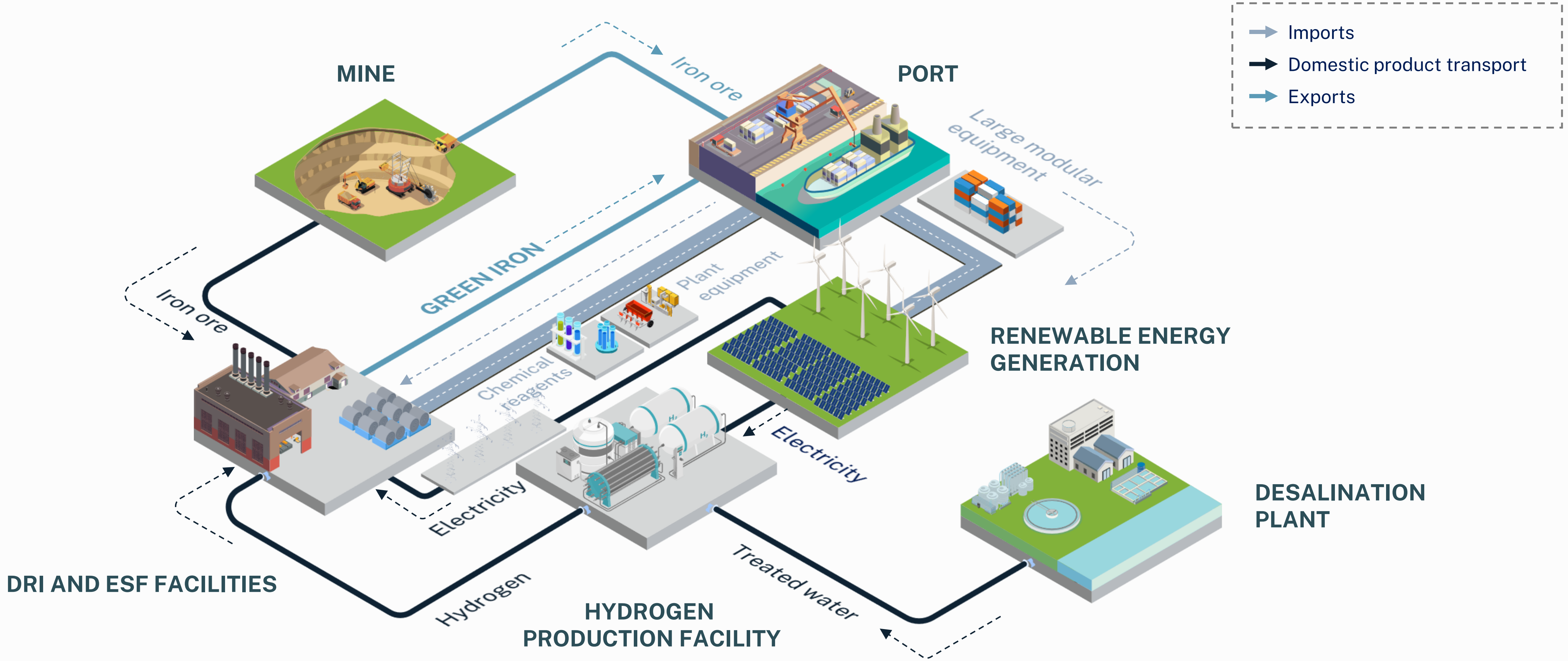
$bn, forecast annual economic activity (GVA) in 2024 dollars, 2025 to 2050



Note: Gross Value Added (GVA) refers to the economic value created by an industry, calculated as the value of output minus the intermediate inputs. This GVA figure represents estimated annual GVA for green iron production only and does not consider the value or costs of enabling infrastructure investment such as renewable energy infrastructure.
Source: Western Australia Government (2024) *Western Australia Economic Profile – June 2024;* Mandala analysis.

Establishing a green iron industry will require active investment across the green iron production lifecycle

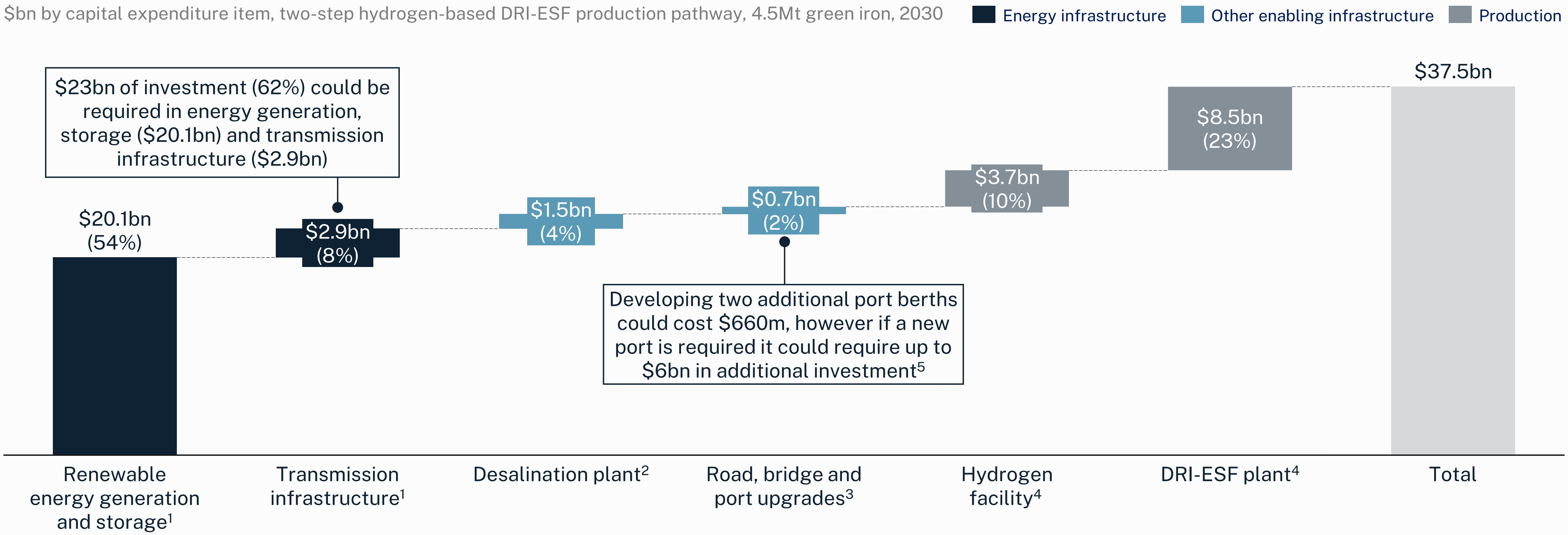
Illustrative green iron production lifecycle, hydrogen-based DRI-ESF production pathway



Achieving WA's green iron potential by 2030 with a two-step process could require at least $37.5bn in capital investments by government and industry

Indicative capital expenditure required in WA to produce green iron under a two-step pathway

$bn by capital expenditure item, two-step hydrogen-based DRI-ESF production pathway, 4.5Mt green iron, 2030



Notes: Estimates are based on using a two-step low carbon hydrogen DRI-ESF process to meet WA's 2030 green iron potential. This reflects the likely requirements of green ironmaking using WA iron ore and the cost of infrastructure development in WA in the immediate term. 1 Based on the average costs per building 1km of transmission line from the Pilbara Transmission Project. 2 Estimated based on the water required to produce WA's green iron potential supply in 2030 and the capital expenditure per gigalitre of water produced from the Dampier Seawater Desalination Plant; additional cost for water pipeline is estimated based on the cost of the Burrup seawater pipeline. 3 Estimated from the cost of the Lumsden Point port, rail and road infrastructure upgrades. 4 Given the limited publicly available data and nascent nature of the technology, the cost of an EAF is used as a proxy for the cost of an ESF. Both involve the passage of electricity between electrodes to heat ores. 5 Based on estimates of the cost of the proposed Balla Balla port development. Source: Minerals Research Institute of WA (2023) Western Australia's Green Steel Opportunity Report; Wang and Walsh (2024) South Australian Green Iron Supply Chain Study; Rio Tinto (2023) Rio Tinto to invest in Pilbara desalination plant; WA Government (2003) Burrup seawater pipeline construction under way; Infrastructure Australia (2023) Lumsden Point development; Main Roads Western Australia (2024) Great Northern Highway and Pinga Street; WA Government (2024) Pilbara Energy Transition Plan; CSIRO (2024) GenCost 2023-24 report; RMI (2019) The disruptive potential of green steel; Fortescue (2020) Pilbara Generation Project; Vogl et al., (2018) Assessment of hydrogen direct reduction for fossil-free steelmaking; Ship technology (2017) Balla Balla Infrastructure Project; Mandala analysis.

This will require targeted government action to accelerate low emissions energy generation, grow enabling infrastructure and scale technologies

Summary of the required green iron industry policy

There is a need for a holistic, clear and targeted approach that supports and incentivises industry and government to address technological, commercial, regulatory and infrastructure barriers

1 Accelerate low emissions energy generation

- Develop shared transmission infrastructure
- Provide targeted grants
- Streamline regulatory process

2 Grow WA's enabling infrastructure network

- Develop additional desalination plants and supporting pipelines
- Increase port capacity
- Widen select roads
- Coordinated regional development

3 Fast-track scale up of technologies

- Fund green iron R&D and commercialisation
- Promote Foreign Direct Investment
- Expand the Research & Development Tax Incentive (RDTI)
- Facilitate offtake agreements
- Ensure competitiveness
- Develop skilled worker pipeline
- Address green iron production in carbon measurement

This can be achieved through a green iron strategy for WA that includes the actions identified in the following 2030 Action Plan

These actions have been mapped to a 2030 Action Plan for WA [1/2]

	Barrier	2030 Action Plan
ACCELERATE GENERATION	Fragmented energy network	▪ Direct existing financing mechanisms to support common-user transmission infrastructure in WA. ▪ Address future transmission infrastructure needs of a green iron industry across WA (Pilbara/NWIS, SWIS and Goldfields).
ACCELERATE GENERATION	High costs of renewable energy generation	▪ Significantly increase funding available through the Powering the Regions Fund for renewables projects that lower the cost of green metals projects.
ACCELERATE GENERATION	Complicated regulatory process	▪ Establish a priority assessment pathway for projects that can reduce net global emissions, particularly in Strategic Industrial Areas. ▪ Clarify and streamline approval requirements across the State and Federal governments.
GROW ENABLING INFRASTRUCTURE	Large amounts of water needed for green hydrogen	▪ Include desalination plants as part of priority pathways for green energy and emissions reduction projects. ▪ Develop common-use water and hydrogen pipelines to support future desalination plants and hydrogen production.
GROW ENABLING INFRASTRUCTURE	Limited import capacity for required supplies	▪ Derisk business cases and progress investment in additional port capacity in the Pilbara and Mid West, including the addition of one berth at Lumsden Point Port and activation of proposed port development at Balla Balla, Anketell or Oakajee.
GROW ENABLING INFRASTRUCTURE	Lack of appropriate routes from port to production sites	▪ Identify core routes for transport of large modular materials needed for the construction of production plants. ▪ Prioritise funding for widening roads and upgrading bridges along these routes.
GROW ENABLING INFRASTRUCTURE	Difficulty in efficiently navigating tenure and heritage requirements	▪ Develop a regional approach to project development that streamlines land access and tenure-related processes. ▪ Implement agreements with Traditional Owners to manage site access, heritage protection and economic opportunities for local communities.

These actions have been mapped to a 2030 Action Plan for WA [2/2]

FAST-TRACK SCALE UP OF TECHNOLOGIES

Barrier	2030 Action Plan
Capital-intensive projects with uncertain longer-term returns **Iron ore for existing tech pathways is limited** **Production technology remains nascent**	▪ Prioritise green iron within existing programs (Powering the Regions, ARENA, Future Made in Australia, etc.) and expand funding criteria to include larger demonstration projects ▪ Ensure availability of grant funding for feasibility and FEED studies to encourage continued timely investment in commercial scale projects. ▪ Specify investment in green iron production and related infrastructure as a priority investment area by Treasury. ▪ Support industry (through funding and agency networks) to collaborate with overseas companies and research institutions. ▪ Increase the current cap on the RDTI and extend the eligible activities to incorporate the research and prefeasibility phases through to larger-scale commercialisation phases. ▪ Facilitate long-term offtake agreements between aspiring iron producers and international green steel producers. ▪ Quickly implement the Hydrogen Production Tax Incentive (HPTI), as proposed under Future Made in Australia and develop a green iron production tax credit that is stackable with the HPTI.
Skilled worker shortages	▪ Incorporate green iron into future workforce strategies to support the development of the skills required to develop and sustain ironmaking operations.
Commerciality of green iron across international markets	▪ Support international alignment on measuring green steel and iron that acknowledges efforts to reduce emissions in ironmaking. ▪ Align draft Australia Sustainable Finance Taxonomy with other transition-related frameworks and remove inclusion of Scope 3 emissions for ore producers. ▪ Expand the Guarantee of Origin Scheme to green iron products and ensure recognition in critical offtake markets. ▪ Create a separate magnetite production variable under the Safeguard Mechanism which recognises the associated energy-intensive ore beneficiation processes deliver an overall net benefit in global emissions across the steel cycle. ▪ Review stationary power variable under Safeguard Mechanism to avoid penalising off-grid projects.

Western Australia will need an additional 7.1GW of power to reach its 2030 potential

The availability of reliable, low cost, low emissions energy will be the fundamental driver of green iron competitiveness, regardless of the production pathway used. Australia faces intense competition to build sufficient low emissions energy at scale to meet domestic demand and drive down the cost curve. At the same time, there is a global race to produce cost-competitive green iron.

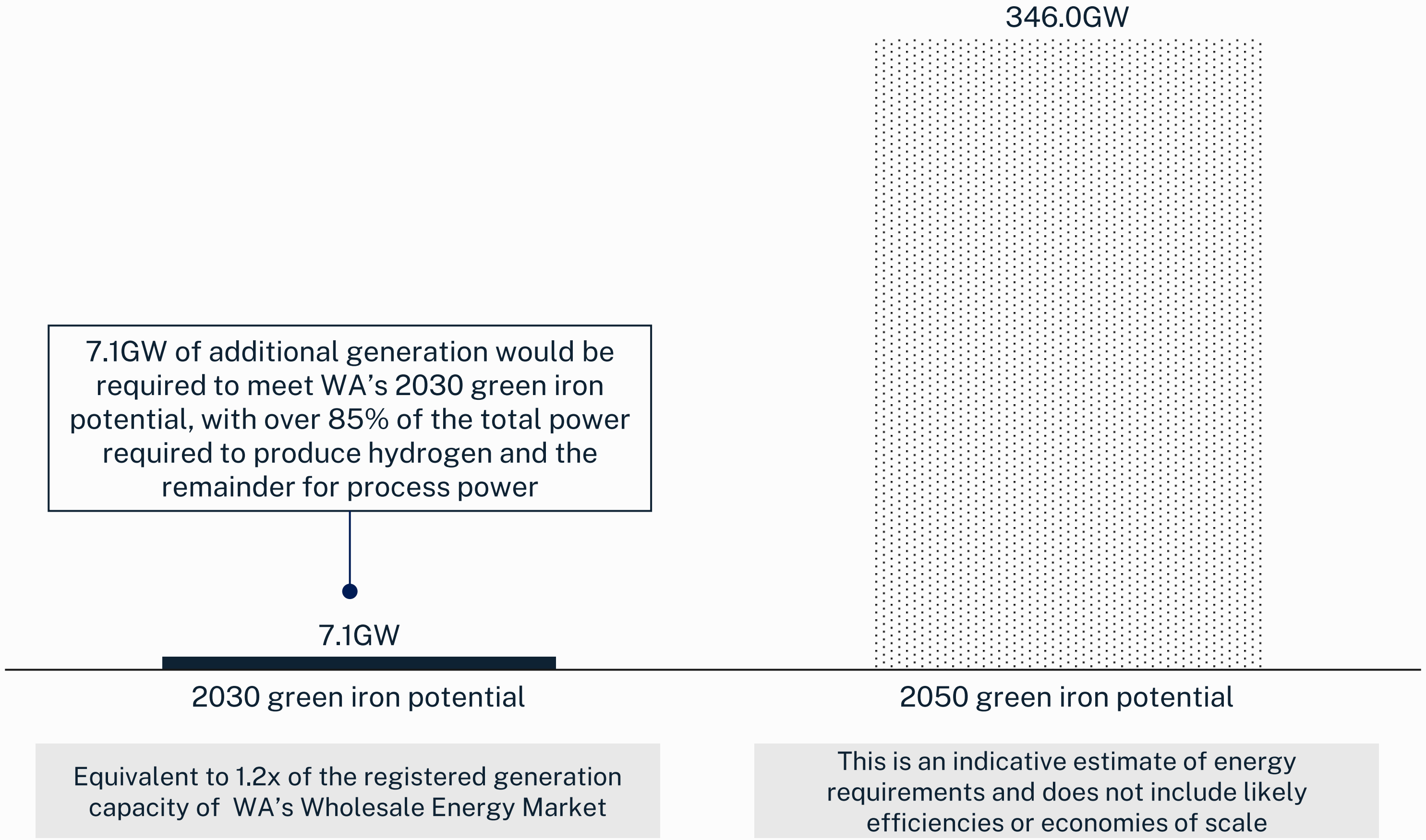
For example, when forecasting requirements for a hydrogen-based two-step green iron pathway, low carbon hydrogen production will require over 85% of the total electricity required. The remaining portion is used for process power. To reach WA's 2030 green iron supply potential, 7.1GW of additional reliable, low cost, low emissions power will be required. This is equivalent to 1.2 times the registered generation capacity of WA's Wholesale Energy Market.

Reaching WA's 2050 green iron potential will require a step-change in low emissions power generation. It is estimated that this could require up to 346GW of electricity. However, this is likely an upper estimate, given technological improvements will make green iron production more efficient. For example, Australian companies are developing electrolysers that are more efficient than current methods. If these trends continue, energy requirements may fall significantly over the coming decades.

Sources: ReNew Economy (2024) *Fortescue opens 2GW factory to build its own hydrogen electrolysers;* Norton Rose Fulbright (2024) *Pilbara Powers Up: Leading the Charge in Australia's Green Energy Transition*

Estimated additional power required to meet WA's green iron potential

Gigawatts (GW), two-step hydrogen-based DRI-ESF production process, by year



Notes: Assumed that 2030 potential green iron supply is 4.5 Mtpa and 2050 supply is 218 Mtpa; assumed a 50/50 mix of wind and solar power; assumed that the power required for an ESF is similar to an EAF. Source: Clean Energy Regulator (2024) *Large-scale renewable energy data;* Renewable Economy (2022) *Australia's best performing wind and solar farms in 2021, and the leading states;* AEMO (2023) *About the wholesale energy market;* Mandala Analysis.

Network development and regulation are major barriers to energy investment

$23 billion in capital investments in energy infrastructure will be required to achieve WA's 2030 green iron potential. Developing new energy assets can take five to six years, driven by lengthy approval and planning processes, meaning this investment is required urgently. Long lead times and regulatory uncertainty can deter investment in energy projects.

Most of this investment ($20.1 billion) is required to develop the generation and storage infrastructure needed to power production plants, with a smaller portion ($2.9 billion) needed for transmission.

There are substantial challenges to developing this infrastructure. This includes the highly fragmented nature of existing energy assets. For example, 60% of power stations in the Pilbara are isolated from the main grid. This means there is a lack of the common transmission infrastructure that can support future projects to achieve economies of scale, grid balancing and risk sharing. While the Government is working to accelerate priority transmission projects through the Pilbara Energy Transition Plan, decisions made on priority projects, corridors and capacity planning for 2030 must facilitate an emerging green iron industry.

The transmission capacity in other areas of WA, such as the Mid West and Kwinana, is also highly stretched. This will continue to create challenges across WA as renewable energy projects scale from just 17% of total generation today.

Key barriers to renewable energy infrastructure development in Western Australia

Fragmented energy network

~60%

Power stations in the Pilbara are not connected to the main network in the region (the North-West Interconnected System)

17%

Electricity generation in WA is from renewables, the second lowest share of any State or Territory in Australia

Complicated regulatory processes

~5 years

Median length of time to complete large-scale solar energy projects

$346m

Lost revenue per month of development delays for a 4.5Mt per year green iron plant

Source: North-West Interconnected System (2020) *Pilbara network facilities*; APA (2024) *Pilbara Energy System*; ANU (2024) *Renewable projects are getting build faster*; DCCEEW (2024) *Australian large-scale renewable energy project development journey*; Government of Western Australia (2024) *WA's energy transition bolstered by $500 million Budget boost*; Department of Planning (2015) *Mid West Reginal Planning and Infrastructure Framework*; Government of Western Australia (2023) *SWIS Demand Assessment 2023 to 2042*; DCCEEW (2024) *Australian electricity generation by state;* Mandala analysis.

Existing and additional policies are required to finance and streamline energy infrastructure development

The Government has established several financing mechanisms for low emissions energy infrastructure, which can be leveraged to accelerate the development of a WA green iron industry.

The Rewiring the Nation fund allocates $20 billion over four years in concessional financing to help build transmission lines, with $3 billion being earmarked for WA. Meanwhile, the $1.9 billion Powering the Regions Fund supports industry decarbonisation through grants of up to $100 million.

As a priority, the WA and Federal Governments should work to direct these existing funds to support the development of large-scale common-user energy transmission infrastructure, which could be accessed by industry on a pay-for-use basis. Investment in transmission infrastructure would form “highways” for electricity between low emissions energy generation facilities and green iron production. Common-user infrastructure would unlock the economies of scale required to encourage investment in new low emissions energy projects.

Additionally, clarity between the role of State and Federal planning and environmental regulations and overall streamlining would assist businesses in navigating years-long approval processes. Existing efforts such as WA amendments to the *Environmental Protection Act* and the Federal Government’s ‘Front Door’ should be developed and built upon in consultation with industry.

	2030 Action Plan
FINANCING	▪ **Direct existing financing to develop common-use transmission infrastructure:** Mobilise existing programs to support transmission infrastructure development. These programs include Rewiring the Nation, Powering the Regions, and the Northern Australia Infrastructure Facility. Government concessional finance programs such as the Northern Australia Infrastructure Facility and National Reconstruction Fund should be reviewed to ensure conditions attract investment in green iron. ▪ **Increase funding to Rewiring the Nation and Powering the Regions funds:** These national programs are valuable and may need to increase, recognising WA green iron production alone could require over $23 billion in renewable energy investment. These funds should be directed towards renewable projects to enable the scale required to lower the cost of power for green metals production and realise WA’s competitive advantages. ▪ **Improve the capacity of existing transmission infrastructure:** Invest in strengthening northern SWIS transmission through identified Stage 2 Mid West to Northern Country 330kV augmentation, to enable more green energy and iron development in the Mid West.
STREAMLINING	▪ **Prioritise approvals for green projects:** Federal and WA Government should establish a priority pathway for assessment of projects that support net global emissions reduction, particularly in identified Strategic Industrial Areas. In WA, this could be in the form of expanding the remit of the WA Green Energy Approvals Initiative to ensure green iron projects are captured. At the federal level, this could include collaborating with industry to deliver the ‘Front Door’ currently in consultation. ▪ **Environmental assessments:** WA recently amended the state’s *Environmental Protection Act* so that a new approvals system allows regulators to assess project proposals in parallel with environmental assessment processes. The impact of the amendment should be reviewed in one year to determine the extent it achieved the desired effect of streamlining projects and whether further action is needed. ▪ **Clarify requirements:** Clarify and streamline approval requirements across State and Federal governments, given significant policy developments across jurisdictions and ongoing overlaps.
PLANNING	▪ **Goldfields Regional Network:** Ensure the Goldfields Regional Network includes sufficient transmission infrastructure capacity to offer an economically viable grid option for future green iron projects. ▪ **Plan for increased demand:** Pilbara Energy Transition Plan should address future transmission infrastructure needs of strategic industries, such as green iron and hydrogen.

Source: CEF (2024) *Superpowering Up;* GT Law (2024) *Unlocking Green Energy: Infrastructure sharing in Western Australia;* DCCEEW (2024) *Rewiring the nation;* Business.gov (2024) *Funding for trade exposed Safeguard facilities;* WA (2022) *Green Energy Approvals Initiative;* DCCEEW (2023) *Capacity Investment Scheme;* WA (2024) *Designated Priority Corridors;* CCIWA (2023) *Green web;* Mandala analysis.

Existing capacity constraints in road, bridge, port and water infrastructure limit growth

At least $2.2 billion will be required to upgrade WA's road, bridge, port and water infrastructure to initially de-risk progress towards achieving WA's 2030 green iron potential.

WA's water infrastructure already faces capacity constraints and meeting WA's 2030 green iron potential could require an additional 18.4GL of water per year. Water demand in the Pilbara and Mid West is expected to continue to grow by up to 4% each year, even without new industries. Meeting this demand, without degrading groundwater sources, will require the construction of new desalination plants and water pipelines (estimated to require approximately $1.5 billion).

Further investment is required for road, bridge and port upgrades. Existing infrastructure, particularly in the Pilbara and Mid West, is already close to capacity and designed for the export of iron ore. It is not able to accommodate the importation of the large modular materials required to build energy infrastructure or industrial plants, large volumes of chemical reagents required for ironmaking, or the export of additional products.

In either the Pilbara or Mid West, a commercial-scale green iron industry will require additional port berths, roads to be widened and the construction or upgrade of heavy-load bridges. Developing two additional multi-user berth facilities could cost $660m, with supporting road and bridge infrastructure costing $64m. If a major new port development is required, this could cost close to $6 billion.

Key barriers to road, bridge, port and water infrastructure development in WA

Increasing water demand

18.4GL

Estimated water required p.a. to produce Western Australia's 2030 green iron potential supply

Up to 4%

Forecast compound annual growth rate for water demand in the Pilbara and Mid West regions from 2012 to 2042

Stretched port capacity

4 years

Until existing port infrastructure in the Pilbara reaches capacity, following 5 years of record-breaking throughput

35 Mtpa

Forecast capacity shortfall (all products) at Port of Geraldton in 2050, if there is high growth in trade

Sources: Mandala analysis; Infrastructure Australia (2023) *Lumsden Point development*; Pilbara Ports (2024) *Record tonnes exported from the Pilbara for fifth consecutive year*; Mid West Ports (2020) *Port of Geraldton Master Plan*; Department of Water (2013) *Pilbara regional water supply strategy*; Department of Water (2015) *Mid West regional water supply strategy*.

Projects need funding support, fast-tracking and local infrastructure

Investments need to be made in the immediate term to ensure the enabling infrastructure for green iron projects can be developed in tandem with energy and production infrastructure.

Existing road and port infrastructure will need upgrading to accommodate the import of large modular materials, renewable energy componentry and chemical reagents, and the export of new value-added green iron products.

To address the large water requirements of hydrogen production, large-scale desalination plants will likely be required. Enabling the development of this infrastructure at a sufficient scale will require Government investment in shared water and hydrogen pipelines to coordinate demand. This can follow a similar common-use model as recommended for transmission infrastructure.

WA's existing streamlining efforts to fast-track green energy projects should be expanded in scope to include supporting infrastructure, to enable faster approval timeframes and investment certainty for industry.

All project development will require an overarching regional approach to realise benefits for all stakeholders, including improving the social and economic outcomes for Traditional Owners and supporting local communities through job creation, skills development, preservation of high-value heritage and environmental assets, and diversification opportunities. Regional approaches can be pursued complementarily to the Strategic Industrial Areas.

	2030 Action Plan
COMMON INFRASTRUCTURE	▪ **Common user ports:** Derisk business cases and progress Government investment in additional port capacity in line with first mover project requirements in the Pilbara and Mid West, including the addition of one berth at Lumsden Point Port and activation of proposed port development at Balla Balla, Anketell or Oakajee. These developments would help progress towards ensuring WA has sufficient importation capacity for chemical reagents and energy infrastructure components, and additional export capacity for new value-added export industries. ▪ **Road widening and bridge upgrades:** Roads from ports to green ironmaking locations will need to be widened, and bridges upgraded, to support the transport of large modular materials needed in the construction of green iron production plants and energy assets. ▪ **Develop common-use water and hydrogen pipelines:** Government will need to fund common-use water and hydrogen pipelines to coordinate demand and drive economies of scale for large water and hydrogen facilities. Developing this supporting infrastructure would also help crowd in additional private investment in these facilities. ▪ **Regional development:** Develop a regional approach to project development that aims to realise significant benefits for local stakeholders, including improving the social and economic outcomes for Traditional Owners, while enabling faster approval timeframes and investment certainty for the industry. These regional approaches can be pursued complementarily to the WA Government's Strategic Industrial Areas.
STREAMLINING	▪ **Broaden priority approvals process for enabling infrastructure:** Pathways for prioritising green projects should extended to infrastructure projects needed for supporting major emissions reduction projects. Desalination projects, for example, are needed for low carbon hydrogen production. ▪ **Water planning:** Revisit the Pilbara Regional Water Plan to consider the implications of future hydrogen and green industries, including the need for additional desalination plants and pipeline infrastructure, given the Plan was first published in 2010. ▪ **Industry engagement:** Engage with industry to identify priority investments in supply chain infrastructure to support the development of a large-scale and low cost green iron industry.

Source: Legacie (2024) *Ngarluma Water Desalination Project*; Pilbara Ports (2024) *Greenfield ports;* WA (2010) *Pilbara Regional Water Plan;* Mandala analysis.

Large investments in new, capital-intensive technologies are high risk

An estimated $12.2 billion in production infrastructure is required to reach WA's 2030 green iron potential. Most of this investment ($8.5 billion) would be required to build the Direct Reduced Iron (DRI) production plant and Electric Smelting Furnace (ESF), with an additional $3.7 billion needed to build hydrogen facilities.

The scale of this investment and the uncertainty of new technology development are key barriers to attracting private investment. This is particularly the case for projects with large upfront capital investments for uncertain long-term returns. Approximately 50% of investors cite cost as a key issue for green steel development (and related processes such as green iron). However, green iron has the potential to become highly competitive over time, provided it receives the necessary support to overcome initial setup barriers.

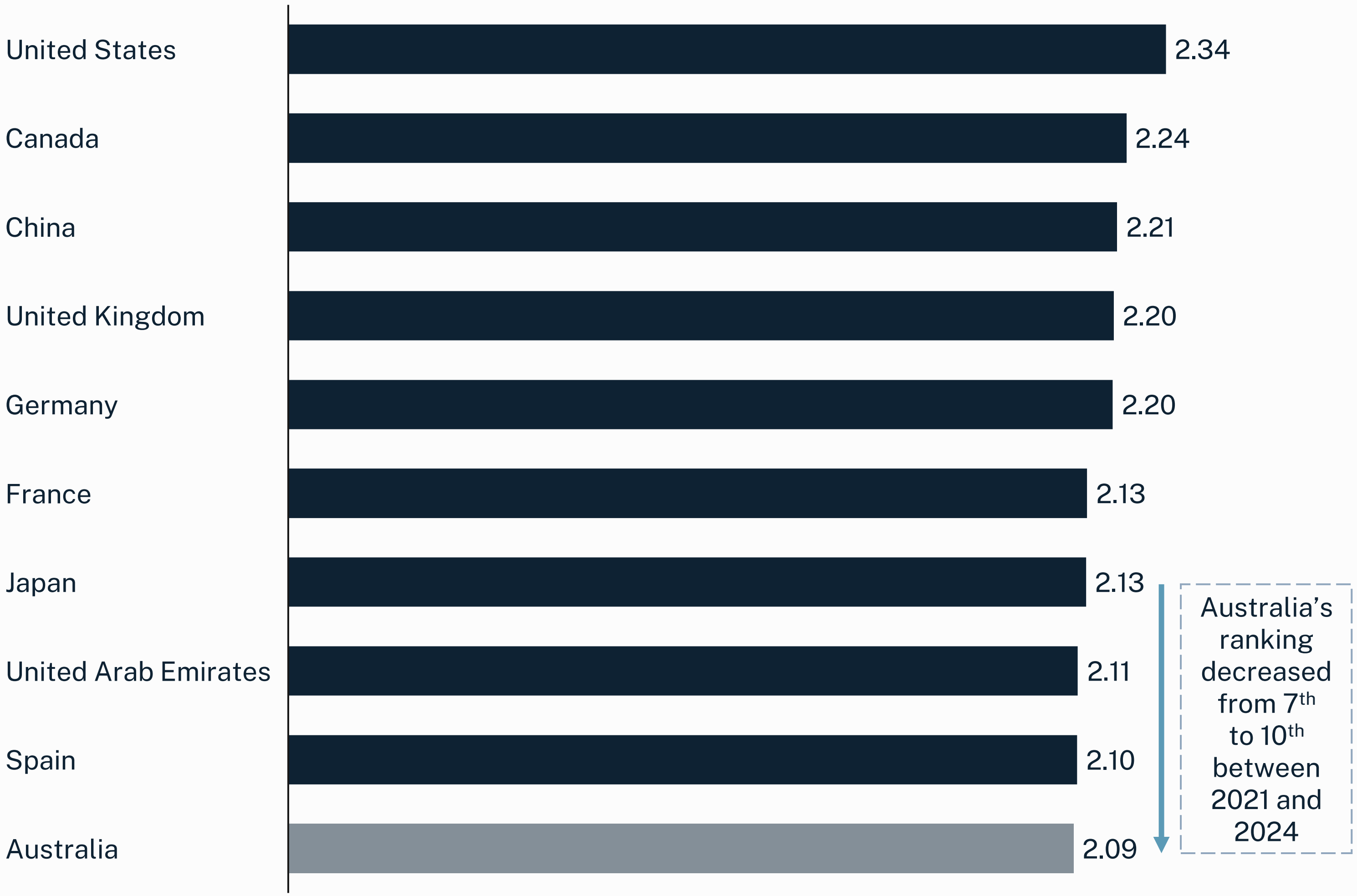
Foreign Direct Investment (FDI) has historically played an important role in underpinning Australia's growth in the resources sector and will continue to be key to future green industries. However, business confidence in investing in Australia has declined over time – where Australia has dropped from 7th to 10th place globally over the last three years.

Sustainable finance taxonomy settings can also deter investment by failing to recognise the contribution that projects could make to global decarbonisation.

Sources: Clayton Utz (2024) *Accelerating foreign investment in Australia's energy transition;* Australasian Centre for Corporate Responsibility (2024) *Ahead of the game: investor sentiment on steel decarbonisation*

Australia's FDI Confidence Index Ranking

Index scores, top 10 ranked countries, 2024



Source: Kearney (2024) The 2024 Kearney FDI Confidence Index®: Continued optimism in the face of instability

Current government policies can be leveraged to advance technology pathways in the green iron industry

Programs supporting research and development, pilots, and feasibility studies need to de-risk and crowd in private investment. The Government has many announced mechanisms to support innovative technology pathways for decarbonisation. These include Powering the Regions initiatives, ARENA funding, the Future Made in Australia Innovation Fund, the National Reconstruction Fund, the Hydrogen Headstart Program, and the Industry Growth Program. These programs should be directed towards supporting green iron production and its enabling infrastructure. Grant funding for feasibility and FEED studies is essential to drive timely investment in commercial-scale green iron projects.

The commerciality of green iron will be an ongoing challenge, particularly as international competitors benefit from industrial subsidies. For first mover, commercial scale green iron projects, government grants and incentives should be stackable to support the commerciality of projects across the value chain.

Commerciality will also be impacted by the ways emissions are priced and scoped in Australia and key export markets. There is, for example, a risk for the ironmaking industry that green steel would be defined more favourably towards the use of scrap steel and not properly account for the emissions reduction activities in the ironmaking process. To address this, the Government will need to consider nuances of green iron production when developing carbon measurement metrics.

	2030 Action Plan
TECHNOLOGY PATHWAYS	▪ **Prioritise green iron projects:** Direct funding programs to green iron technologies, including ensuring availability of grant funding for feasibility and FEED studies, and first mover projects in green iron. ▪ **Widen scope of funding within existing programs:** Increase flexibility in funding rounds for long-term emission reduction projects and expand funding criteria to larger demonstration projects for green iron. ▪ **Research and Development Tax Incentive (RDTI):** Extend eligible activity phases for the RDTI to incorporate research and prefeasibility phases through to larger-scale commercialisation phases; and increase the current cap on the RDTI to encourage greater investment here in Australia. ▪ **FDI promotion:** Specify investment in green iron production as a priority investment area by the Treasury, building on existing priority for net zero transformation. ▪ **Bilateral partnerships:** Support industry (through funding and agency networks) to collaborate with overseas companies and research institutions. ▪ **Accelerated depreciation:** Allow for accelerated depreciation of new green iron facilities.
COMMERCIALITY	▪ **Hydrogen Production Tax Incentive:** Quickly implement the HPTI, as proposed under the Future Made in Australia package. ▪ **Green Iron Production Tax Incentive:** Develop a green iron production tax credit that is stackable with the HPTI. ▪ **International measurement:** Support international alignment on measuring green steel and iron that acknowledges efforts to reduce emissions in ironmaking. ▪ **Offtakes:** Match aspiring green iron producers and first mover green steel producers to develop offtake agreements. A similar practice is done for the critical minerals industry. ▪ **Safeguard Mechanism:** Create separate production variables for energy intensive magnetite iron ore feedstocks to support emissions reduction across the steel value chain. Review the stationary power variable to avoid penalising off-grid projects. ▪ **Australian Sustainable Finance Taxonomy:** Align the draft taxonomy with other net zero transition-related frameworks and remove the inclusion of Scope 3 emissions for iron ore producers. ▪ **Royalty rate:** Conduct a targeted review of the WA royalty regime for processing projects, including iron ore feedstocks. Reduce the royalty rate for magnetite, recognising the role higher-grade iron feedstock plays in reducing emissions from existing ironmaking pathways and the higher costs associated with in-country iron ore value-adding. ▪ **Green certification:** Expand the Guarantee of Origin Scheme to green iron products and ensure recognition in critical offtake markets. ▪ **Skilled labour:** Develop a green iron workforce strategy to support the development of the skills required to develop and sustain ironmaking operations in Australia, to complement existing clean energy workforce initiatives.

Source: ARENA (2024) *Funding boost for hydrogen and low emissions iron and steel research;* Budget (2024) *A Future Made in Australia;* DCCEEW (2024) *National Hydrogen Strategy 2024;* Department of Industry, Science and Resources (2024) *Industry Growth Program;* NRFC (2023) *Renewables and low emission technologies.*

Australian companies are developing an Electric Smelting Furnace...

Australia's largest ore producers collaborate with steelmakers on ESF

BHP and Rio Tinto, two of Australia's leading iron ore producers, are partnering with steelmaker BlueScope to develop Australia's first ironmaking Electric Smelting Furnace (ESF) pilot plant.

This joint investment aims to demonstrate the feasibility of producing low carbon iron from Pilbara ores. It combines existing Direct Reduced Iron (DRI) technology with an ESF to remove the higher levels of impurities found in Australia's lower grade iron ore. ESFs for ironmaking are based on existing, proven technologies in other industrial processes.

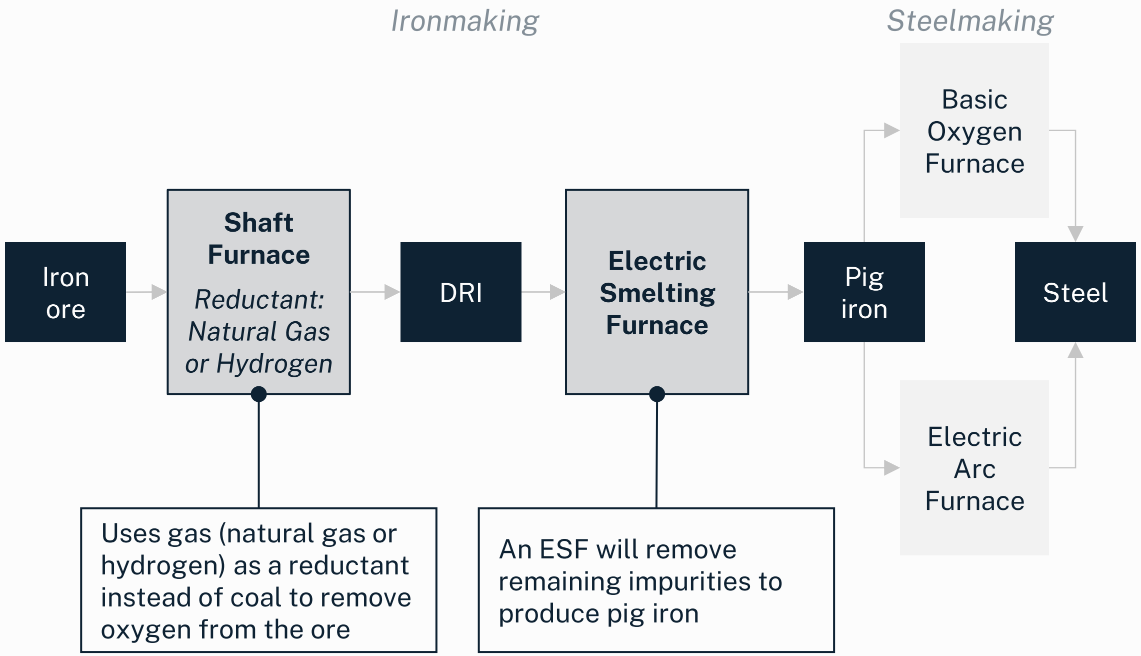
A pre-feasibility study is expected by late 2024, and if approved, the pilot facility could be commissioned in 2027.

Source: Rio Tinto (2024) *Iron ore producers partner with BlueScope on steel decarbonization.*

... to enable the use of lower-grade iron ore in existing DRI production methods

How it works: 2-step - Shaft Furnace and Electric Smelting Furnace

Shaft furnaces are already used in ironmaking. However, many hematite and magnetite ores commonly exported from Australia have higher impurity levels than required for DRI production. Introducing an ESF can allow for the use of Australian magnetite (with high silica levels) and hematite ores in this process.



Source: MRIWA (2023) *Western Australia's green steel opportunity*;
BHP (2024) *Pathways towards steelmaking decarbonization;*
Midrex (2024) *World direct reduction statistics*; Mandala analysis.

An industry and research collaboration is innovating ironmaking reactors...

Commercialising innovative reactor technologies

Fortescue and Roy Hill are collaborating with researchers at the Australian National University and the Heavy Industry Low-carbon Transition CRC to innovate reactor designs and improve green iron pathways for Pilbara ores.

The project is investigating the application of Fluidised Bed hydrogen DRI for lower grade hematite ores (found in the Pilbara). It is targeting a 10% cost reduction from the technologies developed.

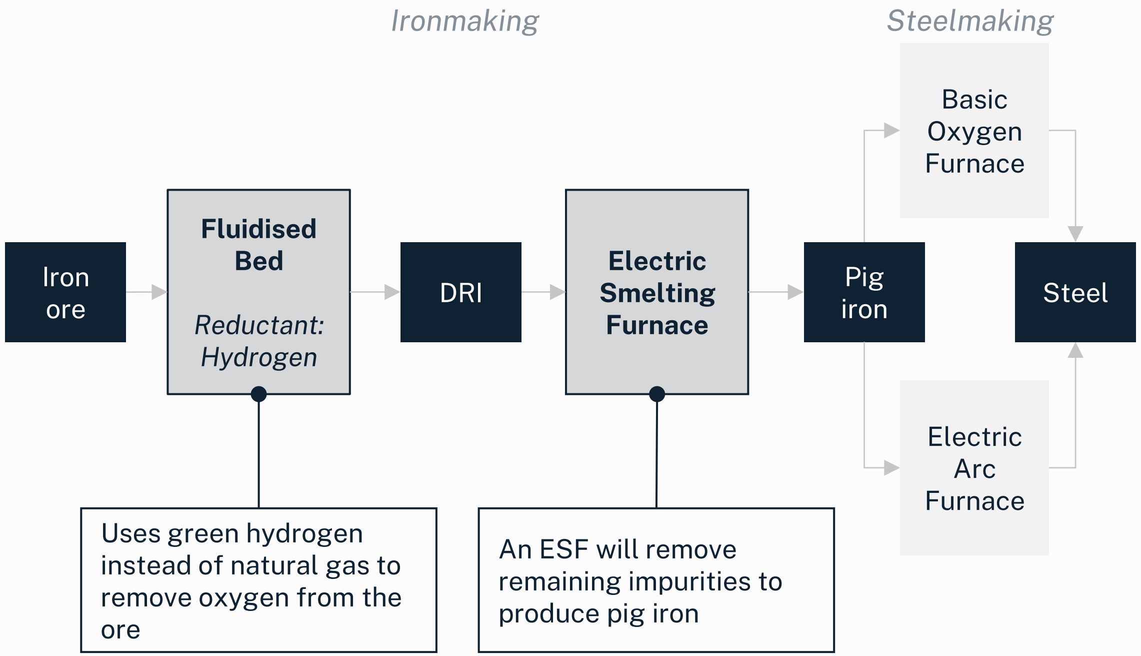
$13.7 million has been invested in the project, with $4.8 million received from ARENA. The project began in March 2024 and will run until April 2028.

Source: ARENA (2024) *De-risking large-scale Australian fine-ore hydrogen ironmaking.*

... to replace traditional furnace technologies with a Fluidised Bed

How it works: 2-step – Fluidised Bed and Electric Smelting Furnace

In a Fluidised Bed Reactor, the high-temperature reduction gas is distributed to give iron ore fines liquid properties. A reduction reaction is caused by mixing the iron ore as if mixing liquid. The application of Fluidised bed technologies for lower grade ores continues to be optimised.



Source: HILTCRC (2024) *Prevention of sticking in H2 fluidized bed DRI production*; POSCO (2022) *Great conversion to low carbon eco-friendly steelmaking*; Mandala analysis.

The Christmas Creek Green Iron Pilot Project is close to production...

Scaling green iron

Fortescue's Christmas Creek Green Iron Pilot Project is a significant step forward in their ambition to produce green iron metal on a commercial scale in the Pilbara region of Western Australia. The facility is expected to start production in late 2025 and produce more than 1,500 tonnes per annum of green iron metal once fully operational.

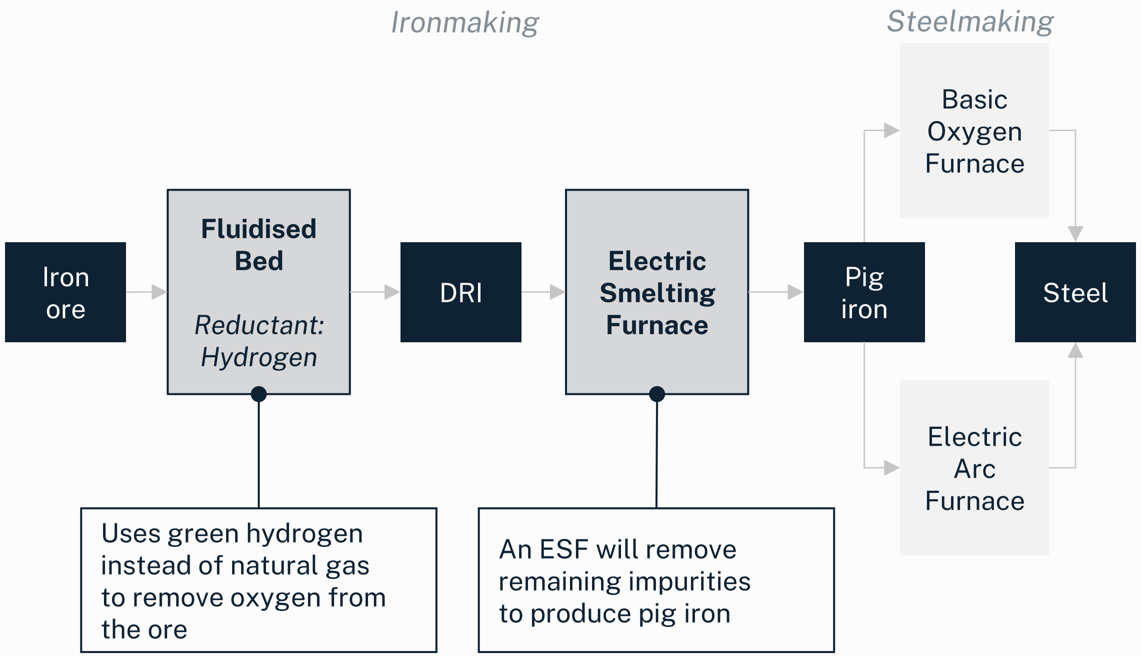
The project is located at Fortescue's Green Energy Hub precinct at Christmas Creek, adjacent to Australia's largest gaseous and liquid hydrogen plant on a mine site – which produces around 530 kilograms of hydrogen daily or around 195 tonnes annually.

Source: Media Release: The Hon Roger Cook (2024) *Ground breaks* [sic] *at green iron plant at Christmas Creek in the Pilbara.*

... and combines fluidised bed and smelting furnace technologies

How it works: 2-step – Fluidised Bed and Electric Smelting Furnace

Iron ore is first reduced in a hydrogen-based fluidised bed into Direct Reduced Iron (DRI). The DRI is then heated by an Electric Smelting Furnace (ESF) to remove impurities and converted into pig iron. The pig iron can be used in either Basic Oxygen Furnace or Electric Arc Furnace steelmaking pathways.



Source: Fortescue (2024) *Green metals;* Mandala analysis.

Australia will have the largest BioIron pilot plant in the world...

Rio Tinto's BioIron™ R&D facility

Rio Tinto will invest $215 million to establish a BioIron™ Research and Development Facility in Western Australia, building on successful trials in Germany. BioIron™ is a process that uses biomass and microwave energy instead of coal to make low carbon iron from Pilbara ore.

The facility will have a pilot plant ten times larger than the existing German plant and is the first time BioIron™ has been tested at a semi-industrial scale, capable of producing one tonne of direct reduced iron per hour.

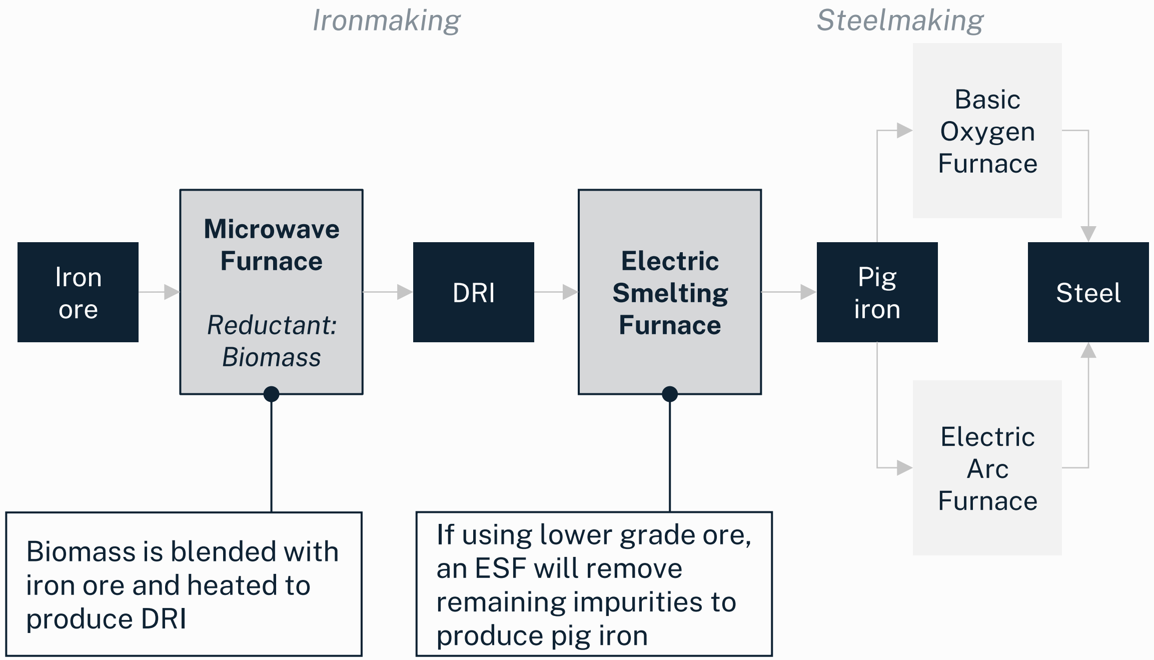
Fabrication of the equipment will begin in 2024 with commissioning of the facility expected in 2026.

Source: RioTinto (2024) *Rio Tinto to develop BioIron™ R&D facility in WA to test low carbon steelmaking.*

... which will replace coal with biomass at a semi-industrial scale

How it works: 2-step – Microwave Furnace and Electric Smelting Furnace

Biomass from agricultural by-products (wheat straw, canola stalks, barley straw) is blended with iron ore and heated by a combination of combusting gases released by the biomass and high-efficiency microwaves that can be powered by renewable energy.



Source: Rio Tinto (2022) *Rio Tinto's BioIron™ proves successful for low carbon iron-making*; Mandala analysis.

Fortescue is developing electrochemical technologies...

Optimising electrolysis for low temperatures

Fortescue is leading a Low Temperature Direct Electrochemical Reduction for Zero Emissions Iron project in Western Australia, supported by ARENA. The technology will be used for lower grade Pilbara ores.

The project aims to develop an optimised iron ore electrolyser, to commercial-ready specifications, that is capable of reducing lower grade ores at temperatures below 130ºC. Existing iron electrolyser technologies require temperatures of up to 1,600ºC.

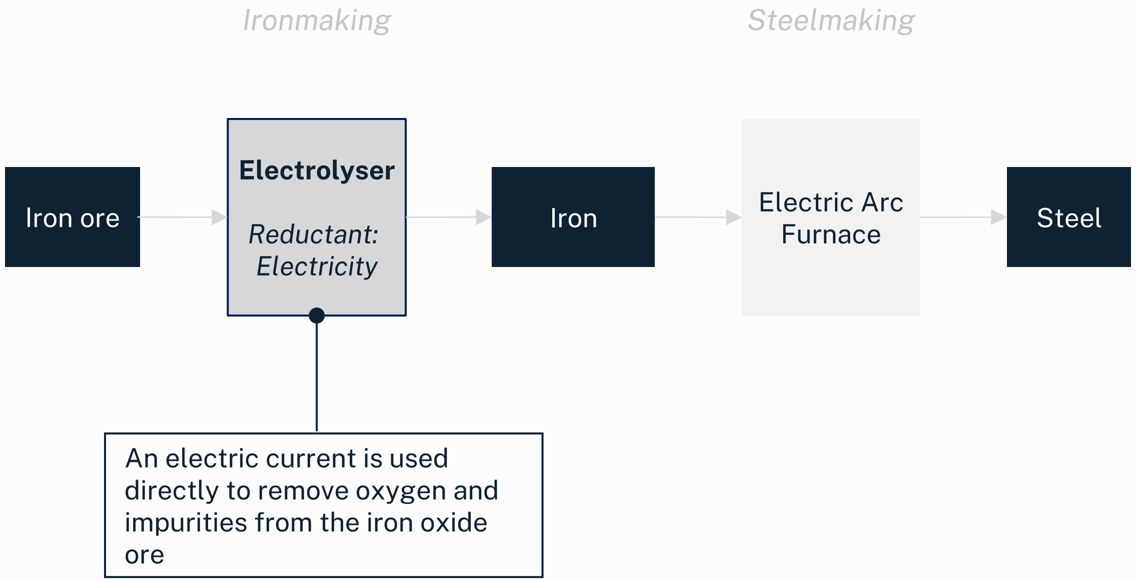
Deakin University and Curtin University are partners on the project, which launched in early 2024 and will be completed in 2026.

Source: Fortescue (2024) *Low Temperature Direct Electrochemical Reduction for Zero Emissions Iron.*

... which could produce green iron without hydrogen

How it works: Single-step ironmaking using an Electrolyser

Direct electrochemical reduction will use an electrolyser, powered by intermittent renewable energy, and an alkaline electrolyte to reduce iron ore to iron in a single step. The process will not require an Electric Smelting Furnace or a Shaft Furnace and will be designed to use hematite ore.



Source: Fortescue (2024) *Low Temperature Direct Electrochemical Reduction for Zero Emissions Iron*; Mandala analysis.

Hematite is 96% of iron ore exports but Western Australia also has substantial magnetite reserves

Overview of common iron ore and indicative WA locations of major deposits

Hematite and hematite-goethite[1]

ABOUT

Hematite ore, when mined, has 50-63% iron content and lower levels of impurities. As a result, it requires minimal processing prior to sale.

96% Iron ore exports – almost entirely from the Pilbara

78% Economic Demonstrated Resources (adjusted for iron content)[2]

99% Australian EDR in WA

Magnetite

ABOUT

Magnetite ore, when mined, has 20-30% iron content and higher levels of impurities than hematite. As a result, it requires capital- and energy-intensive processing into a higher-grade saleable product, typically with 65%+ iron content.

<4% Iron ore exports

22% Economic Demonstrated Resources (adjusted for iron content)[2]

67% Australian EDR in WA

1 The hematite designation used in this report may also include amounts of goethite and other non-magnetic ores. Pilbara iron ore is increasingly goethite in nature. 2 Calculated using EDR data in Australia Minerals (2023) *Australian Magnetite Ore Factsheet* and assuming an average iron level of 60% for hematite ores and 25% for magnetite ores.
Sources: Geosciences Australia (2018) *Iron*; Australia Minerals (2023) *Australian Magnetite Ore Factsheet*; Liberty Steel Group (2023) *High-Quality Magnetite;* SA Govt (*2024*) Iron Ore; CSIRO (2017) *Understanding the effects of goethite iron ore.*

Price levels in the Pilbara are substantially higher than in metropolitan areas, acting as a further barrier to infrastructure development in the region

60%

Higher average construction costs in Port Hedland compared to Perth[1]

15%

Higher Regional Price Index (RPI) levels in the Pilbara compared to Perth[2]

1st

Highest Regional Price Index level of any region in Western Australia (2023)[2]

17%

More businesses in the Pilbara report rising operating costs as being a key business challenge compared to Perth[3]

Notes: The Regional Price Index (RPI) is a measure of the cost of a common basket of goods and services at several different regional locations in WA. It is similar to the Consumer Price Index (CPI) measured by the Australian Bureau of Statistics as a key inflation indicator.
1 Town of Port Headland (2021) *Federal Budget Submission 2020-2021 – Town of Port Hedland;* 2 Department of Primary Industries and Regional Development (2023) *Regional Price Index 2023;* 3 Chamber of Commerce and Industry WA (2023) *Rising costs and skills shortages causing business pain in regional WA.*

As renewable energy generation scales and costs decrease in the medium term, Australia has the potential to be a cost-competitive producer of green iron in 2050

Forecast production cost per tonne of green iron in 2050

A$ per tonne (2024), one step hydrogen-based production process, countries with competitive production potential, 2050

Notes:
1 This study uses cost forecasts for one step low carbon hydrogen DRI ironmaking as the basis for cost competitiveness and 'size of the prize' modelling. This pathway is used as the basis for modelling as it is currently the most progressed pathway and has the best data availability. Other pathways are in development and may have lower cost profiles by 2050 than those used in this report. Production costs include the cost of green hydrogen production, energy, iron ore, labour and capital expenditure on production facilities. If the country does not have adequate iron ore reserves, iron ore shipping costs are also included. Australia's 2050 forecast does not include the HPTI as it is expected to end by 30 June 2040: Australian Tax Office (2024) Hydrogen Production and Critical Minerals Tax Incentives.
2 Countries with production potential were chosen based on long-term hydrogen costs (and renewable energy potential), the availability of iron ore, and whether the country has an existing iron/steel industry.
Source: Wang, C. and Walsh, S. (2024) South Australian Green Iron Supply Chain Study; Mandala analysis.

WA has the potential to capture 14% of global green iron supply by 2050

Green iron technologies are in the early phases of development. Among various technologies under development, the most prospective option involves using DRI with green hydrogen combined with an electric smelting furnace. This has been used to model green iron production over time.

As a commodity product, green iron production is likely to occur where capital and operating costs are lowest. Global cost curves are estimated for green iron production on the most technologically prospective pathway, noting this pathway has not yet been proven commercially viable.

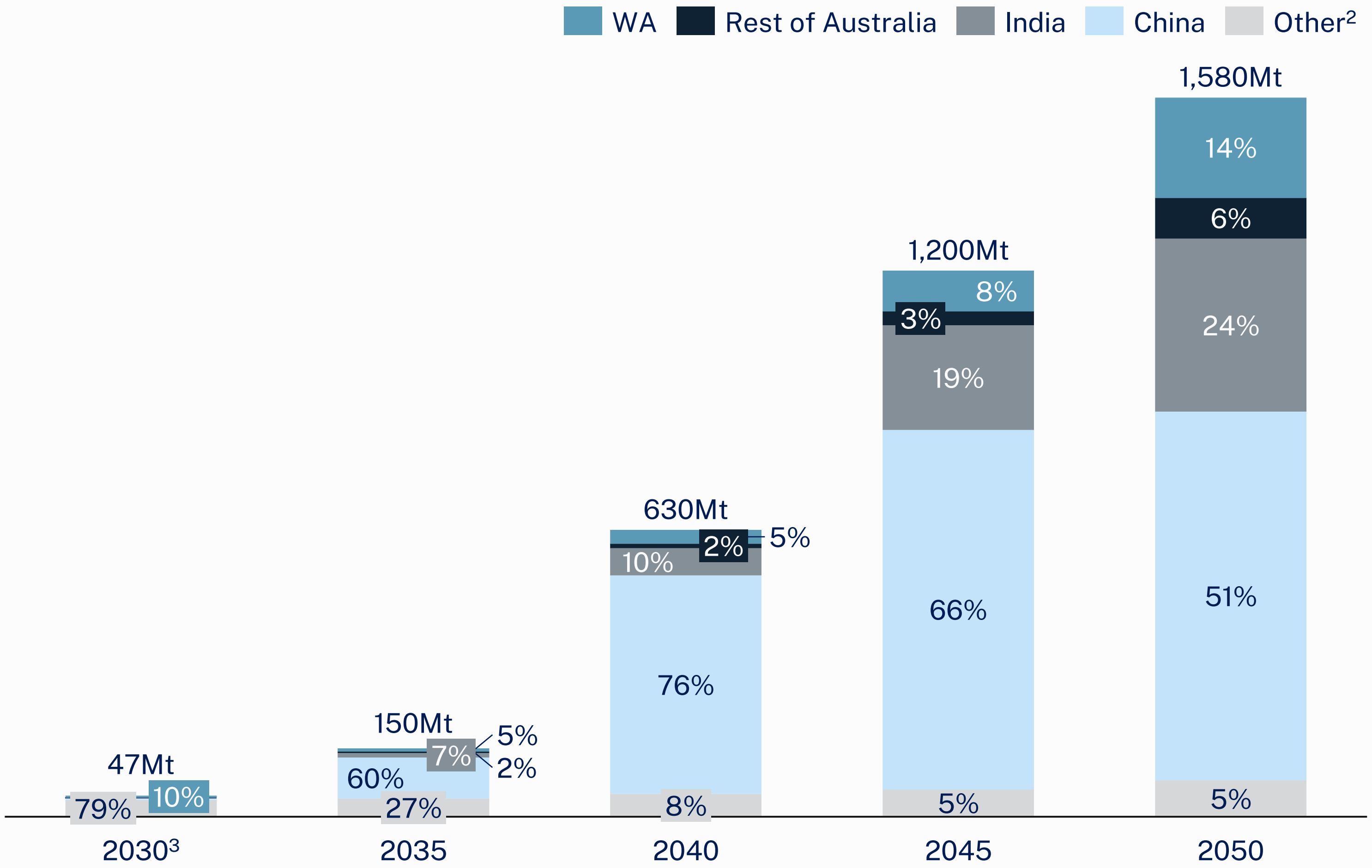
China is forecast to lead as the lowest-cost producer and projected to supply 810Mt (51% of global production) of green iron in 2050 at its maximum capacity.1 India and Australia are expected to be the next lowest-cost producers of green iron with comparable cost profiles by 2050. If Australia maintains its cost competitiveness, it could produce 310Mt (20% of global production) in 2050. 2

Within Australia, WA is well-positioned to become a leading green iron producer – driven by its access to natural resources and strong industrial foundation. Based on current investment trends, WA would account for 14% of global green iron production in 2050.

1 As China's current steel production is plateauing, it is assumed China's current steel capacity is the limit of China's industrial productive capacity. 2 Assumes importing countries do not place restrictions on Australian green iron and other producers do not implement policies that reduce per-unit cost.

Forecast green iron production by most cost-competitive countries

Millions of tonnes (Mt), production for Australia, India and China, 2030-2050



Note: This study uses cost forecasts for one step low carbon hydrogen DRI ironmaking as the basis for cost competitiveness and 'size of the prize' modelling. This pathway is used as the basis for modelling as it is currently the most progressed pathway and has the best data availability. Other pathways are in development and may have lower cost profiles by 2050 than those used in this report.
Source: Mandala analysis.

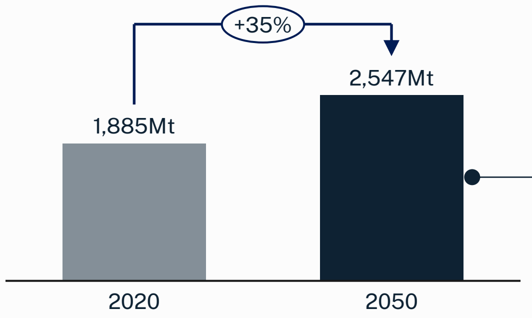
WA's green iron opportunity is based on Australia's competitive position in the global market and current investment trends

1 Determine future steel demand

Description

- Population growth and increasing standards of living will drive the continued increase in steel production globally[1]
- The IEA predicts steel production will increase by more than a third on 2020 levels by 2050[1]
- This is 54% primary steel and 46% made from scrap

Illustration

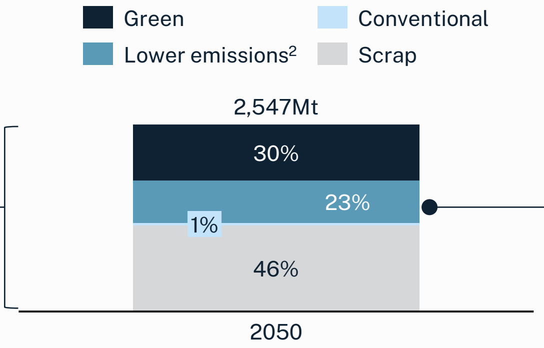


2 Determine green steel demand

Description

- In 2050, 30% of total steel (56% of primary steel) is forecast to be made using green production technologies. A further 23% of total steel (42% of primary steel) has the potential to be made with green technologies[2]
- 46% of all steel is manufactured from recycled steel scrap

Illustration

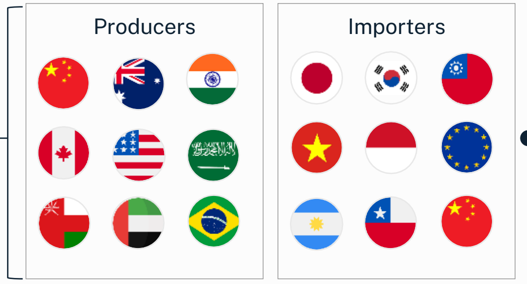


3 Identifying potential producers and importers

Description

- The availability of low cost green hydrogen, iron ore and an established iron/steel industry (or commitment to establishing) determines potential green iron producers and importers
- China, India, North America, Brazil and the Middle East are key potential producers competing with Australia
- NE Asia, SE Asia, Europe and South America choose to import green iron to produce green steel

Illustration



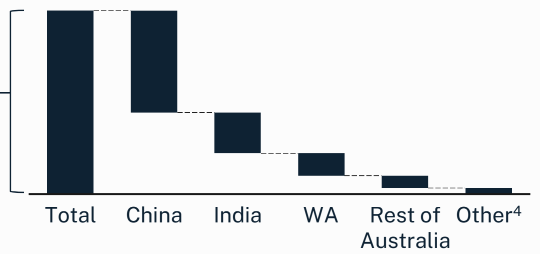
4 Identify WA's green iron export opportunity

Description

- Commodity demand is determined by cost. Based on forecast costs, China is expected to have the lowest cost, then India and Australia[3]
- In this scenario:
  - China is likely to produce green iron for domestic industry and excess production is the first choice of importer countries
  - India utilises domestic iron ore to supply domestic industry
  - Australia captures remaining demand, with WA's share estimated using current investment trends
- This scenario is a forecast of production and potential product destination, based on cost competitiveness and existing steel production. Cost competitiveness is based on a national average, however the average cost of production will vary by facility. As a result, the actual dynamics of the green iron market may be different, similar to the steel market where China currently both imports and exports steel

Illustration

Production volumes



1 IEA (2020) *Iron and Steel Technology Roadmap.* 2 Steel that is 'lower emissions' refers to steel production that can be made with completely or partially green production methods (including conventional production methods combined with CCS) depending on the availability of such production facilities. If no such facilities are available, conventional methods of production may be used. 3 This study uses cost forecasts for one step low carbon hydrogen DRI ironmaking as the basis for cost competitiveness and 'size of the prize' modelling. This pathway is used as the basis for modelling as it is currently the most progressed pathway and has the best data availability. Other pathways are in development and may have lower cost profiles by 2050 than those used in this report. 4 'Other' refers to an assumed share of green iron production that will be driven by domestic policies instead of cost-competitiveness.

Source: IEA (2023) *Steel and aluminium*; Mission Possible Partnership (2022) *Pathways to Net Zero*; Net Zero Industry (2024) *Net-Zero Steel Pathways;* Wood Mackenzie (2023) *Steel decarbonisation to redefine supply chains by 2050*; Mandala analysis.

Production forecasts for most cost-competitive producers

Methodology and assumptions for modelling Australia's green iron opportunity

Australia's competitiveness	▪ Barriers to industry development are addressed in the short term, allowing Australia to reach its full green iron potential, including achieving renewable energy generation scale and cost competitiveness ▪ Global green iron competitiveness is based on cost-competitiveness of green iron per tonne using a one step green hydrogen DRI production method[1] ▪ Australian green iron production is globally cost-competitive, only more expensive than China and on par with India
Global demand	▪ Global demand is equal to demand for 'green' and 'lower emissions' iron
China's production over time	▪ Planned projects in China open according to their planned timelines and projects that initially use a mix of natural gas and hydrogen move to exclusively using green hydrogen by 2030[2] ▪ Chinese production follows the linear trend of production capacity in planned projects until 2035 ▪ From 2035, Chinese production follows an S curve with total production in 2050 equal to its existing iron/steel production capacity[3] ▪ China exports all production after satisfying domestic demand
India's production over time	▪ Planned projects in India open according to their planned timelines and projects that initially use a mix of natural gas and hydrogen move to exclusively using green hydrogen by 2030[2] ▪ Indian production follows the linear trend of production capacity in planned projects until 2040[4] ▪ From 2040, Indian production follows an S curve[3] with total production in 2050 equal to its domestic demand for iron
Western Australia's production over time	▪ Planned projects in Australia open according to their planned timelines and projects that initially use a mix of natural gas and hydrogen move to exclusively using green hydrogen by 2030[2] ▪ Australian production follows the linear trend of production capacity in planned projects until 2035 ▪ From 2035, Australian production grows exponentially until 2045 when it tracks remaining demand after Chinese exports ▪ The composition of Australia's green iron opportunity is technology agnostic ▪ WA's share is determined by current investment trends

1 This study uses cost forecasts for one step low carbon hydrogen DRI ironmaking as the basis for cost competitiveness and 'size of the prize' modelling. This pathway is used as the basis for modelling as it is currently the most progressed pathway and has the best data availability. Other pathways are in development and may have lower cost profiles by 2050 than those used in this report. 2 Iron produced using a mix of natural gas and hydrogen will not be counted as green iron in our analysis. 3 The modelled S curve follows the growth in BF-BOF production capacity in China from the 2003 until 2018 using data from Vogl, V., Olsson, O. and Nykvist, B. (2021). 4 India's starting year for industry-wide adoption of green iron production technologies is assumed to be later than China's. We have assumed this because India has committed to net zero by 2070, 10 years later than China (IEA (2024)), and to reflect potential growth in iron/steel production in India beyond 2050. In both countries, green iron production is cost-competitive with conventional production in 2040.
Source: Mandala analysis.

Determining Australia's green iron opportunity involves identifying global demand for green iron and determining potential production by cheaper producers

Methodology overview

FACTOR	METHOD	INPUTS	SOURCES
Demand	[Forecast global steel production in 2050] X [Share of production that is primary steel production in 2050] X [Share of primary steel production that is green in 2050] X [Tonnes of green iron needed to produce one tonne of green steel]	[Forecast global steel production in 2050] = [Global steel production in 2020] X [36%]	IEA (2020) Mission Possible Partnership (2022)
		[Share of steel production that is primary steel production in 2050] = 54%	Mission Possible Partnership (2022) Net Zero Industry (2024)
		[Share of primary steel production that is green in 2050] = 98%	IEA (2020) Mission Possible Partnership (2022) Net Zero Industry (2024) Wood Mackenzie (2023)
		[Tonnes of green iron needed to produce one tonne of green steel] = 1.17 tonnes	Grattan Institute (2020)
Production	[Forecast global green iron production in 2050] – [Total green iron production in countries with lower green iron production costs than Australia]	[Forecast global green iron production in 2050] = Global green iron demand in 2050	IEA (2020) Mission Possible Partnership (2022) Net Zero Industry (2024) Wood Mackenzie (2023)
		[Total green iron production in countries with lower green iron production costs than Australia] = [Current Chinese iron/steel production capacity] + [Forecast green iron demand in India in 2050]	Global Energy Monitor (2024) Mission Possible Partnership (2022) Net Zero Industry (2024)

Emissions of steel	[Forecast green iron production] X [Emissions per tonne of iron]	[Forecast green iron production]	Mandala analysis (see previous)
		[Emissions per tonne of steel] x [share of emissions for iron production] = 1.4tCO2/t x 89%	IEA (2020), Iron and Steel Technology Roadmap Minerals Research Institute of Western Australia (2023) Western Australia's Green Steel Opportunity

Determining Australia's green iron opportunity involves finding the gross value add and direct ongoing jobs

Methodology overview

FACTOR	METHOD	INPUTS	SOURCES
Gross value added	[Price of green iron] X [Production] – [Total cost of production]	[Price of total product] = [Price of conventional iron] x [Green premium on steel, decreasing over time]	Yahoo Finance (2024) BloombergNEF (2024)
		[Production] = Volumes produced each year	Mandala analysis (see previous)
		[Total cost of production] = Includes costs of hydrogen, ore heating, labour and powering the production plant	Monash University (2024)
Direct ongoing jobs[1]	[Production] / [FTE required per tonne of production]	[Production] = Volumes produced each year	Mandala analysis (see previous)
		[FTE required per tonne of production]	McCoy, Davis, Mayfield, Brear (2022)

1 This refers to jobs that are involved in production. For example, this would include jobs in operating a DRI plant but not in building the DRI plant.

Methodology: Green iron capital expenditure requirements [1/2]

Infrastructure	Calculation	Source
Renewable energy generation and batteries	Generation • Assumes a 50/50 mix of wind and solar power • Average cost per kW of wind and large scale solar • Multiplied by total kW of required installed capacity Storage • Average cost per kW for battery system • Multiplied by total kW installed capacity (upper bound)	Generation • CSIRO (2024) *GenCost 2023-24 report* • Mandala estimate of power required (see separate power requirements method) Storage • Wang and Walsh (2024) *South Australian Green Iron Supply Chain Study* • Mandala estimate of power required (see separate power requirements method)
Transmission infrastructure	• Assumes that a new common use transmission network is required in the Pilbara (as described in the WA Renewable Hydrogen Strategy) • Estimated distance between Port Headland–Newman + Port Headland-Exmouth + Port Headland-Paraburdoo + Port Headland-Nullagine + Port Headland-Marble Bar *[Note: potential transmission pathway is approximated based on the indicative network modelling in the Pilbara Energy Transition Plan]* • Multiplied by (estimated cost of transmission infrastructure in the Pilbara (US$250 million)) / transmission infrastructure built in project (275km)) • Multiplied by exchange rate conversion factor (from USD to AUD)	• WA Government (2024) *Pilbara Energy Transition Plan* • Fortescue (2020) *Fortescue invests in energy infrastructure through Pilbara generation project*
Desalination plant	• Total water required (from Pathway 4, for 1 Mtpa) - Total water required (from Pathway 2, for 1 Mtpa) • Multiplied by Western Australia's annual green iron production potential in 2030 • Multiplied by (Total cost of Dampier Seawater Desalination Plant / Annual water produced from Dampier Seawater Desalination Plant) • Plus cost of supporting pipeline infrastructure (using estimate of Burrup pipeline, adjusted for inflation)	• MRIWA (2023) *Western Australia's Green Steel Opportunity Report* • Mandala green iron forecast demand model • Rio Tinto (2023) *Rio Tinto to invest in Pilbara desalination plant* • WA Government (2003) *Burrup seawater pipeline construction under way*
Road, bridge and port upgrades	• Cost of Lumsden Point road, bridge and ramp upgrades • Plus cost of Lumsden Point Port Development	• Main Roads Western Australia (2024) *Great Northern Highway and Pinga Street* • Infrastructure Australia (2023) *Lumsden Point development*

Notes: Estimates are based on using a two-step low carbon hydrogen DRI-ESF process to meet WA's 2030 green iron potential. This reflects the likely requirements of green ironmaking using WA iron ore and the cost of infrastructure development in WA in the immediate term.

Methodology: Green iron capital expenditure requirements [2/2]

Infrastructure	Calculation	Source
DRI-ESF Plant	DRI plant • Estimated cost of shaft furnace for 1MTPA (Pathway 5) • Multiplied by Western Australia's annual green iron production in 2030 ESF • Capex cost per tonne of product for EAF (Euros, 2012) *[Note: electric arc furnace is used as a proxy for the cost of an electric smelting furnace.]* • Multiplied by exchange rate factor to convert to AUD • Multiplied by inflation adjustment rate to convert to 2023 AUD • Multiplied by Western Australia's annual green iron production in 2030	DRI plant • MRIWA (2023) *Western Australia's Green Steel Opportunity Report* • Mandala green iron forecast demand model ESF • Vogl et al., (2018) *Assessment of hydrogen direct reduction for fossil-free steelmaking* • Mandala green iron forecast demand model
Hydrogen facility	• Estimated cost of hydrogen facility per 1MTPA *[Note: estimated as difference between Pathway 5 – Pathway 2]* • Multiplied by Western Australia's annual green iron production in 2030	• MRIWA (2023) *Western Australia's Green Steel Opportunity Report* • Mandala green iron forecast demand model

Notes: Estimates are based on using a two-step low carbon hydrogen DRI-ESF process to meet WA's 2030 green iron potential. This reflects the likely requirements of green ironmaking using WA iron ore and the cost of infrastructure development in WA in the immediate term.

Methodology: Green iron power requirements

Infrastructure	Calculation	Source
Power required to meet Western Australia's green iron production requirements	• Total energy required to produce tonne of green steel *[Note: assumed that power required for EAF is same as ESF]* • Multiplied by Western Australia's annual green iron production • Multiply by capacity factor *[Note: assumed that installed capacity must be four times greater than firmed capacity required]*	• RMI (2019) *The disruptive potential of green steel* • Mandala green iron forecast demand model

MANDALA