REPORT

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A *Green Iron* plan for Australia

Securing prosperity in a decarbonising world

The Superpower Institute

About The Superpower Institute

Founded in 2023 by economist Ross Garnaut and public policy expert Rod Sims, The Superpower Institute is a not-for-profit organisation dedicated to helping Australia seize the extraordinary economic opportunities of the post-carbon world.

The Institute's focus is on developing the policy settings, market incentives and practical knowledge necessary for Australia to become a major exporter of renewable energy and green industrial products. By leveraging the nation's comparative advantage, the Institute aims to elevate Australia's economic and climate ambition and secure its place as a leader in a decarbonised global economy.

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Image: Primetals Technologies

This report was authored and edited on the Traditional Lands of the Wurundjeri People of the Kulin Nation and the Whadjuk People of the Noongar Nation. We pay our respects to their Elders past and present, and acknowledge the enduring strength of their cultures, knowledge and custodianship.

As Australia advances toward a new era of clean energy trade, we recognise the vital importance of First Nations voices, rights and leadership. A just transition must ensure that First Nations communities share equitably in the benefits of new industries, and that their deep connections to Country inform how we shape a more sustainable and inclusive future.

The Superpower Institute
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Foreword

Much has been written and said about the logic of Australia as a green iron producer. Until this work by TSI there was a significant gap: how do we make it happen?

The work is important in answering that question in two main respects.

First, it demonstrates how the production cost of green iron varies in response to adjustment of crucial variables — location, renewable energy resource quality, capital costs, ore type and production technology. It also quantifies the benefits of trading excess or shortfall energy in proximate wholesale energy markets where this is an option.

This is critical. The first green iron projects will need to be built where the economics are most compelling. It would be a misstep to focus narrowly on high cost locations, risking delay or even failure to grasp the green iron opportunity in Australia.

Second, TSI plots the policy pathway, grounded in the underlying economics of green iron production, to a thriving industry in Australia that can play a major role in global decarbonisation.

The compelling intuition of making green iron in Australia will not be translated to reality without policy action by the Federal and state governments. This report is a blueprint for what is necessary.

The time for action is now, building on the promising Future Made in Australia policy, the National Interest Framework, the Hydrogen Production Tax Incentive and the Green Iron Investment Fund. The foundations are in place; A Green Iron Plan for Australia fills in the crucial detail.

The report is the product of many months of work by TSI's economists, researchers and technical experts. We also acknowledge the valuable contribution from Bivios, our partner in modelling green iron production costs.

If the world is to achieve its climate targets the steel supply chain must be decarbonised. This will be nearly impossible without a prominent role for Australia. I am confident A Green Iron Plan for Australia can set us on the right path.

Baethan Mullen
CEO, The Superpower Institute

We cannot expect markets to fix themselves.

We need policy leadership to back early projects, close the cost gap created by the lack of an international carbon price, and to help lay the foundations for a globally competitive industry.

This plan shows the way.

Executive Summary

Realising the green iron opportunity for Australia

Australia is uniquely positioned to become a world leader in green iron production.

Its natural endowments – abundant iron ore and a comparative advantage in low-cost renewable energy – make Australia the natural home for this emerging global industry. With soundly based policy settings and timely action, this opportunity can underpin prosperity for generations.

Research by The Superpower Institute shows that the future energy trade will not be dominated by fossil fuels, but by trade in goods that embody clean energy. Energy-intensive industries will migrate to regions where cheap renewable energy exceeds domestic needs. Australia is one of those rare regions.

There are three compelling reasons to develop a green iron industry in Australia.

First, green iron is an economic opportunity of historic scale.
Leveraging its advantages in iron ore and renewables, Australia can move up the value chain from exporting raw commodities to higher-value industrial materials. The potential is enormous: if green iron replaces iron ore as a primary export, it could generate up to $386 billion annually by 2060. By comparison, Australia's iron ore exports are typically around $120 billion per year.

Second, green iron offers a large opportunity to contribute to global decarbonisation.
Conventional steelmaking remains one of the largest industrial sources of carbon emissions worldwide. An Australian green iron industry could abate emissions equal to roughly 4 per cent of the global total – more than three times Australia's current domestic emissions.

Third, green iron exports provide a strategic hedge against the decline of fossil fuel exports.
Coal and gas are two of Australia's three largest export industries, currently generating around $120 billion in export revenue each year. Yet most major economies have committed to achieving net-zero between 2045 and 2070. The timeline and trajectory of global decarbonisation may be uncertain, but the direction is clear: fossil fuel demand will contract in the coming decades. Investing today in industries where Australia enjoys a comparative advantage – such as green iron – is the most prudent way to safeguard national income and employment.

Modelling

The Superpower Institute, in partnership with Bivios, has modelled green iron production in five locations in Australia:

- the Pilbara (northwest WA)
- Geraldton (midwest WA)
- Kwinana (southwest WA)
- Eyre Peninsula (SA)
- Gladstone (QLD)

The modelling incorporates:

- 'inflexible' green iron-making technology, which operates continuously, and 'flexible' green iron-making technology, which can ramp up and down
- renewable energy output data for each location
- grid-connected electricity availability and historical pricing data for all locations except the Pilbara
- capital and operating costs for renewable energy, hydrogen electrolysis, green iron production, and associated infrastructure.

Findings

Core findings include:

- **Technology flexibility matters.** Flexible green iron technology, with the ability to ramp production up and down, will likely reduce the cost of producing green iron compared to technologies requiring continuous operation. However, flexible technologies are still under development and will require innovation support to be realised at commercial scale.

- **A grid connection can reduce the cost of green iron.** Connected projects can sell electricity into the grid when prices are high, and buy electricity when prices are low.

- **Location is critical.** Despite the geographic advantage of abundant iron ore deposits, the Pilbara is unlikely to be one of Australia's lower-cost locations for producing green iron, at least initially. Other locations in Australia face lower capital costs, have advantages in existing infrastructure, and some regions have superior renewable energy capacity factors. It may make economic sense to ship ore from the Pilbara to other locations in Australia where green iron can be produced more cheaply.

But Australia's potential green iron producers are disadvantaged by the lack of an international carbon price. This distorts the international market for iron products, and creates an inefficient advantage for fossil-fuel based products.

This market failure is a major reason that there is a cost gap between the international price of carbon-intensive iron products and the estimated production costs of Australian green iron. The cost gap for most producers is substantial. Producers in the Eyre Peninsula and Geraldton have lower costs than other producers, and our model suggests they may be able to compete in small segments of the market where there are particularly high prices. Other producers face a cost gap up to $1000 per tonne, depending on the production technology and site location.

Results from the model show that policies addressing market failures will help Australia seize its green iron potential.

If iron producers paid the expected EU carbon price in 2030 – $155 per tonne – the cost of conventional, fossil-fuel-based iron production would rise significantly and the green premium would narrow. We find that producers in more locations would be able to compete in the international market, and producers in the Eyre Peninsula would be able to compete with a much broader share of the international market for iron products.

Bridging this gap requires targeted policy action – not to subsidise inefficient production, but to correct clear and broadly recognised market failures that conceal the true costs of high-carbon products.

Fixing market failures

The Superpower Institute identifies three key market failures that warrant government intervention:

1. **Unpriced emissions from fossil-based production**
   Because there is no system of international carbon prices, iron and steel producers do not pay the social cost of their carbon emissions. The lack of carbon price distorts the market and makes it difficult for green iron to compete with carbon-intensive iron in international markets. To correct for the lack of an international carbon price, the federal government should provide green iron production tax credits.

2. **Under-provision of common-user infrastructure**
   Like other major industries, green iron production requires large-scale, shared infrastructure – roads, transmission lines, pipelines and storage, and upgraded ports. These assets have strong spillover benefits that private investors cannot capture, so the private sector will not invest in them at the efficient scale. Public investment is essential to ensure this infrastructure is delivered at lowest cost.

3. **Innovation spillovers and early-mover risk**
   In establishing new industries, early producers absorb the costs of technical learning, process optimisation, and supply chain development. They confer large benefits on later producers, without reward. Without policy support, this disincentivises early investment. To correct for positive externalities created by early producers, the government should offer capital support worth up to 30 per cent of the investment cost for a green iron project.

These market failures constrain what Australia could otherwise achieve. The Superpower Institute has developed a detailed set of policy recommendations (Table 1).

With efficient support, Australian green iron can be cost-competitive. A green iron production tax credit worth $170, including the value of the existing Hydrogen Production Tax Incentive (HTPI), would have a very similar effect to a carbon price.

Our proposed production tax credit would address the market distortion created by the missing carbon price. It would narrow or eliminate cost gaps, and expand the number of locations where green iron producers can compete in the international market. It would also mean low-cost producers are better able to compete in the international market.

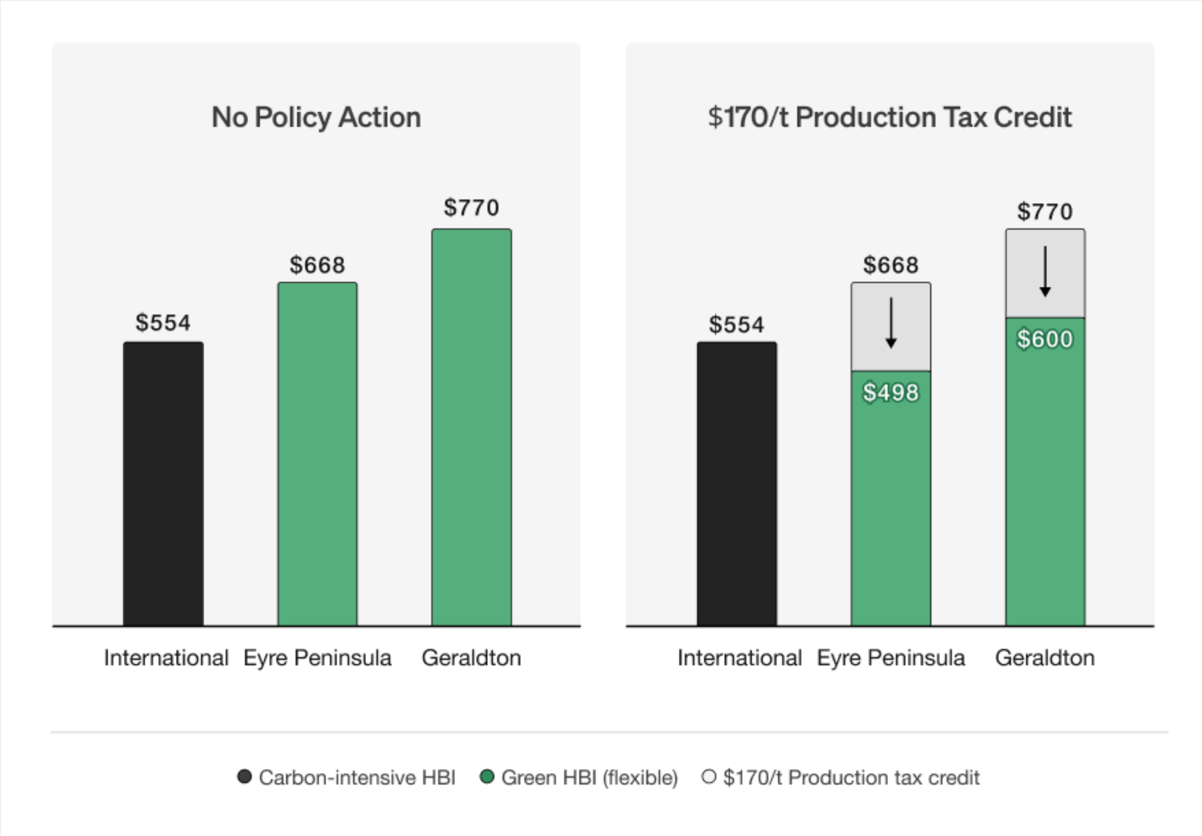

Figure ES.2: A production tax incentive of $170 would eliminate or narrow the cost gap with carbon-intensive iron

Notes: Production costs for Australian HBI are based on a dynamic model of green iron production. Prices for carbon-based iron products are based on World Bank data for international fossil-fuel based HBI.
Source: BIVIOS and The Superpower Institute

A fourth role for the federal government is diplomatic engagement: working with trade partners to help grow international demand for green iron. Japan and South Korea are currently major destinations for Australian iron ore, and are promising destinations for green iron. There is also potential early demand from Europe, where the EU carbon price will drive early demand for green iron. Over the longer term, the opportunity is greatest in China, South Asia, and Southeast Asia.

Our recommendations have substantial cost implications for Australia's budget, but are consistent with the Australian Government's emphasis on productivity growth, and its existing support for green hydrogen and other green exports.

Only a small share of these costs will be borne before 2030, likely in the form of capital support for a small number of early green iron producers, with this support recognising the public benefits of innovation. This will be crucial for building early momentum.

As green iron is produced, likely from the early 2030s, the government will incur additional costs in the form of our recommended production tax credit for green iron. This support will help correct the market failure of the missing international carbon price, and will help ensure green iron is available for our trade partners as they decarbonise their iron and steel sectors. This support for future projects can be reviewed and adjusted in, say, 2030 to reflect the level of take up, international progress towards carbon pricing, and the policies of our trading partners.

These policies should be a national priority. There is no case for delay. Although green iron projects are being explored around the world, no country or company has yet achieved commercial scale. The global race is underway, but the field remains open. With the right policy supports, Australia's first projects could be operational by 2030. These will serve as proof-of-concept, showing what is possible in Australia and attracting investment from our trade partners.

Recommendations

Correcting for the missing international carbon price	
Recommendation 1	In addition to its $2 per kilogram support for green hydrogen, the government should provide support for green iron production to simulate the effects of a carbon price. We estimate total support, including the Hydrogen Production Tax Incentive (HPTI), should be worth at least $170 per tonne of green iron in 2030. This could be achieved with a 'stackable' production tax credit for green iron. The production credit should rise to maintain equivalence to the EU carbon price.
Recommendation 2	Some nascent green iron production technologies do not use hydrogen, but may use significant amounts of renewable energy dedicated to iron-making. Here, the HPTI does not help close the cost gap between green iron and carbon-intensive iron. The government should provide support that simulates the effect of a carbon price for non-hydrogen-based green iron technologies. This could take the form of an expanded production credit for green iron, worth at least $170 per tonne of green iron in 2030.
Supporting positive spillovers from common-user technology	
Recommendation 3	In locations that are most promising for multiple green iron projects, federal and state governments should support new natural-monopoly infrastructure that is essential for green iron, steel, and other green exports: electricity transmission, hydrogen pipelines and storage, ports, and desalination and water supply in areas with no local water supply. This can be direct government investment or support to private investors. Government's role in supporting infrastructure will solve the coordination problem that

	will otherwise delay or prevent investments in green iron production. Infrastructure use should be priced efficiently, so the cost of using infrastructure is not a barrier to early private investment in green iron.
Supporting green production in low-cost locations	
Recommendation 4	We propose an Australian green hydrogen certificate scheme, with green hydrogen producers earning tradeable certificates. Certificates could be purchased and surrendered by green iron producers anywhere in Australia. Iron produced with natural gas could be recognised as 'green' iron production when equivalent green hydrogen certificates are purchased and surrendered. Producers of other green hydrogen-based products would also be included in the scheme.
Supporting positive spillovers from early producers	
Recommendation 5	The federal government should provide capital support for early commercial producers of green iron, with a planned output of at least 0.5 million tonnes per annum. This could build on or draw from the already announced $1bn green iron investment fund. Two levels of support should be available: 1. Early investors in green iron projects, using any kind of green iron technology, should receive capital grants, or equivalent tax benefits, representing 15 per cent of capital costs. We propose that this support should be available for up to three green iron projects. 2. Grants worth an additional 15 per cent of capital costs should be made available for the first few uses of a particular kind of green iron technology deployed in Australia. Support should be capped at $500m per project.
Policies to support international trade dynamics	

Recommendation 6	The government should shape its Guarantee of Origin (GO) certificates to be compatible with the EU Carbon Border Adjustment Mechanism (CBAM). This should be done at the earliest possible date after the EU legislates its requirements.
Recommendation 7	The Australian government should strengthen support for research on countries' economic challenges and trade opportunities as the world decarbonises.
Recommendation 8	The Australian government should work with trade partners to secure financial support for Australian green iron production. This may come in the form of contributions by trade partner governments toward the supports described in Recommendations 1 and 2. Such contributions would recognise the shared benefits of successful Australian green iron production, to both Australia and our trade partners.
Recommendation 9	The federal government should use international platforms to advocate for a system of international carbon prices. It should demonstrate Australia's commitment to the Paris Agreement with policies that impose or simulate the effects of a carbon price consistent with net-zero carbon emissions by 2050.

Glossary of Terms

BF-BOF (Blast Furnace-Basic Oxygen Furnace)	The dominant global method for producing primary steel. A two-step process whereby iron ore is reduced to molten iron in a blast furnace (BF) using metallurgical coal as both a fuel and a chemical reductant. The molten iron is then refined into steel in a basic oxygen furnace (BOF). The BF-BOF is highly carbon-intensive, generating over 2 tonnes of CO_2 per tonne of steel.
Carbon Capture and Storage (CCS)	Technology for capturing carbon dioxide emissions, mainly from fossil fuels combusted in power plants or industrial processes, and storing them underground to prevent release into the atmosphere.
Carbon Price	A cost imposed on emitting carbon to incentivise lower emissions. A price on carbon helps shift the burden for the damage from emissions back to those who are responsible for it.
Common-User Infrastructure	Shared infrastructure where capacity is shared between multiple users under a defined set of terms.
Comparative Advantage	A country with comparative advantage can produce a good or service relatively more cheaply than others (more precisely, at lower opportunity cost), such that specialising in and exporting that product generates gains for all. Australia has a comparative advantage in renewable energy production.
DRI (Direct Reduced Iron)	A form of iron produced by reducing iron ore at lower temperatures than in traditional blast furnaces, typically using hydrogen or natural gas. The process creates a porous, solid material known as 'sponge iron', which can be melted in electric furnaces to make steel.
EAF (Electric Arc Furnace)	A furnace that melts scrap steel or direct reduced iron (DRI) using electrical energy. They are typically used with high-grade DRI, as they cannot efficiently remove impurities (gangue) from lower-grade ores.
ESF (Electric Smelting Furnace)	A high-temperature, continuous-operation furnace that melts direct reduced iron (DRI) using electricity, enabling the removal of impurities (gangue) from lower and mid-grade iron ores. Unlike electric arc furnaces, ESFs can process ores with higher impurity levels and operate more like blast furnaces, with molten metal and slag tapped off without interrupting the process.
Externalities (Positive/Negative)	The unintended side effects of an economic activity that affect others and are not reflected in market prices. Positive externalities (e.g. innovation spillovers) provide value to others, while negative externalities (e.g. pollution) impose costs on others.
FOAK (First of a Kind)	A project or facility deploying a technology at commercial scale for the first time. FOAK projects often face higher capital costs, technical risks and financing challenges compared to later, proven deployments (known as NOAK – Next-of-a-Kind).
Gangue	The non-iron material in iron ore, such as silica and alumina, that must be removed during iron-making to produce high-quality metal. Ores with high gangue content are considered lower grade and require more processing energy to extract usable iron.
Green Hydrogen	Hydrogen produced with emissions of less than 0.6kg of carbon per kilogram of hydrogen. Generally produced by splitting water into hydrogen and oxygen using electrolysis powered by renewable electricity.
Green Iron	Iron produced using renewable energy and green hydrogen, with near-zero emissions
Green Premium	The cost gap between carbon-intensive products and green equivalents.
Green Steel	Steel made using green iron and electric arc furnaces powered by renewable energy.

Hematite	An iron oxide ore (Fe_2O_3); pure hematite has an iron content of nearly 70%. Most of Australia's iron ore exports are hematite. Hematite is less amenable to magnetic beneficiation than magnetite, but can still be used in a variety of iron-making technologies depending on grade.
LCOI (Levelised Cost of Iron)	The average cost to produce a tonne of green iron across a project's life, accounting for capital, operating and energy costs. It enables comparison of cost competitiveness across technologies and locations.
Market Failure	When markets fail to allocate resources efficiently, due to incomplete property rights, misaligned incentives, and/or asymmetries in information. The non-pricing of harmful CO2 emissions is a classic example.
Magnetite	An iron oxide ore Fe_3O_4; pure magnetite has an iron content over 72%. Australian magnetite ore typically contains 20-30% iron in its natural state and must be beneficiated - crushed, magnetically separated and pelletised - before use. It is well-suited to direct reduction due to its magnetic properties and consistent composition.
NEM (National Electricity Market)	Australia's main electricity grid and wholesale market, covering the eastern and southern states. It interconnects five regional markets – Queensland, New South Wales, Victoria, South Australia and Tasmania – allowing electricity to be traded across state lines.
NWIS (North-West Interconnected System)	A separate electricity grid located in the Pilbara region of Western Australia. It connects major mining and industrial operations but is not linked to the National Electricity Market.
Primary Steel	Steel made from iron ore, rather than recycled scrap. It accounts for around 70% of global steel production, with 90% of that made using the carbon-intensive BF-BOF process. Steelmaking overall is responsible for more than 8% of total greenhouse gas emissions.
Production Tax Credit (PTC)	A proposed government support mechanism that would provide a per-tonne subsidy for green iron production. The PTC will help to address key market failures - such as the absence of a global carbon price - closing the cost gap with carbon-intensive alternatives and stimulating early investment in low-emissions technologies.
SWIS (South-West Interconnected System)	The main electricity grid serving the south-west region of Western Australia, including Perth. The SWIS is not linked to the National Electricity Market.
Reductant	A substance used in iron-making to chemically remove oxygen from iron ore (iron oxide), producing metallic iron. Common reductants include carbon (from coal or fossil gas) and hydrogen. The choice of reductant determines the emissions profile of the process.
Superpower Trade	The trade in clean energy embedded in energy-intensive goods, that relies on export countries' comparative advantage in clean energy production.

Note: For more definitions and technical explanations related to iron ore types, grades and processing methods, see *Chapter 2: Green iron technologies will be able to use Australian ore*

Contents

Appendices

01.

Australian opportunity, global benefit: A green metal Superpower

The Superpower Institute's recent report, The New Energy Trade, provides compelling evidence that Australia has a comparative advantage in green industrial exports as the world decarbonises.[1] It shows that if Australia has the right policy settings, there is an opportunity for Australia to prosper as a green export superpower while helping other countries achieve their net zero commitments.

Current trade disruption caused by the actions of the Trump administration in the United States may have profound and lasting effects on the global economy and the trajectory of emissions reductions. At this time, it is not possible to predict how this will play out. The best course of action for the global community outside of the United States is to continue efforts to take action on climate change and to encourage the US to rejoin efforts over time.

Australia's exports are extremely vulnerable to global decarbonisation. International commitments suggest coal use will decline by 35 per cent by 2040 and nearly 50 per cent by 2050, and announced pledges suggest a decline of 62% by 2040 and nearly 80 per cent by 2050.[2]

If declines of this magnitude occur it will hit Australia hard, because Australia is the world's top exporter of metallurgical coal and top combined exporter of thermal coal and Liquid Natural Gas (LNG).[3] Coal and gas are Australia's second and third most valuable export industries,[4] with coal exports typically worth about $70 billion each year, and LNG about $50 billion.[5] If the world decarbonises in line with current commitments, Australia will progressively lose income from fossil

[1] Finighan, 'The New Energy Trade'.

[2] IEA, 'World Energy Outlook 2024'; If the world achieves the goal of holding global warming to 1.5 degrees, coal consumption needs to be largely eliminated by the 2040s, or by the 2050s to limit warming to 2 degrees: see Clarke et al., 'Energy Systems', sec. 6.7.4.

[3] IEA, 'Coal 2023 - Analysis and Forecast to 2026', 60; Geoscience Australia, 'Australia's Energy Commodity Resources 2023'.

[4] The main markets for Australian coal and gas are Japan, China, South Korea, Taiwan, and - for coal - India, with total exports worth $220bn in 2022-23: see Department of Industry, Science, and Resources, 'Resources and Energy Quarterly: September 2024', 38; Office of the Chief Economist, 'Resources and Energy Quarterly September 2024: Historical Tables', tbl. 2 (2).

[5] AUD dollar values, using 5-year average exchange rate: USD/AUD = 1.45, EUR/AUD = 1.6. See Reserve Bank of Australia, 'Historical Data'; The peak value of fossil fuel exports was around $220 billion in 2023, reflecting global supply constraints. The value is expected to settle back to a combined $110-130 billion. Finighan, 'The New Energy Trade', 104.

fuel exports (Figure 1),[6] with resulting job losses concentrated in particular regional and remote areas.[7]

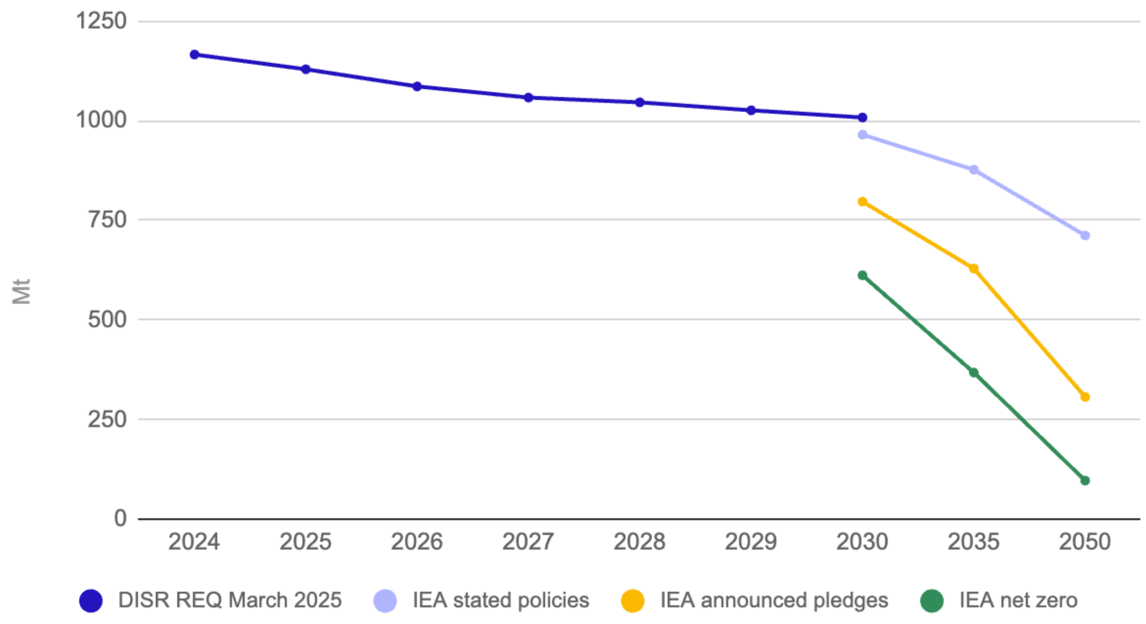

Figure 1: Forecasts for global thermal coal trade under IEA scenarios.
Source: Institute for Energy Economics and Financial Analysis[8]

Even if the pace of decarbonisation is slower and less coordinated than current commitments indicate, green export industries are a natural hedge against uncertainty and the risk of these losses, because the international economic pressures that will erode Australia's fossil-fuel exports are the same pressures that can be harnessed to secure zero-carbon exports. The employment opportunities for green exports include many of the large fossil-fuel production centres in Australia.

As shown in The New Energy Trade, if Australia can successfully develop green exports to their full potential, these industries could replace the value of fossil exports several times over. 'Superpower exports' would make it possible for Australians to enjoy rising living standards and full employment for several generations. If Australia makes green iron with its approximately 40 per cent share of global iron ore production, Australia could earn almost $400 billion a year from green iron exports.[9]

Even if Australia only realises a fraction of its green export potential, a modest green iron industry would help replace lost revenue and employment as fossil fuel industries decline.[10]

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[6] Finighan, 'The New Energy Trade', 104.

[7] There are approximately 100,000 'carbon workers' in Australians, including 55,000 in regional New South Wales, Queensland, and Western Australia. This estimate includes workers in coal and gas industries, and some workers who would retain their jobs if aluminium and steel refineries decarbonise: Wood, Dundas, and Ha, 'Start with Steel', 9.

[8] Knight, 'Australian Coal Exports Face Numerous Downside Risks, New Projections Show'.

[9] $386 billion per year in 2060. Finighan, 'The New Energy Trade', 106.

[10] A modest green steel sector, representing only 7 per cent of global production, together with other green export industries, would create enough regional jobs to nearly compensate for job losses from a declining fossil fuel industry: Wood, Dundas, and Ha, 'Start with Steel', 26.

The challenge facing Australian governments is that green export industries cannot be built overnight, or without addressing market failures. Market failure occurs when production, trade, or consumption results in an inefficient allocation of resources. Economically efficient policies can help correct three market failures that are a barrier to Australian green iron exports.

The missing carbon price

There is no system of international carbon prices requiring producers to pay for the damage inflicted by carbon emissions. The commercial cost of producing iron with fossil fuels does not reflect the social cost of carbon emissions, which is the dominant reason iron produced with coal or natural gas is commercially 'cheaper' than green iron.

Throughout this report, we often refer to the 'lower' cost of producing iron and steel with fossil fuels, or describe carbon-intensive iron as 'cheaper' than green iron and steel. This terminology refers to commercial costs, which do not account for the damage inflicted by carbon emissions.

Common-user Infrastructure

Critical infrastructure for green iron has common-user and sometimes natural monopoly characteristics. This infrastructure will be under-supplied by private markets, resulting in under-investment and/or green iron being produced at a higher cost.

Positive innovation externalities

Early producers of green iron will incur higher costs, but generate shared knowledge that reduces the costs for later producers.

Whether Australia is preparing for large-scale superpower exports or modest exports that protect against declining fossil fuel industries, Australia needs to act now to address these market failures. This report presents the policies that are needed.

This chapter explains why Australia has a comparative advantage in green exports, including green iron, drawing heavily on The New Energy Trade. Section 1.1 explains why the international economy will change as it decarbonises, with energy-intensive production relocating to sources of low-cost renewable energy. Section 1.2 summarises Australia's comparative advantage in renewable energy, and Section 1.3 shows that Australia can use this comparative advantage to export green iron rather than iron ore. Section 1.4 shows that there is early interest in Australian green iron projects, but projects in other parts of the world are more developed.

1.1 The international economy will change dramatically as the world decarbonises

To keep global warming below 2 degrees Celsius, and to have a chance of limiting warming to 1.5 degrees, substantial mitigation is required by the end of the decade.[11] The lowest-cost pathway for achieving 1.5 degrees needs global emissions to fall more than 40 per cent on 2019 levels by 2030.[12] To achieve this, energy systems and industrial processes need to decarbonise quickly.

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[11] Including conditional and unconditional pledges: Meinshausen et al., 'Realization of Paris Agreement Pledges May Limit Warming Just below 2 °C'.

[12] UNEP, 'Emissions Gap Report 2024: No More Hot Air Please'.

If the international community does not contain global warming, damage to the environment will threaten societies, the international economy, and international stability. There are already signs this is occurring. People will endure more frequent and extreme storms, floods, and fires; food and water supplies will be threatened; there will be large relocation of populations. Average global temperatures will continue to increase until the world achieves net zero greenhouse gas emissions.

Policies based on domestic and international commitments will determine whether the international community decarbonises production quickly enough to avoid the worst effects of climate change.

1.1.1 Production will decarbonise over the next few decades

Countries have international commitments to the goal of holding warming 'well below' 2 degrees Celsius, while 'resolving' to pursue actions that limit warming to 1.5 degrees Celsius.[13]

Three quarters of global greenhouse gas emissions are covered by net-zero commitments for the middle of the century.[14] The EU, the US, the UK, and Japan have all committed to reach net zero by 2050, as has Australia. President Xi Jinping has committed China to reach net-zero by 2060, and Prime Minister Modi has committed India to reach net-zero by 2070.[15]

Action on these commitments will change the way goods are produced. About 30 per cent of global emissions are created by industrial processes.[16] While households and many types of transport can be easily electrified, decarbonising 'energy-intensive' industries will be difficult. We use the term 'energy intensive' industries to describe industries that currently use large quantities of fossil fuels – not only to power their operations, but also to achieve high temperatures, and for processes that rely on chemical reactions with carbon. High temperatures and chemical reactions cannot be readily achieved with electrification. Such industries include metal processing, cement, fuels, chemicals, and plastics manufacturing.

Based on countries' current commitments, the market for zero-carbon, 'green' energy-intensive goods, including iron and steel, will grow dramatically and the market for carbon-intensive goods will decline.

1.1.2 Energy-intensive production will relocate to countries where renewable energy is abundant and cheap

As the world decarbonises, carbon emissions will become more expensive. Energy-intensive production will need to relocate to locations with low cost, abundant zero-emission energy. As shown in The New Energy Trade, this will reshape global production and trade.

Current trade patterns reflect the era of cheap fossil fuels. Some countries have enjoyed a comparative advantage in the production of energy-intensive goods, even if they do not have a comparative advantage in energy production and if energy is a major production cost.[17] This is

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[13] Relative to pre-industrial temperatures. Paris Agreement; Meinshausen et al., 'Realization of Paris Agreement Pledges May Limit Warming Just below 2 °C'.

[14] 89 per cent of emissions covered before the US withdrawal from the Paris Agreement. 'Climate Action Tracker (CAT) Net Zero Target Evaluations'.

[15] Burfurd, 'Can Australia Be a Renewable Energy Superpower?'

[16] Bocca and Ashraf, 'Fostering Effective Energy Transition 2022', sec. 2.1.

[17] For example, energy represents 20-40 per cent of the cost of making steel, and 30-40 per cent of the cost of making aluminium. See for example World Steel Association, 'Fact Sheet: Scrap Use in the Steel Industry'; Australian Aluminium Council Ltd, 'Submission in Response to Australian Government Consultation Paper on Climate-Related Financial Disclosure'.

because it is cheap to move fossil fuels around the world. Transport represents about 10 to 15 per cent of the cost of fossil fuels.[18] As a result, for example, Japan and South Korea are major producers of energy-intensive steel, even though they need to import nearly all the required energy.

This will change as the global economy is decarbonised, because transporting zero-carbon energy is extremely expensive. Zero-carbon energy can only be transported between land masses with sea-bed cables or by using expensive processes to convert zero-carbon energy into hydrogen, ammonia, or other chemical carriers that can be shipped. Conversion into a form that is tradeable between land masses or continents, together with transport, more than doubles the cost of renewable energy.[19]

The transition to zero-carbon energy sources and the dramatic increase in the cost of transporting energy will change countries' comparative advantage. Economic pressure will push energy-intensive industries to countries with low-cost, abundant, zero-carbon energy.

Even though some countries will generate nuclear energy, and some carbon emissions will be captured and stored, it is the availability and cost of renewable energy that will determine countries' comparative advantage in a decarbonising world (Box 1).[20]

Box 1. Renewable energy resources will determine countries' comparative advantage in zero-carbon energy-intensive production

There are three ways to decarbonise energy production:

1. electrification with zero-carbon renewable energy
2. electrification with zero-carbon nuclear energy
3. capturing carbon emissions from fossil fuel-based production, potentially extracting residual value from these emissions, and storing the remaining carbon: carbon capture and storage (CCS).

The New Energy Trade presents evidence and detailed analysis showing why nuclear energy and CCS cannot compete with renewable energy as a source of comparative advantage in energy-intensive industries. The findings are summarised here.

Nuclear energy will not determine comparative advantage

Technologies for renewable energy are modular and produced at scale, and costs will continue to decline as more units are produced. But nuclear technology is not modular, and plant installation has become more expensive over time. The only exceptions to this trend are China and Korea, reflecting their particular political and regulatory environments, including state subsidies and ownership.

Reflecting the relative cost of renewable energy versus nuclear energy, and despite reportedly cheap nuclear power, China installed only 1.4 GW of nuclear energy in 2023, alongside 270

[18] According to the IEA, international coal prices are typically above $USD100, with freight costs on major routes typically between $US10 and $US16 between 2020 and 2023. See Burfurd, 'Can Australia Be a Renewable Energy Superpower?'

[19] Converting green electricity into intermediaries (such as liquid hydrogen, ammonia, or methanol), transporting intermediaries, and combusting intermediaries typically leads to energy losses of 66-80%. Transported energy thus costs at minimum 3-4 times more than locally consumed energy, in addition to the additional costs created by these processes: Finighan, 'The New Energy Trade', 10; See also Burfurd, 'Can Australia Be a Renewable Energy Superpower?', 410.

[20] See Finighan, 'The New Energy Trade', 65–76.

GW of solar and wind. Even if plant installation rates accelerate beyond the most generous projections, nuclear energy will still play only a very modest role in decarbonising the energy needs of major economies, including China, India, South Korea, and Japan. Nuclear energy will not determine countries' comparative advantage in a decarbonised world.

Carbon capture and storage will not play a long-term role in the iron and steel-making industries
CCS may have an important role to play in decarbonising non-electrifiable activities.[21] But it is well behind its expected development pathway, in terms of technical achievements and cost. A number of forecasts, including The New Energy Trade and the International Energy Agency, find that it is not expected to be cost-competitive for most purposes.

Carbon capture and storage will not be used as a long-term strategy for decarbonising iron and steel production. CCS retrofits may play a transitional role in iron and steel-making – for example, it may reduce emissions from Chinese blast furnaces in the 2030s, and Indian and Southeast Asian blast furnaces in the 2030s and 2040s. But research in The New Energy Trade concludes that by 2060, blast furnaces with CCS will have been retired. If current trends change, and the cost curve for CCS falls faster than the cost curve for zero-carbon ironmaking technologies, this conclusion will change.

1.2 Australia has a comparative advantage in renewable energy

The availability and cost of supplying renewable energy, together with demand, will create large differences between countries' renewable electricity prices.[22]

China, India, and the EU have good renewable resources based on current levels of demand, but growing demand will push energy-intensive iron production high up the cost curve, making it expensive.[23] Japan and South Korea already have among the highest costs for renewable energy in the world, and the supply of cheap renewable energy is nearly exhausted. All these countries and regions will struggle to meet their mid-century energy needs.

But Australia has abundant renewable energy resources and a small population. With large-scale investments in renewable energy, Australia could secure a supply of low-cost renewable energy supplies that vastly exceed demand, keeping prices low by global standards.

Only a handful of other countries, for example, in the Middle East and the north of Africa, can capitalise on very low-cost renewable energy. The scale of renewable resources is much greater in Australia, with its much greater land area. Australia also has other advantages, including local materials for processing and a lower investment cost than some of these countries.

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[21] CCS will be only be viable at a high price for carbon emissions: Barnard, 'Beneath the Fjord: Inside Northern Lights' Carbon Storage Core'.

[22] See Appendix 1 for a more detailed analysis on Australia's comparative advantage relative to major trade partners and producers of iron and steel.

[23] Finighan, 'The New Energy Trade', 9 shows that most research underestimates future demand for other countries' zero-carbon energy supplies, pushing industrial users up the marginal-cost curve, while Australia is better positioned as a potential low-cost supplier of zero-carbon energy than previous research suggests.

1.3 Australia has a green iron opportunity

1.3.1 Green iron can lead Australia's green export industries

Australia will have a comparative advantage exporting green metals: it not only has excellent renewable energy resources which could be harnessed at low cost, but also rich mineral resources.

Australia has large reserves of iron ore and bauxite and is by far the biggest exporter of both. Australia also has reserves of 'critical' minerals including lithium, copper, cobalt, and nickel,[24] which will become increasingly important as the world decarbonises.[25]

We refer to green metals, processed using renewable energy, as superpower commodities. Of all the potential superpower commodities, green iron has the greatest economic potential.[26]

The long-term economic prospects of green iron are good. Global demand for primary steel, which is produced from iron ore, is expected to grow through to 2050, even though steel recycling rates will increase.[27] And Australia's iron ore exports, which could be used to produce green iron, are the largest global share of all metals, by value and mass.[28] Exports of nearly 900 million tonnes of ore are more than half of the international export market,[29] and about 40 per cent of the world's annual iron ore production.[30]

Australia could use low-cost, abundant renewable energy to process this ore and export green iron.[31] If Australia processes its 40 per cent share of global ore production, these exports would be worth up to $386 billion each year, around three times the value of current iron ore exports.

Green iron exports could also help Australia's iron ore producers navigate global decarbonisation. Green iron could make economically 'stranded' mines viable, and help companies hedge against

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[24] Critical Minerals Office, 'Australia's Critical Minerals List and Strategic Materials List'.

[25] The IEA estimates that demand for critical minerals will at least double by 2030, and quadruple by 2040 to achieve the goals of the Paris Agreement. See IEA, 'Critical Minerals Market Review 2023'; and IEA, 'The Role of Critical Minerals in Clean Energy Transitions'.

[26] Other exports also face technological challenges or higher policy barriers. See Wood, Dundas, and Ha, 'Start with Steel', 18.

[27] The IEA expects that demand for steel will grow by at least 33 per cent through to 2050: see IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking', 11; While there is some uncertainty about scrap availability, the IEA estimates that recycled steel will rise from about 32 per cent of production today to about 45 per cent of metal inputs to steel production in 2050: see IEA, 65; The combination of increased demand with increased recycling implies an increase in primary steel demand on the order of 5-15 per cent: see The Superpower Institute, 'Unlocking Green Metals Opportunities for a Future Made in Australia', 11.

[28] Finighan, 'The New Energy Trade', tbl. 9.3.

[29] About 56 per cent of ore produced globally in 2022-23: see Jaganmohan, 'Iron Ore Exports Leading Countries Global Share 2023'; Department of Industry, Science, and Resources, 'Resources and Energy Quarterly: September 2024'.

[30] Finighan, 'The New Energy Trade'; About 70 per cent of steel that is produced each year is 'primary' steel made from iron ore; the rest is produced from scrap steel: see World Steel Association, 'Fact Sheet: Scrap Use in the Steel Industry'; Nearly 2 billion tonnes of primary steel is produced each year (1.9 billion tonnes in 2023): see World Steel Association, 'World Steel in Figures 2023'; About 650 million tonnes of scrap is also recycled into new steel each year, representing about 30 per cent of metal inputs for total steel production: see World Steel Association, 'Fact Sheet: Scrap Use in the Steel Industry'.

[31] For example, Devlin et al., 'Global Green Hydrogen-Based Steel Opportunities Surrounding High Quality Renewable Energy and Iron Ore Deposits' finds that Australia will be one of the world's lowest-cost producers, competing with other countries that have good renewable energy resources. This includes countries from the Middle East, Central and South America, and China.

declines in demand from traditional trade partners.[32] And because existing technologies for green iron production typically use higher grade ores than the ore exported from Australia,[33] green iron production and innovation in Australia would make sure that green iron technology can support Australian ores.

1.3.2 Australia exports iron ore for carbon-intensive steel-making

Nearly all of Australia's ore is exported to Northeast Asia,[34] including more than 80 per cent to China, over 7 per cent to Japan, and nearly 6 per cent to South Korea.[35] No other country exports iron ore at the same scale as Australia: Brazil's share of global exports is about 20 per cent share, and Canada and South Africa both contribute about 4 per cent of global exports.[36]

Over half of the world's primary steel is produced in China, nearly 5 per cent in Japan, and over 3 per cent in South Korea. Outside the Northeast Asian region, India produces about 7 per cent of the world's steel, while the United States and Russia both produce about 4 per cent.[37]

All the steel made with Australian iron ore, and about 90 per cent of primary steel, is made with the carbon-intensive blast furnace-basic oxygen furnace ('BF-BOF') process.[38] Iron ore is processed into iron metal in a blast furnace (BF), which depends on metallurgical coal. Molten iron is then refined into steel in a basic oxygen furnace (BOF). The BF-BOF process is powered by fossil fuels, and it is the cheapest way to produce primary steel because fossil fuels are cheap to transport. It is also very carbon-intensive: every tonne of steel produced with the BF-BOF process generates an average of 2.2-2.3 tonnes of carbon dioxide, with fossil fuels powering operations, achieving high temperatures inside the blast furnace, and with carbon as the basis for chemical reactions in the blast furnace.[39]

1.3.3 Green iron and steel-making will reshape trade

As the world decarbonises, the high cost of transporting zero-carbon energy will reshape production and trade in iron and steel-making. An important shift will be from BF-BOF steelmaking – with integrated iron and steel production – to separate iron-making and steel-making processes.

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[32] Fortescue views green steel production as a hedge against changing demand patterns from China; see Fortescue, 'Going on Offense: Transforming Hard to Abate Sectors'; A pilot collaboration between BlueScope Steel, RioTinto, and BHP is being used to hedge against changing demand for Pilbara ores: see Macdonald-Smith and Thompson, 'Push to Save Iron Ore Golden Goose'.

[33] See Chapter 2 for more detail on iron ore quality and green iron technology.

[34] These export patterns are broadly typical of the past decade. For data, see Department of Industry, Science, and Resources, 'Resources and Energy Quarterly: September 2024'.

[35] The Observatory of Economic Complexity, 'Where Does Australia Export Iron Ore To?'

[36] Jaganmohan, 'Iron Ore Exports Leading Countries Global Share 2023'; Workman, 'Iron Ore Exports by Country 2023'.

[37] Based on global exports by value. World Steel Association, 'World Steel in Figures 2023'.

[38] IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking', 29; 30 per cent of steel is processed through electric arc furnaces (EAF). Scrap processed in EAF makes up about 20 per cent of global steel production; direct reduction of iron ore and ore-based metallics into EAF processes accounts for the remaining 10 per cent. See World Steel Association, 'Fact Sheet: Steel and Raw Materials'; About 22 per cent of global production uses EAF to process recycled scrap: See Devlin et al., 'Global Green Hydrogen-Based Steel Opportunities Surrounding High Quality Renewable Energy and Iron Ore Deposits'.

[39] IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking', 43; World Steel Association, 'Sustainability Indicators 2023 Report', 3.

Processing iron ore into iron metal is the most energy-intensive,[40] simple, and least labour-intensive step in the steel-making process.[41] Because it is expensive to move zero-cost energy from one country to another, economic pressure will push green iron production to countries with relatively abundant, low-cost zero-carbon energy.[42] Steel-making is less energy-intensive than iron-making, and less likely to relocate.[43] Australia's comparative advantage in steel-making won't be as strong as its advantage in producing iron.

It will make economic sense for steelmakers to import green iron from countries with abundant, low-cost renewable energy, rather than producing green iron at high cost. Large quantities of renewable energy will be required to electrify the iron-making process and to produce the green hydrogen that can replace carbon as the basis of chemical reactions in the iron-making process.

Shipping costs will influence trade patterns, and the trade in green iron and steel will probably be reshaped within existing regional patterns. Australia will continue to have a cost advantage shipping green iron within the Asian region, compared to other potential suppliers such as Brazil, the Middle East, and Africa. Australia is well-positioned to ship green iron to existing steel-making countries – including Japan, South Korea, China, and Taiwan – and to emerging steel-making economies in South and Southeast Asia, including India, Indonesia, Vietnam, and the Philippines.

Australia's green iron exports can be shipped to a larger international market than its iron ore. Shipping costs are a smaller share of green iron production costs than iron ore and energy.[44] Although economies of scale apply when shipping large volumes of iron ore, these economies of scale will be less important for smaller-volume and higher-value iron metal. This may open new markets for Australian green iron, including countries where Australian iron ore is not currently competitive, such as Germany.

1.4 With the right policy settings, Australia could be a green iron superpower

1.4.1 There is early interest in Australian green iron

There is already interest in producing and exporting Australian green iron (Boxes 2 and 3). Executives of the two largest investors in European green iron plants – ArcelorMittal and H2 Green Steel – have both remarked that Europe will not be able to produce most of its own green iron. Instead, Europe

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[40] Iron-making is responsible for 70 to 90 per cent of emissions generated in the steelmaking process; see for example Wang, Ryman, and Dahl, 'Potential CO2 Emission Reduction for BF–BOF Steelmaking Based on Optimised Use of Ferrous Burden Materials'; MRIWA, 'Western Australia's Green Steel Opportunity'; Bailey, Lockwood, and Wakim, 'Decarbonization Pathways and Policy Recommendations for the United States Steel Sector'.

[41] Jozepa, 'UK Steel Industry: Statistics and Policy'.

[42] Wilmoth et al., 'Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future', 10; Finighan, 'The New Energy Trade'; Devlin et al., 'Global Green Hydrogen-Based Steel Opportunities Surrounding High Quality Renewable Energy and Iron Ore Deposits'.

[43] The average carbon intensity of BF-BOF steel is 2.3 tonnes of carbon per tonne of steel: IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking', 43; World Steel Association, 'Sustainability Indicators 2023 Report', 3; Iron-making in a BF is responsible for about 1.5 tonnes: Suer, Traverso, and Ahrenhold, 'Carbon Footprint of Scenarios towards Climate-Neutral Steel According to ISO 14067'.

[44] Shipping costs are not expected to affect assessments of comparative advantage: See Devlin et al., 'Global Green Hydrogen-Based Steel Opportunities Surrounding High Quality Renewable Energy and Iron Ore Deposits'.

must:[45] *[m]ake the green iron where the electricity is cheaper and then ship the green iron to where you have the steel plants, where you have the know-how and the existing infrastructure.*

Box 2. POSCO's proposed project in the Pilbara

POSCO, a Korean steelmaker, is the world's seventh largest producer of steel.[46]

In early 2022 POSCO announced it was exploring the possibility of producing iron in Western Australia, in partnership with Taiwan's China Steel Corporation and Japan's Marubeni Corporation. In December 2022 POSCO declared its intention to invest US$40 billion in a combination of Australian green hydrogen production and green iron manufacturing facilities. Initial announcements targeted up to 12 million tonnes of green iron each year, requiring 1.2 million tonnes of green hydrogen by 2040; updated targets are for 2 million tonnes of green iron production. 'Flexible' Midrex technology will be used, which can use natural gas or hydrogen to process iron ore into iron.

In 2023 POSCO acquired a fifty year lease at Boodarie near Port Hedland in the Pilbara region of WA with the intent of building a plant to produce green iron.

Regulatory approvals for the first stage of the project are currently under consideration.

Box 3. South Australia's green iron strategy

In June 2024 the Premier of South Australia announced the state's Green Iron Strategy. The strategy included the launch of an expression of interest process to identify companies that could develop a green iron industry and supply chain in South Australia.

Production facilities would be located in South Australia's Upper Spencer Gulf. A new green iron plant, with capacity of 2.5 million tonnes per annum, would add 2,500 jobs during its construction, at least 800 more ongoing operational jobs, and $3 billion per annum to South Australia's gross state product.[47]

In February 2025 the Australian and South Australian governments announced $500 million dollars worth of funding to support the transition of the Whyalla steelworks.[48]

But there is nothing inevitable about a green iron industry in Australia. Other countries and regions can harness renewable energy at relatively low cost, including North Africa and the Middle East.

Until countries reach their net-zero targets, green iron will also need to compete with iron produced from natural gas, or with 'grey' hydrogen produced from natural gas.[49] This iron has lower emissions

[45] Parkes, 'Our hydrogen-based green steel could be cost-competitive with dirty equivalents within ten years. Here's how'.

[46] World Steel Association, 'Top Steel-Producing Companies 2023/2022'.

[47] Government of South Australia, 'South Australia's Green Iron and Steel Strategy'.

[48] Minister for Industry and Science, 'Albanese and Malinauskas Labor Governments Saving Whyalla Steelworks and Local Jobs with $2.4 Billion Package'.

[49] CSIRO, 'Green, Blue, Brown: The Colours of Hydrogen Explained'.

than iron made in blast furnaces, and producers can keep costs down with cheap natural gas in regions such as the Middle East.

1.4.2 Progress on green iron production around the world

A small number of plants have been built with the potential to produce green iron, and more are under construction. Nearly all these projects use 'hydrogen-ready' direct-reduction technology, which can use natural gas, grey hydrogen, green hydrogen, or combinations in various proportions. Direct-reduction technologies are discussed in detail in Section 2.2.

There are different degrees of commitment to green iron, made with green hydrogen. Some projects will use green hydrogen produced on-site; some projects aim to buy green hydrogen when it becomes available; some 'green hydrogen ready' projects have not committed to transition away from fossil fuels.

There are several green iron plants under construction in Europe, most with on-site production of green hydrogen. Some projects have committed to using green hydrogen when it becomes available, but several projects report that the transition will be delayed by limited availability and high cost. ArcelorMital has paused industrial-scale projects in Belgium, France, Germany, and Spain, citing a shortage of green hydrogen and concerns about weak demand for green iron.[50]

A small number of 'hydrogen-ready' projects in China have been completed, with others planned in South Korea and Thailand. There are another ten direct-reduction projects under construction in China, and it is estimated that by 2030, China's direct reduction capacity will exceed 10 million tonnes.[51] None of these projects has on-site green hydrogen or commitments to use green hydrogen in the near or mid-term.

The most advanced green iron project – using green hydrogen rather than grey hydrogen or natural gas – is in Namibia. The HyIron project uses on-site green hydrogen production, and although initial plans are to produce low volumes of green iron, there are plans to rapidly increase output as the company gains knowledge and expertise.[52]

International projects are summarised in Table 7 in Appendix 2.

1.4.3 This report shows what policies are needed

A system of international carbon prices, designed to reach net-zero in the middle of the century, would be the best way to decarbonise global production and trade. In the absence of global carbon pricing, governments have to use less efficient domestic policies to correct the global market failure.

The good news is that if Australia can get its policy settings right, it can protect against the decline in fossil-fuel exports and become a green export superpower, with a large share of global green iron exports.

And green exports, including green iron, will not only benefit Australia.

[50] Segal, 'ArcelorMittal Delays Green Steel Investments Due to Unfavorable Policy, Market Environments'.
[51] SMM, 'Another New Project For Hydrogen Direct Reduction Iron Has Been Announced. How Profitable Such Projects Are Remains To Be Seen'.
[52] HyIron, 'Project Oshivela'.

Australia's main iron ore companies – Rio Tinto, BHP and Fortescue Metals – supply iron ore to steelmaking processes that emit almost a billion tonnes of carbon dioxide per year.[53] If Australia replaces its iron ore exports with green iron production, Australian green iron could eliminate up to 4 per cent of global emissions.[54]

The remainder of the report is structured as follows:

- Chapter 2 shows that green iron production is possible with existing and new technologies.
- Chapter 3 introduces a model of green iron production to show how different technologies and production pathways might emerge in the early years of a green iron industry.
- Chapter 4 highlights the most important insights from the production model.
- Chapter 5 builds on results from Chapter 4 to show how the federal government can correct for three market failures: the lack of an international carbon price, the positive economic spillovers that will be created by early producers of green iron, and the positive spillovers created by common-user infrastructure, where state and territory governments also have a role.
- Chapter 6 shows how the Australian government should use diplomacy to help create international demand for green iron.

[53] 991.5 Mt of carbon-equivalent emissions: 9.16 Mt CO2e from extraction of iron ore and metallurgical coal (Scope 1 & 2); 982.36 from transportation and steelmaking (Scope 3). Compiled from company statements: BHP, 'ESG Standards and Databook 2024', sec. Energy and GHG by Asset; Fortescue, 'FY24 Sustainability Report', 28 & 91; Rio Tinto, 'Sustainability Fact Book 2023', sec. GHG Emissions.

[54] Finighan, 'The New Energy Trade', 102 calculates that iron and steel production generates 8.6 per cent of global emissions; this is consistent with other headline estimates in the literature.

02.

Green iron technologies will be able to use Australian ore

Technology for making primary steel will change as production is decarbonised. Existing green iron technologies typically use higher-grade ores than the ore exported from Australia, but emerging green iron technologies, and the use of Electric Smelting Furnaces alongside existing technology, will mean that Australian ore can be used to produce green iron.

Nearly all primary steel is made with blast furnace-basic oxygen furnace (BF-BOF) technology. BF-BOF technology can process all grades of iron ore into industrial-quality steel. (See Box 4 for a summary of the steelmaking process.)

'Direct reduction' iron-making technologies are a rapidly growing alternative to the BF-BOF process. They currently use fossil fuels to process iron ore. Direct reduction technologies can also process different grades of iron ore, but lower-grade ores create lower-quality 'direct-reduced' iron (DRI). An extra 'smelting' step is required before lower-grade DRI can be made into high-quality steel in electric arc furnaces (EAF) or blast furnaces.

Because BF-BOF technology can easily process lower grades of ore, DRI technologies specialise in processing high-grade iron ore. Smelting is not part of the traditional DRI production pathway.

However, BF-BOF technology cannot be easily or cheaply decarbonised.

To meet future demand for green primary steel, direct reduction technologies will need to process lower-grade ores. Smelting technology will need to be added to steelmaking pathways that use low and mid-grade ores (Figure 2).

Figure 2: Direct-reduction technology will be used to process low, mid, high, and very-high grade iron ore into green steel.

Notes: This is a simplified depiction of iron and steel-making processes designed to capture dominant and most likely processes. Direct-reduced iron can be used in a Basic Oxygen Furnace.

Source: The Superpower Institute analysis

This chapter shows how iron-making technology will change as the industry decarbonises. Section 2.1 shows why current steelmaking technologies will not be used in a decarbonised global economy. Section 2.2 shows that direct-reduction technologies can produce near-zero carbon steel. Section

2.3 explains why high-grade Australian ores are already suitable for existing green technologies. Section 2.4 shows that electric smelting furnaces and emerging technologies will help process low and mid-grade Australian ores.

Box 4. A quick guide to iron ore, iron-making, and steel-making

Iron ore is a combination of iron oxide and 'gangue' – the non-iron components of iron ore, such as silica and alumina.

Iron oxide is a combination of elemental iron (Fe) and oxygen (O), with the proportion of iron and oxygen determining whether ore is magnetite, hematite, or goethite.[55] Australia has large reserves of magnetite and hematite ores, but nearly all iron ore exports are lower-cost hematite.[56]

Magnetite – the compound Fe_3O_4 – contains over 72 per cent iron. But typical magnetite ore contains only 20 to 30 per cent iron, since it is mixed with a substantial proportion of non-iron-bearing material. Magnetite ore is therefore 'beneficiated' to improve its quality. It is first crushed and sorted. Due to the magnetic properties of the ore, magnets can be used to separate and sort iron particles from gangue particles. After sorting, magnetite ore is converted into pellets, which typically have 65-to-70 per cent iron content.[57]

Hematite – the compound Fe_2O_3 – is nearly 70 per cent iron. Australian hematite ore is usually 56-62 per cent iron when it is first mined.[58]. Because hematite does not have the same magnetic properties as magnetite, it is not as easy to beneficiate.

The international market distinguishes between grades of ore based on iron content. 'High grade ore' has a minimum 65 per cent iron content. Lower and mid-grade ores have a larger share of gangue.

Different iron-making technologies can process ores with different grades and characteristics. Ore grade, rather than ore type, determines iron processing pathways and suitability for different iron-making technologies. Magnetite and hematite are both available in higher and lower grades.

Three processes are required to turn iron ore into steel.

Reduction: The iron-making process 'reduces' iron oxide into iron metal: a chemical reaction separates and removes oxygen (O) from iron metal (Fe). Chemical 'reductants' include carbon and hydrogen. If carbon (C) is used as a reductant, it bonds with oxygen in the iron ore, creating carbon dioxide (CO_2). If hydrogen (H) is used, it bonds with oxygen in the iron ore to create water (H_20).

Melting: To separate and remove gangue from iron metal.

Refining: A small amount of carbon is added to iron metal to produce steel. Remaining impurities are removed and alloys are added. Other elements can also be added depending on the desired qualities of the steel.

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[55] Magnetite has chemical composition Fe_3O_4 – three atoms of iron (Fe) and four of Oxygen (0). Hematite has composition Fe_2O_3.

[56] Australia also has goethite ore (FeO.OH), which is rarely present in a pure form, and is most commonly mixed with hematite ore.

[57] Summerfield, 'Australian Resource Reviews: Iron Ore 2019'.

[58] Summerfield.

2.1 Primary steelmaking is currently a carbon-intensive process

Steel-making is responsible for more than 8 per cent of global emissions, and about 12 per cent of emissions from fossil fuels.[59] Nearly all of this is from the production of primary steel, made from iron ore, which is about 70 per cent of yearly global production. Secondary steel is steel recycled from scrap, representing about 30 per cent of global production, and it is a relatively low-carbon process that produces about 0.7 tonnes of carbon per tonne of steel.[60]

Because the quantity of scrap steel is limited, and because demand for steel continues to grow, decarbonising primary steelmaking needs to be the global priority.

2.1.1 Primary steelmaking using a blast furnace and basic oxygen furnace cannot be cheaply or easily decarbonised

About 90 per cent of the world's primary steel is made using the BF-BOF process,[61] which generates an average of 2.2-2.3 tonnes of carbon dioxide for each tonne of steel produced.[62]

Blast furnaces combine the 'reducing' and 'melting' stages of ironmaking. Carbon is used to reduce ore into iron, in the form of metallurgical ('coking') coal. Temperatures in a blast furnace are higher than the melting point of iron, which helps separate and remove gangue. Blast furnaces can therefore be fed low, mid, and high-grade iron ore.

After it is melted in the blast furnace, iron metal is processed into steel in a basic oxygen furnace.

Reducing iron ore into iron metal in a blast furnace is the most emissions-intensive step in the BF-BOF steelmaking process, responsible for at least 70 per cent of emissions from BF-BOF steelmaking, and as much as 90 per cent.[63]

Coking coal is essential to the operation of blast furnaces because its lumpy, solid physical structure provides space for gases to rise through the furnace and to mingle with iron ore. This means that

[59] Figures on steel's contribution to global emissions typically range from 7 to 9 per cent; for example, World Steel Association, '#steelfacts'; Finighan, 'The New Energy Trade', 28 reports 8.6 per cent of global emissions and 12 per cent from fossil fuels.

[60] World Steel Association, '#steelfacts'; World Steel Association, 'Sustainability Indicators 2023 Report'; IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking', 29; The remaining 30 per cent of steel is processed through electric arc furnaces (EAF). Scrap processed in EAF makes up about 20 per cent of global steel production; direct reduction of iron ore and ore-based metallics into EAF processes accounts for the remaining 10 per cent. See World Steel Association, 'Fact Sheet: Steel and Raw Materials'; Devlin et al., 'Global Green Hydrogen-Based Steel Opportunities Surrounding High Quality Renewable Energy and Iron Ore Deposits'.

[61] Sometimes scrap steel and iron are blended together in the steelmaking process. This makes it difficult to be precise about the exact share of ore-based and scrap-based steel processed with each technology. Over 70 per cent of the world's steel is made using the BF-BOF process. World Steel Association, 'Fact Sheet: Steel and Raw Materials'; See also Swalec and Grigsby-Schulte, 'Pedal to the Metal 2023'. Global Energy Monitor's Global Steel Plant Tracker, which accounted for 92 per cent of OECD global capacity estimates, suggests that BF-BOF dominance has dropped to 62 per cent as of 2023 but 9 per cent of the database has an unknown production path. A much smaller share of primary steel is made in the DR-EAF process: although about 30 per cent of the world's steel is processed in electric arc furnaces, most of this is recycled scrap.

[62] IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking', 43; World Steel Association, 'Sustainability Indicators 2023 Report', 3.

[63] See for example: Wang, Ryman, and Dahl, 'Potential CO2 Emission Reduction for BF–BOF Steelmaking Based on Optimised Use of Ferrous Burden Materials'; MRIWA, 'Western Australia's Green Steel Opportunity'; Bailey, Lockwood, and Wakim, 'Decarbonization Pathways and Policy Recommendations for the United States Steel Sector'; also see footnote 38.

blast-furnace technology cannot be decarbonised without using carbon capture and storage, which is unlikely to be technically or economically competitive with other decarbonisation pathways (Box 1 in Chapter 1).

BF-BOF production dominates primary ore consumption because the integrated process, which depends on coking coal, is the lowest-cost way to produce iron and steel at scale. In a decarbonised world, without expensive carbon capture and storage, integrated BF-BOF production will not be viable.

2.1.2 Primary steelmaking using direct reduction of iron and an electric arc furnace

Direct reduction iron-making processes reduce iron ore at lower temperatures than blast furnaces, and produce a soft 'sponge' iron, known as 'direct reduced iron' (DRI).

There are different technologies available, but most direct reduced iron is made in vertical shaft furnaces.[64] Iron ore, usually in pellet form, is fed into the top of a vertical shaft furnace, before descending through a gas reductant that rises from the base – usually natural gas, which is largely methane, or methane derived from coal.[65] Methane (CH_4) reforms to hydrogen (H) and carbon monoxide (CO), and during the direct-reduction process, carbon monoxide reacts with iron oxide (Fe and O) to produce iron metal (Fe) and carbon dioxide (CO_2). The hydrogen (H) in methane also reacts with iron oxide (Fe and O), generating water (H_2O) as a waste. The presence of hydrogen makes methane-based reduction processes less emissions-intensive than iron-making processes using coal.

Because fine particles of iron ore can block the flow of gas, iron ore needs to be in a coarse physical form before it can be used in a vertical shaft furnace. Some naturally occurring iron ore 'lump' can be used, but most iron ore feed is in the form of pellets. Pellets are produced by grinding and milling iron ore into particles smaller than 0.1mm, then agglomerating these into spheres that are 9mm to 16mm in diameter.

If directly-reduced iron needs to be stored or transported, the Hot Briquetted Iron (HBI) process compresses the DRI into dense 'briquettes' to prevent the re-oxidation of the iron metal.[66]

Because the direct-reduction process does not reach the same temperatures as a blast furnace, it does not remove gangue. The grade of direct reduced iron, therefore, depends on the grade of iron ore.

After the direct-reduction process, currently using high-grade ore, solid HBI is fed into an electric arc furnace or basic oxygen furnace. Electric arc furnaces use electricity to melt iron metal and refine it into steel.

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[64] Rotary kilns make about 30 per cent of direct-reduced iron, and vertical shaft furnaces make the remaining 70 per cent. Midrex, '2023 World Direct Reduction Statistics', 2.

[65] Methane from gas is reformed into carbon monoxide (CO) and hydrogen (H).

[66] The International Maritime Organisation (IMO) IMSBC Code requires 'HBI produced by reduced iron oxide lumps, pellets, or fines, be compressed at a temperature of at least 650°C/1202°F to achieve an apparent density of at least 5,000 kg/m3'. IIMA, 'Hot Briquetted Iron (HBI): A Guide to Shipping, Handling & Storage. International Iron Metallics Association'.

Excess gangue increases electricity consumption, waste volume, and reduces yield.[67] Electric arc furnaces therefore process scrap steel – which has already had gangue removed – or direct-reduced iron with less than about 6 per cent gangue. We describe ore as 'DRI-EAF-grade' if it meets this threshold. DRI-EAF-grade pellets can be made from magnetite or hematite (Figure 3).[68]

Hematite: Fe_2O_3

Iron (Fe)	Oxygen (O)	Gangue
70	30%	0%
69	29.6%	1.4%
68	29.1%	2.9%
67	28.7%	4.3%
66	28.3%	5.7%
65	27.9%	7.1%

Minimum 67%
to achieve sufficiently low levels of gangue for the DRI-EAF process

Magnetite: Fe_3O_4

Iron (Fe)	Oxygen (O)	Gangue
71.4	27.6%	0%
71	27.1%	1.9%
70	26.7%	3.3%
69	26.3%	4.6%
68	26%	6%
67	25.6%	7.4%
66	25.2%	8.8%
65	24.8%	10.1%

Minimum 68%
to achieve sufficiently low levels of gangue for the DRI-EAF process

Figure 3: Very high-grade iron ore produces low-gangue direct-reduced iron (DRI), which can be fed directly into electric-arc furnaces technology
Source: The Superpower Institute analysis

Most seaborne iron ore products used in the pellet-based DRI-EAF industry are derived from hematite iron ore producers, with iron metal (Fe) content in the range of about 66.5 to 67.5 per cent, implying non-iron oxide contents in the range of 3.5 to less than 5 per cent.

Primary steelmaking using fossil fuels in the DRI-EAF process produces about 1.4 tonnes of carbon per tonne of steel (Table 1).[69]

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[67] Nicholas and Basirat, 'Solving Iron Ore Quality Issues for Low-Carbon Steel Technology'.

[68] Prusti et al., 'Pelletization of Hematite and Synthesized Magnetite Concentrate from a Banded Hematite Quartzite Ore'.

[69] World Steel Association, 'Sustainability Indicators 2023 Report'.

Table 1: Carbon-intensive primary steel-making processes

	BF-BOF	DR-EAF
Share of all Steelmaking (Scrap about 30%)	About 65%	About 5%
CO_2 emissions per tonne of crude steel	2.3 tonnes	1.4 tonnes
Reductant	Coking coal	Natural gas
Form of iron ore	Lump (no preparation) Fines (processed into sinter) Concentrate (processed into pellets)	Lump (no preparation) Concentrate (processed into pellets)
Iron making	Blast furnace (BF)	Direct reduction (DR)
Steel making	Basic oxygen furnace (BOF)	Electric Arc Furnace (EAF)

2.2 Direct-reduction processes can be decarbonised

Direct-reduction iron-making can be decarbonised. Some green direct-reduction technologies are already available, and others are being developed.

Vertical shaft technology is the most widely used direct reduction technology that can be decarbonised. Other technologies include:

- fluidised bed reactors
- fash technology
- iron electrolysis
- smelting reduction vessels.

There are three ways to decarbonise direct reduction processes:

- Technologies that use carbon-based gases as a reductant can use green hydrogen rather than natural gas. Green hydrogen is produced when zero-carbon energy is used to power an electrolyser, which separates water into hydrogen and oxygen.
- Technologies that use solid carbon can use renewable biochar rather than coal.
- Iron electrolysers that separate iron metal and oxygen can use zero-carbon electricity rather than carbon-based electricity.

2.2.1 Vertical shaft furnaces

Vertical shaft furnaces can be decarbonised by using green hydrogen rather than natural gas as a reductant,[70] producing water rather than carbon dioxide as waste.

Existing technology can already be used to make green iron. Midrex makes about 80 per cent of vertical shaft furnaces, and HYL/Energiron technology another 17 per cent.[71] Both can be adapted to use either pure hydrogen or a mix of gas and hydrogen as a reductant.[72]

Midrex flexible technology will be used by the Thyssenkrupp green iron project in Germany,[73] the Stegra project in Sweden, the Blastr proposal in Finland, the Hydnum project in Spain, and the GravitHy project in France (Table 2). Energiron's flexible technology will be used in Germany's Salzgitter Flachstahl green iron project, Sweden's HYBRIT project, Tata's project in the Netherlands, HBIS's project in China, Meranti's project in Thailand, and Vulcan's proposal in Oman.

Vertical shaft technology relies on lumpy or pelletised ore, which is currently limited in Australia. There are small-scale pelletising operations with Australian ore from Tasmania's Savage River and South Australia's Middleback Ranges.[74] But most Pilbara ores are unlikely to be used in vertical shaft furnaces. Pilbara magnetite ores require intensive grinding to help separate iron from silica – an energy-intensive process in which fine iron particles are lost, increasing costs and reducing productivity.

Pilbara ores are likely to be better-suited to direct-reduction technologies that can use iron fines, including fluidised bed reactors, flash smelting technology, and iron electrolysis.

2.2.2 Fluidised bed reactors

Fluidised bed reactors directly reduce iron ore fines, with the reductant gas rising into a bed of fines. This process is repeated across a sequence of vessels, as iron ore fines are progressively reduced to iron metal. Fluidised beds do not need iron ore to be lumpy or pelletised.

Some fluidised bed technologies use fossil fuel reductants: Circofer technology uses coal, and Finmet technology uses natural gas.

But several technologies can use hydrogen, including Circored, Finored, HyREX, and HYFOR technologies.[75] If these technologies use green hydrogen, they will produce green iron.

Fluidised bed technology has been used commercially. Finmet technology was used in Western Australia's Port Hedland between 1999 and 2004, and has operated in Venezuela since 2000.[76]

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[70] Reduction with hydrogen, rather than natural gas, requires additional heating of the reductant gas.

[71] Midrex, '2023 World Direct Reduction Statistics', 2.

[72] Midrex, 'MIDREX H_2, The Future of Ironmaking.'; Tenova, 'ENERGIRON'.

[73] Midrex, 'Thyssenkrupp Steel Selects MIDREX Flex™ for Immediate CO2 Emissions Reduction - Midrex Technologies, Inc.'

[74] Geoscience Australia, 'Australian Mineral Facts: Iron'.

[75] Circored technology can run on natural gas (in addition to hydrogen).

[76] Finmet technology was introduced in 1999 in Port Hedland and 2000 in Venezuela: Brent, Mayfield, and Honeyands, 'Fluidised Bed Production of High Quality Hot Briquetted Iron for Steelmaking'; Regarding Port Hedland closing in 2004: Wisenthal and Ball, 'Last White Elephant as Iron Plant Closes'; Regarding ongoing operation in Venezuela: Midrex, '2023 World Direct Reduction Statistics', 15.

Circored technology operated with hydrogen in ArcellorMittal's Trinidad and Tobago plant between 1999 and 2005.[77]

POSCO's HyREX smelting reduction vessel technology uses hydrogen in a process that integrates fluidised bed technology and smelting furnace technology; if green hydrogen is used, it produces green iron. An industrial-scale demonstration plant is being built in South Korea,[78] which will be scaled up to commercial production from 2026 using hydrogen produced from fossil fuels.

2.2.3 Flash smelting technology

Flash smelting technologies rapidly react iron ore fines with a reductant gas in a heated vessel. Flash smelting technology is also used to process metals other than iron, including copper and nickel.[79]

CALIX's hydrogen-based Zesty flash smelting technology has been trialled at low production volumes in Victoria.[80]

2.2.4 Electrolysis technology

Vertical shafts, fluidised bed reactors, and flash smelting all use chemical reductants to separate iron metal (Fe) from oxygen (O).

Electrolysis uses an electrical process to reduce iron ore. Iron ore is first dissolved in a chemical solution, before an electric current is used to separate and remove oxygen.

Different technologies use different chemical solutions and variations on the process. If the chemical solution is based on fossil fuels, this is a source of emissions. If the production of chemical solutions is decarbonised, and if zero-carbon electricity is used to power the electrolysis process, electrolysis can produce green iron.

Some molten oxide electrolysis technologies require temperatures over 1500 degrees Celsius, which is a barrier to ramping up and scaling down production; lower-temperature technologies will be more flexible but are less well developed.

Electrolysis has been demonstrated at a laboratory scale.[81] Electrolysis technologies are being developed by Element Zero, Fortescue Metals Group, Boston Metals, Helios, and Electra.[82] Boston Metals is building a critical minerals pilot plant in Brazil.[83]

2.2.5 Smelting Reduction Vessels

Smelting reduction vessels are not strictly direct-reduction technologies: they use direct-reduction technologies alongside an integrated smelting step, which produces melted iron metal rather than

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77 Metso, 'Circored™ Hydrogen-Based Reduction as One Route to CO2 Neutral Steelmaking'.

78 POSCO, 'Carbon Neutral Hyrex - Breakthrough Hydrogen Reduction Ironmaking Technology with near-Zero Emission'; Green Steel World Editorial Team, 'POSCO's HyREX: Cutting-Edge Green Steel Technology to Watch out For'.

79 Metso, 'Flash Smelting Technology'.

80 Walsh, 'Calix's ZESTY Study Finds High Potential for Economic Green Iron'; Flash smelting can also use carbon as a reductant. For example, China-Zhang is a coal-based flash smelting process: Chen, 'China's "Explosive" Ironmaking Breakthrough Achieves 3,600-Fold Speed Boost'.

81 World Steel Association, 'Electrolysis in Ironmaking'.

82 Element Zero uses a eutectic solution; FMG uses a membrane process; Boston Metal's motel oxide electrolysis process uses silica electrolyte; Helios uses molten sodium; Electra uses acid.

83 Pulice, 'Q&A: Boston Metal Brazil's sales to start in early 2025'.

solid direct-reduced iron.[84] But unlike blast furnaces, which also produce melted iron, they can be used to produce green iron.

HIsmelt and HIsarna are the most commercially progressed smelting reduction vessel technologies. Several HIsmelt plants operate in China and several more are under construction. A HIsarna pilot plant has been operational at Tata Steel in the Netherlands for several years,[85] and Tata Steel is studying the deployment of HIsarna technology at locations in India.

Most smelting reduction vessels use coal as a reductant. Unlike blast furnaces these processes use non-coking coal. To produce green iron, biochar can be used instead of coal.[86]

Table 2: Summary of pathways to decarbonise iron-making
Source: The Superpower Institute analysis

Technology	How to decarbonise	Ore size	Example green technologies	Development stage of green technology and estimated technology readiness level (TRL)	Example projects
Vertical shaft furnace	Green hydrogen rather than natural gas	Lumps and pellets	Midrex and Energiron	Existing technology Estimated TRL:9	POSCO proposed plant, Western Australia
Fluidised bed reactors	Green hydrogen rather than natural gas	Ore fines	Circored, Finored, HYFOR HyREX combines fluidised bed reactors and electric smelting furnace technology	Existing technology Successful pilot plant, demo under development Estimated TRL:7-9	Circored and Finored have operated at commercial scale; Estimated TRL:9 HYFOR is in final engineering for demo plant; Estimated TRL:7 Constructing HyREX plant in South Korea, TRL:7
Flash smelting	Green hydrogen rather than natural gas	Ore fines	Calix's Zesty technology	Demonstrated at pilot scale, demo under development Estimated TRL:6-7	Pilot plant operating in Victoria, demo plant engineering complete, seeking funding and location
Electrolysis	Green electricity rather than carbon-intensive electricity	Ore fines	Element Zero FMG, Boston Metal's MOE, Helios, Electra	Successful laboratory demonstrations Estimated TRL:5-6	All have achieved TRL:5 and are in various stages of scaling to TRL:6, except FMG, which remains at lab

[84] Finex is an integrated two-stage process with fluidised bed reactors and a melter: Primetals Technologies, 'FINEX® — Innovative and Environmentally Friendly Ironmaking'; HIsmelt is a single-stage furnace: AusIMM, 'The Production of Green Steel Using HIsmelt'; Hisarna is an integrated cyclone furnace combined with HISmelt technology: Meijer et al., 'The Hisarna Ironmaking Process'; Corex is an integrated two-stage shaft technology and melter: Primetals Technologies, 'Corex®-Efficient and Environmentally Friendly Smelting Reduction'.

[85] TATA Steel, 'HISARNA: Building a Sustainable Steel Industry'.

[86] For example, biochar can replace coal in the HIsmelt process: Meijer et al., 'The Hisarna Ironmaking Process'.

Smelting reduction vessels	Green hydrogen rather than natural gas Or, Biochar rather than coal	Ore fines	HISmelt	Industrial plants under development Estimated TRL:7-9	HISmelt plant operating in China, TRL:9

2.3 Green iron made with lower-grade ores requires electric smelting

Unlike blast furnaces, direct-reduction technologies and smelting reduction vessels will be able to make green iron. But direct reduction technology currently reduces very high-grade ore, because direct-reduced iron is fed into electric arc furnaces, which cannot produce high-quality steel from iron made with lower and mid-grade ores.

As blast furnaces become obsolete, lower and mid-grade iron ores will need to be integrated into direct-reduction processes.

2.3.1 Electric smelting furnaces will make it possible to process lower and mid-grade ores in electric arc furnaces

Electric smelting furnace (ESF) technology is the most promising technology for removing gangue from lower and mid-grade direct-reduced iron. This would create DRI-ESF-EAF and DRI-ESF-BOF production pathways for a range of Australian iron ores, and may be cost-competitive even without ore beneficiation.[87]

Like an electric arc furnace, electric smelt furnaces melt iron by passing electricity between electrodes. Unlike an electric arc furnace, smelting furnaces operate continuously rather than in batches. Directly reduced iron is fed into the smelting furnace, with solids gradually reducing and melting on top of layers of iron and gangue that have already melted. The furnace is used in a similar way to a blast furnace: melted metal and gangue are periodically drained from the furnace through 'tap holes', without stopping furnace operation.[88]

Smelt furnace technology has been developed and used in other metal-making industries,[89] and has been used to process direct-reduced iron in New Zealand,[90] but needs to be adapted for iron-making with lower and mid-grade ores.

The energy used in an electric smelting furnace adds additional capital and operational costs – one reason that direct reduction and electric smelting have not competed with blast furnace technology to process lower-grade iron ore. But pressure to decarbonise will make electric smelting technology an important part of the iron-making process.

Electric smelting technology will also be used to adapt steelmaking processes in existing BF-BOF operations: producers will be able to replace blast furnaces with direct reduction technology and

[87] Rahbari et al., 'Production of Green Steel from Low-Grade Ores'.

[88] Gadd et al., 'Pathways to Decarbonisation, Episode Seven: The Electric Smelting Furnace'.

[89] For example, the ferroalloy, titanium and nickel industries.

[90] Rio Tinto, 'BlueScope, BHP and Rio Tinto Select WA for Australia's Largest Ironmaking Electric Smelting Furnace Pilot Plant Study'.

electric smelting furnaces, and continue to use lower and mid-grade iron ores while maintaining existing steel making processes (Figure 4).

METSO electric smelting furnace technology is being developed at a pilot plant in Finland,[91] and a number of other international steelmakers are also investing in the technology, including Tata Steel Europe, ThyssenKrupp, voestalpine, and POSCO.[92] In Australia a consortium including Bluescope, BHP, Rio Tinto, and Woodside are developing the technology with the goal of processing Pilbara ores.[93]

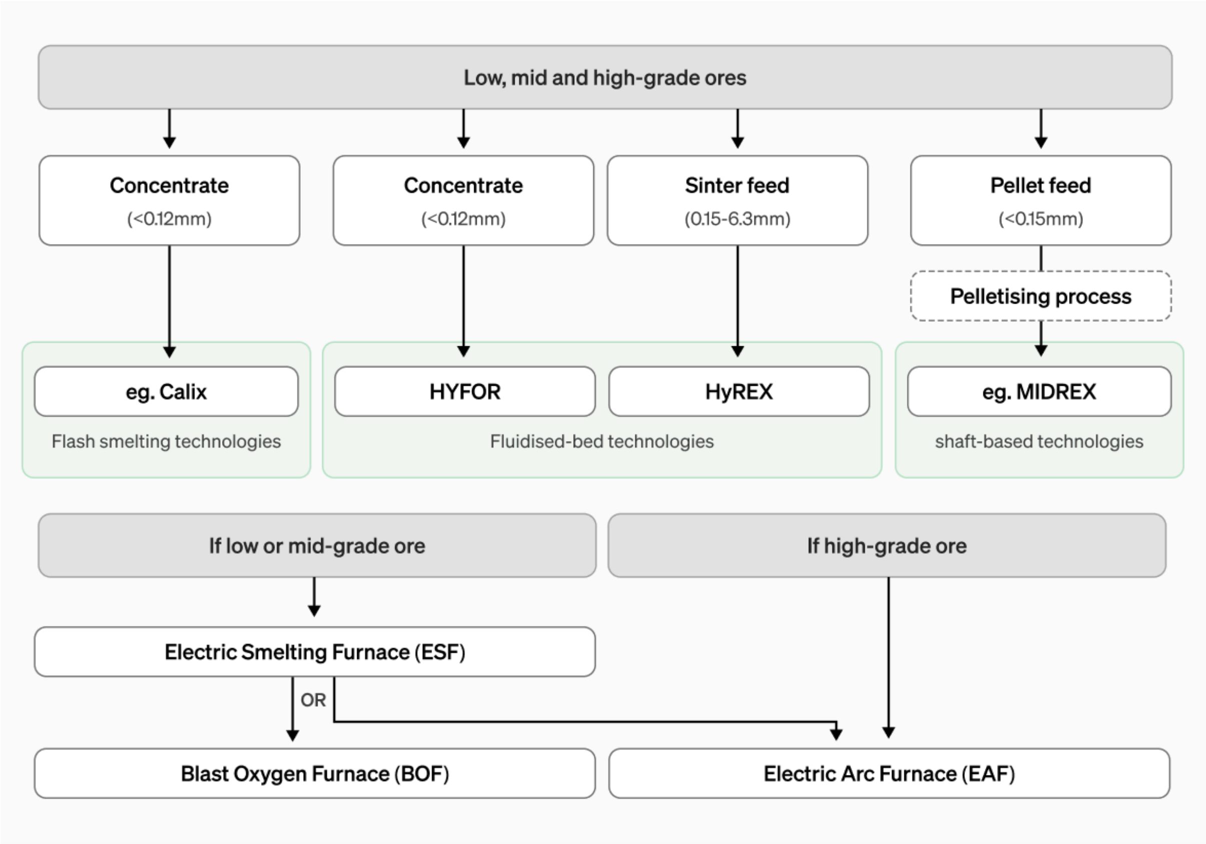

Figure 4: Likely pathway for zero-carbon green iron ore processing
Source: Primemetals Technology, International Iron Ore & Green Steel Summit 2024

2.4 Australian ores can be used to make green iron

Most Australian mines can only supply the lower and mid-grade ores that are currently used in the BF-BOF process.[94] Electric smelting furnace technology will be essential for processing these ores into green iron, because they remove gangue from lower grade iron ores, and because they can be powered by zero-carbon energy.

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[91] Metso, 'DRI Smelting Furnace'.
[92] Gadd et al., 'Pathways to Decarbonisation, Episode Seven: The Electric Smelting Furnace'.
[93] BlueScope, 'Australia's Leading Iron Ore Producers Partner with BlueScope on Steel Decarbonisation'.
[94] World Steel Association, 'Fact Sheet: Steel and Raw Materials'; Gadd et al., 'Pathways to Decarbonisation, Episode Seven: The Electric Smelting Furnace'.

Refining and scaling up direct-reduction alternatives to vertical shaft furnaces will also be important, because Pilbara ores cannot be easily pelletised for use in vertical shaft furnaces.

Australia has large reserves of higher-grade magnetite ores, which do not require processing in an electric smelting furnace. These reserves are concentrated in South Australia and Western Australia.[95] Magnetite has not historically been mined or exported in large quantities, but these reserves will become more valuable as Australia becomes a green iron producer.[96]

The most commercially-developed green iron technologies use green hydrogen as a reductant.[97] An Australian green iron industry will therefore depend on green hydrogen and large investments in renewable energy for its manufacture. If green hydrogen is not available, or if its price is too high, producers will not make green iron in Australia.

In Chapter 3 we present the results of a model of green iron production. This model captures the relationship between different Australian ores and different processing technologies, including the pelletising of ore for use in vertical shaft furnace technology, and the use of electric smelting furnaces for lower-grade Pilbara ores.

[95] Australia Minerals, 'Australian Magnetite Ore 2023 Factsheet'.
[96] Wang et al., 'Picture This: Green Hydrogen Plants next to Green Steelworks to Boost Efficiency and Kickstart Both Industries'.
[97] Often referred to as 'gH2-DRI'.

03

A model of green iron investment, production, and costs

To show how market conditions and market failures affect the cost of green iron we have partnered with Bivios[98] to develop a sophisticated model of green iron investment and production.

The model identifies the lowest-cost combination of capital investments, technology choices, and output for three industries on the green iron production path:

- renewable energy
- green hydrogen
- green iron.

We model production in five locations, with two types of iron-making technology.

The model captures the most important features of zero-carbon energy-intensive production. The model:

- is 'dynamic': it shows how zero-carbon energy-intensive goods will be produced with variable renewable energy, based on hourly weather data and hourly energy market data
- shows how green industries will interact with the Australian energy system, and the way producers can both use and supply energy into the energy market
- shows how new technologies will reduce the cost of producing green iron
- helps illustrate how green iron production will evolve, with early production locations shaped by existing infrastructure, before scaling up as new infrastructure and economies of scale create new opportunities.

Section 3.1 describes the model. Section 3.2 summarises our main results, including the lowest-cost combination of infrastructure investments and green iron production for each technology in each location and the resulting cost of green iron.

Chapter 4 reports the most important analytical insights from the model.

[98] Bivios is a sustainability consultancy with expertise in dynamic models and green production.

3.1 How we model green iron production

Each green iron 'project' includes the production of renewable energy, green hydrogen, and green iron. We model production volumes, costs, financial outcomes, and emissions using forecast capital costs for 2030 reported in 2025 dollars.

We start with production costs for producers in an established green iron industry, rather than 'first-of-a-kind' producers. 'First-of-a-kind' producers face greater uncertainty and higher borrowing costs, and we report these costs in Section 4.6.

Our results are estimates; they are not formal cost predictions, which depend on private commercial information. These estimates help identify the potential range of production costs, and demonstrate some of the tradeoffs between different locations, technologies and capital investments, and therefore the different ways producers can reduce costs. Results from the model are also useful for estimating the effects of market failures, and the policies to correct for these failures.

Our results are based on 'behind the fence' costs: where possible, our results reflect the benefits from connecting to existing electricity grids where this enables energy trading in a liquid 'spot' market for energy. For many large green iron projects connection to the grid will require network upgrades, including investments in new transmission and connections. We discuss investments in common-user infrastructure in Section 5.2.

We do not advocate for one green iron technology ahead of another, or for production in a particular location. The model does, however, demonstrate some relative cost advantages and disadvantages between the different configurations of location and technology.

3.1.1 The model simulates green iron production

The model simulates green energy, hydrogen, and iron production over a year, and identifies the combination of technology investments and production volumes that achieves the lowest 'levelised cost' of producing green iron (LCOI). Each green iron plant that we model has an output of 2.5 million tonnes (megatonnes) of iron per year (Figure 5).

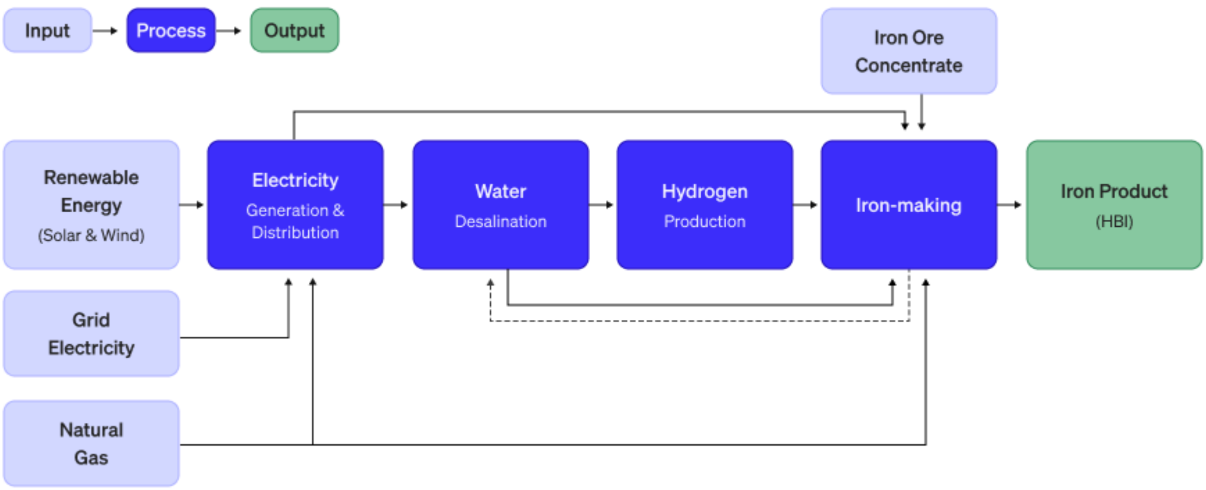

Figure 5: Summary of the green iron production model

Notes: Use of each input varies by location, technology, and ore type.
Source: Bivios and The Superpower Institute

The 'iron-making' stage includes:

1. pre-processing, such as pelletisation of iron ore
2. the direct-reduction process, which produces direct reduced iron (DRI)
3. post-processing: DRI made with low and mid-grade ore requires additional processing in an electric smelting furnace (ESF). Direct-reduced iron is pressed into hot briquetted iron (HBI).

The iron-making process does not include the beneficiation of iron ore; ore is purchased at a price that reflects the grade of iron.

Inputs for the model are based on extensive research, but we acknowledge there is uncertainty. A full list of the inputs into the model is provided in a spreadsheet, which can be downloaded from the Superpower Institute website. Further details on the model are provided in Appendices 3-8.

3.1.2 The model captures the relationship between variable renewable energy and fixed capital investments

Green iron is produced in a dynamic environment with inputs that vary through time – for example, renewable energy production changes with the weather.

Capital investments constrain the dynamic operation of a green iron production system: there is a limit to the amount of renewable electricity that can be generated by a fixed quantity of wind turbines and solar panels, a limit to the amount of energy that can be stored in a battery, a limit to the amount of hydrogen that can be produced by an electrolyser, and a limit to the amount of electricity that can be fed through a transmission line. Capital investments include:

- local solar panels
- local wind turbines
- behind the meter ('BTM') transmission – the quantity of energy that can be transmitted between renewable energy sources, green hydrogen producers, and green iron producers
- gas turbines
- batteries
- hydrogen production
- hydrogen storage
- iron production.

Capital investments are made to minimise the cost of producing green iron based on:

- the features of each technology
- complementarities between technologies
- the cost of different capital combinations.

For example, a producer with inflexible iron-making technology needs a constant supply of hydrogen and energy. The producer could:

- invest in extremely large-scale renewable energy generation, to make sure energy is nearly always available

- invest less in renewable energy and transmission, but invest more in energy or hydrogen storage
- choose a location with access to an electricity grid, which would reduce investments in renewable energy and storage, but require energy to be purchased from the market – including transmission and network charges.

Alternatively, the producer could invest in flexible green iron-making technology, with production levels that can be more easily ramped up or down: if renewable energy or green hydrogen is unavailable or supply reduced, production can be cut or reduced. But to maintain the same total quantity of green iron output over a year, producers need to invest in a larger flexible green iron plant, to capitalise on periods when renewable energy and hydrogen are available.

This kind of investment decision is not new: all producers need to weigh up the benefits and costs of different combinations of capital. But large-scale production, using variable renewable energy rather than a constant supply of fossil fuels, introduces new challenges and opportunities. A dynamic model provides important insights into the trade-offs between different investment combinations.

3.1.3 The model includes two green iron-making technologies

We model two different iron-making technologies - an 'inflexible' technology and a 'flexible' technology.

'Inflexible' technology needs to produce iron continuously, or equipment is damaged. It is technologically well-developed and commercially established. We model inflexible technology operating at 100 per cent capacity[99], requiring a continuous supply of green hydrogen or natural gas for reducing iron ore into iron.[100] An example of inflexible technology is the MIDREX vertical shaft furnace direct-reduction technology. Vertical shaft technology requires ore to be pelletised, and we include pelletisation in the pre-processing stage of iron-making; this involves additional capital and operational costs.

'Flexible' technology can ramp production levels up and down without causing damage to equipment, and therefore lends itself to more variable sources of energy and reductants. Flexible technology is not as technologically developed as existing, inflexible technologies. We model a single flexible technology that can be ramped up and down without constraints, representing a technology such as Calix's ZESTY flash-smelting process,[101] which has been successfully piloted and is progressing to demonstration-scale production.[102] This flexible technology uses iron ore fines, and does not require pelletisation in the iron-making process. The model does not include other flexible technologies, such as fluidised bed furnace technology or direct electrolysis of iron.

The inflexible iron-making technology needs a year-round supply of hydrogen or natural gas, and may therefore require more hydrogen storage than flexible green iron technology.

The model does not account for the risks associated with technologies at a lower level of technical or commercial readiness. These are reflected in 'first-of-a-kind' production costs, which we discuss in Section 4.6.

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[99] This constraint is relaxed for the Pilbara scenario, where there is no firming power available, to 98%.

[100] It may be possible to schedule some plant shutdown activities in the winter season, when green hydrogen availability will be lowest, but our model does not include a shutdown period.

[101] There is no publicly available information on the capex cost impact of achieving this flexibility in production. We have assumed a 20% increase in the cost of the iron making technology for flexible operation.

[102] Calix, 'ZESTY Green Iron and Steel Proves Its Credentials'.

3.1.4 The model includes different types of iron ore

Production is modelled for different grades of iron ore, based on the characteristics of iron ore in each location, or the characteristics of ore transported to each location. Different grades of iron ore have different costs and benefits.

Lower-grade ores are typically cheaper, but when they are used to make direct-reduced iron (DRI), the DRI needs to be processed in an ESF to remove gangue (Section 2.3). This extra processing adds to capital and operating costs. Higher-grade ore is more expensive, but does not require investments in electric smelting technology.

For our model we have assumed lower-grade Pilbara iron ore requires processing in an ESF. Pilbara ore is used in three of our green iron processing locations: Pilbara, Kwinana, and Gladstone. Higher-grade local ore supplied to the Eyre Peninsula and to Geraldton does not require processing in an ESF.

Because iron ore grades vary across Australia, ore grade influences the lowest-cost combination of capital investments in each location.

3.1.5 The model includes five locations

The model reports investment decisions, production outputs, and costs for five locations:

- The Eyre Peninsula in South Australia
- The Pilbara in Western Australia
- Kwinana in Western Australia
- Geraldton in Western Australia
- Gladstone in Queensland

The east-coast National Electricity Market (NEM) and Western Australia's South-West Interconnected System (SWIS) both transmit electricity and facilitate a centrally dispatched wholesale electricity market. Prices in these wholesale markets vary based on short-term supply and demand. Energy producers can buy and sell into the wholesale market.

All of our chosen locations, except the Pilbara, could potentially connect green iron projects to either the NEM or the SWIS and benefit from buying and selling energy into the wholesale markets that operate using those grids.

The electricity grid in the Pilbara, the North-West Interconnected System (NWIS), does not have a 'wholesale' electricity market.[103] While a green iron project in the Pilbara could connect to the NWIS, doing so would not provide the same opportunities for energy trading afforded to projects connected to the NEM and the SWIS.

For easy reference throughout this report we use the term 'grid-connected' to mean that a project has access to both an electricity grid and the option to trade energy in a wholesale market.

[103] AER, 'State of the Energy Market 2007' pages 205-209. The NWIS is also characterised by a particularly low two per cent share of variable renewable energy: Logiudice, 'Pilbara Energy Transition: Evolution of the Pilbara Electricity Access Regime and Networks Rules', April 2025: this reduces opportunities to benefit from electricity sales to, and purchases from, the market; The NWIS is evolving, with substantial investments planned to support green industry: Prime Minister of Australia, '$3 Billion Rewiring The Nation Deal to Power WA Jobs and Growth'. These investments may reduce the capital intensity of individual renewable energy, green hydrogen, and green iron projects.

Being connected to a wholesale electricity market means producers can buy energy when the price is low and sell renewable energy into the wholesale market. Prices in our model are based on historical data for wholesale electricity prices and an estimate of network charges in each location.[104]

The revenue from selling renewable energy can offset some of the costs of producing green hydrogen and green iron, reducing the production costs that need to be recovered from green iron buyers. When we discuss the cost of producing green iron, inclusive of revenues from renewable energy sales, we refer to the 'effective cost' of producing green iron.

Each location also has a 'capital cost multiplier' to capture local building and operating costs.

Locations have been chosen based on their renewable energy resources and their proximity to iron ore resources, or in the case of Kwinana and Gladstone, ports that allow iron ore to be transported for processing.

Table 3: Summary of characteristics of different iron-making locations

Notes and sources: See Appendices 3-8 for more detail

Location	Connected to wholesale electricity market	Capital cost multiplier	Type of iron ore	Processing
Eyre Peninsula (SA)	Yes	1.08	Eyre Peninsula high-grade magnetite	Pelletisation of ore for 'inflexible' technology
Pilbara (WA)	No	1.34	Pilbara lower-grade hematite	Pelletisation of ore for 'inflexible' technology DRI processed in Electric Smelting Furnace for both 'flexible' and 'inflexible' technologies
Kwinana (WA)	Yes	1.12	Pilbara lower-grade hematite	Pelletisation of ore for 'inflexible' technology DRI processed in Electric Smelting Furnace for both 'flexible' and 'inflexible' technologies
Geraldton (WA)	Yes	1.24	Central WA high-grade magnetite	Pelletisation of ore for 'inflexible' technology
Gladstone (Qld)	Yes	1.11	Pilbara lower-grade hematite	Pelletisation of ore for 'inflexible' technology DRI processed in Electric Smelting Furnace for both 'flexible' and 'inflexible' technologies

[104] The model does not include the effect of buying and selling large amounts of electricity on wholesale electricity prices. The sale or purchase of large volumes of electricity into the grid will dampen variation in the wholesale market, so our results may overstate the benefits of trade.

3.2 Optimal investments, production decisions, and costs

We report the levelised cost of producing iron (LCOI) for green iron produced with green hydrogen with less than 0.6 kilograms of carbon per kilogram of green hydrogen.[105] The emissions constraint limits the quantity of non-renewable energy that can be used to make green hydrogen.

The lowest-cost combination of capital investments varies with location and technology. The resulting cost of producing iron reflects differences in ore types and processing requirements, the capital cost multiplier, and renewable energy capacity factors (Figure 6 and Figure 7).

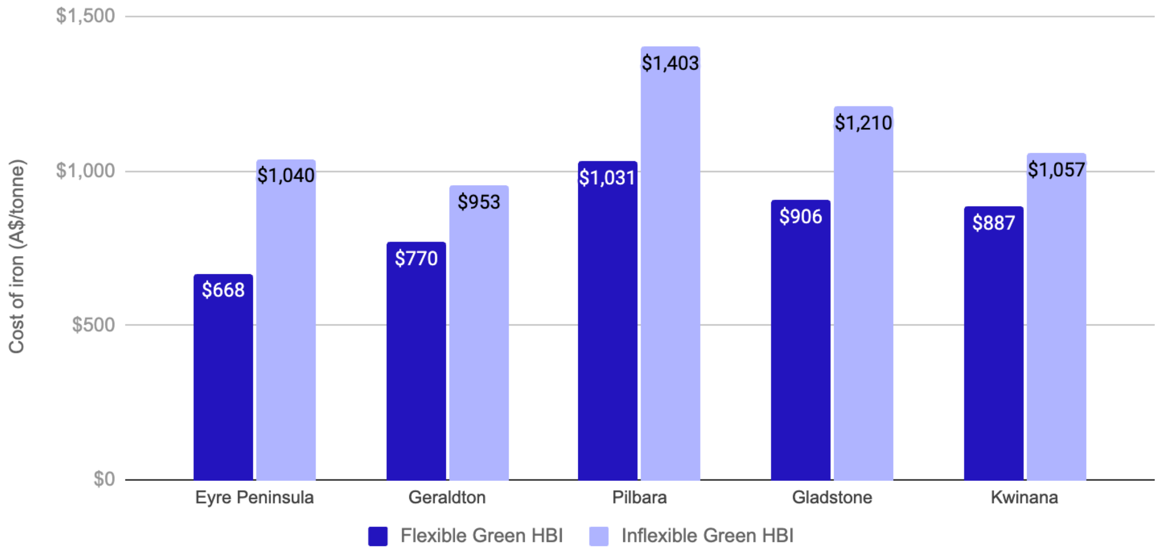

Figure 6: The cost of producing green iron varies by location and technology type

Notes: Cost is for green iron produced with green hydrogen with 0.6 kg of carbon per kg of green hydrogen. See Appendix 4 for detailed results. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.
Source: Bivios and The Superpower Institute analysis

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[105] This is the emissions intensity required for hydrogen to be eligible for the Hydrogen Production Tax Incentive (HPTI) tax credit of $2 per kg of hydrogen.

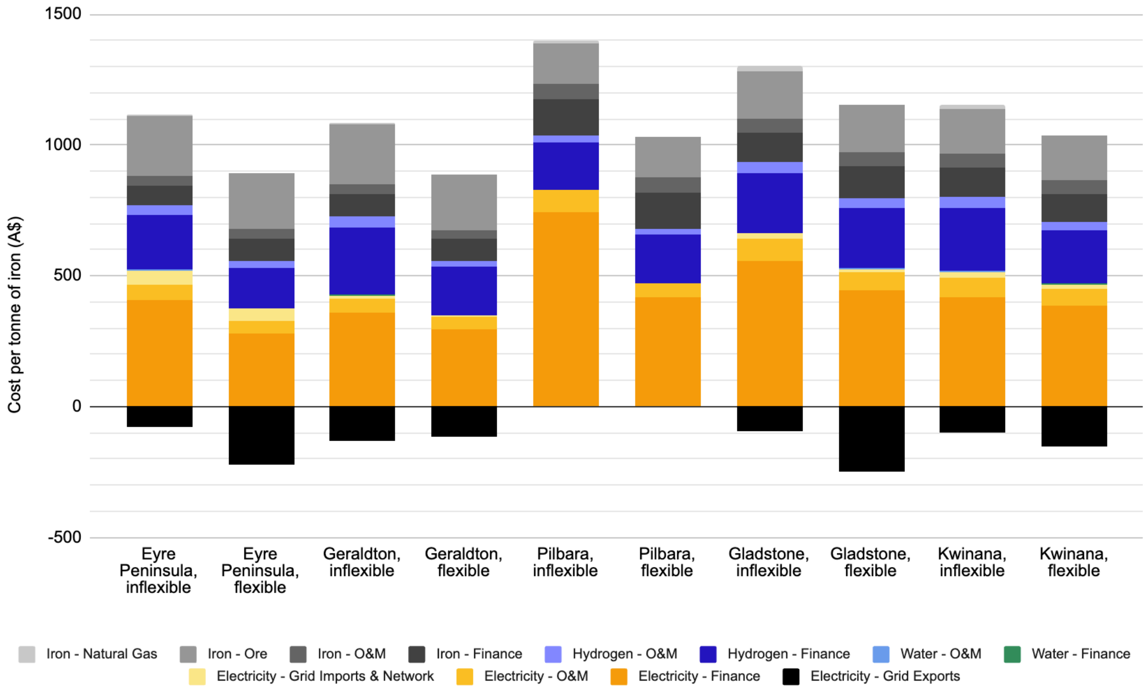

Figure 7: Breakdown of cost components by location and technology type

Notes: Cost of iron is for green iron produced with green hydrogen with up to 0.6 kg of carbon per kg of green hydrogen. 'Electricity' refers to renewable energy. 'O&M' refers to operation and maintenance costs. 'Hydrogen' refers to green hydrogen. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously. Water costs are included but not visible. See Appendix 4 for detailed results.

Source: Bivios and The Superpower Institute analysis

In all locations, capital investments dominate the cost of producing iron – in particular, the cost of renewable energy, green hydrogen technology, and iron-making technology.

The two most striking results relate to renewable energy investments:

- Variation: investments in renewable energy are the largest source of cost variation across locations and technology types.
- Scale: commercial levels of green iron production require very large investments in renewable energy.

3.2.1 There is large variation in renewable energy costs

The cost of capital investments reflects the quantity of capital investment and the cost of capital investment. The quantity depends on technology choice and location, with location determining ore type, weather patterns, and whether a producer can be grid-connected. The cost of capital is also determined by location, reflecting local costs of installation.

The largest investment in renewable energy is required for inflexible technology in the Pilbara – over 9,000 megawatts (MW). At the other extreme, flexible technology in Geraldton requires just under 4,500 megawatts of installed capacity.

This reflects tradeoffs described in Section 3.1: inflexible technology cannot ramp up and down, and requires a larger investment in renewable energy to maintain production of hydrogen and iron. Green iron producers in the Pilbara face the additional costs associated with not having access to a grid that facilitates a short term trading wholesale market (see section 3.1.5). Pilbara producers could connect to the NWIS and make arrangements for supply with a retailer and potentially enter power purchasing agreements (PPAs), but this does not provide the same benefit as access to a short term trading market. A short term trading market gives a green iron producer the option to only rely on the grid when wholesale prices are low or when variable renewable energy resources are producing at low output. Together, these factors push up the quantity of renewable energy required for inflexible technology in the Pilbara.

The cost of renewable energy investments for inflexible technology in the Pilbara is nearly $27 billion. This reflects the large quantities required, and the Pilbara's higher cost of building capital assets. In contrast, investments for flexible technology in the Eyre Peninsula cost about $10 billion.

Investments in energy storage also reflect a producer's capacity to vary production and to draw on electricity supplied by an electricity market. Again, the highest requirements are for inflexible technology in the Pilbara, at about 9,500 megawatt hours of battery storage. But down the coast in Geraldton, where a producer can be grid-connected, producers using flexible technology only need to invest in about 800 megawatt hours of storage.

3.2.2 Green iron needs large investments in renewable energy

In all locations, and for both technology types, commercial levels of green iron production will require large investments in renewable energy capacity: the average share of costs from energy generation and storage is more than 60 per cent.

Demonstrating the scale of energy required, green iron production in South Australia's Eyre Peninsula requires more than 10 terawatt hours (TWh) of electricity.[106] This is equivalent to nearly two-thirds of South Australia's electricity generation of 15.7 TWh in 2024 (Figure 8).

[106] Producing 1 tonne of green iron requires approximately 0.5 MWh of electricity

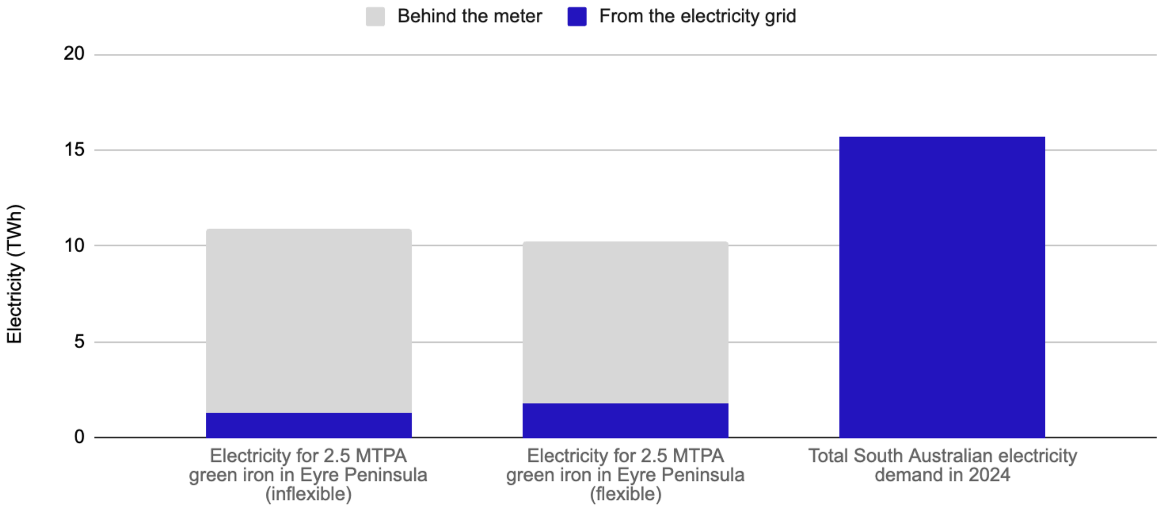

Figure 8: Green iron production requires very large quantities of renewable energy

Notes: Electricity requirements for 2.5 million tonnes of green iron produced with green hydrogen with 0.6 kg of carbon per kg of green hydrogen. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.

Source: Bivios and The Superpower Institute analysis

04

Insights into an Australian green iron export industry

Chapter 3 showed how we model green iron production and baseline results. This chapter reports the most important insights from the modelling.

Sections 4.1 and 4.2 show how energy will be used to make green iron in Australia: how variable energy sources can be harnessed to successfully produce industrial quantities of green iron (Section 4.1), and how a grid connection can lower costs for green iron producers, while increasing the supply of renewable energy for other consumers (Section 4.2).

Section 4.3 shows why green iron will become progressively more competitive with carbon-intensive iron as costs fall: how technical innovation will improve green iron technology, and why technology costs will fall as green hydrogen and iron are produced at larger scale. Section 4.4 shows how infrastructure constraints increase costs, while Section 4.5 shows that the lowest cost sites for renewable energy and green hydrogen production may be far away from iron ore deposits. Section 4.6 shows that early producers of green iron will face higher costs, but create information that benefits later producers. Section 4.7 shows that it is cheaper to produce iron with natural gas,[107] but the emissions intensity of iron increases, and the availability of affordable gas is uncertain and limited.

Drawing on these results we describe how a green iron industry can be established, before growing and spreading into different locations across Australia (Section 4.8).

4.1 Renewable energy can be used to produce green iron at an industrial scale

Green iron production has high capital costs, including renewable energy and storage, hydrogen production plants and storage, and green iron plants.

Keeping plants running continually is relatively simple when the energy is supplied by fossil fuels or hydroelectricity, but it is more challenging when energy is supplied by variable renewable energy sources, such as wind turbines and solar farms.

[107] As noted in Chapter 1, cost comparisons are based on commercial costs incurred by producers, excluding the social cost of carbon.

Our model shows that it is possible to produce green iron in Australia, at an industrial scale, using renewable energy. Depending on the location of a project and the technology used, variability is managed with:[108]

- electricity storage (batteries), to reduce the variability in the supply of electricity to the hydrogen plant and the iron plant
- electricity purchased from the market for hydrogen production and iron production when renewables are unavailable, subject to the emissions intensity constraints of the Hydrogen Production Tax Incentive
- hydrogen storage, to reduce the variability of supply to the iron plant
- reduced hydrogen production
- reduced iron production, if using flexible iron-making technology.

Our model identifies investments that can deliver 2.5 million tonnes of green iron each year, in each location, and with flexible and inflexible iron-making technologies.

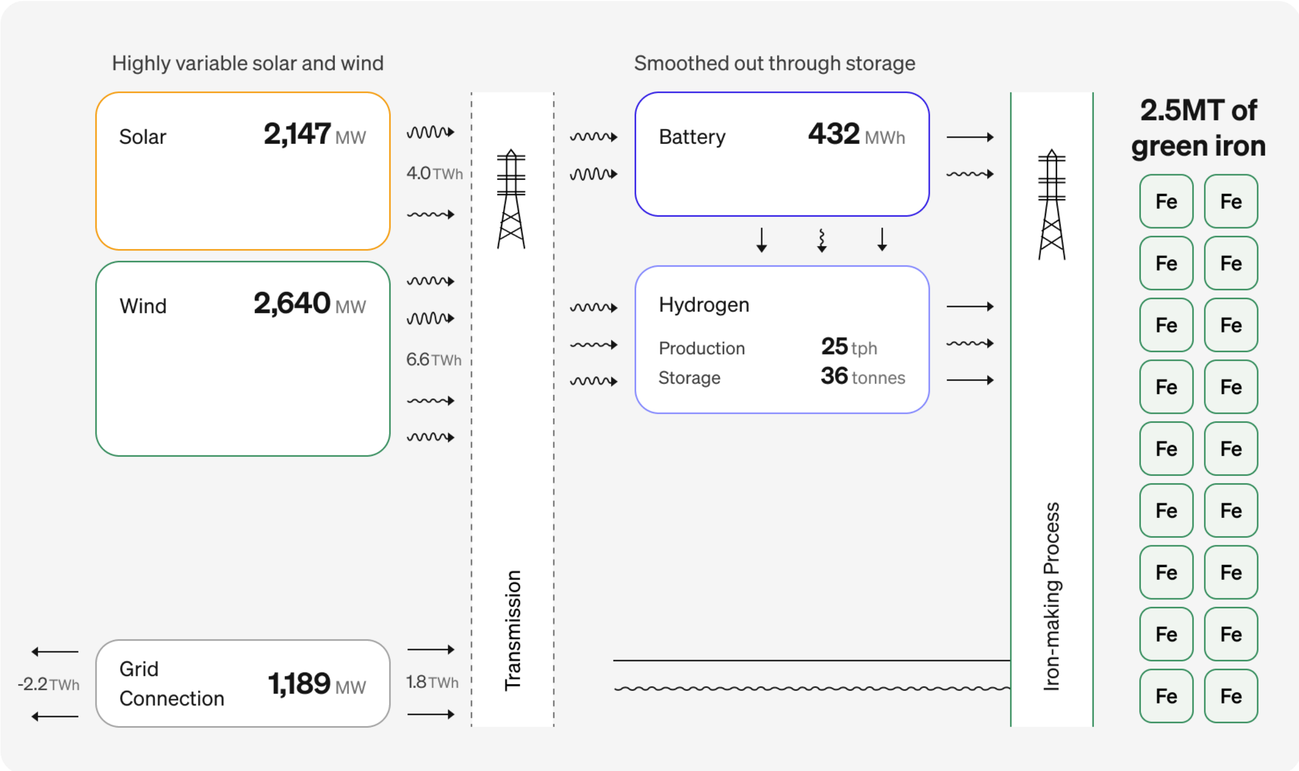

Figure 9: Variable renewable energy and storage can be used to produce industrial quantities of green iron

Notes: Figures are model results for a flexible technology operating on the Eyre Peninsula. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.

Source: Bivios and The Superpower Institute analysis

Actual investments and production paths may not look exactly like our results, and will be based on companies' private commercial information, existing resources, and expertise. But our dynamic

[108] Our main model does not include the use of gas turbines to reduce variability in the electricity supply. This modelling simplification may increase our estimated costs of production. We discuss the role of gas turbines in Section 4.7.

model, capturing hourly variation in weather patterns, shows that it is possible to make Australian green iron at commercial quantities.

4.2 Grid-connection can reduce the cost of green iron and encourage investment in renewable energy

Grid connection has three benefits for green iron producers.

1. It can be a source of electricity when renewable energy from the project's own solar and wind farms is not available.
2. Where the grid supports a wholesale market, as in the NEM and the SWIS, green producers can sell green energy to the electricity market and generate revenue when there is more renewable electricity available from the project than required.
3. Green producers using flexible technology can reduce hydrogen and iron plant operations and sell renewable electricity back to the market if it is more profitable than continuing hydrogen and iron production.

Grid-connected green iron producers can also provide benefits for other wholesale market customers. When electricity is scarce and expensive across the market, hydrogen producers and green iron producers using flexible technology can reduce or cut production, reducing demand in the wholesale market. When electricity is abundant and cheap, green producers can use power from the wholesale market to produce and store hydrogen, or to ramp up green iron production.

This arbitrage is possible in large electricity grids for two reasons. The first is geographic: large grids cover large areas, so the sun can be shining in the Eyre Peninsula, and more than 200 kilometers away, it can be cloudy in Adelaide. The second reason is that time zones vary across Australia's large east coast National Electricity Market: when people are arriving home in Brisbane, turning on appliances, and driving up the demand for electricity, people in Adelaide are still at work.

Our model captures benefits to early producers who are more likely to benefit from price variation in wholesale electricity markets.[109] Based on the assumptions in our model, a connection to an electricity market can reduce the cost of iron by as much as 17 per cent, from $801 to $668, when flexible technology is used in South Australia's Eyre Peninsula (Figure 10).

[109] Our model takes the electricity market 'as given' and does not capture the effect of large-scale renewable energy, green hydrogen, and green iron producers on the electricity market. These large projects will reduce price variation in the grid and opportunities to buy electricity at low prices, and to sell at high prices. Our model may therefore overstate the financial benefits of buying from and selling to the grid, and therefore may overstate reductions in the final cost of producing green iron.

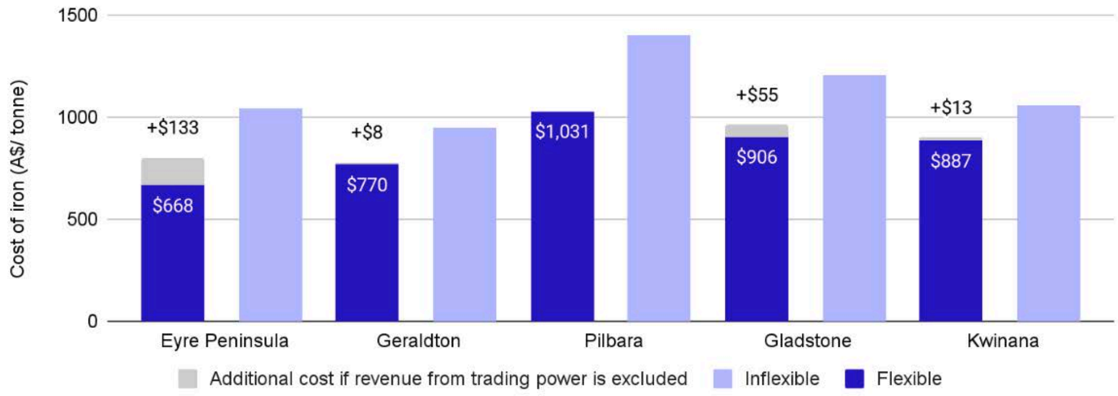

Figure 10: Trading electricity on the spot market reduces the cost of green iron

Notes: Projects in all locations except the Pilbara have the opportunity to 'trade power': to buy from and sell renewable energy into the electricity market. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.
Source: Bivios and The Superpower Institute

A green iron project also offers a large, flexible source of renewable energy for the electricity market. At high prices, which encourage producers to sell renewable energy and reduce production, a green iron project contributes to the electricity supply and consumers benefit from lower prices.

High peak prices in an electricity market are a potential source of profits. Because profits from the electricity market effectively lower the average cost of producing green iron, they encourage additional investments in renewable energy, with green iron projects helping to meet long-term demand.

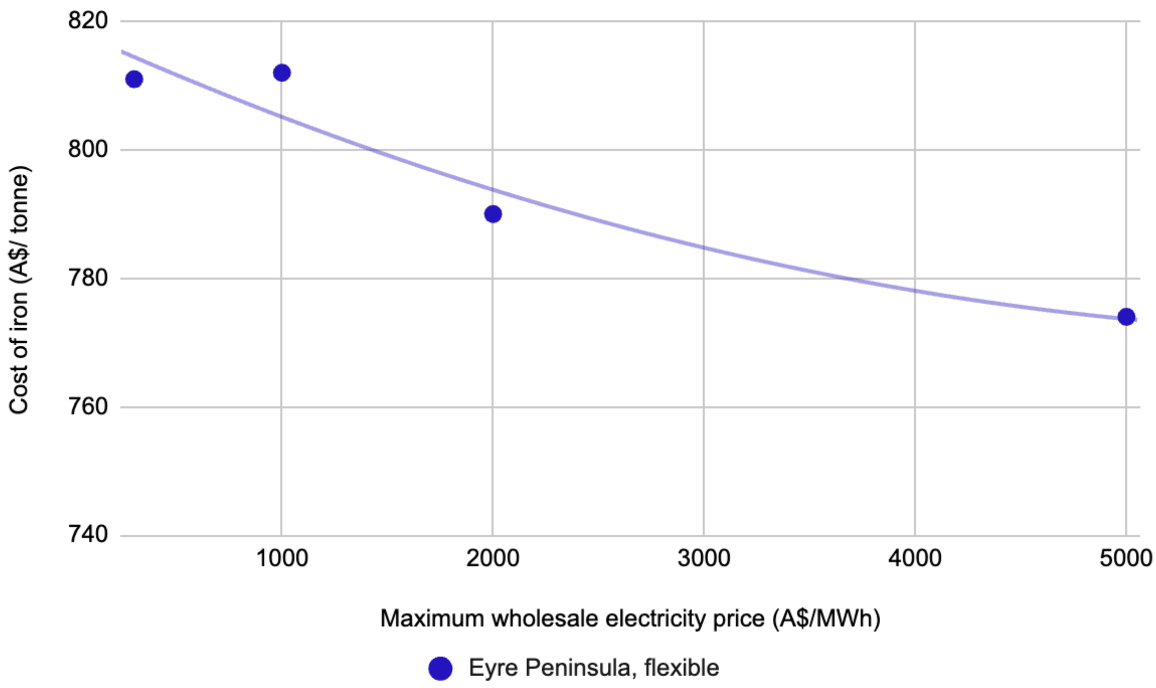

Figure 11: Higher peak electricity prices effectively reduce the cost of iron

Notes: 'Peak prices' refers to the wholesale electricity price. Electricity prices were capped at different levels to model the effect on the average cost of iron. Wholesale electricity prices are hourly NEM spot market prices for the same years as the solar and wind data input into the model at each location. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.

Source: Bivios and The Superpower Institute analysis

As green industries grow, and as price variation in electricity markets moderates, opportunities to sell renewable energy at high prices and buy electricity at low prices will be reduced. This will weaken the incentive to connect to the grid for this purpose.

The pace at which price variation is reduced will depend on the relative share of variable renewable energy in the market – which will increase variation – versus the share of storage in the form of batteries, which will reduce variation. While these trends are hard to predict, large-scale renewable energy generators that enter the market strategically, alongside green producers that can ramp production up and down, will increase grid reliability.

Results from our model also demonstrate how green hydrogen and iron producers get particularly large benefits from grid connections when the grid has a large share of renewable energy generation. The low cost of producing green iron in the Eyre Peninsula is partly because 75 per cent of South Australia's electricity is from renewable sources.[110] This makes it possible to buy larger quantities of electricity from the market without exceeding the carbon intensity limits of the Hydrogen Production Tax Incentive (HPTI). In a modelled, hypothetical example of green iron production in the Eyre Peninsula, the cost increases with the carbon intensity of the grid (Figure 12).

[110] Climate Council, 'South Australia and Australia's Race to Renewables'; Open Electricity, South Australia'.

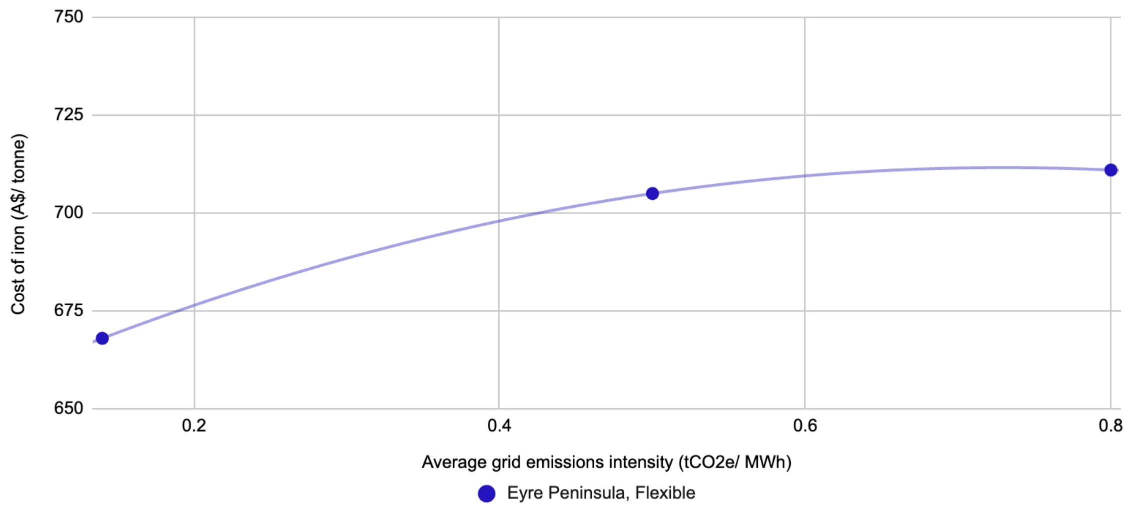

Figure 12: The cost of green iron is lower when producers are connected to an electricity grid with lower carbon intensity

Notes: We model a hypothetical scenario varying grid intensity for a green iron producer in the Eyre Peninsula, using flexible technology. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.

Source: Bivios and The Superpower Institute analysis

The addition of large-scale renewable energy to existing energy markets, installed to support green hydrogen and green iron production, will contribute to the goal of decarbonising Australia's energy system.

4.3 Innovative technologies and increased use of green technologies will help make green iron competitive with carbon-intensive iron

Green iron production will motivate the development of new technologies that reduce the cost of production while using variable renewable energy. Our model only includes two green iron technologies, but clearly demonstrates the benefits of flexible green iron production being used alongside flexible hydrogen production.[111]

In all locations, flexible technology achieves a lower cost of green iron per tonne. The average variation in the cost of iron production between the inflexible and flexible technology types is illustrated in Figure 13.

[111] We model hydrogen production with a proton exchange membrane (PEM) electrolyser. See Appendix 7 for further detail on model inputs.

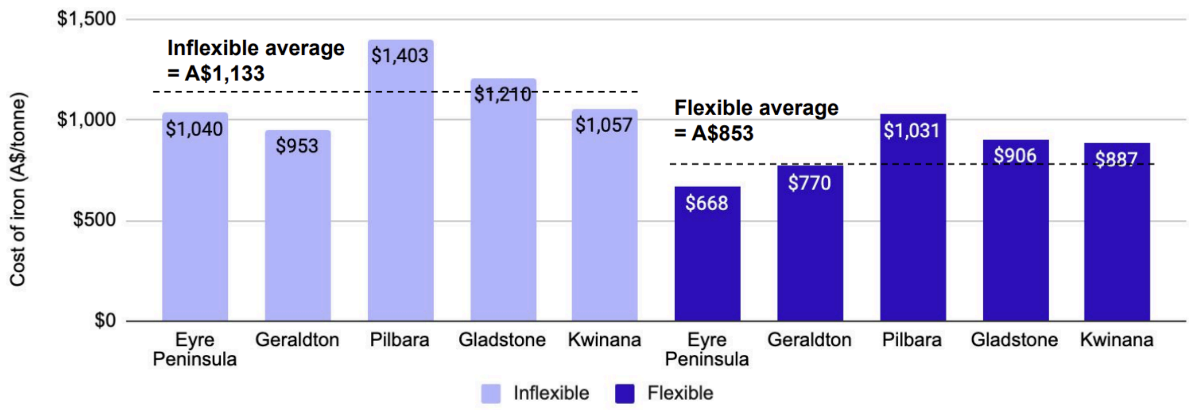

Figure 13: The use of flexible iron-making technology can reduce the average cost of iron production.

Notes: 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously. Source: Bivios and The Superpower Institute analysis.

The two benefits of a flexible technology are:

1. Green hydrogen is not required 100 per cent of the time. Achieving a 100 per cent supply of green hydrogen requires sufficient low-emissions electricity to be available, combined with electricity and hydrogen storage. This can lead to higher capital costs, which drive up the cost of iron (Figure 14).
2. A flexible green iron technology provides more scope for the hydrogen electrolysers to operate flexibly. This enables a producer to shut down electrolysers and sell energy to an electricity market when prices are high.

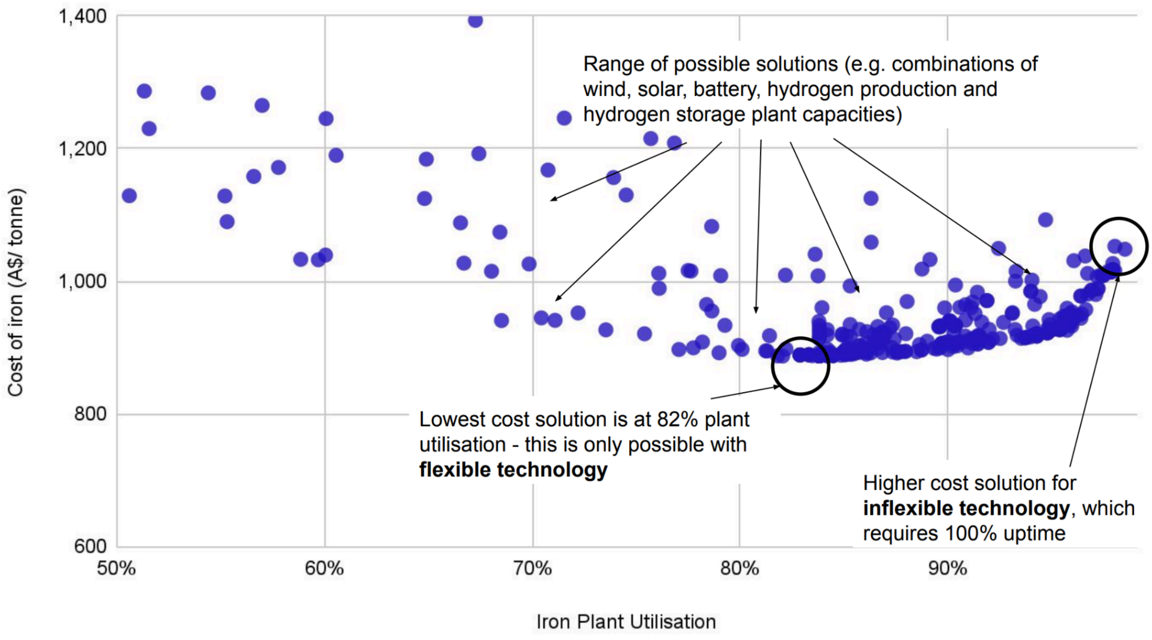

Figure 14: Inflexible technologies require 100 per cent iron plant utilisation, driving up the cost of green iron

Notes: Each point represents the cost of green iron based on different investment combinations in renewable energy, storage, hydrogen production, and hydrogen storage. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.

Source: Bivios and The Superpower Institute analysis

Our model does not capture the benefits of flexible technologies that do not rely on green hydrogen, such as green iron electrolysis, but we expect similar benefits.

If the costs of flexible technology are much higher than our assumptions, the benefits of flexible production will be reduced or lost. Information on the capital costs of emerging iron-making technologies is very limited, and we have assumed that the flexible technology has a 20% higher capital cost for the iron-making plant.

But even if the cost of flexible technology is higher than our assumptions, cost reductions will emerge as green technologies are deployed and produced at scale.

Our model finds that, on average, capital expenditure represents more than sixty per cent of the cost of producing green iron. This includes the cost of renewable energy generation and storage technologies, green hydrogen technology, and green iron-making technology. Hydrogen storage and distribution costs will also affect the rate of green iron cost reductions.[112]

The cost of technology typically falls when it is produced in large volumes, with costs falling as the number of units increases and as production technology is improved through time.[113] Solar and wind technologies have already benefited from decades of production. The cost of installed wind projects fell about 70 per cent between 1983 and 2022,[114] while the cost of land-based wind fell 60 per cent

[112] Shafiee and Schrag, 'Carbon Abatement Costs of Green Hydrogen across End-Use Sectors'.

[113] 'Wright's Law'; see Wright, 'Factors Affecting the Cost of Airplanes'; Roser, 'Learning Curves'.

[114] US projects, on a capacity-weighted average basis, from USD4,804/kW to USD1,370/kW. Analysis of Wiser et al., 'Land-Based Wind Market Report: 2023 Edition'; Center for Sustainable Systems, 'Wind Energy Factsheet'.

between 2012 and 2022.[115] Since 1976, solar PV costs have fallen by more than 99 per cent (Figure 15).[116]

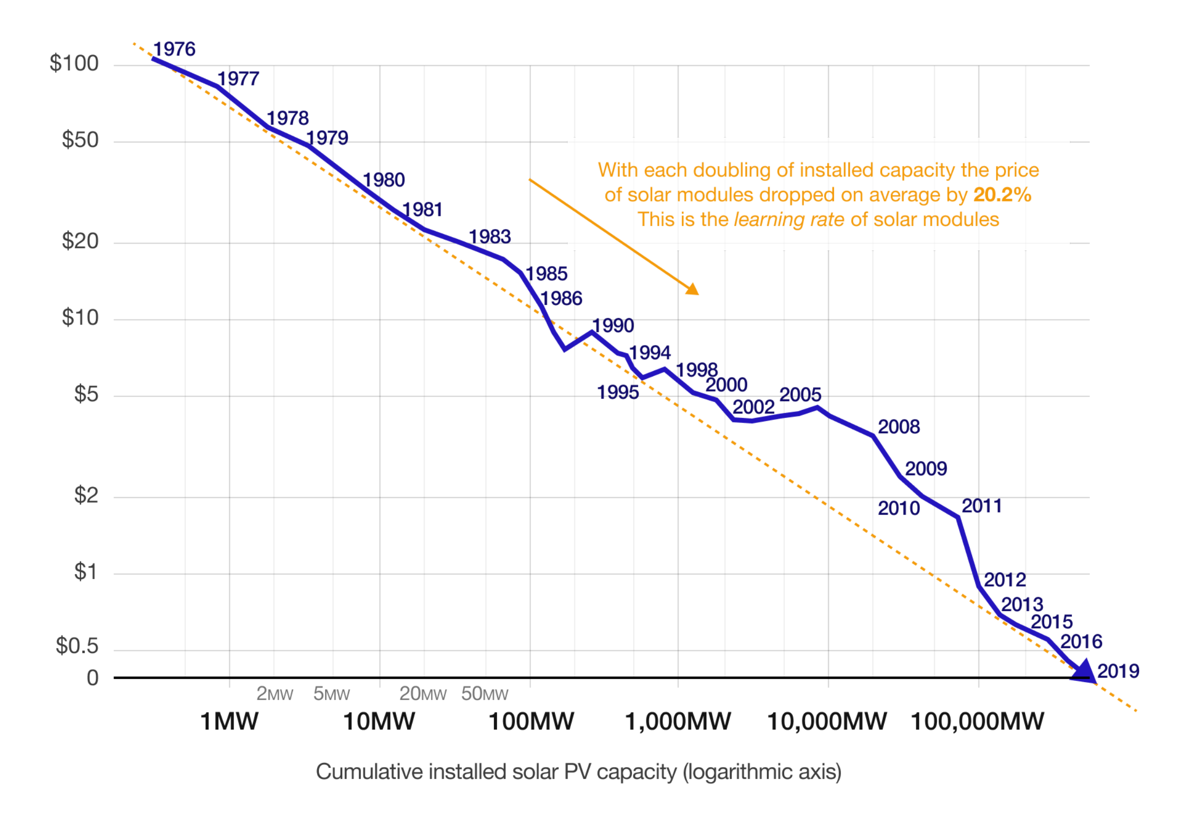

Figure 15: The cost of solar technologies has fallen 99 per cent since 1976

Notes: Prices are adjusted for inflation and in 2019 US$
Source: Roser (2020)[117]

Technologies for firming renewable energy are much younger, but costs are already falling.

Between 2013 and 2024, the average price of lithium-ion cell batteries fell 85 per cent.[118] Australian estimates suggest the price of two, four, and eight-hour batteries has fallen 13, 11, and 14 per cent from 2019 through to 2023, respectively.[119] The largest year-on-year reductions were reported in the most recent 2024-25 GenCost Draft Report, with the cost of eight-hour batteries falling 38 per cent year-on-year to 2024.[120] Rapid cost reductions are expected to continue, with prices forecast to fall

[115] Based on a levelised cost of energy (LCOE) of USD$32/MWh in 2022: Analysis of Wiser et al., 'Land-Based Wind Market Report: 2023 Edition'; Center for Sustainable Systems, 'Wind Energy Factsheet'.

[116] IEA, 'Evolution of Solar PV Module Cost by Data Source, 1970-2020.'

[117] Roser, 'Why Did Renewables Become so Cheap so Fast?'

[118] Although the cost of installing energy storage technology in the United States did not change substantially between 2015 and 2022, levelised construction costs per kW are based on aggregate installation of battery storage. The average construction cost of battery storage in the United States was US$1,120/kW and US$1,205/kW in 2015 and 2022, respectively - figures adjusted to USD 2022: EIA, 'Construction Cost Data for Electric Generators'; Parkinson and Hill, '"Mind Blowing:" Battery Cell Prices Plunge in China's Biggest Energy Storage Auction'.

[119] Breakdown of 2-, 4-, and 8-hour battery storage was first reported in 2019; see Graham, Hayward, and Foster, 'GenCost 2024-25: Consultation Draft', 81.

[120] To $344/kWh in 2024: Graham, Hayward, and Foster, 81.

another 13 per cent by 2030, and 30 per cent by the middle of the century.[121] And as storage technologies mature, the cost of firm renewable energy is expected to fall by about one and a half per cent each year through to 2030, from $122 in 2023 to $109 per MWh.[122]

Hydrogen electrolysers have not yet enjoyed the cost reductions that come with widespread use, technological advancement, and economies of scale. Sales are growing from a low base.[123]

Until 2020, hydrogen electrolyser cost reductions in the range of 74 to 78 per cent were expected by 2030, and a 87 to 93 per cent reduction by 2050.[124] But between 2022 and 2024, the cost of installing electrolysers actually rose 57 per cent,[125] due to rising material costs, supply chain constraints in the aftermath of COVID, and increased demand for limited production capacity.[126] And recent experience shows that green hydrogen production systems are more complex than originally expected.[127]

The most recent forecasts are for more modest cost declines of 21 to 37 per cent between 2024 and 2030, and further reductions between 43 and 70 per cent between 2040 and 2050. Like other modular technologies, electrolysers will get cheaper over time, even if the pace is uncertain.

Improvements in the quality of green technologies, as well as reductions in price, will also help drive down the cost in green iron. For example, electrolysers will get more efficient, producing more green hydrogen with the same amount of renewable energy.

The cost of producing green iron will be reduced by the combination of technological innovation and larger-scale production of equipment. This will help make green iron competitive with carbon-intensive iron products.

4.4 Common-user infrastructure reduces the cost of green iron within a green production site

This section addresses findings from our modelling relating to common user infrastructure for producing renewable energy, green hydrogen, and green iron. Our policy recommendations for dealing with common user infrastructure are detailed in section 5.2.

Examples of common user infrastructure include energy transmission that connects many producers to established grids, and shared hydrogen storage and transport.

Transmission constraints can limit the potential benefits of connecting to electricity markets. For example, our modelling shows that constraining the size of the grid connection for a producer on the Eyre Peninsula will limit their opportunity to sell renewable energy into the wholesale market, increasing the costs they need to recover from green iron buyers.

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[121] A 30 per cent reduction from 2024 prices, to $225/kWh mid-century: Graham, Hayward, and Foster, 78.

[122] An average annual rate of 1.6 per cent, based on levelised cost of electricity, with 90 per cent of electricity provided by solar PV and wind generation with firming. The 2030 price is estimated to fall between $89 and $128 in 2030; $109 is the mid-point between estimates: Graham, Hayward, and Foster, ‘GenCost 2023-24: Final Report’, 92.

[123] IEA, ‘Global Hydrogen Review 2023’.

[124] Reductions from the 2019 baseline of $3510 per kilowatt: Graham et al., ‘GenCost 2020-21: Final Report’, 77.

[125] ETN, ‘GH2 Hurdle: Electrolyzer Costs Have Jumped 50 Percent, Warns BloombergNEF’.

[126] IRENA, ‘Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal’; Badgett et al., ‘Updated Manufactured Cost Analysis for Proton Exchange Membrane Water Electrolyzers’.

[127] Ramboll, ‘What Will It Take to Reduce CAPEX in Green Hydrogen Production?’

For the inflexible technology, which needs to operate 100 per cent of the time, constraining the size of the grid connection increases the scale and cost of investments in solar power, wind power, batteries, and hydrogen storage. A grid connection of less than 500 megawatts (MW) increases the effective cost of green iron from about $1000 per tonne to more than $1200 if the connection is constrained below 200 megawatts.

For the flexible technology, constraining the grid connection reduces the opportunity to profit from buying and selling electricity into the wholesale market. These profits can help offset the cost of producing green iron. By restricting the opportunity to profit, a constrained grid connection increases the effective cost of producing iron. Again, the benefits of grid connection are substantial (Figure 16).[128]

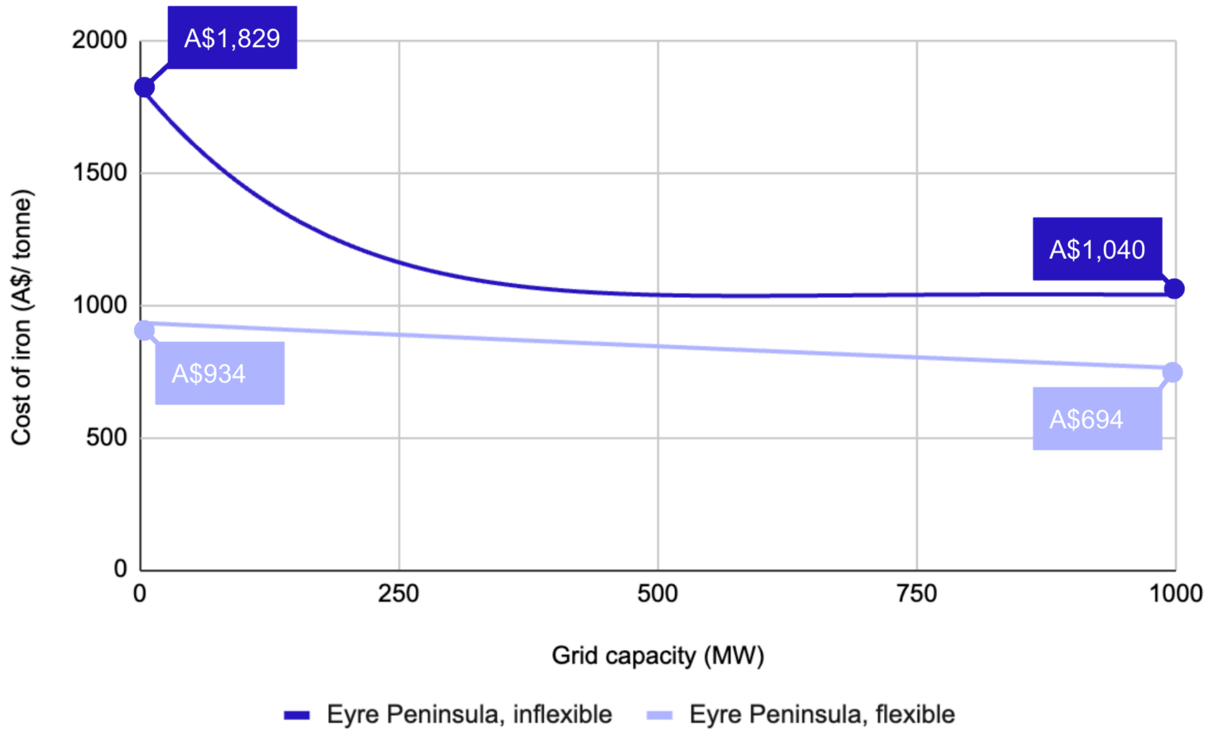


Figure 16: Constraining the size of a grid connection limits the benefits of connecting to a wholesale electricity market, increasing costs that need to be recovered by green iron producers

Notes: Based on modelled costs for renewable energy, green hydrogen, and green iron production in the Eyre Peninsula. ‘Flexible’ technology can be ramped up and down. ‘Inflexible technology’ needs to produce continuously.
Source: Bivios and The Superpower Institute analysis.

Common-user infrastructure for storing and transporting hydrogen will also reduce the cost of production.

Hydrogen storage is a relatively expensive component of production costs. When less hydrogen storage is available, this drives up the cost of producing green iron with an inflexible technology,

[128] The cost of additional grid connection capacity is not included in our model.

because larger investments in renewable electricity generation are required to make sure enough hydrogen is available for continuous iron-making (Figure 17).

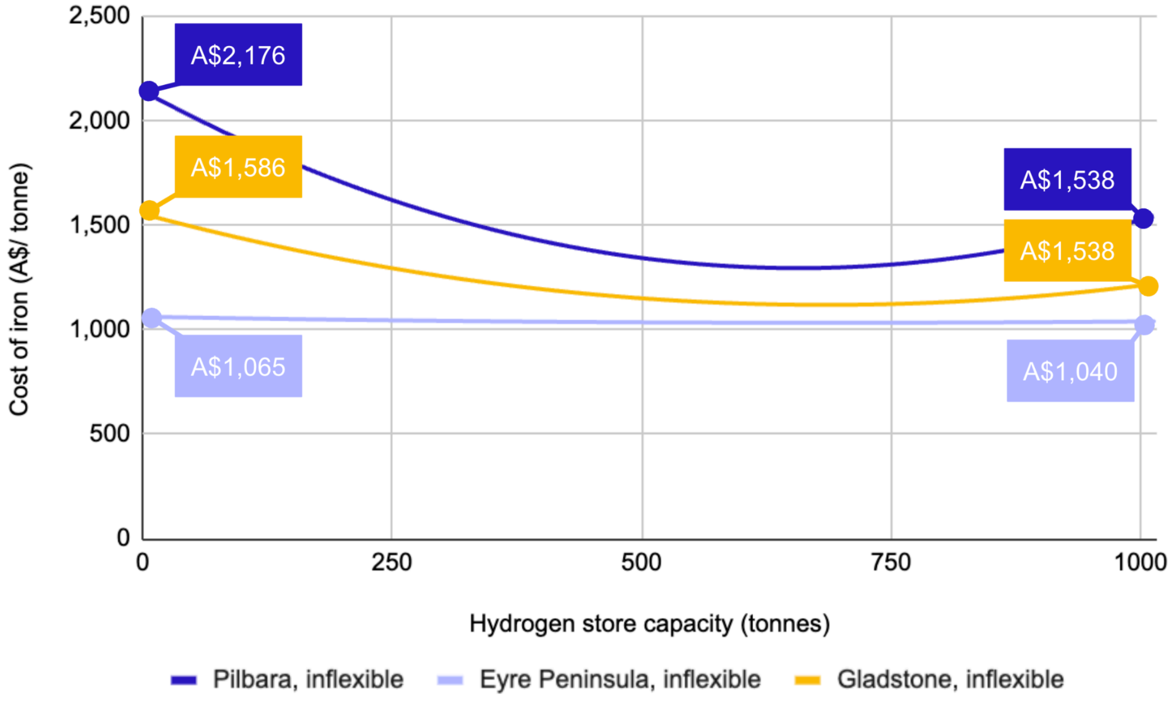


Figure 17: Larger hydrogen storage reduces the cost of iron for inflexible technologies

Notes: 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.
Source: Bivios and The Superpower Institute analysis

Hydrogen storage constraints do not have the same effect when flexible technology is used, because a constant supply of hydrogen is not required to maintain constant production.

Fresh water is important for producing hydrogen and iron, but it is relatively low cost and not an economic barrier to producing green iron. In our model it represents 0.1 to 0.14 per cent of the total cost of green iron (Figure 7).[129]

4.5 The lowest cost sites for renewable energy and green hydrogen production may be far away from iron ore deposits

Some green iron projects will include producers of renewable energy, green hydrogen, and green iron, all in a single location and close to significant iron ore deposits. This makes sense where those sites also have good, low-cost renewable energy.

However, as our modelling shows, the region with the largest iron ore deposits in Australia, the Pilbara, also has the highest costs of production of green iron. This is mostly due to the capital costs of building renewable energy and electrolyser capacity in the Pilbara.

[129] This includes the cost of a reverse osmosis plant to supply electrolysers and the iron making facility, water storage, pipework and pumping to distribute water between co-located facilities.

Green iron production costs could be lowered by producing renewable energy and green hydrogen in one location, and then green iron in a different location. In Section 5.2.1, we describe and recommend a hydrogen certificate scheme that would make this possible, by allowing green iron producers to virtually 'use' green hydrogen produced in another location.

To demonstrate the benefits, we consider a hypothetical scenario.

We model the cost of producing renewable energy and green hydrogen in Leigh Creek, South Australia,[130] and consider the cost of producing green iron with this green hydrogen in the Pilbara. We compare these costs with our original estimates of the cost of producing green iron in the Pilbara, using green hydrogen produced in the same region.

Clearly, the infrastructure for transporting hydrogen from South Australia to the Pilbara does not exist, and would be prohibitively expensive to build. This is why we recommend a certification scheme supporting virtual green hydrogen 'swaps': to harness the benefits of cost differentials in different locations.

Compared to the cost of using green hydrogen produced in the Pilbara, the cost of producing green iron with inflexible technology would decrease by nearly 25 per cent: from $1403 to $1043 using a hydrogen swap. The cost of producing green iron with flexible technology would also decrease by more than 20 per cent, from $1031 to $815 using the hydrogen swap (Figure 18).

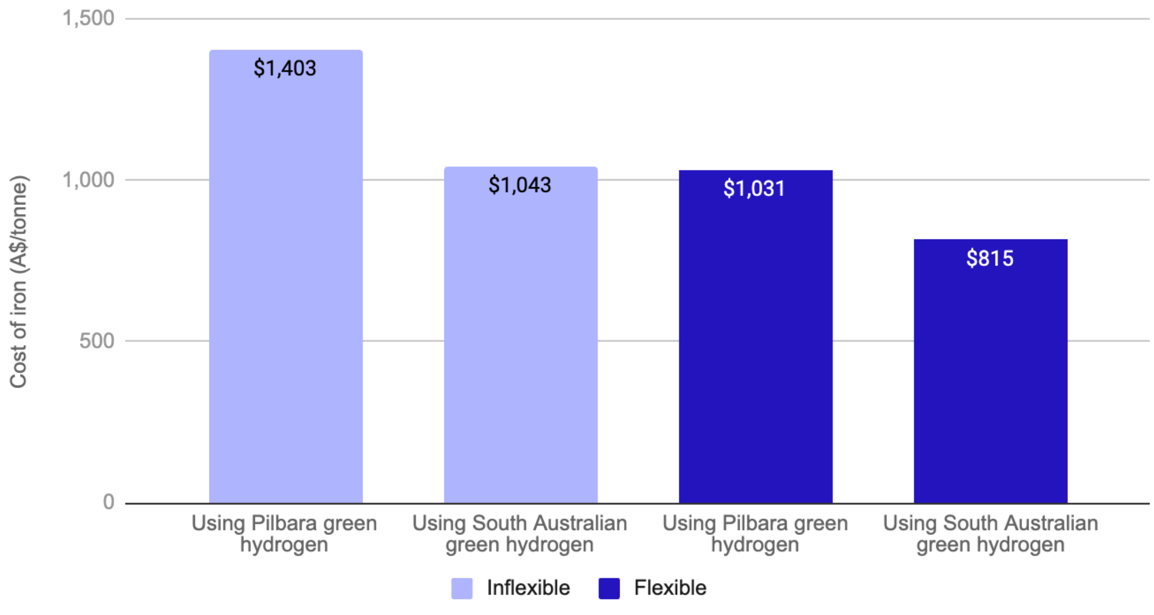


Figure 18: The cost of producing green iron in the Pilbara would be lower using green hydrogen produced in South Australia

Notes: We model the cost of producing renewable energy and green hydrogen costs in Leigh Creek, South Australia. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.
Source: Bivios and The Superpower Institute analysis

[130] While this location may not be the lowest cost site in Australia for green hydrogen production, those costs are much lower than in the Pilbara.

4.6 Early producers face higher costs but create knowledge that benefits later producers

The results presented in Chapter 3 are for an established green iron industry,[131] where early-project risks and costs do not affect the cost of production.

But early producers face a higher cost of capital – the cost of borrowing – reflecting greater risks to their project that come from ‘learning by doing’. They also face higher costs of building capital assets, because manufacturers of equipment that embody new technologies are also learning how to deliver and manufacture their product at low cost.

We model ‘first-of-a-kind’ (FOAK) costs by adjusting the weighted average cost of capital, and the costs of building capital assets for new green iron-making and electric smelting technologies (Table 4).

Table 4: Adjustments to capture first-of-a-kind costs

Model input	**Adjustments for first-of-a-kind production**	
	Inflexible technology	Flexible technology
Weighted average cost of capital[132]	+ 1.5 %	+ 1.8 %
Capital cost of iron-making plant	+ 12.5 %	+ 27.5 %
Capital of the electric smelting furnace	+ 12.5 %	+ 12.5 %

First-of-a-kind costs are reflected in the per-tonne cost of green iron. Although we report single estimates for FOAK costs, they are by definition uncertain, and we use our results to demonstrate how FOAK costs will vary by location and technology type, reflecting different patterns of capital investment and different costs of capital.

Based on our model, for example, for producers using flexible technology in South Australia’s Eyre Peninsula, first-of-a-kind costs increase the cost of green iron by $62 per tonne, equivalent to a ten per cent increase. For producers using inflexible technology in the Pilbara, costs increase by $421 – about 30 per cent.[133] First-of-a-kind producers who opt for flexible technology in the Pilbara incur a smaller cost increase of $168, but this still represents an increase of about 15 per cent (Figure 19).

[131] This is sometimes referred to as “Nth-of-a-kind” production, where “N” is larger than the first several producers.

[132] For locations connected to wholesale energy markets the WACC increase is not applied to electricity system components; the green iron project risk is lower for these system components as we assume electricity could be sold to other buyers. In the Pilbara the WACC increases for electricity system components; only green hydrogen and iron plants can buy electricity so renewable energy investments share the project risk profile.

[133] This large increase is partly because we apply a higher cost of capital to early-producer renewable energy investments in the Pilbara, reflecting greater off-take risk; see Appendix 7 for details on inputs.

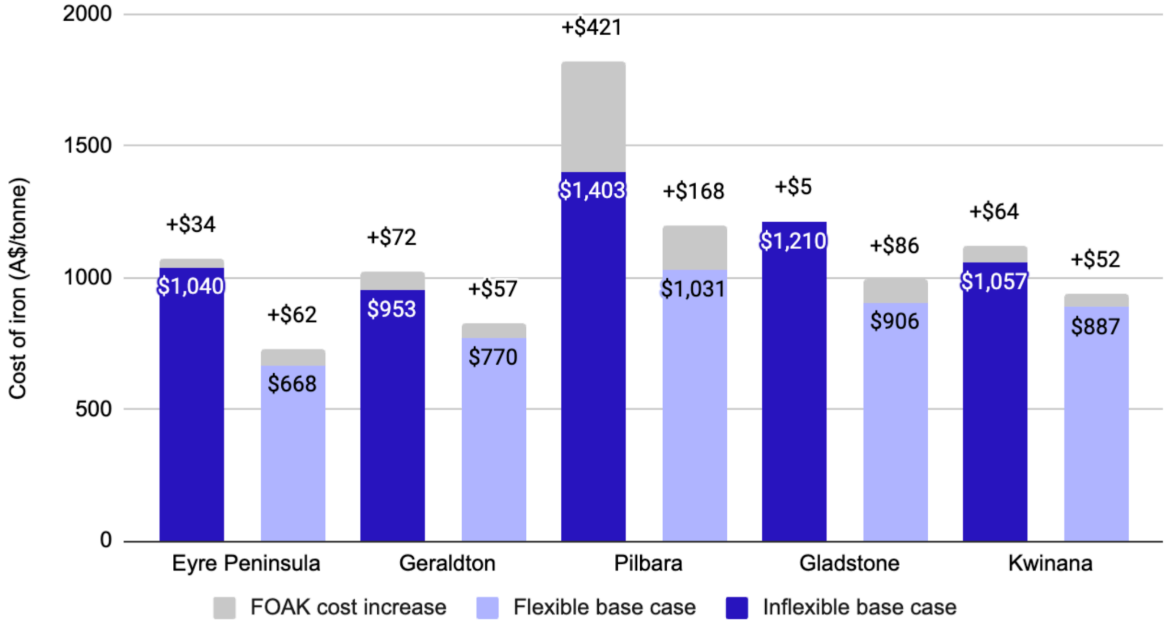


Figure 19: First-of-a-kind projects will have higher production costs for green iron

Notes: Differences in first-of-a-kind cost increases reflect differences in the lowest-cost combination of capital investments. The lowest-cost combination of investments is optimised based on a producer's location, cost of capital, and technology choice.

Source: Bivios and The Superpower Institute

In practice, these 'first-of-a-kind' costs may apply to a few early producers, if there is not enough time to benefit from the experience of the first producer. Early producers will encounter unforeseen challenges not considered in this model and not anticipated by other market participants. Early producers, therefore provide a valuable service: they reveal real-world information and deliver lessons in market development, in project design and implementation. Later producers can use this knowledge to achieve lower costs of green-iron production.

4.7 Using gas rather than green hydrogen lowers costs but increases emissions

As described in Chapter 2, natural gas can be used as a reductant used in DRI iron-making processes. Green iron uses green hydrogen instead. Based on location-specific gas costs,[134] it is currently cheaper to produce iron with natural gas than green hydrogen, but doing so increases carbon emissions. Natural gas can also be used as a source of power, with gas turbines 'firming' the supply of energy from renewables or from a connected electricity market.

We model costs and emissions intensity under two scenarios: when gas is used to firm power, and when gas is used to both firm power and be used as a reductant.

[134] We model natural gas costs based on ACIL Allen industrial gas forecasts for capital cities (Adelaide, Brisbane, Perth), which are also used in AEMO's 2025 Gas Statement of Opportunities. We adjust for location with transport costs. Prices are Eyre Peninsula $12.89; Pilbara $9.15; Geraldton $9.05; Kwinana $9.45; Gladstone $13.42. See Appendix 7 for details.

If gas is used to firm power in an off-grid location, it increases emissions intensity relative to a system powered exclusively by renewable energy. If gas is used to firm power in a location connected to an electricity grid, there is only a small increase in emissions intensity. The resulting increase in emissions is limited if producers minimise gas use to meet the requirements of the green Hydrogen Production Tax Incentive (HPTI): 600 kg of carbon dioxide per tonne of hydrogen.

When gas is also used as a reductant, displacing green hydrogen, the HTPI emissions constraint will not be met, and the emissions intensity of iron is much higher.

We also model the effects of a carbon price to evaluate its effect when producers use gas to firm power and as a reductant.

We use a price of $155 per tonne of carbon dioxide, based on forecast prices in the EU Emissions Trading Scheme. Actual carbon prices – in Europe and in other countries – will depend on policy, but the EU price is forecast to reach between $110 and $225 per tonne in 2030, with an average forecast price of $155 (Figure 20).

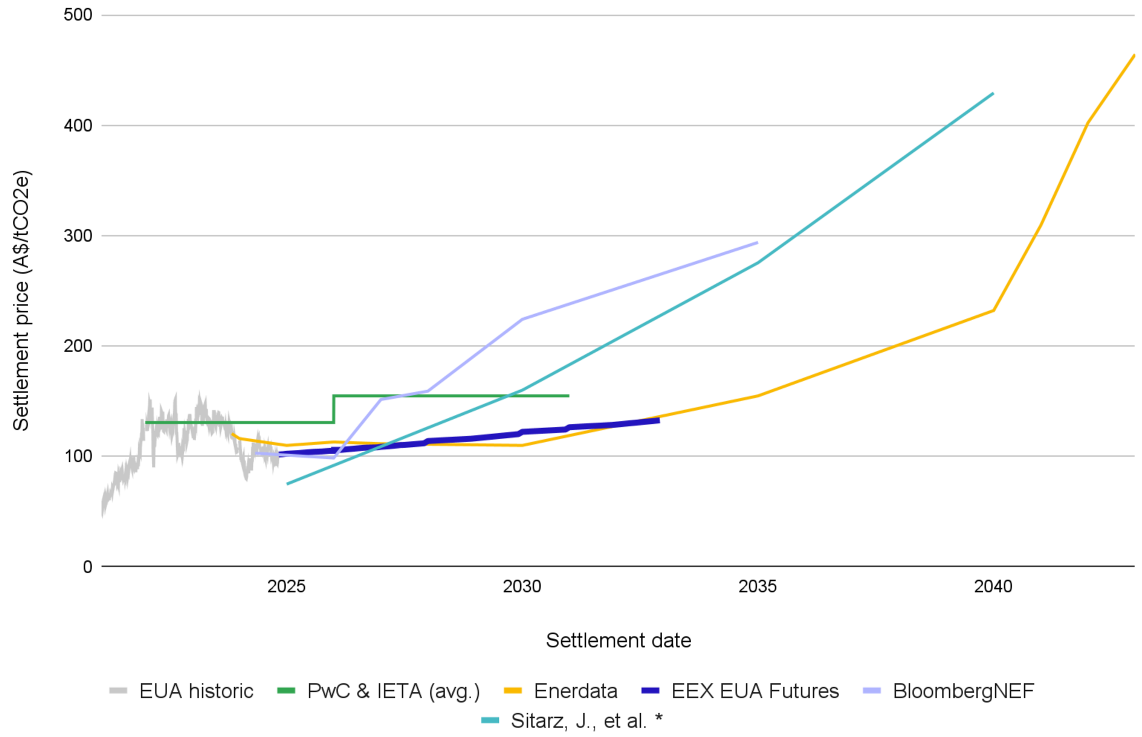


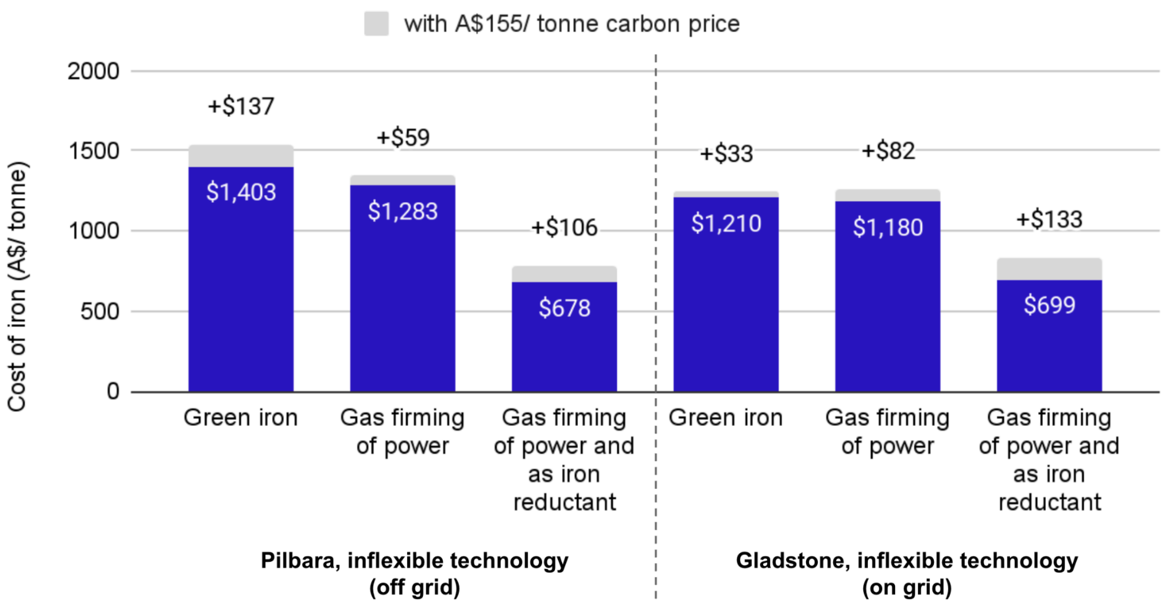
Figure 20: The EU carbon price is rising

Note: Prices originally in Euros. Prices have been converted into 2024 Australian dollars. * "Myopic foresight | fit for 55 final agreement" model.
Sources: Enerdata,[135] Sitarz, J., et al.,[136] BloombergNEF,[137] PwC & IETA,[138] EEX EUA Futures.[139]

For producers connected to a carbon-intensive electricity market, a carbon price pushes producers to increase their use of local renewable energy and to decrease the quantity of electricity they draw from the grid.

For off-grid producers, the carbon price does not change the emissions intensity of production. Based on inputs to our model, firming electricity with gas remains cheaper than expanding renewable energy capacity. This reflects the more general result that completely decarbonising off-grid production, when using inflexible green iron-making technology, is very expensive.

We illustrate these findings with results for green iron produced with inflexible technology off-grid in the Pilbara and on-grid in Gladstone. Both locations use the same ore and production processes. Electricity requirements are large because direct-reduced iron produced with Pilbara ore needs to be processed in an electric smelting furnace (ESF). In Gladstone, the carbon price pushes producers to increase renewable energy from 64% to 80% of total electricity use. In both locations, gas reduces the cost of production and increases the emissions intensity of iron (Figure 21 and Figure 22).



[135] Enerdata, 'Carbon Price Forecast under the EU ETS'.
[136] Sitarz et al., 'EU Carbon Prices Signal High Policy Credibility and Farsighted Actors'.
[137] BloombergNEF, 'EU ETS Market Outlook 1H 2024: Prices Valley Before Rally, May 2024'.
[138] IETA & PwC, 'GHG Market Sentiment Survey 2023'.
[139] EEX, 'Market Data'.

Figure 21: Using gas reduces the cost of producing iron

Notes: Both locations use the same technology and iron ore, and use an electric smelting furnace before directly-reduced iron (DRI) is processed into hot briquette iron (HBI). 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously. The carbon price is $155. Gas prices are location-specific; see Appendices 3-8 for details.

Source: Bivios and The Superpower Institute analysis

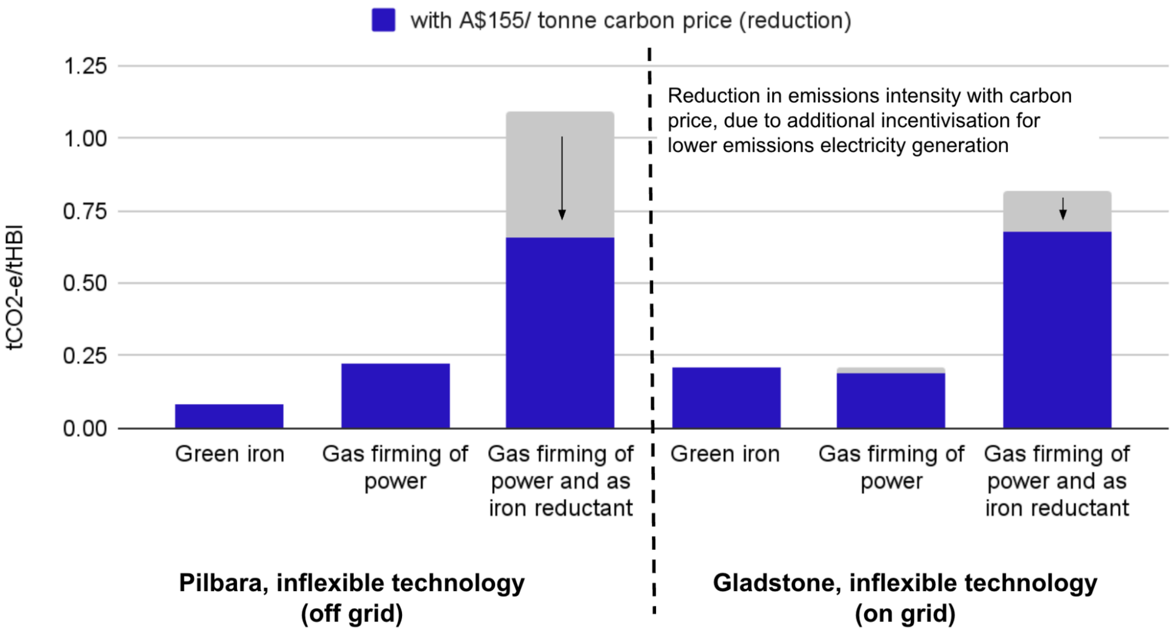


Figure 22: Using gas as a reductant substantially increases the emissions from production

Notes: Grey shaded areas show the emissions reduction if a carbon price of $155 is applied. Both locations use the same technology and iron ore, and use an electric smelting furnace before directly-reduced iron (DRI) is processed into hot briquette iron (HBI). 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.

Source: Bivios and The Superpower Institute analysis

4.8 Green iron technologies and production locations will broaden as the industry grows

Insights from our model help anticipate how an Australian green iron industry is likely to emerge and then grow.

Early producers will face 'first-of-a-kind' costs, including a higher cost of capital when borrowing, and higher 'sticker prices' for new technologies. These producers will probably use a mix of strategies to reduce these costs and risks.

They will likely build smaller-scale plants to minimise capital costs and risks and choose a location that has good access to iron ore, water, a port, and an existing electricity market. This will reduce the scale of capital and infrastructure investment early producers need to make before they can start producing green iron. A connection to an electricity market will be particularly useful, particularly if green iron is produced with a flexible iron-making technology. Variations in market prices for electricity will provide early opportunities to sell renewable energy when prices are high, helping to offset green hydrogen and green iron production costs and to effectively reduce the cost of green iron.

These early projects will create valuable knowledge that benefits later producers.

Later producers will face lower risks and a lower cost of capital. They will benefit from accumulated knowledge, ongoing technical innovation, and lower prices for existing technology. This will allow later producers to build larger projects and to benefit from economies of scale.

Later producers will also benefit less from price variation in existing electricity grids, which will decrease as large-scale renewable energy producers and green iron producers connect.

Some producers will choose to create self-contained 'island grids' for green iron production, connected to renewable energy and green hydrogen.

Others will continue to connect to electricity grids, which will contribute to reshaping the energy market, driving transmission investments in new locations and changing demand and supply patterns. Planned transmission investments in Western Australia's SWIS and NWIS are an early example, designed to support increased renewable energy supply in areas with potential for large-scale green iron industries.[140]

[140] Western Australian Government, 'Joint Media Statement - $3 Billion Rewiring the Nation Deal to Power WA Jobs and Growth'.

05

How to fix market failures and support green iron exports

Some of the insights from our model of green iron production reveal how market failures distort the market for green iron (Chapter 4).

Market failure occurs when production, trade, or consumption results in an inefficient allocation of resources. When market failure occurs, careful interventions in the market can usually improve outcomes across a society.

There are three main sources of market failure in the iron and steel market:

- **The missing carbon price:** in the absence of a system of global carbon prices, it is cheaper to produce iron with coal or natural gas – and to emit large quantities of carbon – than to produce green iron.
- **Common-user Infrastructure:** critical infrastructure for green iron has common-user and sometimes natural monopoly characteristics. This infrastructure will often be under-supplied if left to the market, resulting in under-investment and/or green iron being produced at a higher cost.
- **Positive innovation externalities:** early producers incur higher costs, but generate shared knowledge that reduces costs for later producers.

This chapter shows what federal and state governments should do to correct these market failures.

Sections 5.1 to 5.3 draw on results from our model to make recommendations on how to fix market failures and support green iron. Section 5.1 shows why existing subsidies for green hydrogen are an important, albeit second-best solution, to the missing international carbon price. Section 5.2 shows why the federal and state governments should invest in common-user infrastructure, including energy transmission, hydrogen transport, and hydrogen storage. Section 5.3 shows why the federal government should provide additional support for the first few producers of green iron.

Section 5.4 raises an issue not captured in our model: lengthy planning and approval processes are an expensive barrier to green industry projects. Australia's comparative advantage in green exports justifies state and federal government policies and programs that significantly reduce uncertainty and delays.

5.1 Policies that correct for the missing carbon price will help green iron compete on a level playing field

5.1.1 Carbon pricing would remove a distortion and level the playing field

The market for green iron is distorted by the missing carbon price – the lack of an international system of carbon prices that reflect the social cost of carbon (Box 5).

Box 5. The social cost of carbon

The price of carbon should reflect the 'social cost' of carbon:[141] the cost of long-term damage inflicted by a tonne of carbon, and therefore the long-term benefit of abating a tonne of carbon.[142]

The international community has agreed that damage inflicted by carbon emissions should not exceed the damage from global warming of 2 degrees Celsius above pre-industrial levels; the community has also agreed that warming should be held as close to 1.5 degrees Celsius as possible. This requires rapid carbon reductions and net-zero emissions by the middle of the century.[143] The required carbon price is one that reflects the social cost of carbon and achieves net-zero in 2050.

If producers and consumers do not pay the social cost of carbon, people will collectively emit more carbon, and do more damage, than the damage associated with 1.5 degrees – or even 2 degrees – of global warming.

On the supply side of the iron and steel market, international carbon prices would push up production costs in proportion to carbon intensity. The missing international carbon price has the same effect as a subsidy for carbon: carbon-intensive steel is cheaper than it should be, because steel-making costs do not include the social cost of carbon.

Until there is a system of international prices that reflects the social cost of carbon, the goal of government support should be to simulate the outcome of carbon pricing.

The missing carbon price distorts the market for iron

The missing carbon price is a market failure which distorts global trade in iron, creating an inefficient advantage for fossil-fuel based production.

[141] Garnaut, *The Superpower Transformation: Building Australia's Zero-Carbon Future*.

[142] These costs and benefits accumulate through time. A discount rate is applied to future costs and benefits, and the social cost of carbon is reported as a present-day value. OECD, 'Cost-Benefit Analysis and the Environment: Further Developments and Policy Use'.

[143] Meinshausen et al., 'Realization of Paris Agreement Pledges May Limit Warming Just below 2 °C'.

There is a small international market for coal-based pig iron and fossil fuel-based HBI, which are potential competitors for green iron.[144] Both can be processed into steel in electric arc furnaces,[145] and in basic oxygen furnaces.[146]

Prices vary substantially depending on the country of import, but the HBI price is between $345 and $712 per tonne, with a 5-year weighted average price of $554.[147] The price for pig iron typically sits between about $690 and $924, with a 5-year weighted average price of $779 (Figure 23 and Figure 24).[148]

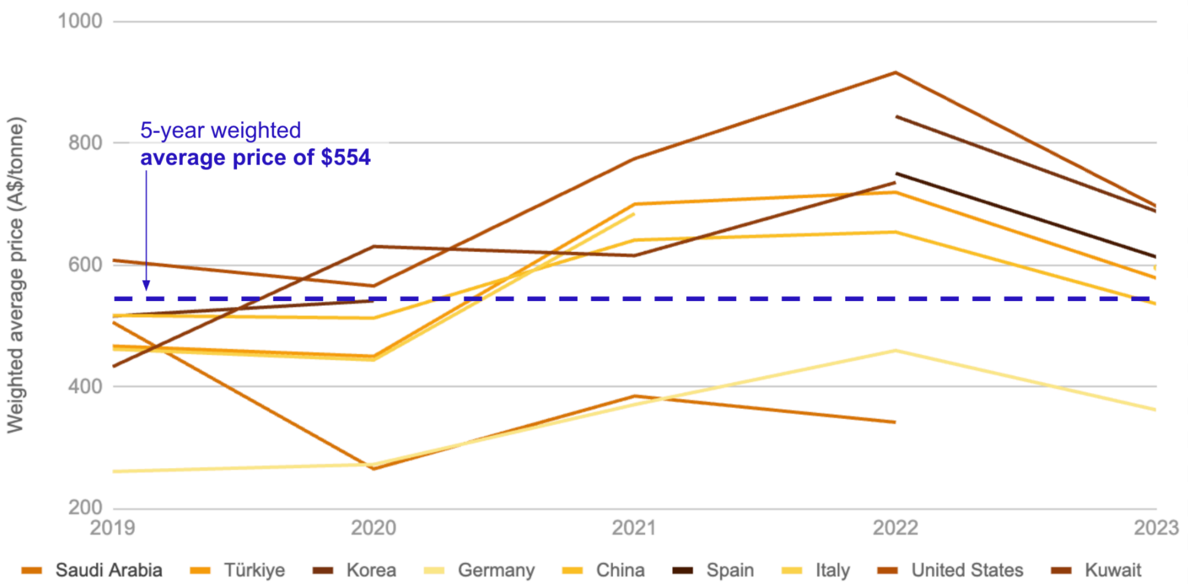


Figure 23: The price of hot briquetted iron for major importers

Notes: Prices are in 2024 Australian dollars. Top 10 importing jurisdictions by trade value of ferrous products obtained by direct reduction.

Source: World Bank Integrated Trade Solution Datasets[149]

[144] Fossil fuel-based HBI can be produced with coal or natural gas.
[145] Net Zero Stratford, 'You Asked – Electric Arc Furnaces'.
[146] IIMA, 'The Use of Hot Briquetted Iron (HBI) in the Basic Oxygen Furnace (BOF) for Steelmaking'.
[147] There is an average difference of about $155 between pig iron and direct reduced iron: World Bank Data.
[148] World Integrated Trade Solution (WITS), 'Data on Export, Import, Tariff, NTM'.
[149] WITS, 'Ferrous Products Obtained by Direct Reduction of Imports by Country 2023'.

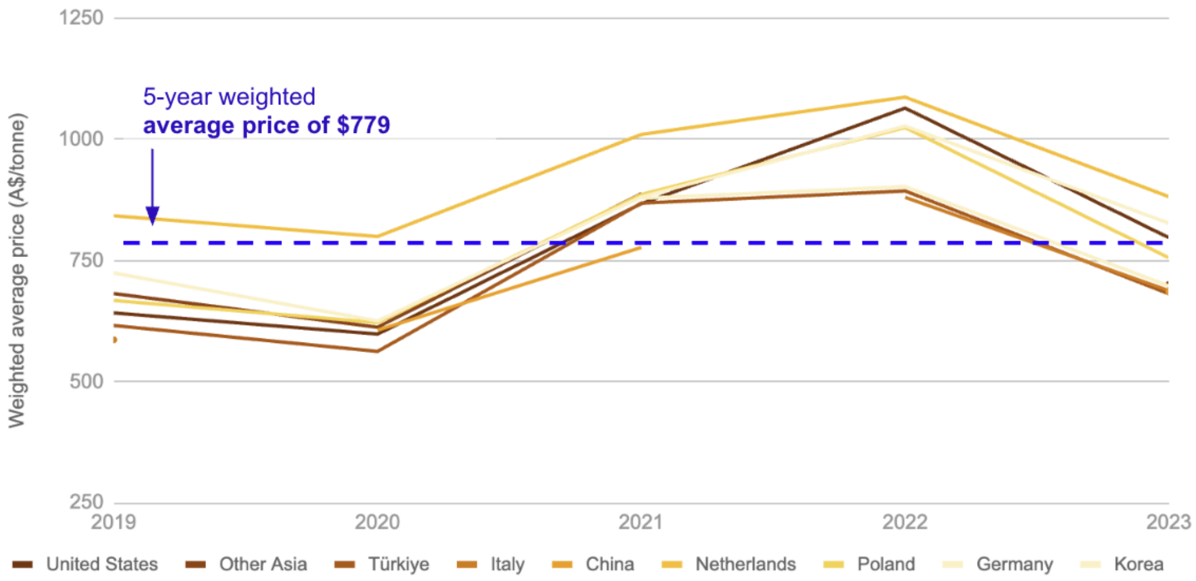


Figure 24: The price of pig iron for major importers

Notes: Prices are in 2024 Australian dollars. Top 10 importing jurisdictions by trade value of pig iron, non-alloy, containing less than 0.5% phosphorus.
Source: World Bank Integrated Trade Solution Datasets[150]

The most widely used carbon-intensive iron is produced in the integrated BF-BOF process, which produces finished steel at around $640 per tonne.[151] We use $400 as an illustrative price for a tonne of iron produced in the blast-furnace process for immediate use in a basic oxygen furnace.

When iron and steel producers do not pay the social cost of carbon emissions, the commercial cost of production understates the true cost. Carbon-intensive iron appears 'cheap' compared to green iron. The cost gap between carbon-intensive products and green equivalents is often referred to as a 'green premium.'

The cost gap means Australian producers are disadvantaged when competing with fossil-fuel based iron and steel production.

Our model suggests that green iron producers in the Eyre Peninsula and in Geraldton, using flexible technology, are the only producers who do not face a very substantial cost gap for all iron products. This does not mean there is no need for a carbon price; a carbon price addresses a distortion in the market whereby fossil-fuel based iron is cheaper than it should be.

Based on our average modelled price of about $570 for Australian gas-based DRI,[152] the cost gap with green Australian DRI ranges from nearly $100 to over $800. Using the 5-year average weighted price of $554 for international fossil fuel-based HBI, the cost gap ranges from $110 to $850. For producers in Kwinana, Gladstone, and the Pilbara, the cost gap with international pig iron is over

[150] WITS.

[151] Hot rolled band steel: Steel Benchmarker, 'Price History'. World price is USD440, converted from 1.45 AUD to 1 USD.

[152] We use the average price for this analysis, based on iron production costs using local gas prices.

$600. And with a representative price of only $400, producers in all locations face a large cost gap with pig iron produced in a blast furnace: $270 to over $1000.[153]

These estimates depend on modelled costs of production, illustrative prices for carbon-intensive iron, and prices from the small international market for traded iron. But the message is clear: when there is no carbon price, substantial cost gaps prevent green iron producers from competing with carbon-intensive iron products in most Australian locations. It is a distortion that the government should address.

A carbon price would level the playing field

If producers paid the social cost of carbon, the current market distortion would be removed and the cost gap between carbon-intensive and green iron would narrow dramatically, and close completely in some locations.

Using an average forecast of $155 per tonne of carbon dioxide,[154] the cost of producing carbon-intensive iron would increase dramatically to reflect the carbon intensity of different types of iron-making.

The cost of pig iron, produced in a blast furnace and emitting two tonnes of carbon dioxide per tonne of iron, would increase by more than $300. The cost of fossil fuel-based international DRI would increase by about $170, reflecting about 1.1 tonnes of carbon dioxide emissions per tonne of iron.[155] With average emissions of about 0.5 tonnes of carbon per tonne of iron, the cost of Australian gas-based iron would increase by about $80.

Based on results from our model, and a carbon price of $155, a producer using flexible technology in the Eyre Peninsula would be able to compete with international producers of carbon-intensive HBI, pig iron, and iron produced as part of the BF-BOF process

A carbon price would mean that producers using flexible technology in Geraldton, Kwinana, and Gladstone, or inflexible technology in the Eyre Peninsula and Geraldton, would be able to compete with pig iron traded in the international market (Figure 25).

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[153] Industry estimates from Europe suggest prices of about $760/tonne for conventional BF-BOF steel, a premium of about $190 for grey HBI-BOF steel ($950/tonne) and a premium of about $590 for green-DRI-BOF steel ($1350/tonne). Industry estimates provided in confidence. Our production cost gap is larger than industry consensus of $0 to $150 per tonne of green HBI; see Russell, 'Green Steel Needs Incentives to Work and Japan Has a Plan'.

[154] See Section 4.7 for forecast prices in the EU Emissions Trading Scheme.

[155] Emissions intensity of 1.1 tonnes of carbon dioxide per tonne of fossil-based DRI, which can be produced with coal or gas. Emissions intensity of 2 tonnes of carbon dioxide per tonne of fossil-based pig iron. BF-BOF, DRI-EAF, scrap-EAF steelmaking carbon intensity from IEEFA, 'The Facts about Steelmaking: Steelmakers Seeking Green Steel', with emissions from scrap-EAF used to infer emissions from fossil-based DRI. Adjustments to exclude emissions from BOF stage of the BF-BOF process based on Baig, 'Cost Effectiveness Analysis of HYL and Midrex DRI Technologies for the Iron and Steel-Making Industry'.

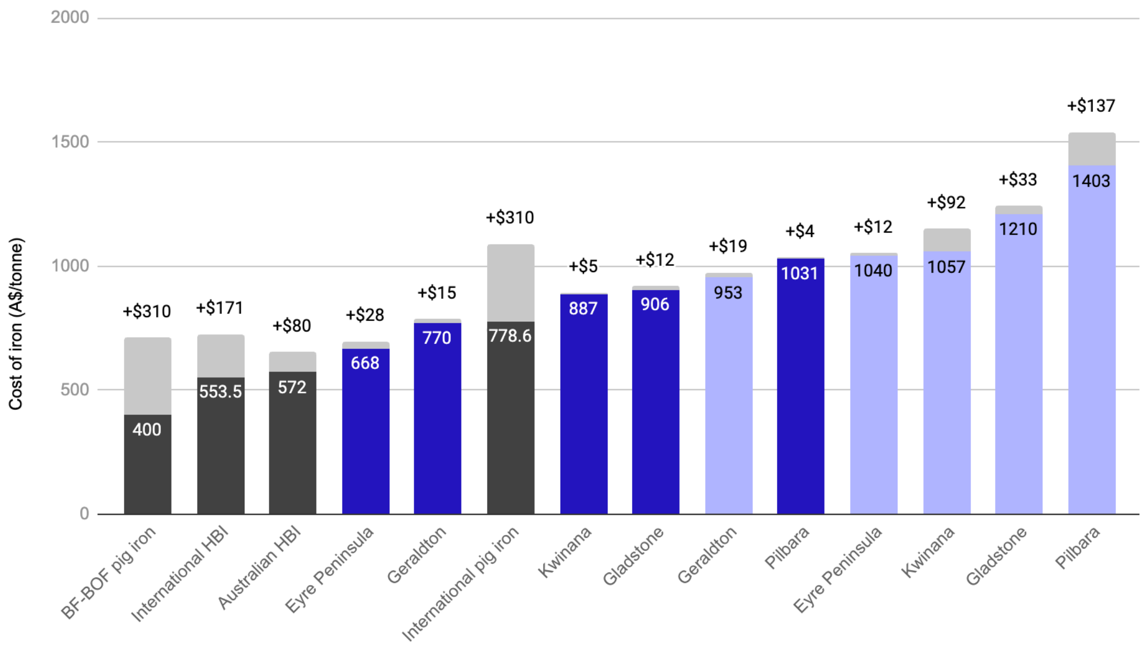

Figure 25: A carbon price would dramatically reduce the cost gap between carbon-intensive iron and green iron

Notes: Based on median costs of iron production and average price for gas-based HBI prices in Australia. Based on a carbon price of $155, consistent with forecasts for the EU market in 2030. Calculations for carbon price assume 2 tCO2e/ t pig iron, 0.518 tCO2e/ t Australian HBI, and 1.1 tCO2e/ t HBI.'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.

Source: The Superpower Institute and Bivios analysis; BF-BOF, DRI-EAF, scrap-EAF steelmaking carbon intensity from IEEFA, with emissions from scrap-EAF used to infer emissions from fossil-based DRI. Adjustments to exclude emissions from the BOF stage of the BF-BOF process based on Baig (2016).

As carbon prices rise to achieve net-zero, green iron and steel will become progressively more competitive in different locations across Australia.[156]

5.1.2 Subsidies can help correct for the missing carbon price

A system of international carbon prices, with carbon price adjustments at borders, would provide a level playing field for green iron and be the most efficient policy instrument. Subsidies are a second-best option, and can simulate the effect of a carbon price. Although subsidies don't make carbon-intensive iron and steel more expensive, as a carbon price would, they correct relative prices by reducing the cost of green iron for international buyers. Subsidies, or production tax credits, can be used to narrow the cost gap.

Subsidies are not perfect: unlike a carbon price, subsidies are relatively inflexible. They are fixed between review periods and apply uniformly to all producers. They can encourage rent-seeking, and it can be politically difficult to remove or reduce subsidies. And importantly, unlike a carbon tax,

[156] SteelConsult finds that European green iron could be cost-competitive with carbon-intensive iron by 2035 at a carbon price of about AUD 240 per tonne. Industry estimates are provided in confidence: Confidential Industry Estimates, 'SteelConsult International'; CRU is less optimistic, and finds that green iron needs a carbon price closer to $450 per tonne in 2030 to be cost competitive: CRU, 'Steel Decarbonisation: How Will Green Steel Be Priced?'

subsidies do not raise revenue; instead, they impose a cost on governments. But subsidies are the second-best alternative, and preferred over other policy instruments, for two reasons.

The first is that subsidies do not require direct government involvement in green iron production or purchases. Government policies should correct market failures and allow the private sector to invest in green iron production.

The second is that subsidies are transparent. Government expenditure and green-iron outcomes can be clearly documented to support policy evaluation, accountability, and credibility.

The Commonwealth Government's Future Made In Australia policy includes support for green hydrogen production in the form of a $2 per kilogram production tax incentive (the HPTI). This helps correct for the missing carbon price, and will reduce the cost of producing green iron by about $108 per tonne.[157] This is a good start, but it is not enough to achieve the same effects as a carbon price. Additional government support is needed.

To correct for the missing carbon price, we propose government support worth at least $170 per tonne of green iron. This support is based on the cost of carbon embedded in international fossil fuel-based DRI, at a price of $155 dollars per tonne of carbon dioxide. $170 should be the total value of support for green iron, per tonne, including the value of the green Hydrogen Production Tax Incentive (HPTI). The value of support should be adjusted to reflect the changing EU price of carbon, which will likely increase through time.

A green iron production tax credit, worth $170 including the value of the HPTI, would have a very similar effect to a carbon price. It would address the market distortion and expand the number of locations where green iron producers can compete with the international market for carbon-intensive pig iron. And, based on our model, a green iron production tax credit would mean that a green iron producer in the Eyre Peninsula can compete in the market for international and Australian fossil-based HBI, as well as competing with pig iron (Figure 26).

[157] Based on 54 kilograms of green hydrogen per tonne of green iron.

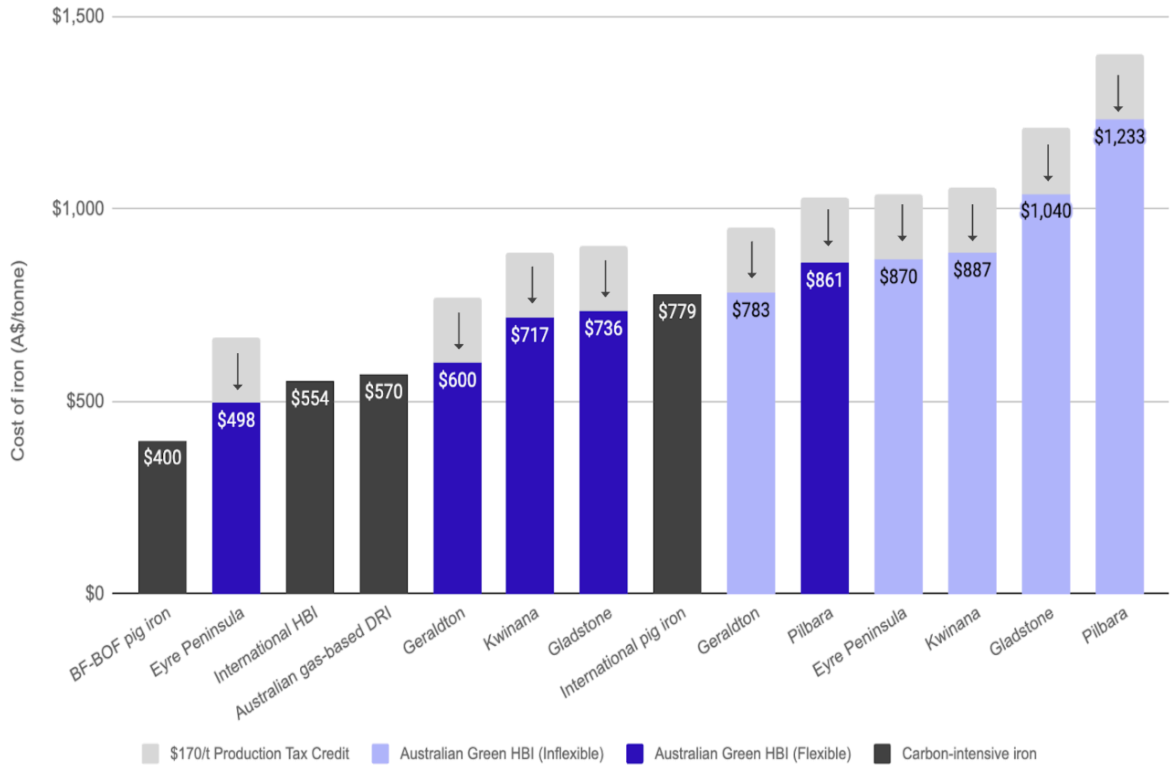

Figure 26: Impact of $170/t green iron production tax credit on the cost of iron in each location, compared to carbon-intensive iron production routes

Note: Figures are in 2024 AUD. BF-BOF pig iron reflects a proxy production cost for BF-BOF ironmaking, which is not typically traded. 'International HBI' and 'International pig iron' reflect the cost of traded HBI and pig iron where data is available. 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.
Source: The Superpower Institute and Bivios analysis; World Bank World Integrated Trade System (WITS); BF-BOF, DRI-EAF, scrap-EAF steelmaking carbon intensity from IEEFA, with emissions from scrap-EAF used to infer emissions from fossil-based DRI. Adjustments to exclude emissions from the BOF stage of the BF-BOF process based on Baig (2016)

This support should be technology-neutral, and apply to hydrogen-based green iron technologies (Recommendation 1) and non-hydrogen-based technologies (Recommendation 2).

There may be a period when green iron producers benefit from both Australian government support and policies in importing countries. For example, green iron exporters will benefit when trade partners increase the price of carbon emissions, or when trade partners use other policies to help green goods compete with carbon-intensive goods.

Australian and trade-partner policies might jointly create greater benefits than the missing system of international carbon prices. But it is unlikely that these conditions will persist, because governments have an incentive to align their policies and minimise fiscal pressure. The Australian government should regularly review its support for green iron to make sure that it simulates the effects of a missing international carbon price, accounting for policies in trade partner countries as well as Australia.

TSI has considered whether to apply a production subsidy to Australian gas-based DRI production. Coordination, or 'transition', problems may mean that green iron producers cannot initially source enough green hydrogen to produce near-zero-carbon green iron. There is some suggestion that, in a transition period, the government should support the use of natural gas as a reductant.

TSI has decided against recommending production-based support for gas-based iron for three reasons.

First, the bundle of policies to support green exports, including green iron, should reflect Australia's comparative advantage. The New Energy Trade comprehensively demonstrates that Australia's comparative advantage is in production that harnesses Australia's abundant renewable energy resources – not natural gas.

Second, our modelling shows that the combination of recommendations presented in this chapter will make it possible for low-cost Australian green iron producers to compete with carbon-based iron. Support for Australian gas-based iron will make this task harder for producers using green hydrogen.

Third, policies need to balance support for green exports with the goal of a strong budget. This challenge is exacerbated by the lack of a domestic carbon price, which would generate substantial budget revenue while taxing the carbon embedded in fossil fuels, including natural gas. While subsidies simulate the effects of a carbon price, they place fiscal demands on the budget, and should be directed to their most valuable use: support for industries that capitalise on Australia's comparative advantage.

This does not prevent producers from using natural gas as a 'transition' reductant. If producers blend natural gas and green hydrogen as a reductant, green hydrogen could qualify for the Hydrogen Production Tax Incentive, and the share of green iron attributed to green hydrogen use would also qualify for our proposed green iron production tax credit.

Recommendation 1

In addition to its $2 per kilogram support for green hydrogen, the government should provide additional support for green iron production to simulate the effects of a carbon price. We estimate total support, including the Hydrogen Production Tax Incentive (HTPI), should be worth at least $170 per tonne of green iron in 2030. This could be achieved with a 'stackable' production tax credit for green iron. The production credit should rise to maintain equivalence to the EU carbon price.

Recommendation 2

Some nascent green iron production technologies do not use hydrogen, but may use significant amounts of renewable energy dedicated to iron-making. Here, the HPTI does not help close the cost gap between green iron and carbon-intensive iron. The government should provide support that simulates the effect of a carbon price for non-hydrogen-based green iron

> technologies. This could take the form of an expanded production credit for green iron, worth at least $170 per tonne of green iron in 2030.

5.1.3 Consumer premiums help, but are no substitute for carbon prices

Until market failures are corrected and the green iron market has matured, green iron will be more expensive than carbon-intensive iron. But together with government support, early investments in green iron have been supported by Asian and European buyers paying a voluntary 'consumer premium' between USD 100-200 per tonne.[158]

Demand is largely from companies in the automotive, construction, and renewable energy industries trying to reduce emissions in their supply chains,[159] selling to customers prepared to pay a premium for 'green' goods. This is possible because, for a small premium, green steel can dramatically reduce embedded emissions. For example, green steel adds less than USD 200 to the final price of a car – much less than 1 per cent of the overall cost. It is the cheapest way to cut a large share of product emissions.[160]

The consumer premium on green steel is expected to persist through to the early 2030s.[161] This will help create momentum for first-mover green iron and steel producers, and governments should support green consumer schemes (Section 6.5). But customer premiums will only cover a limited number of products, so they will not be sufficient, and they will not be sustained.

Voluntary customer premiums are not a substitute for policies that address the missing carbon price.

5.2 Investments in common-user infrastructure address market failures

Much of the infrastructure for large-scale green industrial projects has two important characteristics: it is 'common user' infrastructure, and it has 'natural monopoly' characteristics. We refer to this as 'common-user' infrastructure for ease (Box 6).

[158] Fastmarkets, 'Five Factors That Could Accelerate or Decelerate the Adoption of a Green Steel Premium in the US: LME Week'; Expected premiums for low—and zero-carbon steel are USD200 to 350 per tonne by 2025, and USD300 to 500 per tonne by 2030: McKinsey, 'The Resilience of Steel: Navigating the Crossroads. McKinsey'.

[159] Energy Transitions Commission, 'Steeling Demand: Mobilising Buyers to Bring Net-Zero Steel to Market before 2030'.

[160] Hasanbeigi et al., 'Green Steel Economics'; Bui et al., 'Technologies to Reduce Greenhouse Gas Emissions from Automotive Steel in the United States and the European Union'.

[161] McKinsey, 'Global Materials Perspective'.

Box 6. Common-user infrastructure with natural monopoly characteristics

Common-user infrastructure can be accessed and used by multiple producers. It is a public good when there are large "positive spillovers" in the form of benefits for people, businesses, and communities other than the investor or user. For example, electricity transmission investments may stimulate new, larger businesses, and therefore community development throughout a region. But because private investors are not compensated for all these spillover benefits, they will not invest at a socially optimal scale.

Infrastructure has natural monopoly characteristics if it is expensive to build but has low operating costs,[162] if the infrastructure can meet all users' needs, and if it is difficult for a second infrastructure provider to profitably enter the market.

A private provider does not have an incentive to provide the socially optimal, 'efficient' level of this infrastructure, or to charge socially optimal, 'efficient' access fees. This is a form of market failure, and more than a century of economic theory and practice supports a role for government in natural monopoly infrastructure.

One potential role for government is to regulate access arrangements, including prices, for natural monopoly infrastructure. This can increase economic efficiency by reducing economic rents and by promoting access that unlocks upstream or downstream investments.

There is likely to be some role for government in common user infrastructure related to green iron. This is because it will not be economically feasible for certain infrastructure to be built by any one green iron project proponent, and these costs will need to be spread across multiple users. Government can directly invest in infrastructure to overcome this problem, or it can mitigate the risk of underutilisation by making payments to a private infrastructure owner for a period. Access to the privately-owned infrastructure in these circumstances would need to be regulated; this brings risks associated with setting access terms that promote efficient investment in and use of the infrastructure.

Common-user infrastructure suffers from a "chicken and egg" coordination problem: some green industries will not be viable until there is new common-user infrastructure, but common-user infrastructure is not viable until there are green industries.[163]

Australian governments, together with state and territory governments, can resolve scale, spillover, and coordination problems by investing in socially efficient levels of common-user infrastructure – as they have since the nineteenth century. Historical investments in common-user infrastructure encouraged private investment in the agricultural, mining, energy, and manufacturing industries. Private producers accessed public ports, roads, electricity grids, and gas pipelines, and contributed to generations of Australian growth and prosperity. New public investments in common-user infrastructure would help attract private investment into Australia's green export industries, contributing to the prosperity of future generations.[164]

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[162] Sometimes described as high 'fixed costs' but very low 'marginal costs.'

[163] In theory, if future stakeholders had perfect foresight, they could coordinate to fund infrastructure at an efficient level. In practice, most future beneficiaries, and the scale of benefits, are unknown.

[164] An example of this kind of investment is the planned expansion of transmission and shared infrastructure in Western Australia's North West Interconnected System (NWIS); see: Prime Minister of Australia, '$3 Billion Rewiring The Nation Deal to Power WA Jobs and Growth'.

Our model shows that infrastructure constraints increase the cost of producing green iron within a site (Section 4.4). Regions with the greatest potential for efficient, large-scale green metals production will usually require significant public investments in transmission for renewable energy, infrastructure for transporting and storing inputs such as green hydrogen, and other common-user infrastructure. Because electricity markets are jointly managed by federal and state governments,[165] state governments will have a critical role to play in planning, funding, and coordinating investments in transmission.

Government finances are limited, and should be directed to infrastructure investments that deliver the greatest social benefit. This will likely be large pieces of infrastructure shared by multiple users. Where certain infrastructure can be built privately or where benefits are likely to be narrow, the government should have no role.

Common-user infrastructure should be built at a scale that allows for expansion of demand, based on an assessment of the likely developments over the decade ahead. And access should be priced efficiently, with fees that recover costs at a rate based on full utilisation of the infrastructure. This price structure means early producers would not pay higher prices than subsequent producers.

Infrastructure will be under-utilised in its early years, relative to capacity. Combined with efficient pricing, with early users paying similar fees as later users, this will create costs from underutilisation.

The federal government should be largely responsible for investments in common-user infrastructure for green iron, including the costs from under-utilisation.

If the federal government is the sole source of funds, a federal government business enterprise should be responsible for managing investments. The enterprise should pay the government's cost of capital and use the government discount rate to evaluate investment options. Revenue shortfalls should be on budget.

If a state agency or private company is contracted to supply common-user infrastructure, the federal government should provide 80 per cent of the capital as debt or as a guarantee of debt. In this case, user fees should reflect the reduction in costs that flows from the lower cost of debt. The federal government should make an annual payment to the provider to cover the cost of early underutilisation, subject to an assessment of user pricing and infrastructure size. Underutilisation payments should not continue indefinitely; we suggest they end in 2040.

Recommendation 3

In locations that are most promising for multiple green iron projects, federal and state governments should fund new natural-monopoly infrastructure that is essential for green iron, steel, and other green exports: electricity transmission, hydrogen pipelines and storage, ports, and desalination and water supply in areas with no local water supply.

Building this infrastructure ahead of demand will solve the coordination problem that will otherwise delay or prevent investments in green iron production.

[165] Energy Innovation Toolkit, 'About Australian Energy Markets'.

> Infrastructure use should be priced efficiently, so the cost of using infrastructure is not a barrier to early private investment in green iron.

5.2.1 Green hydrogen certificates would help reduce the cost of green iron production

As our modelling shows, green iron production costs can vary widely between locations in Australia. One important driver of these results is the capital costs of building renewable energy assets in different locations.

Some of the best iron ore deposits will not be close to the lowest-cost locations for building renewable energy and hydrogen production infrastructure. Section 4.5 demonstrated this by showing the potential cost reduction for Pilbara green iron if South Australian green hydrogen could be used. We also highlighted the challenge and prohibitive cost of the physical transport of hydrogen to make this possible.

There is a role for policy in overcoming this coordination challenge. To lower the cost of green iron and to build demand for green hydrogen, we propose a green hydrogen certificate scheme.

A green hydrogen certificate scheme would operate in a similar way to the Renewable Energy Target, which underpinned the expansion of green energy until recently. A renewable hydrogen certificate scheme is already in operation in NSW and one is under development in Victoria (see Box 7).

Box 7. Existing and proposed renewable hydrogen certificate schemes

Under NSW's Renewable Fuel Scheme (RFS), producers can generate a tradeable certificate for every gigajoule of green hydrogen they produce. Liable parties must buy and surrender certificates to meet their obligations under the NSW renewable fuel production target, or pay a penalty. Liable parties include gas retailers and large gas users that do not purchase their gas through a retailer. The RFS strengthens financial incentives to produce and buy green hydrogen, with the target gradually increasing to 8 PJ in 2030.[166]

In Victoria, the government has announced its intention to introduce an Industrial Renewable Gas Guarantee in 2027. The scheme would operate in a similar way to the NSW RFS, with certificates created for production and an annual target gradually increasing to reach 4.5 PJ by 2035. The Victorian scheme proposes that both biomethane and renewable hydrogen would be eligible for certificate production. The scheme contemplates renewable gas being used only for gas-powered generation.[167]

[166] NSW Government, 'Renewable Fuel Scheme FAQs'.

[167] DEECA, 'Victorian Industrial Renewable Gas Guarantee: Victoria's Renewable Gas Directions Paper'.

Under our proposal, green hydrogen producers could generate tradeable certificates, and end-users would be credited for 'using' green hydrogen when they buy and surrender green hydrogen certificates – even if the green hydrogen is not physically used by the certificate purchaser. A certificate scheme would allow renewable energy, green hydrogen, and green iron to be produced in the lowest-cost locations.

For example, an iron producer in the Pilbara could buy and surrender green hydrogen certificates for green hydrogen produced in South Australia or in another part of Australia. The physical hydrogen could be blended into the natural gas network and used close to where it is produced. This is already occurring in parts of South Australia (Box 8) at a small scale. The green iron producer could then use natural gas rather than hydrogen as a reductant. The net effect, in emissions and incentives for green hydrogen production, would be equivalent to the situation where hydrogen was produced and used in the Pilbara.

Our model shows that a hydrogen certificate scheme could reduce the cost of producing green iron in the Pilbara by more than 20 per cent (Section 4.5).

Box 8. Blending hydrogen into natural gas networks in South Australia

Hydrogen Park South Australia (HyP SA) is an Australian example of renewable hydrogen being blended with natural gas in an existing gas network. The project is a development by Australian Gas Infrastructure Group (AGIG), with the support of the South Australian Government.

The project involves a 1.25MW Siemens Proton Exchange Membrane electrolyser producing green hydrogen at Tonsley Innovation District, which is supplied as a 10 per cent blend, by volume, with natural gas. Customers on the gas network are households, businesses and schools in Adelaide's southern suburbs of Mitchell Park, Clovelly Park, and Marion.

The project reports a reduction of emissions, attributable to the use of renewable hydrogen in place of gas, of over 21 thousand kilograms of CO_2 since operations commenced in 2021.

AGIG has plans for similar projects in Gladstone and Albury-Wodonga.[168]

A certificate scheme helps overcome coordination challenges during the earliest phases of green hydrogen and green iron. The emissions benefits are the same: green hydrogen displaces natural gas – but in a different location to the green iron producer. The scheme should be time-limited – we propose a review in 2035 – and green hydrogen investors can weigh up the benefits of joining existing gas networks, or building in locations that directly supply users, such as green iron plants.

A certificate scheme also allows hydrogen and iron producers to benefit from the difference in gas prices between eastern and western gas markets: a hydrogen producer in eastern Australia could sell into the higher-priced eastern gas market, with higher prices – and therefore revenue – reducing the costs they need to recover from buyers of hydrogen certificates. Iron producers in the West Coast gas market would be able to purchase gas at a lower price, reducing the cost of producing green iron.

[168] AGIG, 'Hydrogen Park South Australia'.

The requirements for a green hydrogen certificate scheme would be simpler than the European Union's green certification scheme, which is based on the concept of green inputs being delivered to the 'production gate'.[169] Green iron producers could use Guarantee of Origin (GO) certificates to meet detailed EU CBAM requirements – these are accommodated within the proposed design of GO certificates, which includes voluntary reporting to comply with EU regulations. Alternatively, producers could use GO certificates under simpler 'swap' arrangements to certify green hydrogen used in iron exported to countries that do not have the same requirements as the EU.

This proposal would need to overcome the technical challenges of blending large quantities of hydrogen into existing gas networks, but has large potential benefits while green hydrogen and green iron industries get established, when common-user green hydrogen storage and transport infrastructure can reduce producers' costs and coordination problems.

> ### *Recommendation 4*
>
> We propose an Australian green hydrogen certificate scheme, with green hydrogen producers earning tradeable certificates. Certificates could be purchased and surrendered by green iron producers anywhere in Australia. Iron produced with natural gas could be recognised as 'green' iron production when equivalent green hydrogen certificates are purchased and surrendered.
>
> Producers of other green hydrogen-based products would also be included in the scheme.

5.3 Innovation subsidies will help correct market failures

5.3.1 Early producers create knowledge that benefits everyone

Green iron production is held back by market failures that affect early producers.

Early producers create positive externalities in the form of shared knowledge: they discover how new technologies perform in the Australian environment, problem-solve to reduce costs, solve technical challenges, encourage compatible regulatory arrangements, and train workers in the use of new green technologies. Finding ways to reduce costs is difficult even in the context of a model; it is even harder in the real world.

Subsequent producers can draw on early producers' experience to lower their own production costs. But early producers know they will not be compensated for hard-won knowledge, dampening the incentive to invest. And early producers pay higher costs for new technologies than later producers, and a higher cost of capital because first-mover projects are riskier.

There is a role for government investment:

- when innovation leads to knowledge spillovers, which have positive externalities, and
- when the knowledge accumulates in industries in which Australia is expected to have a comparative advantage.

[169] DCCEEW, 'Guarantee of Origin - Emissions Accounting Approach Paper'.

The scale of the external benefit depends on the value of the knowledge generated. Australia has tax incentive schemes for early-stage investors, but these benefits are capped at $200,000.[170] Because Australia's potential income from green iron is so large, and because Australia has a comparative advantage in green iron, the value generated by early green iron producers is larger than conventional early investment projects in other industries.

5.3.2 A Superpower Innovation Investment Scheme

The government should provide financial support for early producers of green iron to compensate for the additional costs they bear while generating shared knowledge. Without government intervention, and compared to the efficient scale and timing of investment, there will be too little investment, too late.

Early producers incur additional costs that range up to more than $400 per tonne of iron, reflecting higher borrowing costs and higher prices for new technologies (Section 4.6).

An innovation support scheme should:

- Recognise that the largest knowledge gains are generated by the earliest producers. We use the term 'early producers' to refer to the first producer and any producers who follow so closely that they do not benefit from existing knowledge.
- Reflect the scale of early-producer costs, but not be tailored to specific project costs: outcomes will be less certain than our modelled estimates, particularly for flexible technologies that are under development.
- Recognise that early green iron projects will generate knowledge that is applicable to all future producers.
- Recognise that early projects will generate some knowledge that is specific to particular green iron and green hydrogen technologies.
- Recognise that early projects adopting first-of-a-kind technologies will face greater risks and deliver more knowledge and so should be rewarded accordingly.

We propose up-front capital support, as it has the highest impact on producers' cost of capital, and does not dampen the incentive to produce efficiently. To help align producers' incentives with taxpayers' goals, producers should retain a large stake in project outcomes. The government should consider payment floors and ceilings,[171] and funding should be structured to reflect the likely economic life of different capital investments.

An alternative is a financially equivalent tax mechanism, allowing producers to expense capital expenditure immediately and to uplift CAPEX for tax deductions. Producers should also be allowed to cash out credits if they have no taxable income against which credits can be deducted.

Our recommended support for innovation has two components.

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[170] ATO, 'Tax incentives for innovation'.

[171] This proposal has similarities to the US Industrial Demonstrations Program, worth more than US$20 billion, which contributes up to 50 per cent of the costs of innovative green industrial projects. Payments are capped at US$500 million; minimum size is US$35 million: U.S. Department of Energy, 'Funding Notice: Industrial Demonstrations'. If implemented through the tax system, the design is closely related to the R and D tax credit currently in operation.

We propose that early investors in green iron projects, using any kind of green iron technology, should receive capital grants, or equivalent tax benefits, representing 15 per cent of capital costs. This reflects that any kind of green iron production in Australia will deliver important benefits for Australian producers, even if the technology has been deployed elsewhere in the world previously. An example of this would be the deployment of a Midrex shaft DRI plant. We propose that this support should be available for up to three green iron projects.

Grants worth an additional 15 per cent of capital costs should be made available for the first few uses of a particular kind of green iron technologies deployed in Australia. This would reflect the additional risks and knowledge that could be generated by the deployment of technologies that have not been used anywhere else in the world.

If the Government preferred to make payments as production credits, the rates of credit could be set to generate a similar present value to the proposed capital grants.

Our model shows that this support scheme would compensate for the early-mover costs we model, and allow a margin for costs that will be revealed in the real world (Figure 27).

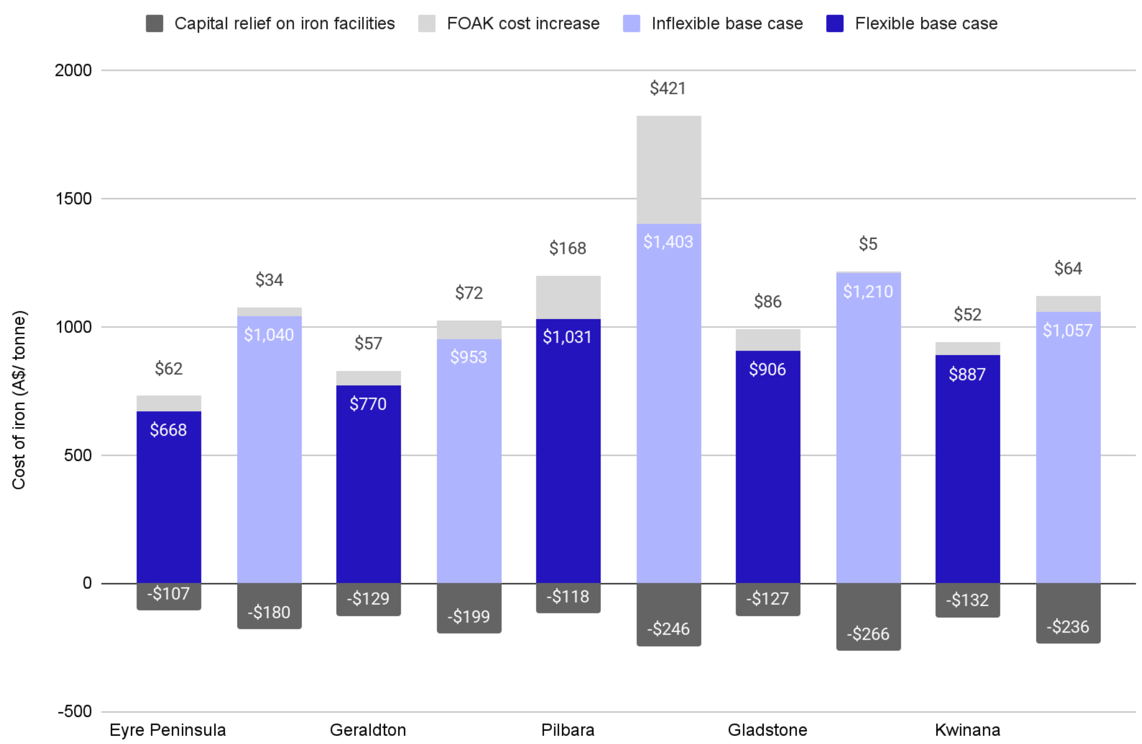

Figure 27: Impact of capital cost relief on the cost of iron in different locations, compared to estimated first-of-a-kind (FOAK) costs in each location

Notes: 'Flexible' technology can be ramped up and down. 'Inflexible technology' needs to produce continuously.
Source: Bivios and The Superpower Institute

This funding should be used to support projects with commercial-scale production – at least 0.5 million tonnes of green iron. For projects with multiple stages, all stages included in the initial project plan should qualify.

This support could build on or draw from the Federal Government's announcement of a $1 billion green iron investment fund.[172]

Recommendation 5

The federal government should provide capital support for early commercial producers of green iron, with a planned output of at least 0.5 million tonnes per annum. This could build on or draw from the already announced $1bn green iron investment fund. Two levels of support should be available:

1. Early investors in green iron projects, using any kind of green iron technology, should receive capital grants, or equivalent tax benefits, representing 15 per cent of capital costs. We propose that this support should be available for up to three green iron projects.
2. Grants worth an additional 15 per cent of capital costs should be made available for the first few uses of a particular kind of green iron technologies deployed in Australia.

Support should be capped at $500m per project.

5.3.3 Innovation support should be technology-neutral but not encourage investments in gas

For early green iron producers, green hydrogen might not be available in the right quantities or in the right location. Natural gas is an alternative reductant, but it is not consistent with Australia's comparative advantage - other locations such as the Middle East and the US produce gas much more cheaply. In any event, using gas increases emissions relative to green iron (Section 4.7).

Government policies need to strike a balance between support for technology that can be used to make green iron and recognition that there will be early coordination and supply challenges.

A particular concern is that gas-based DRI could be 'locked in' and a transition to green hydrogen would be drawn out or never occur. Government policy should aim to avoid this scenario.

This is one reason we propose a green hydrogen certificates policy: it makes it easier for early green iron producers to buy green hydrogen produced in low-cost locations.

Producers who want to make gas-based direct-reduced iron are unlikely to invest in Australia, and are much more likely to invest in countries with cheaper gas, such as Oman and other countries in the Middle East and North Africa.

Our recommended policy mix supports early users of green iron technology, including technology that uses both gas and hydrogen: knowledge spillovers will benefit all green iron producers. This does not strengthen their incentive to use gas rather than renewable energy and green hydrogen, and we do not support shared-user infrastructure for gas, which is not consistent with Australia's comparative advantage.

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[172] Prime Minister of Australia, 'Albanese and Malinauskas Labor Governments Saving Whyalla Steelworks and Local Jobs with $2.4 Billion Package'.

We also support policies that correct for the missing carbon price, in the form of the Hydrogen Production Tax Incentive, and recommend lower borrowing costs for renewable energy that powers green iron production. These policies do not support gas-based production, on the grounds that gas use is not consistent with Australia's comparative advantage in a decarbonised world.

5.4 Regulatory and planning delays create large costs for early movers

Lengthy, inefficient approval processes cause expensive delays for investors in renewable energy projects,[173] and will create the same problems for green hydrogen and green iron projects. Planning costs reduce Australia's appeal as a destination for investors.

For example, POSCO's recent submission to Western Australia's EPA planning process states:

"...more likely, alternative locations would be overseas where land access is easily obtained, and [planning] costs are likely to be lower... Delays would see increased likelihood of alternative locations being utilised."[174]

An Australia-wide problem is duplication across a joint federal-state planning process.

Projects that affect 'matters of national environmental significance' (MNES) need to be referred to and approved by the federal government under the Environmental Protection and Biodiversity Conservation (EPBC) Act. Approvals must be signed off by the federal Minister for the Environment or their delegate.

Audits, statutory reviews, and Senate Committee inquiries have found that the EPBC Act contributes to substantial project delays, uncertain outcomes and inefficient project delivery. The number of renewable energy projects requiring federal approval has increased, there is a backlog of projects for assessment, and the time taken to clear assessment milestones is increasing.[175]

Legislation at the state and territory level also contributes to uncertainty and delays, demonstrated by substantial variation in outcomes. For example, the average approval time for wind projects in New South Wales is at least six times longer than in South Australia, Victoria, or Queensland.[176]

TSI also notes and supports existing efforts to reduce delays. At the federal level, the National Energy Priority List provides additional planning support for renewable energy projects with a capacity of 30 Megawatts or more.[177] At the state level, for example, South Australia now supports the coordinated development of renewable energy, green hydrogen, and green iron projects through the Hydrogen

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[173] CEIG, 'Quick Fixes to EPBC Coupled with Renewed Legislative Efforts Can Unlock Renewable Investment – New Report'.

[174] Preston Consulting and Port Hedland Iron, 'Port Hedland Iron Project - Stage 1 Supplementary Report'.

[175] CEIG and Herbert Smith Freehills, 'Delivering Major Clean Energy Projects', 3; The Clean Energy Investor Group has made recommendations to increase the efficiency, consistency, and predictability of the federal government's implementation of the EPBC Act. This includes a recommendation encouraging landscape-level assessments for state's renewable energy zones, rather than project-by-project assessments; Noting the scale of the task to accelerate firmed renewables infrastructure deployment rates, CEF also recommends the introduction of an Overriding Public Interest (OPI) test to streamline approvals process: Pollard and Buckley, 'Green Metal Statecraft: Forging Australia's Green Iron Industry'.

[176] CEIG and Herbert Smith Freehills, 'Delivering Major Clean Energy Projects in NSW: Review of NSW Statutory Planning Approvals Processes', 13.

[177] DCCEEW, 'National Renewable Energy Priority List'.

and Renewable Energy Act 2023,[178] while Western Australia has amended its Environmental Protection Act (EPA) to speed up approvals: decision-making authorities can now issue approvals in parallel, while EPA assessments are underway.[179] Western Australia also permits Crown lands to be leased to renewable energy proponents while their proposal is being assessed.[180] But progress across states is uneven, and new legislation is too recent to have demonstrated success. States and territories should report the time taken to reach a decision for large-scale renewable energy and green production projects; the federal government should do the same for referrals under the EPBC Act.[181]

[178] Department of Energy and Mining, 'South Australia's Green Iron and Steel Strategy: Partner of Choice to Decarbonise Global Steel'; Premier of South Australia, 'Landmark Laws to Unlock Hydrogen and Renewable Energy'.

[179] Government of Western Australia, 'Streamlining Environmental Approvals Processes'.

[180] Government of Western Australia, 'Cutting Green Tape to Support Renewable Energy Projects in WA'.

[181] The ANAO audits referrals under the EPBC Act, ANAO, 'Referrals, Assessments and Approvals of Controlled Actions under the Environment Protection and Biodiversity Conservation Act 1999', but there is no real-time, easily-accessible tracking.

06

Developing an international market for green iron exports

This chapter shows that the Australian government will need to work with trade partners to help build early international demand for Australian green iron exports. There is also a role for state governments, which have their relationships with international governments. Efforts at both levels can help maintain momentum across political cycles and tiers of government.

International demand is essential to a successful green iron industry in Australia, and Section 6.1 shows how the European Union's Carbon Border Adjustment Mechanism (CBAM) will contribute to demand for green iron. Section 6.2 shows that policies in Australia's largest trading partners are not ambitious or urgent enough to create regional demand for green iron imports; as a result, there is not currently strong demand from buyers of green iron in Australia's main export destinations (Section 6.3). But there are good reasons to be optimistic about future demand for green iron (Section 6.4), and the Australian government can work with Australia's trading partners to promote green iron production in Australia as mutually beneficial (Section 6.5).

6.1 The EU CBAM demonstrates how a carbon price creates demand for green iron

A thriving green iron export sector will depend on demand from international steelmakers: Australia does not have a large steel-making industry,[182] and Australia's comparative advantage is stronger in iron-making than steel-making, because it is the more energy-intensive process (Chapter 1).

While the international community works towards a coherent system of prices, the European Union's carbon price provides a glimpse around the corner. It is designed to achieve net-zero emissions in 2050, and it will support international markets for green goods, including iron.

Industrial production in the EU is shaped by its Emissions Trading Scheme (ETS), which has put a price on carbon since 2005. In 2023, the EU introduced a companion policy: a Carbon Border Adjustment Mechanism (CBAM).

The CBAM prices the carbon embedded in energy-intensive imports, including iron and steel, aluminium, cement, hydrogen, some chemicals – including carbon-intensive fertilisers – and electricity. The price on carbon will increase progressively until the full ETS price applies from 2034. The EU also plans to apply the CBAM to more complex products.

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[182] Australia and New Zealand accounted for just 0.3% of global steel production in 2023: World Steel Association, 'World Steel in Figures 2023'.

The CBAM reduces 'carbon leakage': if EU producers pay the ETS price on carbon but producers outside the EU do not, carbon-intensive imports can more easily outcompete low-carbon EU products. This displaces production to countries with weaker carbon-reduction policies, so carbon emissions would 'leak' from Europe to the rest of the world. A CBAM levels the playing field and so supports demand for green products. It also creates an incentive for exporters to Europe to implement their carbon prices to 'capture' carbon tax revenue.

The EU carbon price, the CBAM, and green transition policies mean European countries are the likely leaders in green steel consumption and production, despite recent challenges.[183]

As a group, EU countries are the world's second-largest steel producers, with crude steel production reaching approximately 130 million tonnes in 2024 – a decrease from around 152 million tonnes in 2021.[184] The EU Commission expects that around 30 per cent of EU primary steel production will be decarbonised with renewable hydrogen by 2030.[185]

But with the CBAM helping to create a new market for green iron, EU companies will need to import up to 13 million tonnes of green iron by 2030, and up to 18 million tonnes by 2045.[186]

Europe's ETS and CBAM show how carbon pricing creates a market for green goods – whether produced in Europe or imported into Europe. Although Australia only exports a very small amount of iron ore to Europe,[187] EU carbon pricing creates a potential market for Australian green iron.

6.1.1 Green iron exports need credible emissions certification schemes

CBAMs apply the local carbon price to the carbon embedded in imports. To make sure Australian goods are fairly priced under the EU CBAM, Australian carbon measurement systems need to be recognised by the EU.[188]

The Australian government's 'Guarantee of Origin' (GO) scheme passed into law in late 2024 with the goal of alignment with international standards, including the EU CBAM. The scheme includes Renewable Energy Guarantee of Origin (REGO) certificates and Product Guarantee of Origin (PGO) certificates. The GO scheme for green hydrogen is being fast-tracked and expanded to include green iron, steel, aluminium, and liquid fuels.[189]

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[183] Challenges include tight margins, competition from cheap imports from China, rising energy costs from geopolitical factors and green transition policies, and weak domestic demand: Glushchenko, 'How European Steel Industry Can Survive the Perfect Storm'.

[184] WorldSteel Association, 'December 2024 Crude Steel Production and 2024 Global Crude Steel Production Totals'.

[185] RepowerEU Plan, 'Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions'.

[186] EU companies are planning to make about 42 million tonnes of green steel by 2030, but only 33 million tonnes of green iron. By 2045, EU companies are planning about 35 million tonnes of green iron and 48 million tonnes of green primary steel. Analysis assumes primary steelmaking rather than use of scrap, is based on data from Green Steel Tracker, and assumes 1.1 tonnes of green iron is required to produce 1 tonne of green steel. See Torres-Morales, Maltais, and Gong, 'Demands for Renewable Hydrogen and Electricity to Drive the EU's Green Iron and Steel Transition'.

[187] For example, in 2023 Australian iron ore exports to the European Union were valued at less than AUD30 million: WITS, 'European Union Non-Agglomerated Iron Ores and Concentrates Imports by Country in 2023'.

[188] If embedded carbon is not measured and certified with an EU-verified scheme, default EU estimates will be used. There is a risk that default estimates will over-state the level of carbon in Australia's green exports, making them less competitive in the EU market.

[189] DCCEEW, 'Guarantee of Origin Scheme'.

The EU has not finalised legislation on accreditation principles and processes,[190] but verified accreditors will be able to report embedded carbon emissions from 2026, when the CBAM Definitive Phase begins. It will be important for Australian green iron producers to be recognised under the CBAM.

> *Recommendation 6*
>
> The government should shape its Guarantee of Origin (GO) certificates to be compatible with the EU Carbon Border Adjustment Mechanism (CBAM). This should be done at the earliest possible date after the EU legislates its requirements.

6.2 Trade partners' policies are not yet ambitious enough to create demand for green iron

As promising as the green iron opportunity in Australia is from a supply-side perspective, the industry will not succeed in the long term without strong interest and support on the demand side from our trade partners.

6.2.1 Trading partners have decarbonisation commitments

Until there is a system of international carbon prices, demand for green iron will depend on governments' commitments to reaching net zero and the strength of policies for achieving these commitments.

Australia's major iron ore trading partners have formalised targets to dramatically reduce greenhouse gas emissions. Levels of speed and ambition vary, but the direction is clear. Key trade partners Japan and South Korea have committed to net-zero greenhouse gas emissions by 2050, and China is aiming for 2060. Other major economies also have targets: the EU has a 2050 target, and India a 2070 commitment.[191] All have set interim targets for near-term action.[192]

Current commitments are not yet strong enough to meet 2 degrees Celsius warming targets, let alone 1.5 degrees.[193] But commitments can strengthen through time, and countries are required to provide new and more ambitious interim targets every five years. Despite an Executive Order mandating US withdrawal from the Paris Agreement,[194] which will take effect in early 2026, other countries continue to strengthen their goals.[195]

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[190] European Commission, 'Carbon Pricing – Accreditation of Verifiers and Verification Principles'.

[191] In 2021 the US committed to reach net zero carbon emissions by 2050. On January 20, 2025, the US began the process of withdrawing from the Paris Agreement. The White House, 'Putting America First In International Environmental Agreements'.

[192] CAT, 'The Climate Action Tracker'.

[193] Meinshausen et al., 'Realization of Paris Agreement Pledges May Limit Warming Just below 2 °C'.

[194] The White House, 'Putting America First In International Environmental Agreements'.

[195] Department of Energy Security and Net Zero and The Rt Hon Ed Miliband MP, 'UK Shows International Leadership in Tackling Climate Crisis'.

6.2.2 Current trade partner policies will not create near-term demand for Australian green iron

Countries have different approaches to meeting their targets. A growing number of countries have some form of carbon pricing,[196] but at prices well below the social cost of carbon. Other countries are pursuing a broader range of strategies, including economy-wide transition plans,[197] sector-specific pathways,[198] and policies to support lower emission technologies and products.[199]

The policies that will matter most for Australian green iron exports sit with existing iron ore trading partners – Japan, South Korea, and China – and potential trade partners in South and Southeast Asia and Europe.

Japan, South Korea, and China have policies to reduce emissions from their steel sectors. These include production targets, pricing and subsidy-based incentives, research and development support, permit systems that encourage lower-carbon production, interventions to increase the supply of renewable energy and hydrogen, and policies to increase demand for green steel products (Table 5).

[196] Nearly a quarter of all global greenhouse gases are covered by some form of carbon price: World Bank, 'State and Trends of Carbon Pricing 2024'.

[197] See, eg, China's "1+n" policy framework for carbon peaking and carbon neutrality: Ministry of Ecology and Environment, 'China's Policies and Actions for Addressing Climate Change (2022)'.

[198] See, eg, EU: European Commission, 'Transition Pathways for European Industrial Ecosystems'.

[199] The White House, 'Building a Clean Energy Economy: A Guidebook to the Inflation Reduction Act's Investments in Clean Energy and Climate Action'.

Table 5: Key trade partner carbon prices and decarbonisation policies

Sources: Carbon Price data from World Bank Group, 1 April 2024. Carbon Price / ETS details from International Carbon Action Partnership (ICAP) country profiles. Economy-wide and Steel Transition Policies from Climate Action Tracker country profiles.

	Carbon price / ETS		Transition policy[200]	
Country	**Price (AUD/tCO_2e)[201]**	**Details[202]**	**Economy-wide**	**Steel**
China	$18	Intensity-based scheme for the energy sector; steel and concrete included in 2025.	"1+n" policy has detailed targets and policies across all sectors of the economy. Uses a range of pricing, planning and subsidy mechanisms	Goal to peak steel sector emissions before 2030. Target of 15% total crude steel production from EAF facilities by 2025 and 20% by 2030. Steel was recently brought under ETS.[203]
Japan	$3	Voluntary scheme; proposal to make mandatory for all large industry from 2026, including steel. Some regions, e.g. Tokyo, have their own schemes.	GX Basic Policy sets out comprehensive economy-wide targets and policies, primarily planning and subsidy-based incentives	Target of 10 million tonnes of "green steel" in 2030, supported by an industry roadmap and a subsidy program. Target of 30% reduction in emissions by 2030, versus 2013 baseline. Subsidy of up to AUD 557 per 'clean energy vehicle' (EV/PHEV) depending on the proportion of low-emission steel.
South Korea	$9	Mandatory scheme covering over 70% of GHG emissions, but excluding steel	Framework Act on Carbon Neutrality and Green Growth provides overarching transition policies; primarily planning/permitting tools	Target to produce 1 million tons of steel with HyREX technology by 2030.

China has recently expanded its emissions trading scheme (ETS) to include steel manufacturing, and Japan's ETS will include steel from 2026.[204] These are positive steps that will strengthen decarbonisation efforts in the short term, but carbon prices are too low to transform steelmaking industries at the pace required to hold global warming as close as possible to 1.5 degrees Celsius. A useful comparison is the EU carbon price, which has consistently been above $95 since 2021 – well above prices in Australia's steelmaking trading partners.

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[200] CAT, 'The Climate Action Tracker' Country profiles for China, Japan, and South Korea.

[201] World Bank Group, 'State and Trends of Carbon Pricing Dashboard' Conversion from AUD to USD based using 5-year average exchange rate: USD/AUD = 1.45; see footnote 5, Chapter 1. Converted to the nearest dollar.

[202] ICAP, 'ETS Map'.

[203] Transition Asia, 'Steel Enters China's National Emissions Trading Scheme'.

[204] Transition Asia, 'Key Policy Developments in Japan for the Steel Industry'.

One advantage of Australia introducing carbon pricing is that it will support movements towards carbon pricing in trading partners. Carbon pricing based on the social cost of carbon, on both sides of a trading relationship, also allows green iron production in Australia to compete efficiently with carbon-intensive iron.

Demand for green iron will instead, for the time being, depend on policies specific to the steel sector.

China's plan to reach peak steel emissions by 2030 is a step in the right direction, but policies reflect China's net-zero target for 2060 rather than 2050. South Korea's goal of one million tonnes of green steel is modest and is likely to be met by domestic production rather than green iron imports.

Japan's policies are more promising, but lack detail. Japan has a goal of producing 10 million tonnes of green steel by 2030, and a subsidy for low-emission steel used in the manufacturing of clean energy vehicles that will help create demand.[205] But without detail on the carbon intensity of green steel, the definition of green or low-emission steel, or technology pathways to decarbonise the industry, it is difficult to judge the scale of ambition. And although Japan's target of 30 per cent emissions reductions in the steelmaking sector by 2030 appears ambitious, it is set against a high 2013 baseline. Progress against this target is largely attributed to falling production,[206] and only requires a further reduction of less than 10 per cent relative to 2022 emissions.[207]

Policies in Australia's trade partners reflect growing ambition, with an expanded role for carbon pricing, but do not yet match the scale and urgency of the decarbonisation challenge. Decarbonisation in line with net-zero commitments requires carbon prices that reflect the social cost of carbon or policies that achieve the same reductions in carbon emissions. Current policies are unlikely to create demand for green iron, but Australian government support will help make green iron available, encouraging ambition as our trade partners decarbonise their iron and steel sectors.

As noted in Chapter 5, this support can be adjusted to reflect international progress towards carbon pricing and the policies of our trading partners.

6.2.3 There may be opportunities to export green iron to new trading partners

The EU's carbon price and Carbon Border Adjustment Mechanism create early export opportunities for Australian green iron (Section 6.2).

ASEAN countries are also potential trading partners. Current steelmaking capacity is low, at about 88 million tonnes per annum. This is projected to increase to around 182 million tonnes by 2030.[208] Although the majority of iron ore imports are from Brazil, imports from Australia represent about one-third of the total.[209]

There is also an opportunity to trade with countries in our region with existing EAF capacity, which could use Australian green iron as an input.

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[205] Russell, 'Green Steel Needs Incentives to Work and Japan Has a Plan'.

[206] CAT, 'Policies & Action, Japan'; The Japan Iron and Steel Federation, 'Activities of Japanese Steel Industry to Combat Global Warming: Report of "JISF's Carbon Neutrality Action Plan"', 58.

[207] UNFCCC, 'Japan's First Biennial Transparency Report'.

[208] Ju and Hui Tan, 'Southeast Asian Steel Capacity Expansion Unsustainable: SEAISI'.

[209] SEAISI, 'ASEAN Iron Ore & Scrap Scenario'.

ASEAN countries

Decarbonisation policies in the Association of Southeast Asian Nations (ASEAN) countries are not yet strong enough to support trade in green iron, but because steel production is growing rather than established, there may be opportunities to integrate green iron into new production pathways.

Almost all ASEAN countries have targets to achieve net-zero emissions. While Indonesia's goal is 2060, Thailand, Vietnam and Malaysia have 2050 targets.

As with key trading partners, policies to support net-zero ambitions are not strong enough yet to support demand for Australian green iron, but our recommended support will help green iron compete with carbon-intensive iron.

Indonesia,[210] Thailand[211] and Vietnam[212] are developing emissions trading systems, although coverage is limited and prices are unlikely to be high enough to support green iron imports.[213] And despite some incentives to support green steel demand and production, current plans across ASEAN countries are dominated by expanded BF-BOF capacity.[214]

But there is a window of opportunity for Australia to establish early trade in green iron. Blast furnaces are planned rather than established, and will dramatically increase ASEAN carbon emissions and make progress to net-zero harder.[215] Australian green iron can help ASEAN nations grow their industrial capacity without compromising their international commitments.

India

A 2070 net-zero target and weak decarbonisation policies mean India is unlikely to be an early destination for Australian green iron, despite being the world's second-largest steel producer.

India produced over 140 million tonnes of steel in 2023,[216] and it is projected to have the strongest growth in steelmaking capacity.[217] India has a large domestic supply of iron ore, and imports only modest amounts from Australia.[218]

The Indian Ministry of Steel has published its 'Greening the Steel Sector in India' roadmap,[219] but it will not motivate a transition to low or near-zero-carbon steel. The Indian government's definition of "green" steel includes steel with up to 2.2 tonnes of embedded carbon per tonne of steel – the international average for carbon-intensive BF-BOF steel. And steel can earn the government's highest "green star" rating if it is produced with up to 1.6 tonnes of carbon per tonne of steel. Together with plans to dramatically expand its steelmaking sector,[220] India's policies will lead to substantial growth in carbon emissions.

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[210] ICAP, 'Indonesian Economic Value of Carbon (Nilai Ekonomi Karbon) Trading Scheme'.

[211] ICAP, 'Thailand ETS Map'.

[212] ICAP, 'Vietnam ETS Map'.

[213] For example, Indonesia's ETS will cover the power sector and the price sits at about $6.50 per tonne of carbon. See: ICAP, 'Indonesia Launches Emissions Trading System for Power Generation Sector'; and ICAP, 'Indonesian Economic Value of Carbon (Nilai Ekonomi Karbon) Trading Scheme'.

[214] Ju and Hui Tan, 'Southeast Asian Steel Capacity Expansion Unsustainable: SEAISI'.

[215] Ju and Hui Tan.

[216] World Steel Association, 'Total Production of Crude Steel'.

[217] Climate Group and ResponsibleSteel, 'India Net Zero Steel Demand Outlook Report'.

[218] Fairweather and Sutton, 'Economic Developments in India'.

[219] Ministry of Steel, 'Greening the Steel Sector in India: Roadmap and Action Plan'.

[220] Zong and Li, 'India's Expansion Plans to Reshape Asia's Stainless Steel and Raw Materials Markets'.

Our recommended support will help green iron compete with carbon-intensive iron in the near term, but until India's government prioritises less emissions-intensive growth, India is very unlikely to be a long-term destination market for green iron.

6.3 Companies' commitments are not yet ambitious enough to create strong demand for green iron

A small number of steelmakers in Australia's trading partners have decarbonisation plans that are more ambitious than their governments' commitments and policies.

POSCO Group produces more than half the steel manufactured in South Korea.[221] It has a net-zero target for 2050 and a 2030 goal to reduce emissions by 37 per cent against a 2021 benchmark. POSCO also has a more developed decarbonisation pathway than most companies, with a 59 per cent reduction target for 2040.[222] POSCO's decarbonisation targets are reflected in its development of green iron projects, including a project proposed for the Pilbara (Box 2 in Chapter 1).

Two major Chinese companies have 2050 net-zero targets, which are more ambitious than China's 2060 net-zero commitment. Baowu Steel Group is the world's largest producer of steel, and has a net-zero target for 2050 and an interim target of a 30 per cent emissions reduction target by 2030, benchmarked against a 2020 baseline.[223] Early efforts have focused on reducing emissions from blast furnace technology,[224] alongside the completion of a single 'green hydrogen-ready' plant for 1 million tonnes of iron. HBIS Group also has a 2050 net-zero commitment, with a 30 per cent reduction target for 2030 against a 2022 baseline, and has constructed a 'green hydrogen-ready' plant with demonstrated production of up to 600 thousand tonnes of iron each year. Further details for these projects are set out in Appendix 2.

Corporate commitments are not collectively strong enough to decarbonise the steelmaking sector at the pace required.

Fewer than half the world's 50 largest steel producers have net-zero targets for 2050.[225] And although some of the companies with 2050 targets also have nearer-term targets, very few interim targets are ambitious, or supported by detailed decarbonisation plans.[226]

Japanese steelmakers have adopted the Japanese Government's target of 30 per cent reductions by 2030, but it is against the high benchmark of 2013 emissions. Collectively, these producers only need to reduce emissions by 10 per cent before 2030.[227] South Korea's second-largest steelmaker, Hyundai, is targeting a modest 12 per cent emissions reduction by 2030 against a 2021 benchmark,

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[221] South Korea produced 63.5 million tonnes of steel in 2024: World Steel Association, 'December 2024 Crude Steel Production and 2024 Global Crude Steel Production Totals'; POSCO produced 33.1 million tonnes in 2024: Yermolenko, 'POSCO Reduced Steel Production by 1.1% y/y in 2024'.

[222] POSCO International, 'POSCO International Will Be Carbon Neutral by 2050'.

[223] Staff and Yep, 'China's Decarbonization Goals Get Boost from Baowu's Carbon Reduction Plans'; and SMM, '"China Baowu Carbon Neutralization Action Plan" Released to Explore New Ideas of Green Low-Carbon Metallurgy in the Industry'.

[224] World Steel Association, 'China Baowu: Development and Application of Low-Carbon Metallurgical Technology Based on HyCROF'.

[225] Leadit, 'Green Steel Tracker'.

[226] Swalec and Torres, 'A Matter of Transparency: 2024 Insights on the Steel Industry's Evolving Commitments to Reach Net Zero by 2050'. See Appendix 9 for summary of major steelmarkers' commitments.

[227] An emissions reduction of less than 10 per cent by 2030, versus emissions in 2022.

and will require very rapid emission reductions to achieve net zero in 2050.[228] And most producers in China do not have net-zero or interim decarbonisation targets.

6.4 Three reasons to anticipate higher future demand

Although government and corporate decarbonisation policies are not yet strong enough to create demand for Australian green iron exports, our recommended support for early producers, alongside production tax credits, will help Australian green iron compete with carbon-intensive iron. And there are three good reasons to expect a faster, smoother decarbonisation transition than current commitments suggest – and therefore future demand for green iron.

The first is that green iron can be used in existing BF-BOF production pathways. The second is that cycles of expensive investments in blast furnaces create natural prompts to consider production pathways that use imported green iron. The third is that government policies can achieve remarkably quick shifts in production methods – when there is political will, Australian green iron will provide a way to decarbonise steel production.

6.4.1 Trade partners already import direct-reduced iron

Iron products – Hot Briquette Iron (HBI) and pig iron – can be used in existing BF-BOF production pathways. There are no technical barriers to using Australian green iron.

The market for HBI and pig iron is currently small as a share of the market for globally traded iron ore products – about 2 per cent, by volume.[229] But as the world decarbonises, economic pressures will push iron production to countries where renewable energy is abundant and cheap, dramatically increasing the trade in green HBI.

South Korea and Japan already have experience integrating iron imports into their steelmaking processes, importing about 600 thousand tonnes of HBI each year.[230] Both countries pay a price ranging from $130 to $290 per tonne above average global prices.[231] China imports about 376 thousand tonnes, at prices close to the global average. The European Union imports an average of 2.5 million tonnes of HBI each year – mostly into Italy and Germany – at prices close to the global average.[232] India imports 617 thousand tonnes of hot briquette iron each year, but weak policies for steel decarbonisation mean it is unlikely to be a destination for Australian green iron (Figure 28).

[228] Hyundai Steel, 'Hyundai Steel's Roadmap to Carbon Neutrality'.

[229] 1.54bt of non-agglomerated iron ore trade in 2023 and an average of 29.5mt of HBI and pig iron products traded from 2019 to 2023. See WITS, 'Non-Agglomerated Iron Ores and Concentrates Exports by Country'; WITS, 'Ferrous Products Obtained by Direct Reduction of Imports by Country 2022'.

[230] South Korea: 545 thousand tonnes; Japan 58 thousand tonnes, equivalent to about 10% of imported iron ore by weight for both countries. Almost all South Korean and 80 per cent of Japanese HBI imports come from Malaysia. WITS, 'Ferrous Products Obtained by Direct Reduction of Imports by Country 2022'.

[231] World Bank data does not include granularity on characteristics of HBI products imported, leaving weighted average price paid as an imprecise indicator (i.e., notwithstanding potentially higher costs to certain countries due to transport, specific product characteristics, etc.) of quality of HBI.

[232] Based on weighted imports and prices from 2010.

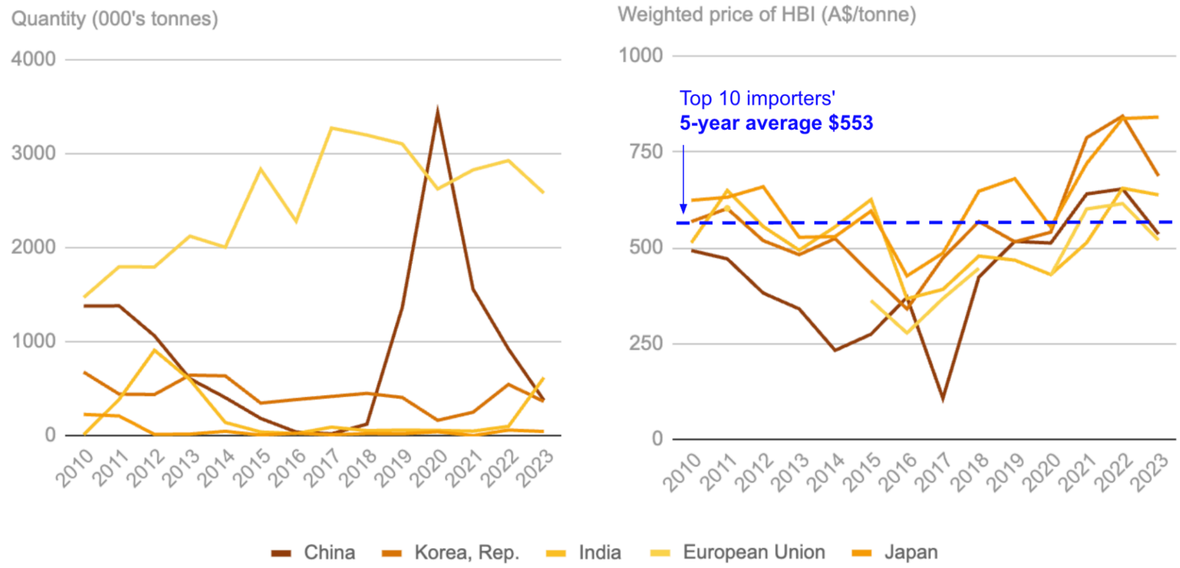

Figure 28: South Korea and Japan already import premium iron

Note: Figures are in 2023 AUD. World refers to the average global weighted price of HBI imports.
Source: World Bank World Integrated Trade Solution (WITS)[233]

Australia can capitalise on trade partners' experience importing iron for use in existing production pathways, to progressively increase the share of green iron feeding existing blast furnaces.

6.4.2 Investment cycles create opportunities for green iron

If green iron imports are available, blast furnace relining cycles create a natural opportunity for producers to consider the benefits of green iron imports.

Blast furnaces typically need to be relined every 13-17 years.[234] It is an expensive investment that prolongs carbon-intensive production.[235] Costs in South Korea and Japan range between $450 and $550 million, representing 9-14 per cent of the cost of setting up a typical blast furnace.[236] Other estimates suggest relining requires 33 to 50 per cent of the capital expenditure needed for new furnace construction, with costs ranging from $405 to $435 million.[237] There is also an additional cost

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[233] WITS, 'Ferrous Products Obtained by Direct Reduction of Imports by Country 2023'.

[234] POSCO, 'Port Hedland Green Steel Project - Decarbonisation Project - Emissions Assessment', 82; Vogl, Olsson, and Nykvist, 'Phasing out the Blast Furnace to Meet Global Climate Targets', 2650; All relines in the Global Energy Monitor dataset, including partial and full relines, occur every 14 years on average, and every 20 years when considering only full relines: Armbruster, Grigsby-Schulte, and Swalec, 'Pedal to the Metal 2024', 8.

[235] The cost and timing of BF relines vary significantly and depend on factors such as the degree of deterioration, quality of materials used in the repair, and areas of repair. See Sadri et al., 'Principles for Blast Furnace Refractory Lining Inspection and Monitoring'.

[236] Based on the setup capital cost of a 4 million tonne per annum blast furnace. Posco relining Pohang Blast Furnace No. 4 cost AUD552 million: Kolisnichenko, 'POSCO Invests $381.7 Million to Modernize Blast Furnace No. 4 in Pohang — News — GMK Center'; Nippon No. 2 Blast Furnace of Hokkai Iron & Coke Corporation cost estimate AUD443 million: Nippon Steel, 'Relining of No. 2 Blast Furnace of Hokkai Iron & Coke Corporation and Refurbishing of No. 3 Coke Oven of Nagoya Works'; BHP, 'Pathways to Decarbonisation Episode Two'; Baig, 'Cost Effectiveness Analysis of HYL and Midrex DRI Technologies for the Iron and Steel-Making Industry'.

[237] Vogl, Olsson, and Nykvist, 'Phasing out the Blast Furnace to Meet Global Climate Targets'.

from stopping production during the 2-4 month installation period,[238] equivalent to between $425 and $850 million for a plant producing 4.5 million tonnes each year.[239]

Forty-six million tonnes of annual blast furnace capacity will soon need to be relined across Europe and parts of the Asia Pacific, with an additional 25 million tonnes of annual capacity due for relining by 2030. Most of the blast-furnace capacity due for relining is in Japan, with substantial relining also required in European blast furnaces (Figure 29).[240]

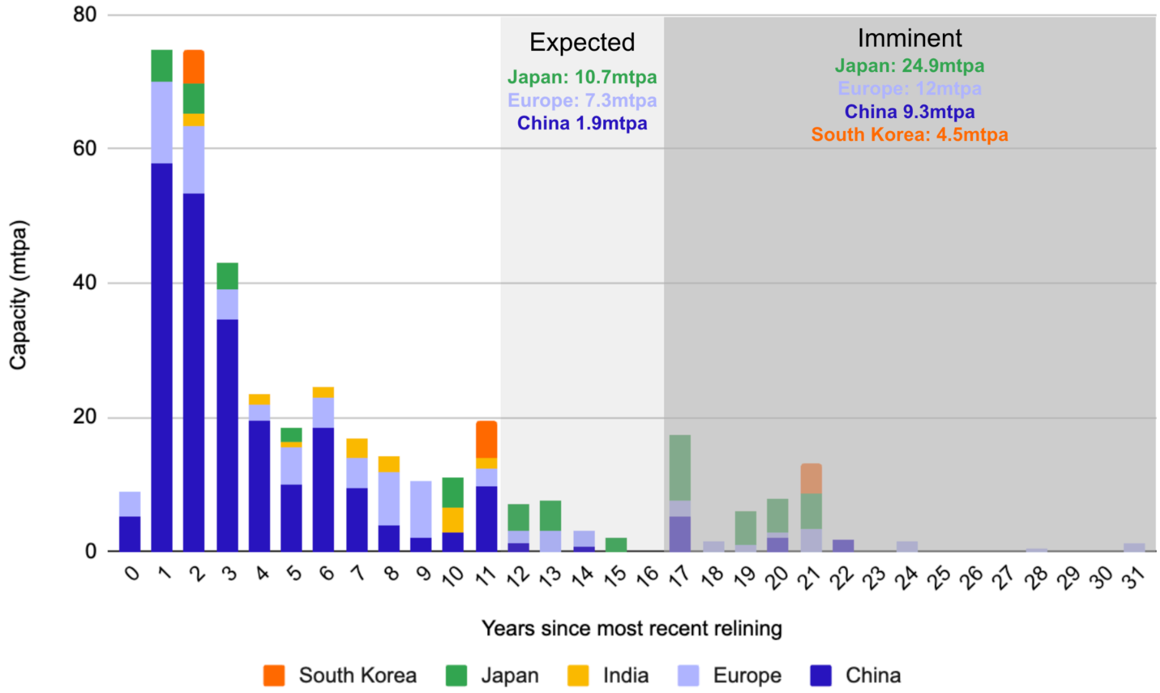

Figure 29: Many Japanese blast furnaces require relining

Note: Imminent relining decision is defined as 17+ years since last relining. Expected reline is defined as 12-17 years since last reline. Outlier EU BF units are British Steel Scunthorpe and SSAB Oxelösund units. The former has been earmarked for retirement and the latter has been announced to be retired in 2025. Data is constrained to furnaces with publicly available information on relines.
Source: GEM BF Tracker[241]

If countries have 2050 net-zero commitments, and if companies run blast furnaces until they require relining, countries need to phase out relining before 2035. This is a natural prompt to transition to lower-carbon steelmaking in electric arc furnaces, fed with green iron imports.

[238] ArcelorMittal, 'Blast Furnace Relining Has Commenced in Belgium'; Salzgitter AG, 'Blast Furnace A Fired up Again after Relining'; Voestalpine, 'Blast Furnace 5 Again Blown In'.

[239] For a 4mtpa BF selling at the average global price of $640/tHBI.

[240] Agora finds that more blast furnaces need to be relined, sooner, with more than 70 per cent of global operating blast furnace capacity expected to reach the end of its operating life by 2030: Agora Industry, 'Global Steel Transformation Tracker'; If 'end of operating life' is defined as less than 17 years this conclusion is broadly consistent with conclusions based on Global Energy Monitor data. Our more conservative analysis is consistent with others; see, for example: Chen et al., 'Pursuing Zero-Carbon Steel in China', 9; IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking'.

[241] Global Energy Monitor, 'Global Blast Furnace Tracker'.

6.4.3 Industries will reconfigure quickly when governments prioritise decarbonisation

South Korea, Japan, and China already have production pathways that incorporate imported iron, and investment cycles are natural prompts for steel producers to switch to green iron imports. And if governments commit to rapid decarbonisation of their steel sectors, industries can and will transition particularly quickly.

Two case studies demonstrate how economic, environmental, and social pressures have seen large-scale industries relocate within remarkably short timeframes: Japan's aluminium smelting industry, in response to the 1970s oil crisis, and China's steelmaking in Hebei province (Boxes 9 and 10).

Box 9. The Japanese government shut down aluminium production after the 1970s oil crisis

During the 1960s, Japan's energy-intensive aluminium sector grew at nearly 20 per cent each year, with investments continuing into the early 1970s. Nearly three-quarters of the energy was provided by oil-fueled power plants. But the oil crisis of 1973-74 made it impossible for Japanese aluminium to compete with producers using cheaper energy, including smelters largely powered by hydroelectric power in Canada and the US.[242]

By 1977, aluminium smelting was classified as a "Depressed Industry". 1978 saw the introduction of Japan's "Industry Stabilisation Law",[243] with a third of production scrapped and government programs to maintain employment. The Iranian Oil Crisis of 1979 deepened the economic pressure caused by high energy prices, and by 1980, imported aluminium exceeded domestic production. 1983's "Law on Temporary Measures for the Structural Improvement of Specified Industries" led to nearly all remaining aluminum production being scrapped,[244] again with government support for employees.[245] This was the trigger for heavy investment in Australian smelters in Newcastle, Gladstone and Portland, which made Australia a major exporter of aluminium.

Box 10. The Chinese government can quickly reshape its steelmaking industry

In 2013, China introduced 'capacity replacement' rules to reduce production capacity in carbon-intensive sectors, including steelmaking. Replacement conditions were strictest in 'environmentally sensitive' areas, including the populous cities of Beijing and Tianjin, and the surrounding Hebei province.[246]

[242] Samuels, 'The Industrial Destructuring of the Japanese Aluminum Industry', 391.
[243] Committee on the History of Japan's Trade and Industry Policy RIETI, 'Japan's Industrial Structure'.
[244] Samuels, 'The Industrial Destructuring of the Japanese Aluminum Industry', 391.
[245] Rajan and Gupta, 'HRM Strategies in Structurally Depressed Industries: The Japanese Approach'.
[246] Transition Asia, 'Decoding China's Steel Capacity Replacement Policies'.

6.5 The Australian government should work with trade partners to build demand for green iron

Australia's trading partners will benefit from importing green iron, and these benefits will become more obvious as net-zero deadlines get closer. But in the early stages of the green-iron transition, the Australian government has a role to play in working with trade partners to recognise the mutual benefits of Australian green iron production.

6.5.1 The government should demonstrate the benefits of importing green iron

It is only 25 years until Japan and South Korea need to meet their net-zero commitments, and 35 years before China needs to reach net zero.

The New Energy Trade shows that this transition will be less costly if steelmaking nations import green iron from Australia, which has a comparative advantage in zero-carbon energy-intensive goods: it will be cheaper than making iron with local zero-carbon energy, or importing green hydrogen or ammonia. Countries that do not transition to the lowest-cost production pathways for green steel will make it harder for their steel-using manufacturing industries to compete in international trade. Green iron imports will give countries the best chance of retaining steelmaking and manufacturing industries.

Even if countries or companies hope to decarbonise their steelmaking industries by investing in gas-based DRI, investments in Australian green iron are a valuable hedging strategy. Firms will develop early knowledge and establish trade relationships that will be important if carbon prices rise faster than expected, or if CCS technology proves too costly for decarbonising gas-based DRI.

But major trading partners do not yet recognise the scale of long-term benefits from importing green iron, so policies for the steelmaking sectors lack urgency and ambition. This is true even in Japan and South Korea, which will face the most immediate and acute economic pressures as the world decarbonises. This will be costly – for example, Japan's plans to import green hydrogen and to decarbonise steelmaking using carbon capture and storage will be expensive and outcomes are very uncertain.

The Australian government should work closely with our trade partners to build the economic evidence base for appropriate macroeconomic and trade policies as the world decarbonises.

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[247] Hebei closed more than 60 million tonnes of steel capacity and slashed coal use by 40 million tonnes over the 2013-2017 period: Reuters, 'China's Hebei Vows More Heavy Industry Capacity Cuts by 2020'.
[248] The Fastmarkets team, Li, and Zong, 'China's 2024 "Blue Sky War" to Add Uncertainty to Iron and Steel Markets: 2024 Preview'.
[249] Transition Asia, 'Decoding China's Steel Capacity Replacement Policies'.

This work can be done in the context of strong existing relationships. Australia has high-level climate change and clean energy partnerships with China, Germany, India, Japan, Singapore, South Korea, the UK, the US, and the Netherlands.[250] But these arrangements largely focus on technology research and development. Trade-oriented partnerships focus on green hydrogen exports, including alliances with Germany[251] and the Netherlands;[252] Australia also has a decarbonisation partnership for joint projects with Austria.[253] The only government-level collaborations that prioritise green steel are with South Korea and Japan, supporting collaboration on low and zero emissions technologies.[254]

Although current world events create uncertainty, centring on disruption caused by US trade policy, it would be costly to allow this to divert Australia from the path we are on, particularly with trade partners outside of the US. Existing strategic relationships provide continuity and certainty for Australia's trade partners. These relationships can be the basis of mutually beneficial collaboration on green iron projects, resolving coordination challenges as our trade partners decarbonise their steelmaking industries while Australia establishes a green iron export industry.

Existing arrangements complement but are no substitute for research to quantify the shared benefits of trade. Evidence on the benefits of trade provides the economic motivation for trade partners to support green iron projects in Australia, while efficient Australian government support makes production and trade possible.

Recommendation 7

The Australian government should strengthen support for research on countries' economic challenges and trade opportunities as the world decarbonises.

6.5.2 The government should establish co-funding mechanisms with trade partners

The Australian government will provide support for green iron through the Hydrogen Production Tax Incentive, and we have recommended capital support for early producers (Section 5.3).

These policies reduce the cost of green iron for Australia's trade partners. Alongside research into the shared benefits of trading green iron (Recommendation 7), the government should also work with trade partners to support investors leading green iron projects and to secure financial support for projects producing green iron in Australia.

Because climate change is a global problem, and because trade benefits both countries, our preferred arrangement would be for trade partners to match the level of support provided by the

[250] DCCEEW, 'Australia's International Climate and Clean Energy Partnerships'.

[251] AHK, 'German-Australian Hydrogen Alliance'; DCCEEW, 'Joint Media Release: $660m to Advance Australia and Germany's Cooperation on Energy and Climate'.

[252] Kingdon of the Netherlands, 'The Energy Transition and Green Hydrogen - Finding Solutions Together'.

[253] Australian Government, 'Australia–Austria Industrial Decarbonisation Demonstration Partnerships Program'.

[254] Department of Industry, Science and Resources, 'Strengthening Low Emissions Technology Cooperation with the Republic of Korea'; Department of Industry, Science and Resources, 'Japan-Australia Partnership on Decarbonisation through Technology'.

Australian government through its Hydrogen Production Tax Incentive, our proposed Green Iron Production Tax Credit, and capital support for early producers.

Governments could provide this support with a mix of subsidies or regulations that achieve the same effect, including carbon pricing.

Japan and South Korea already have schemes supporting low-carbon hydrogen imports.[255] These schemes provide subsidies, development of certification standards, and support for transport and other infrastructure. These policies could be the basis for extended and more ambitious programs that also cover imports produced with low-carbon hydrogen, or new programs tailored to support green iron imports.

The Australian government will need to work closely with trade partners and industry to help design incentives and frameworks. This could take place through existing multilateral arrangements, like the Asia-Pacific Economic Cooperation (APEC), or bilateral arrangements, like the Australia-Republic of Korea Green Economy Partnership Arrangement on Climate and Energy[256], or the Japan-Australia Economic Dialogue.[257] With heightened interest in the Regional Comprehensive Economic Partnership and the Trans-Pacific Partnership, these are also promising arenas for deepening cooperation in trade that supports the decarbonisation transition.

Recommendation 8

The Australian government should work with trade partners to secure financial support for Australian green iron production. This may come in the form of contributions by trade partner governments toward the supports described in Recommendations 1 and 2. Such contributions would recognise the shared benefits of successful Australian green iron production, to both Australia and our trade partners.

6.5.3 The government should support consumer demand for green iron and steel

Consumer premiums for green steel are supporting early investments in green iron (Section 5.1.2). Although voluntary premiums are no substitute for government-led decarbonisation policies, the Australian government should support and strengthen international consumer certification schemes.

Different organisations have different definitions of green steel, including the World Steel Association,[258] ResponsibleSteel,[259] the International Organisation for Standardisation (ISO);[260] the

[255] JOGMEC, 'Japan Organization for Metals and Energy Security Support'; Baker McKenzie Resource Hub, 'Global Hydrogen Policy Tracker: South Korea'.

[256] DCCEEW, 'Australia and the Republic of Korea Strengthen Cooperation on Climate and Energy'.

[257] The Treasury, 'Japan-Australia Economic Dialogue Joint Statement'.

[258] Purvis and Walters, 'What We Mean When We Talk about Low-Carbon Steel'.

[259] ResponsibleSteel, 'ResponsibleSteel Launches New Version of International Standard to Drive down Steel Emissions and Improve Sustainability across the Supply Chain'.

[260] ISO 14404-4, 'Calculation Method of Carbon Dioxide Emission Intensity from Iron and Steel Production Part 4: Guidance for Using the ISO 14404 Series'.

Industrial Deep Decarbonisation Initiative (IDDI),[261] the SteelZero Initiative,[262] the Science-Based Targets Initiative for Steel[263] and the RMI Sustainable Steel Principles.[264] The EU,[265] US,[266] China,[267] Japan,[268] and South Korea also have their own definitions.[269] Schemes vary in their treatment of emissions levels, whether emissions are measured in absolute or intensity-based units, whether scope 1, 2 or 3 emissions are included, and technology requirements.

Competing schemes create certification costs for producers, and erode buyers' confidence and willingness to pay for 'green'. Clarifying and consolidating these schemes would build market confidence, reduce the risk of 'green washing',[270] and support public and private sector purchasing initiatives to strengthen market demand.[271]

6.5.4 The government should continue to advocate for carbon pricing

To hold global warming well below 2 degrees Celsius, and to have a chance of limiting warming to 1.5 degrees, the international community will need a system of international carbon prices that reflect the social cost of carbon, supported by carbon border adjustments. Without an international system of carbon prices, the Australian government has to use a mix of domestic policies and diplomacy to overcome this market failure. Budget constraints limit the extent to which domestic policies can replace the incentives provided by international carbon pricing.

A system of carbon prices would support green iron and steel production: investments would reflect countries' comparative advantage in each stage of production, and trade would reduce the collective cost of decarbonising an industry that generates about 8 per cent of global emissions. Australia would be a green export superpower.

This report recommends policies that simulate the effects of a carbon price, including production tax credits for green hydrogen, and measures to reduce the cost of investing in renewable energy. It also shows that intergovernmental engagement is essential for establishing early trade.

But because Australia's economy and environment will be particularly badly damaged by climate change, and because Australia has a comparative advantage in green exports, including iron, the Australian government needs to clearly demonstrate its support for international decarbonisation efforts, and in particular for an international system of carbon prices. Australia's advocacy will be more effective if it has carbon pricing in place itself.

[261] UNIDO, 'Industrial Deep Decarbonisation Initiative'.
[262] Climate Group Steelzero, 'Building Demand for Net Zero Steel'.
[263] SBTi, 'Steel Science-Based Target-Setting Guidance'.
[264] Kooijmans, 'The Sustainable STEEL Principles: Forging a New Paradigm'.
[265] European Commission, 'Green Public Procurement Criteria and Requirements'.
[266] Office of the Federal Chief Sustainability Officer, 'Federal Buy Clean Initiative'.
[267] Climate Bonds Initiative, 'A Green Steel Decade for China'.
[268] The Japan Iron and Steel Federation, 'Guidelines for Green Steel upon the Application of the Mass Balance Approach Version 2.0'.
[269] KEITI, 'Eco Label & Green Consumption'.
[270] Hasanbeigi and Sibal, 'What Is Green Steel? Definitions and Scopes from Standards, Initiatives, and Policies around the World. Global Efficiency Intelligence'.
[271] Climate Group Steelzero, 'Building Demand for Net Zero Steel'; ResponsibleSteel, 'We're Shaping a More Responsible Steel Industry'.

Recommendation 9

The federal government should use international platforms to advocate for a system of international carbon prices. It should demonstrate Australia's commitment to the Paris Agreement with policies that impose or simulate the effects of a carbon price consistent with net-zero carbon emissions by 2050.

Appendices

Appendix 1: Australia has a comparative advantage in renewable energy in a decarbonising world

The New Energy Trade shows that Australia has abundant renewable energy resources and low demand. With the right investments and policies, Australia could have a comparative advantage in renewable energy.

The price of renewable energy in each country depends on the cost of supplying an additional unit of energy, at the quantity that meets total demand.

Renewable energy costs depend on natural resources and installation costs

Australia has remarkable renewable energy resources. It is large, with solar irradiance levels comparable to solar-rich areas like northern Africa and the Middle East.[272] Australia also has excellent wind resources, particularly along its western, southern, and southeastern coasts, with high wind speeds extending hundreds of kilometres inland and across elevated regions.[273] Many regions have a high ‘combined’ renewable energy capacity factor because wind and solar production patterns are complementary, reducing intermittency.[274]

Australia also benefits from low seasonality in its renewable energy resources, supplying relatively consistent year-round energy at low cost. Strongly seasonal weather patterns require expensive investments that are productive in one season but sit idle in another. For example, wind capacity varies dramatically between monsoon and non-monsoon seasons in equatorial areas.

These excellent renewable energy resources can be harnessed with investments in technology, transmission, and storage. It is the combination of renewable resources and low investment costs that delivers abundant, low-cost renewable energy.

A major cost is land for large-scale solar installations or wind turbines. Australia is unusually rich in marginal land that has no high-value competing uses, and can therefore be cheaply acquired.

Australia also has a low cost of capital – the cost of borrowing money to invest in large projects. Together with project-specific risks, country-level risks are a major determinant of the cost of capital. These include political, regulatory, and economic risks, such as the sustainability of a country’s sovereign debt and currency risk. Country-level risk has a dramatic effect on the cost of renewable energy projects: estimates suggest that if large-scale solar projects shared Europe’s low political and economic risk ratings, the cost of capital would be reduced by 8 per cent in China, 43 per cent in Brazil, 32 per cent in India, 36 per cent in Indonesia, 31 per cent in Mexico, and 26 per cent in South Africa.[275] Australia’s political, regulatory, and economic stability will help it harness its abundant resources at low cost.

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[272] Geoscience Australia, ‘Solar Energy’; Energy & Mining, ‘World-Class Resources’.

[273] Geoscience Australia, ‘Wind Energy’; Geoscience Australia, ‘Renewable Energy Capacity Factor Maps’.

[274] Prasad, Taylor, and Kay, ‘Assessment of Solar and Wind Resource Synergy in Australia’; Wu and West, ‘Co-Optimisation of Wind and Solar Energy and Intermittency for Renewable Generator Site Selection’.

[275] IEA, ‘Tools and Analysis – Cost of Capital Observatory’.

Demand for renewable energy

While the global supply of renewable energy is practically unlimited, the *cheapest* renewable energy resources are relatively scarce. Competitive energy-intensive industries require high capacity factors, low seasonality, and cheap land.

As countries install renewables, they progressively deplete cheaper renewable energy resources and move on to more expensive resources that are higher up the supply curve. The more a country's demand for electricity rises, the more it will move up its renewable energy supply curve into high marginal prices. Countries avoid high marginal electricity prices if they have levels of demand that can be met along the low-cost stretch of a supply curve.

A country's demand for renewable electricity is a major determinant of the renewable energy price. In The New Energy Trade, Finighan distinguishes between two components of a country's demand for energy: 'tradeable' and 'non-tradeable' energy demand.

'Tradeable' demand is from industries that can physically relocate from one country to another: this component of demand can be 'traded' away if producers move to another country. A country's tradeable demand depends on the size and energy intensity of industries that produce easily traded products, such as iron.

'Non-tradeable' demand includes the electricity used to light, heat, and cool buildings, to power vehicles, and or to power industries whose products are not easily traded. This kind of electricity demand cannot be traded away; it must be satisfied with zero-carbon energy produced domestically, or imported at high cost.

For a country to be competitive in green exports in a decarbonised world, it is not enough to have abundant renewable energy. If a country's non-tradable demand is large enough to exhaust abundant resources, then it cannot competitively support energy-intensive industries. This will be the case in major economies including China, India, and Europe.

If a country's non-tradable demand is small compared to its cheap renewable energy resources, it will have a large capacity to support tradable demand, and therefore green export industries.

Compared to key trading partners and steelmaking nations, Australia has high renewable energy capacity factors and low seasonality, even at the levels of demand associated with mid-century electrification and decarbonisation of industrial processes (Table 6).[276]

[276] See Finighan, 'The New Energy Trade' page 9 for a detailed explanation.

	Solar capacity factor	Seasonality	Wind capacity factor	Seasonality
Australia	**26%**	Low to moderate	**30-35%** onshore at multi-TW	Low to moderate
China	**17%**	Moderate to high	**<25%** in north at multi-TW, **<20%** elsewhere	High to very high
India	**18%**	High	**<14%** onshore at multi-TW	Very high to extreme
Japan	**13%**	Low	**<20%** onshore at multi-GW	Moderate to high
South Korea	**14%**	Low to moderate	**<20%** onshore at multi-GW	High to very high
Germany	**11%**	Very high	**<20%** onshore at multi-GW	Moderate to high

Table 6: Australia has excellent renewable energy resources

Notes: Marginal wind and solar capacity factors, at the estimated scale of electricity demand if countries electrify industrial processes.
Source: Finighan (2024)[277]

[277] Finighan.

Appendix 2: International green iron projects

Table 7: Summary of international green iron projects.

Notes: Summary including projects that use ‘green-hydrogen ready’ technology; producers may not transition away from fossil fuels.

Sources: See ‘Company/project name’ column.

Country	Company / project name	Progress in early 2025	Technology	Target mtpa	Source of green hydrogen / gas	Planned commencement	Notes
Belgium	ArcelorMittal[278]	Financial investment decision (FID) delayed					
Canada	ArcelorMittal[279]	Construction is yet to begin	Energiron ‘hydrogen-ready’	2.5	Not stated	2028	The project has missed key milestones.
China	HBIS Group[280]	Completed	Energiron ‘hydrogen-ready’	1.2	Not stated		Has demonstrated production of 600,000 tonnes per annum.
China	Baowu Steel Group[281]	Completed	Energiron ‘hydrogen-ready’	1	Not stated		A combination of gas and grey hydrogen will be utilised, with the ability to use green hydrogen in the future.
Finland	Blastr[282]	Second round of financing, yet to reach FID	Midrex ‘hydrogen-ready’	2.5	On-site	2027	
France	ArcelorMittal[283]	FID delayed					

[278] Segal, ‘ArcelorMittal Delays Green Steel Investments Due to Unfavorable Policy, Market Environments’.

[279] Beattie, ‘ArcelorMittal Dofasco Misses Key Milestones in $1.8B “green” Steel Project Promised for 2028’.

[280] HBIS, ‘First in Global, HBIS Launching Hydrogen Shaft Furnace & Zero Carbon Emission Arc Furnace Project, A New Short Process Project’.

[281] Danieli, ‘New Energiron® DRI Plant Starts Production at Baowu’.

[282] Blastr Green Steel, ‘Blastr Green Steel Chooses Primetals Technologies as Its Technological Partner for the Ultra-Low CO2 Emissions Steel Plant in Inkoo, Finland - MIDREX H2™ Chosen for the Direct Reduction Plant’.

[283] Segal, ‘ArcelorMittal Delays Green Steel Investments Due to Unfavorable Policy, Market Environments’.

France	GravitHy[284]	Will be commissioned in 2028	Midrex 'hydrogen-ready'	2	On-site	2028	
Germany	ArcelorMittal [285]	FID delayed					
Germany	Salzgitter Flachstahl[286]	Under construction	Energiron 'hydrogen-ready'	2.1	On-site	2026	The goal of exclusively green hydrogen from 2033. Offtake agreement with Volkswagen.
Germany	Thyssenkrupp[287]	Under construction	Midrex 'hydrogen-ready'	2.5	Regional producers	2027	Will initially use natural gas; green hydrogen planned for 2028 but likely to be delayed.
Mexico	DeAcero[288]	Construction being planned	Energiron 'hydrogen-ready'	1	Not stated	2026	
Mongolia	HBIS Group[289]	Under construction	Not announced	2	On-site	2025	A green hydrogen production plant is reported on-site; commitment to green versus grey hydrogen unclear.
Namibia	HyIron [290]	Construction of the first project is nearly complete	HyIron rotary shaft furnace	0.015	On-site	2025	The initial production target of 15,000 tonnes per year, increasing to 200,000 tonnes in 2025 and 1-2 million tonnes in 2030.
Netherlands	Tata Steel[291]	First phase': Contracts awarded for	Energiron 'hydrogen-ready'	3	Under contract -- likely Norwegian green hydrogen	2030	

[284] Spaener, 'Focus on Green Metal Industries at Bright World of Metals'; Parkes, 'Green Steel Group Plans Giant Electrolyser Array in France for Hydrogen-Derived "Direct Reduced Iron"'; Rio Tinto, 'Rio Tinto and GravitHy Join Forces to Accelerate the Decarbonisation of Steelmaking in Europe'.

[285] Segal, 'ArcelorMittal Delays Green Steel Investments Due to Unfavorable Policy, Market Environments'.

[286] Danieli, 'Salzgitter Flachstahl Selects Energiron DR Technology'; Hydrogen Insight, 'Salzgitter Begins Construction of 100MW Green Hydrogen Plant to Supply Low-Carbon Steelmaking'.

[287] Midrex, 'Thyssenkrupp Steel Selects MIDREX Flex™ for Immediate CO2 Emissions Reduction - Midrex Technologies, Inc.'; Hydrogen Insight, 'Thyssenkrupp Will Run Direct Iron Reduction Plant on Fossil Gas "longer than Expected" Due to High Price of Green Hydrogen'.

[288] Pipoli, 'Mexico's Deacero to Add to Green Steel Portfolio with New Plant'.

[289] SMM, 'Another New Project For Hydrogen Direct Reduction Iron Has Been Announced. How Profitable Such Projects Are Remains To Be Seen'.

[290] HyIron, 'Project Oshivela'.

[291] Bolotova and Kahramanova, 'Tata Steel Moves Forward with First Phase of "Green Steel" Plan in the Netherlands'; Martin, 'Tata Steel to Import Liquid Hydrogen from Norway to Netherlands for Green Steelmaking'.

		engineering of DRI and EAF					
Oman	Mitsui [292]	MoU announced	Midrex	5	Local gas	2027	
Oman	Vulcan (Jindal Steel Group)[293]	Under construction	Energiron 'hydrogen-ready'	6	Regional producers	2027	Offtake agreements are in place, including Volkswagen
Saudi Arabia	Bauwu Steel Group[294]	MoU announced	'Hydrogen ready' – type not announced	2.5	Local gas	2026	MoU with Aramco and PIF.
South Korea	Posco[295]	Construction is being planned	HyREX Fluidised Bed	2.5	Committed to green hydrogen from 2050	2030	Pilot plant produced DRI. Construction of the demonstration plant is expected in 2027, with commercial production from 2030. 2.5 million tonnes per annum is the target for DRI production by 2040.
Spain	ArcelorMital	FID delayed					
Spain	Hydnum Steel[296]	Construction being planned; priority project status.	Midrex 'hydrogen-ready'	1.5	Regional producers	2026	1.5 million tonnes per annum from 2026 and 2.6 million tonnes per annum from 2030. Offtake agreement with Gonvarri Industries.
Sweden	Stegra[297]	Under construction	Midrex 'hydrogen-ready'	2.1	On-site	2026	
Sweden	Hybrit[298]	Pilot successful; builders contracted for	Energiron 'hydrogen ready'	1.2	On-site	2035	

[292] Global Flow Control, 'Kobe Steel Is Working with Mitsui on a Low CO2 Iron Metallics Project in Oman'; Institute for Energy Economics and Financial Analysis, 'Hydrogen Holds Great Potential for Australia's Onshore Green Iron Production'.

[293] 'Vulcan Green Steel'.

[294] Aramco, 'Aramco, Baosteel and PIF Sign Agreement to Establish First Integrated Steel Plate Manufacturing Complex in Saudi Arabia'.

[295] Yermolenko, 'POSCO Starts Construction of Electric Arc Furnace at Gwangyang Plant'; Sung, 'POSCO Gears up for Carbon-Free Steelmaking with Hydrogen'.

[296] Vale, 'Vale and Hydnum Steel Sign MoU to Develop Iron Ore Briquette Plant at a Green Steel Project in Spain'; Therm Process, 'Hydnum Steel and Primetals Plan Green Steel Mill in Spain'.

[297] Midrex, 'Midrex and Paul Wurth Selected by H2 Green Steel'.

[298] Duckett, 'Sweden's Green Steel Pilot Project a Success with Commercialisation Now Underway'.

		construction of demonstration plant					
Thailand	Meranti[299]	Site acquired; financial investment decision expected in 2025.	Energiron ‘hydrogen ready’		Not stated	2027	
United Arab Emirates	JFE, Itochu. Emsteel Group [300]	Announced	Not announced	2.5	Local gas	2025	Gas-based DRI/HBI production facility.

[299] Meranti Steel, ‘Press Release May 2023’.

[300] JFE Steel Corporation, ‘JFE Steel, Itochu, Emirates Steel Arkan & Abu Dhabi Ports Group Sign MOU to Establish a Supply Chain of Ferrous Raw Material for Green Ironmaking with Low Carbon Emission’; Emsteel, ‘Emirates Steel Arkan, ITOCHU and JFE Steel in Talks to Create Green Iron Supply Chain’.

Appendix 3: Model description

The model simulates the dynamic behaviour of a complete green iron production system over an example year.

The simulation is run multiple times to identify the investments and production levels that deliver the lowest levelised cost of iron (LCOI). Each run of the simulation uses different combinations of investments and production volumes.

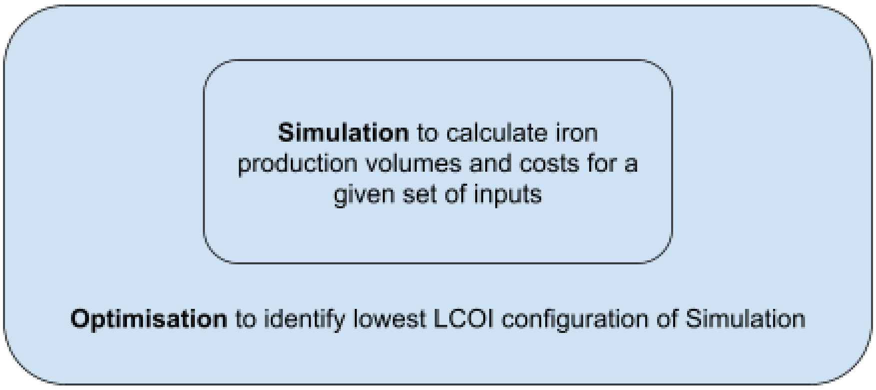

Figure 30: The simulation is run multiple times to explore the range of LCOI outcomes that can be achieved by the capacity of different facilities

How the model simulates an iron production system

The simulation runs in hourly steps for a full year (8,760 hours).

Within each hour, the simulation estimates the energy required to meet iron-making needs. If the energy requirements can be met, then the iron-making system produces at full capacity in that hour.

If there is not enough energy available, the system will try to use stored energy (e.g., from electricity stored in a battery, or hydrogen). Electricity will also be drawn from the grid up to the limit imposed by connection constraints and the Hydrogen Production Tax Incentive (HPTI) carbon-intensity limit. If there is still not enough energy, other forms of production are constrained (e.g., water and hydrogen).

The model prioritises the supply of electricity to production processes in the following order:

1. water processing (low energy use; a necessary input for all downstream processes);
2. iron-making;
3. hydrogen-making.

This approach ensures that the iron plant operates whenever hydrogen is available from simultaneous production or drawn from storage.

Two other conditions can affect iron production:

1. a hydrogen emissions intensity constraint
2. the relative value of revenue from selling electricity to the wholesale market, versus revenue from producing hydrogen for iron production.

The hydrogen emissions intensity constraint ensures that, on average over a year, hydrogen is produced within an emissions intensity constraint of 600 kilograms of carbon dioxide per tonne of hydrogen. This ensures producers are eligible for the HPTI. This emissions intensity constraint limits the use of electricity purchased from the wholesale market to produce hydrogen.

To capture the effect of producers selling renewable energy into an electricity market, we model a simple 'selling' rule: if the wholesale price of electricity is above a 'breakeven' price in a given hour, hydrogen production is curtailed and any available renewable electricity is sold into the electricity market.[301] This ensures producers do not buy electricity when market prices are high, and allows producers to capitalise on high prices by selling available renewable energy. The 'breakeven' price is calculated based on an estimate of the value of electricity to the iron final product, based on an estimate of the final product's market value.

How the model identifies the lowest-cost combination of investments and production levels

Each run of the simulation, described in the previous section, will generate an LCOI result. To find the lowest LCOI for each combination of location and technology, an optimisation process is required.

The Bivios model uses a genetic algorithm to identify the mix of investments and production levels that delivers the lowest LCOI for a given location and technology. A genetic algorithm generates an initial population of results by randomly varying the facility capacities. The most promising configurations, with the lowest LCOI, are used to 'bias' subsequent iterations towards solutions likely to deliver a lower LCOI. This process is repeated until the LCOI cannot be reduced any further.

This model, with variations to investments and production levels, requires several hundred runs; between 7 and 10 generations are usually required to deliver a repeatable, stable estimate of the lowest LCOI.

[301] A sophisticated electricity-trading strategy is beyond the scope of our model.

Appendix 4: Model results by location and technology type

Table 8, Table 9 and Table 10 list the results of the optimisation process for each location. The input parameters for each location can be downloaded from The Superpower Institute website.

Notes:

1. 'BTM Transmission' capacity refers to the transmission required to transmit renewable energy from the generation site to the iron-making location. This cost is assumed to be borne directly by the iron-making project in all cases (even if in reality some or all of the transmission infrastructure would be operated as part of an electricity grid).
2. The 'Electricity Grid' capacity is the maximum capacity required for importing and exporting power to achieve the lowest cost of iron. There is no connection cost included. Further studies would be required to determine the optimal grid connection size, taking into account the location-specific costs of providing a grid connection.

Category	Item	Units	Eyre Peninsula, inflexible	Eyre Peninsula, flexible	Geraldton, inflexible	Geraldton, flexible
Facility capacities	Solar PV	MW	2,499	2,147	2,668	2,317
	Wind Turbines	MW	4,013	2,640	2,587	2,177
	BTM Transmission	MW	2,355	1,912	2,432	1,961
	Electricity Grid	MW	797	1,189	826	1,402
	Battery	MWh	1,701	432	1,106	129
	Hydrogen Production	tph	27	25	29	25
	Hydrogen Storage	tonnes	753	36	760	22
	Iron Production	tph	285	441	285	2,317
Utilisation	H2 Production	%	57%	63%	53%	60%
	Iron Production	%	100%	65%	100%	77%
	Proportion of elect used from grid	%	12%	18%	2%	2%
	Proportion of elect generated exported	%	14%	18%	26%	20%
	Total electricity (exc. exports)	TWh	10.9	10.2	11.1	10.4
Emissions	Iron emissions intensity	tCO2e/ t	0.08	0.04	0.11	0.06
	Annual total emissions	ktCO2e/ yr	194	107	283	144
Capital costs	Solar PV	mA$	3,193	2,744	3,914	3,399
	Wind Turbines	mA$	10,978	7,221	8,126	6,839
	BTM Transmission	mA$	207	168	830	669
	Battery	mA$	483	123	361	42
	Hydrogen Production	mA$	3,310	3,019	4,137	3,601
	Hydrogen Storage	mA$	1,781	84	2,064	60
	Iron Production	mA$	2,835	3,142	3,217	3,013
	Other balance of plant	mA$	568	551	697	622
	Total capital costs	**mA$**	**23,356**	**17,052**	**23,345**	**18,244**

Annual costs	Financing costs	mA$	1,733	1,303	1,759	1,404
	Operations and maintenance	mA$	344	264	344	258
	Iron ore	mA$	566	529	567	532
	Natural gas	mA$	19	0	13	0
	Wholesale electricity	mA$	106	88	22	14
	Network charges - grid	mA$	28	40	5	4
	Network charges - renewables	mA$	0	0	0	0
	Grid revenue	mA$	-198	-556	-331	-288
	Total annual costs	**mA$**	**2,597**	**1,669**	**2,379**	**1,923**
Levelised costs	Electricity (after grid revenue subtracted)	A$/ MWh	101	38	66	56
	Hydrogen	A$/ kg	10.27	7.48	9.46	7.57
	Iron	**A$/ tonne**	**1,040**	**668**	**953**	**770**

Table 8: Modelled capacities, costs, and levelised costs of renewable electricity, green hydrogen, and green iron for the Eyre Peninsula and Geraldton

Category	Item	Units	Pilbara, inflexible	Pilbara, flexible	Gladstone, inflexible	Gladstone, flexible
Facility capacities	Solar PV	MW	5,106	3,299	3,587	3,148
	Wind Turbines	MW	4,226	2,209	4,785	3,968
	BTM Transmission	MW	6,143	2,262	0	0
	Electricity Grid	MW	0	0	2,092	1,904
	Battery	MWh	9,420	4,772	4,915	599
	Hydrogen Production	tph	18	23	28	35
	Hydrogen Storage	tonnes	537	40	917	177
	Iron Production	tph	291	368	286	391
Utilisation	H2 Production	%	87%	67%	57%	46%
	Iron Production	%	98%	77%	100%	73%
	Proportion of elect used from grid	%	0%	0%	4%	3%
	Proportion of elect generated exported	%	0%	0%	15%	23%
	Total electricity (exc. exports)	TWh	12.8	12.2	12.9	12.2
Emissions	Iron emissions intensity	tCO2e/ t	0.08	0.00	0.19	0.07
	Annual total emissions	ktCO2e/ yr	188	0	475	170
Capital costs	Solar PV	mA$	8,215	5,308	4,711	4,133
	Wind Turbines	mA$	14,558	7,611	13,453	11,156
	BTM Transmission	mA$	681	251	723	860
	Battery	mA$	3,369	1,707	1,435	175
	Hydrogen Production	mA$	2,786	3,626	3,482	4,386
	Hydrogen Storage	mA$	1,598	119	2,228	430
	Iron Production	mA$	5,129	5,253	4,115	4,548

	Other balance of plant	mA$	604	728	651	797
	Total capital costs	**mA$**	**36,940**	**24,603**	**30,797**	**26,485**
Annual costs	Financing costs	mA$	2,646	1,864	2,243	1,995
	Operations and maintenance	mA$	439	326	447	405
	Iron ore	mA$	383	382	455	454
	Natural gas	mA$	34	0	50	0
	Wholesale electricity	mA$	0	0	48	22
	Network charges - grid	mA$	0	0	11	7
	Network charges - renewables	mA$	0	0	0	0
	Grid revenue	mA$	0	0	-231	-620
	Total annual costs	**mA$**	**3,502**	**2,573**	**3,022**	**2,263**
Levelised costs	Electricity (after grid revenue subtracted)	A$/ MWh	162	96	111	57
	Hydrogen	A$/ kg	12.79	9.13	11.01	9.40
	Iron	**A$/ tonne**	**1,403**	**1,031**	**1,210**	**906**

Table 9: Modelled capacities, costs, and levelised costs of renewable electricity, green hydrogen, and green iron for Pilbara and Gladstone

Category	Item	Units	Kwinana, inflexible	Kwinana, flexible
Facility capacities	Solar PV	MW	4,459	3,298
	Wind Turbines	MW	2,962	3,123
	BTM Transmission	MW	0	0
	Electricity Grid	MW	787	1,890
	Battery	MWh	695	48
	Hydrogen Production	tph	29	30
	Hydrogen Storage	tonnes	920	144
	Iron Production	tph	285	347
Utilisation	H2 Production	%	54%	52%
	Iron Production	%	100%	82%
	Proportion of elect used from grid	%	4%	3%
	Proportion of elect generated exported	%	18%	22%
	Total electricity (exc. exports)	TWh	13.0	12.4
Emissions	Iron emissions intensity	tCO2e/ t	0.22	0.10
	Annual total emissions	ktCO2e/ yr	559	259
Capital costs	Solar PV	mA$	5,908	4,370
	Wind Turbines	mA$	8,403	8,859
	BTM Transmission	mA$	1,263	1,149
	Battery	mA$	205	14
	Hydrogen Production	mA$	3,720	3,894
	Hydrogen Storage	mA$	2,257	353

	Iron Production	mA$	4,140	4,078
	Other balance of plant	mA$	683	709
	Total capital costs	**mA$**	**26,578**	**23,426**
Annual costs	Financing costs	mA$	1,928	1,752
	Operations and maintenance	mA$	427	367
	Iron ore	mA$	434	434
	Natural gas	mA$	35	0
	Wholesale electricity	mA$	48	33
	Network charges - grid	mA$	12	9
	Network charges - renewables	mA$	0	0
	Grid revenue	mA$	-245	-378
	Total annual costs	**mA$**	**2,639**	**2,215**
Levelised costs	Electricity (after grid revenue subtracted)	A$/ MWh	81	64
	Hydrogen	A$/ kg	9.70	8.33
	Iron	**A$/ tonne**	**1,057**	**887**

Table 10: Modelled capacities, costs, and levelised costs of renewable electricity, green hydrogen, and green iron for Kwinana

Appendix 5: Other estimates of the LCOI for green HBI

Country/ Region (Source)	2030 LCOS ($AUD/t)	2030 LCOI ($AUD/t)	Notes
Australia (Devlin)	826.5	537.225	High solar share in RE mix; 62 percent Fe-content
Australia (Ellesdorfer)	870	565.5	
Australia (TA)	942.5	612.625	H2-DRI-EAF($3/kg H2)
Brazil (Devlin)	942.5	612.625	63 percent Fe content; High solar fraction in RE mix; competitive costs
Brazil (Ellesdorfer)	1015	659.75	
Brazil (TA)	1015	659.75	H2-DRI-EAF($3/kg H2)
Chile (Devlin)	1015	659.75	63 percent Fe content; High solar fraction in RE mix
China (Devlin)	1044	678.6	61 percent Fe content; competitive costs
China (TA)	1087.5	706.875	H2-DRI-EAF($3/kg H2)
EU (TA)	1087.5	706.875	H2-DRI-EAF($3/kg H2)
India (Devlin)	1087.5	706.875	Solar-dominated RE mix; 63 percent Fe-content;
Japan (TA)	1087.5	706.875	H2-DRI-EAF($3/kg H2)
South Korea (TA)	1087.5	706.875	H2-DRI-EAF($3/kg H2)
Sweden (Devlin)	1087.5	706.875	High Fe-content (70 percent); lowest solar fraction in RE mix
Sweden (Ellesdorfer)	1160	754	
USA (Devlin)	1174.5	763.425	63 percent Fe content; Balanced RE mix (solar and wind)
USA (TA)	1406.5	914.225	H2-DRI-EAF($3/kg H2)

Table 11: Summary of estimated costs of producing green iron

Globally, this ranges from AUD 530 produced in Australia to AUD 910 produced in Sweden, with price projections from other countries ranging in between.

Most studies and reports estimate the levelised cost of steel rather than the levelised cost of iron. We calculated the iron-specific cost fraction of LCOS using Ellesdorfer et al's LCOI for 2030 for Australia, Brazil and Sweden - this was 65%. We then applied this iron-specific cost fraction to LCOS projections across other countries provided by Devlin et al and Transition Asia. These approximate LCOI provides a useful comparison for our modelling results.

Appendix 6: Sensitivity analysis

The sensitivity of the modelled cost of iron has been evaluated for:

1. The variability in the optimisation process
2. A selection of static inputs (i.e., those that do not vary over time for each simulation run)
3. The dynamic (e.g., hourly) inputs of solar, wind, electricity price and electricity grid emissions data

The sensitivity of the inputs to the first of a kind (FOAK) costs has also been evaluated.

There are ten different combinations of locations and technology types presented in this report (5 locations and 2 technologies). For brevity, only the sensitivity results for the Eyre Peninsula are presented here.

Note that in the remainder of this Appendix, the term ‘baseline’ refers to the results presented elsewhere in this report.

Variability in optimisation results

The optimisation process involves generating hundreds of different combinations of the sizes of the components of the iron production system. The optimisation process uses a genetic algorithm to find the lowest cost of an iron solution.

A genetic algorithm uses weighted random numbers to ‘seed’ each new generation of results. This means that the results from the optimisation will vary with each run.

The baseline results presented in this report are from a single, arbitrarily selected run of the optimisation process. To test the sensitivity of the results to the optimisation process, we have run the optimisation process 41 times for both the flexible and inflexible cases in the Eyre Peninsula. The distribution of these results is illustrated in Figure 31 and key statistics are presented in Figure 32.

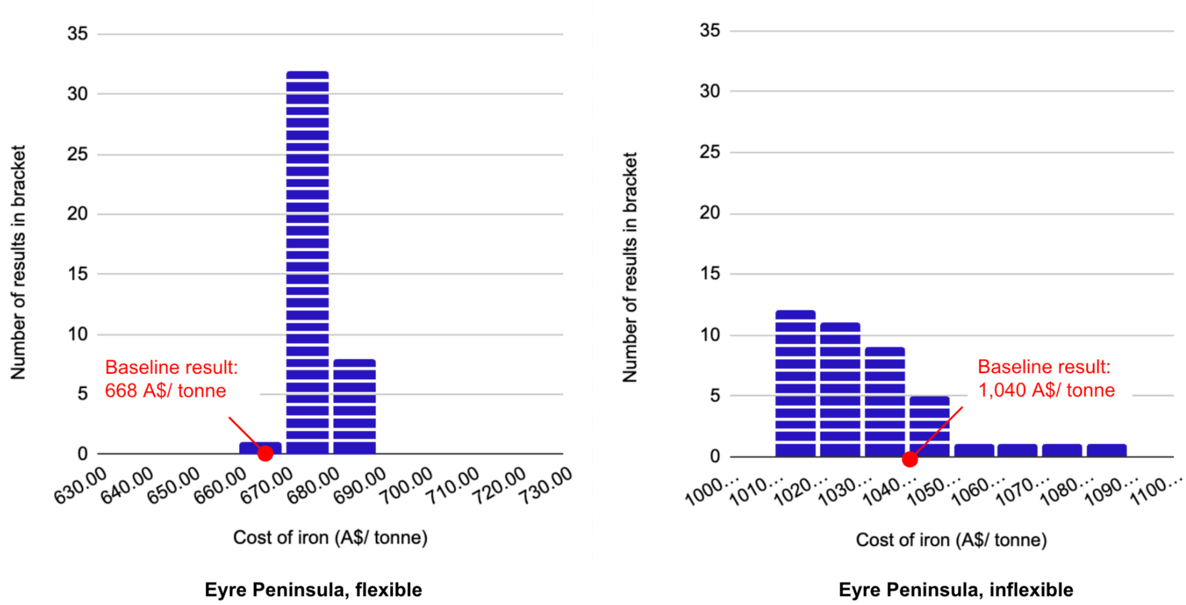

Figure 31: Distribution of model results for the optimised cost of iron in the Eyre Peninsula (each 'box' is a single model run)

Metric	Cost of iron (A$/ tonne)	
	Inflexible	**Flexible**
Minimum	1,012	669
Maximum	1,072	685
Average (mean)	1,034	676
Standard deviation	19.17	4.18

Figure 32: Statistics on the distribution of model results for the optimised cost of iron in the Eyre Peninsula

The distribution of results is broader for the inflexible technology. This can be explained by the slope of the optimisation front at 100% iron plant utilisation, which is the requirement that the inflexible technology must meet. This is illustrated in Figure 33.

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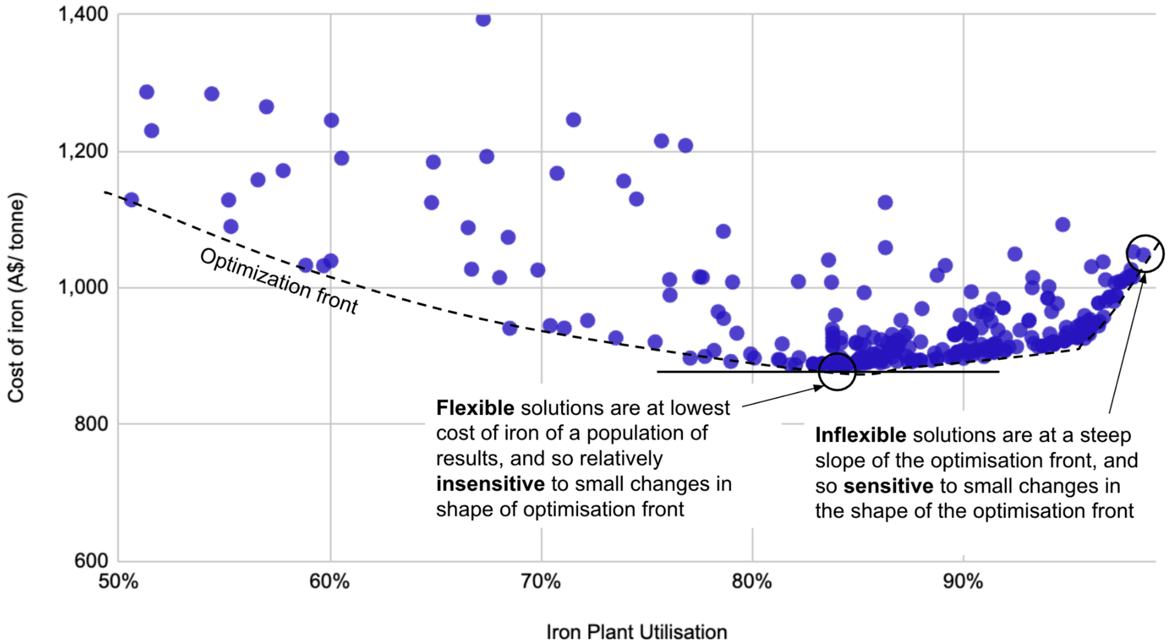

Figure 33: The different slope of the optimisation front at different iron plant utilisation levels impacts the variability in optimisation results for the cost of iron

Sensitivity to static inputs

A sensitivity analysis for important static model inputs is shown in Figure 34. The low and high values of each input are listed in Table 12.

Of the inputs shortlisted for sensitivity analysis, the weighted average cost of capital (WACC) has by far the largest impact on the cost of iron. This is expected, given that the majority of the cost is from capital.

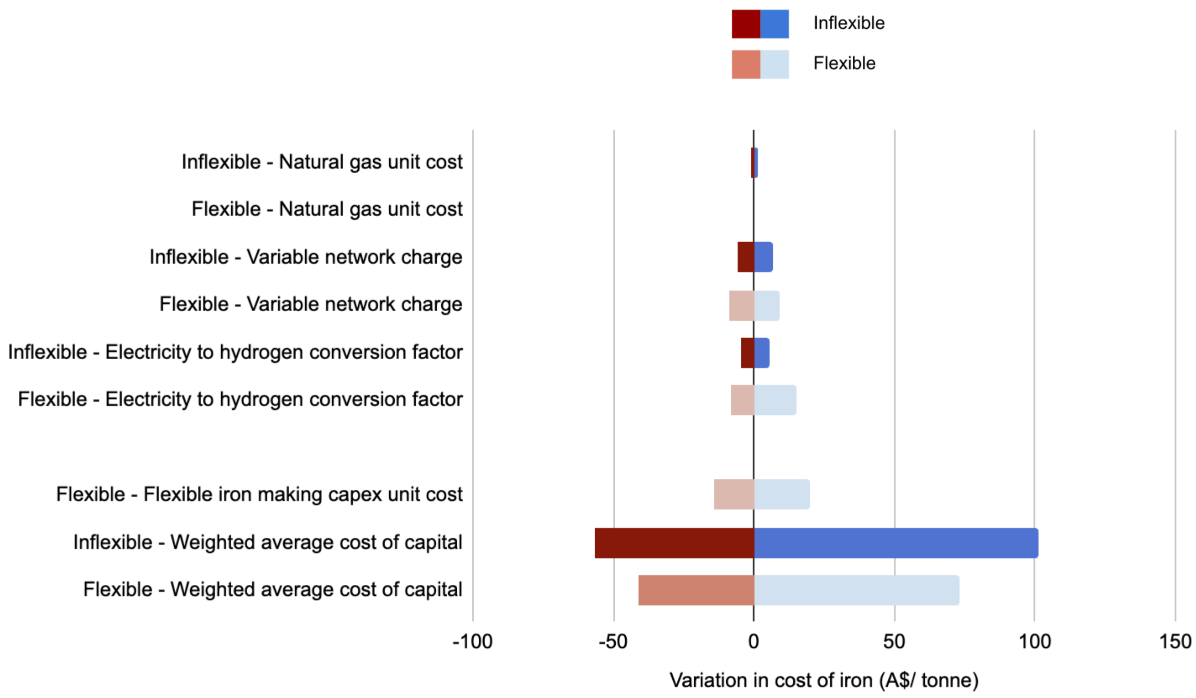

Figure 34: Sensitivity analysis for select static inputs to the model

Input	Units	Low value	Medium value (baseline)	High value
Variable network charge	A$/ KWh	0.01	0.022	0.035
Electricity to hydrogen conversion factor	MWh/ t H2	50	55	60
Natural gas unit cost[302]	A$/ GJ	10.95	12.89	14.79
Iron making capex unit cost (flexible only)	mA$/ tph	5.41	6.49	8.05
Weighted average cost of capital	%	3.60%	4.50%	6.00%

Table 12: Range of static inputs analysed for select inputs

Sensitivity to dynamic inputs

The model uses hourly inputs of solar and wind power output, electricity spot market prices and electricity grid emissions for each location for an example year.

This creates a risk that the optimised solution is 'overfitted' to the specific hourly data used. To explore the impact of the hourly data on the results of the Eyre Peninsula, the baseline configurations

[302] Note that the reported figures are specific to the Eyre Peninsula but vary by location based on ACIL Allen industrial gas forecasts.

for the flexible and inflexible solutions were re-run against hourly data from other years. The results are presented in Figure 35.

The baseline year was 2023. Two other years were studied: 2021 and 2022. 2021 had lower average electricity prices, whilst 2022 had much higher electricity prices.

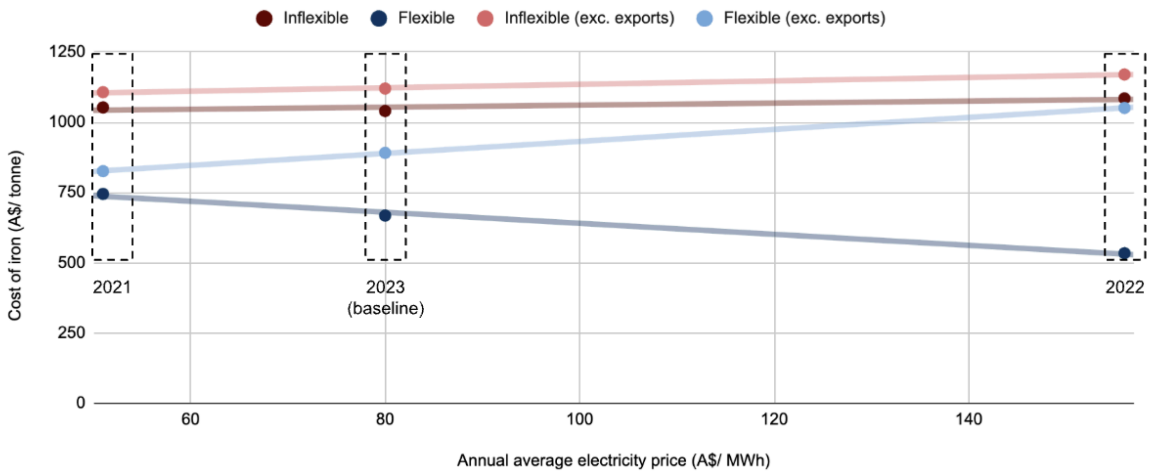

Figure 35: Variation of the cost of iron with hourly input data

The inflexible technology delivers a relatively constant cost of iron between the different years studied. This suggests that the model is not significantly impacted by year-to-year variations in solar and wind energy availability.

The flexible technology results vary much more, and are correlated to the average electricity price. The flexible technology cost of iron is offset by the revenue from selling electricity back to the grid at times of peak prices and by curtailing hydrogen (and if necessary, iron) production. Higher (and likely more volatile) electricity prices appear to reward this approach.

Sensitivity to First of a Kind (FOAK) inputs

To estimate the FOAK costs presented in Section 4.6 increases to iron making capital costs and the weighted average cost of capital were assumed.

Figure 36 presents the impact on the cost of iron of varying these assumptions for the inflexible and flexible cases in the Eyre Peninsula.

The high and low values assumed for these inputs are shown in Table 13 for the inflexible technology and Table 14 for the flexible technology.

There is greater uncertainty in the FOAK costs associated with the less proven flexible technology. Therefore, the potential increase in the FOAK costs is greater in absolute terms than for the inflexible technology. Relative to the cost of iron per tonne, they are also greater still, due to the lower cost of iron estimated for the flexible technology.

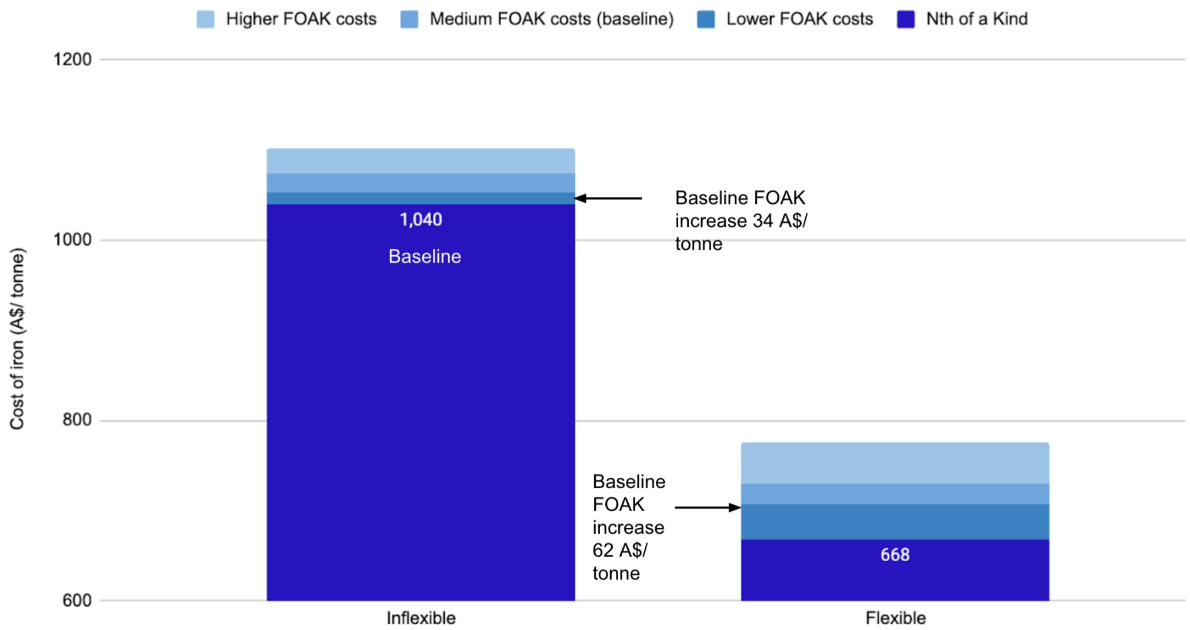

Figure 36: Sensitivity of First of a Kind additional costs to variations in First of a Kind input assumptions

Input	Units	Lower FOAK costs	Medium FOAK costs (baseline)	Higher FOAK costs
Iron making capex unit cost	mA$/ tph	5.15	6.08	7.63
Weighted average cost of capital	%	5.5%	6.0%	6.5%

Table 13: Variation in FOAK assumptions for inflexible technology in the Eyre Peninsula

Input	Units	Lower FOAK costs	Medium FOAK costs (baseline)	Higher FOAK costs
Iron making capex unit cost	mA$/ tph	7.06	8.28	10.30
Weighted average cost of capital	%	6%	6.3%	7%

Table 14: Variation in FOAK assumptions for flexible technology in the Eyre Peninsula

Appendix 7: Baseline model inputs

For complete access to the model inputs and calculations, see the Model Methodology page on The Superpower Institute website.

Group	Sub-group	Item	Units	Description
Electricity	Grid	Network Variable Charge	A$/kWh	Electranet, Powerlink, and Western Power pricing schedules for high voltage industrial loads were considered as inputs, but ultimately it was decided to assume values based on consultation and general calculations, given the complexity and opacity of charging structures. The network charge accounts for an insignificant portion of overall project costs since the majority of energy used is generated BTM. L/M/H values are $10/MWh, $22/MWh, and $35/MWh.
	Solar PV	Loss Factor	% (fraction)	DC-AC inverter conversion losses.[303]
		Life	years	Based on Aurecon figures.[304]
		Unit Opex	mA$/MW	[Calc]. Based on implied opex as percentage of capex from 2024 Aurecon figures.[305] L/H -/+ 10%.
		Unit Capex	mA$/MW	Based on GenCost 2024-25 figures.[306] Low: Global NZE by 2050 Mid: Global NZE post 2050 High: Current policy
	Wind Turbines	Loss Factor	% (fraction)	DC-AC inverter conversion losses.[307]
		Life	years	Based on Aurecon figures[308]. L/H = +/- 10%
		Unit Opex	mA$/MW	[Calc]. Based on implied opex as percentage of capex from 2024 Aurecon figures. L/H -/+ 10%.
		Unit Capex	mA$/MW	Based on GenCost 2024-25 figures.[309] Low: Global NZE by 2050 Mid: Global NZE post 2050 High: Current policy
	BTM Transmission	Distance	km	The general assumption that some BTM transmission will be required to connect energy-generating and using areas of the plant. Assumes 50km of base transmission required to connect the plant, with additional required for Geraldton, Kwinana and Gladstone scenarios to connect to energy-generating assets. Additional is based on the distance between the proposed plant location and the centroid of the associated REZ + 20% (km).
		Loss Factor	% (fraction) / 100 km	Energy lost via transmission.[310]
		Life	years	Based on Electranet asset life span outcomes.[311]

[303] Park et al., 'Inverter Efficiency Analysis Model Based on Solar Power Estimation Using Solar Radiation'.
[304] Aurecon, '2024 Energy Technology Cost and Technical Parameter Review', 173.
[305] Aurecon, 35.
[306] Graham, Hayward, and Foster, 'GenCost 2024-25: Consultation Draft', 76.
[307] Park et al., "Inverter Efficiency Analysis Model Based on Solar Power Estimation Using Solar Radiation."
[308] Aurecon, '2024 Energy Technology Cost and Technical Parameter Review', 173.
[309] Graham, Hayward, and Foster, 'GenCost 2024-25: Consultation Draft', 84.
[310] Nationalgrid, 'Factsheet: High Voltage Direct Current Electricity-Technical Information', 7.
[311] AER, 'ElectraNet Transmission Determination 2018 to 2023', 5–6.

Group	Sub-group	Item	Units	Description
		Unit Capex	mA$/(km GW)	CAPEX for 330 kV single circuit transmission line (1200 MVA each). Levelised by 1.2GW transmission capacity. Includes cost of overhead. Inflated to 2023AU$[312]. L/H -5%/+20%
	Battery	Hour 1 Level	% (fraction)	Assumed
		Max Charge Rate	% (fraction)	Implied by 8-hour storage.
		Max Depth of Discharge	% (fraction)	A GenCost assumption based on maintaining the health of the battery.[313]
		Round trip efficiency	% (fraction)	Percentage of electricity lost in the storage process.
		Life	years	[Calc.] Based on the Aurecon 20-year useful life assumption and adjusted for 60% degradation. L/H +/- 20%[314].
		Unit Opex	mA$/MWh	[Calc]. Based on implied opex as a percentage of capex from 2024 Aurecon figures. L/H -/+ 10%.
		Unit Capex	mA$/MWh	8-hour total (battery + BOP) based on GenCost 2024-25 figures.[315] Low: Global NZE by 2050 Mid: Global NZE post 2050 High: Current policy
	Distribution (between facilities)	Life	years	Assumed
		Unit Capex	mA$/MW	Based on a 1GW green hydrogen plant design. Scaled up to 1.5/2/2.5GW capacity for L/M/H, given historic model runs and energy requirements.[316] Unit includes: HV electrical system, four state-of-the-art 380/66kV 300MVA transformers with open-air switchgear, 66/1.5kV transformers equipped with gas-insulated switchgear.
	Gas Turbines	Capacity	MW	Not included in base cases
		Natural Gas -> Electricity	GJ/MWh	Static heat rate for a generic new entrant OCGT.[317]
		Natural Gas -> Emissions	GJ/tCO2e	Inverse calculation from DCCEEW Scope 1 emissions (Table 5).[318]
		Life	years	GenCost assumption.[319]
		Unit Opex	mA$/MW	[Calc]. Based on implied opex as a percentage of capex from 2024 Aurecon figures. L/H -/+ 10%.
		Unit Capex	mA$/MW	[Calc]. Based on GenCost 2024-25 figures for open cycle gas turbines.[320] Low: Global NZE by 2050 Mid: Global NZE post 2050 High: Current policy

312 Infrastructure Australia, 'Infrastructure Market Capacity: Supporting Appendices', 71.
313 Graham, Hayward, and Foster, 'GenCost 2023-24: Final Report', 37.
314 Aurecon, '2024 Energy Technology Cost and Technical Parameter Review', 174.
315 Graham, Hayward, and Foster, 'GenCost 2024-25: Consultation Draft', 78.
316 ISPT, 'A One-GigaWatt Green-Hydrogen Plant', 15-31.
317 AEMO, 'Heat Rates'.
318 DCCEEW, 'Australian National Greenhouse Accounts Factors Workbook', 16.
319 Aurecon, '2024 Energy Technology Cost and Technical Parameter Review', 62.
320 Graham, Hayward, and Foster, 'GenCost 2024-25: Consultation Draft', 83.

Group	Sub-group	Item	Units	Description
Water	Production	Electricity -> Water	MWh/t	Electricity required in desalination.[321]
		Life	years	Lifetime of a desalination plant.[322]
		Unit Opex		[Calc]. Based on implied opex as percentage of capex from 2024 Aurecon figures. L/H -/+ 10%.
		Unit Capex	mA$/tph	[Calc] Convert $40,000/ML to mA$/tph. Deduct product storage and distribution (10% of 80% construction cost).[323]
	Storage	Hour 1 Level	% (fraction)	Assumed
		Life	years	Assumed
		Unit Capex	mA$/t	Aurecon assumes 5% CAPEX of waterProduceUnitCapex. Doubled to ensure suitable storage (i.e., ~15,000ML)[324]
	Distribution (between facilities)	Life	years	Assumed
		Unit Capex	mA$/tph	Aurecon assumes 5% CAPEX of waterProduceUnitCapex.[325]
Hydrogen	Production	Electricity -> Hydrogen	MWh/t H2	[Multiple sources]. Low is IRENA 2020 lower bound figure for PEM efficiency; qualitatively defended as more likely than DOE target (46MWh/tH2) given current political environment. High is Aurecon PEM efficiency assumption, considered as commercially viable for construction by 2024. The middle represents the average. Also note that "the thermodynamic efficiency limit for electrolysis is 40 kWh/kgH2... The CSIRO concluded that "it is generally considered that efficiencies better than 45 kWh/kg are unlikely to be achieved".[326]
		Water -> Hydrogen	t water/t H2	9kg water/kg H2 is the theoretical requirement for electrolysis. Total system requirements and the cooling tower require additional.
		Life	years	80,000 hours at 90% annual capacity.[327]
		Unit Opex	mA$/tph	[Calc]. Based on implied opex as percentage of capex from 2024 Aurecon figures. L/H -/+ 10%.
		Unit Capex	mA$/tph	[Calc]. Based on GenCost 2024-25 GenCost figures, which featured a significant increase in electrolyser costs compared to previous editions.[328] Calculations assume HHV (39kWh/kgH2), and 285.8kJ energy to split H2 from H2O. Mid AUD/kW from GenCost 2024-25 is varied by efficiency assumptions used in this report (i.e., 50/55/60) to produce L/M/H cost estimates while maintaining internal consistency.

[321] Apolinario and Castro, 'Solar-Powered Desalination as a Sustainable Long-Term Solution for the Water Scarcity Problem: Case Studies in Portugal'.
[322] Wateruse Association Desalination Committee, 'Overview of Desalination Plant Intake Alternatives', 11.
[323] Aurecon, '2024 Energy Technology Cost and Technical Parameter Review', 132.
[324] Aurecon, 132.
[325] Aurecon, 132.
[326] Pendlebury, Meares, and Tyrrell, 'Hydrogen: The New Australian Manufacturing Export Industry and the Implications for the National Electricity Market (NEM)'.
[327] Wang and Walsh, 'South Australian Green Iron Supply Chain Study', 7; Davis et al., 'Methods, Assumptions, Scenarios & Sensitivities', 122.
[328] Graham, Hayward, and Foster, 'GenCost 2024-25: Consultation Draft', 85.

Group	Sub-group	Item	Units	Description
		H2 Emissions Intensity Limit	t CO2e / t H2	To receive the HTPI, a kilogram of hydrogen must have "a production emissions intensity that is less than or equal to 0.6 kilograms of carbon dioxide per 1 kilogram of hydrogen".[329]
	Storage	Hour 1 Level	% (fraction)	Assumed
		Max Charge Rate	% (fraction)	Assumed. Not constraining charge or discharge.
		Life	years	Low from Net Zero. High from IRENA. Middle takes average[330]
		Unit Opex	mA$/t	~2% CAPEX, as per reference: opex / CAPEX 150 bar case.[331]
		Unit Capex	mA$/t	[Multiple sources]. Low is based on DNV 700 bar compression storage figure with conversion of 131GJ/tH2. Middle and high are from the 2018 CSIRO Hydrogen Roadmap. Figures are based on 150 and 350 bar compression, respectively, and include tank, compressor, associated infrastructure, and installation costs. Figures have been inflated to AUD2024.
	Distribution (between facilities)	Life	years	Hydrogen pipeline life.[332]
		Unit Capex	mA$/tph	[Calc]. Assumed 5km of distribution pipe. [333]L/H = -/+ 10%.
Ironmaking	Pre-processing	Iron Ore -> Pre-processed Iron	t iron ore/t Pre-processed iron	[Calc]. [Explainer]. Where relevant to the technology route, concentrated fine is required for one ton of pellets. It is assumed that five per cent of moisture is lost in the process. L/H = -/+ 10%.
		Hydrogen -> Pre-processed Iron	t H2/t Pre-processed iron	No hydrogen is involved in pelletization. Natural gas is used for ore heating.
		Electricity -> Pre-processed Iron	MWh/t Pre-processed iron	[Multiple sources]. The referenced value is for electricity consumption only (i.e., excludes heating). Does not vary by ore type.[334]
		Natural Gas -> Pre-processed Iron	GJ/t Pre-processed iron	[Multiple sources]. Natural gas is used for heating the ore. Differences between SA and Pilbara are derived from the varying heating requirements of magnetite and hematite.[335]
		Life	years	Lifetime of pelletiser.[336]
		Unit Opex	mA$/tph	Base 3% Capex assumption.
		Unit Capex	mA$/tph	[Calc].

[329] Parliament of Australia, 'Hydrogen Production Tax Incentive'.
[330] Davis et al., 'Methods, Assumptions, Scenarios & Sensitivities', 127; IRENA, 'Green Hydrogen Supply: A Guide to Policy Making', 18.
[331] Bruce et al., 'National Hydrogen Roadmap - Pathways to an Economically Sustainable Hydrogen Industry in Australia', 84.
[332] Khan, Young, and Layzell, 'The Techno-Economics of Hydrogen Pipelines', 20; IEA, 'Global Hydrogen Review 2024: Assumptions Annex', 8.
[333] ANZ, 'Hydrogen Transportation', 5.
[334] Joint Research Centre of the European Commission, 'Best Available Techniques (BAT) Reference Document for Iron and Steel Production', 188.
[335] Joint Research Centre of the European Commission, 'Greenhouse Gas Intensities of the EU Steel Industry and Its Trading Partners', 30; Wilmoth et al., 'Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future', 31.
[336] Vogl, Åhman, and Nilsson, 'Assessment of Hydrogen Direct Reduction for Fossil-Free Steelmaking', 739.

Group	Sub-group	Item	Units	Description
				Capex of pelletisation plant. Not required in the Zesty process.[337]
	Reduction	Pre-Processed Iron -> Raw Iron	t Pre-processed iron/t Raw iron	[Calc]. [Explainer]. Differences are driven by metallisation rates of Midrex (assumed 94%) and Zesty (assumed 95%) technologies, as well as the Fe content of Pilbara and Eyre Peninsula pellets. L/H = -/+ 10%.
		Hydrogen -> Raw Iron	t H2/t Raw iron	The stoichiometric 54kg/tDRI is assumed across Midrex and Zesty technologies. Reports for H2-DRI Midrex technology vary. Upper bound reported as high as 76kg/tDRI. Zesty assumption as per technical report.[338]
		Electricity -> Raw Iron	MWh/t Raw iron	[Calcs]. For Midrex: ore and reducing gas heating with 90% efficiency, plus non-heating electrical requirements for auxiliary equipment. Zesty electricity requirements, excluding hydrogen production.
		Water -> Raw Iron	t water/t Raw iron	Not an input for Zesty technology.[339]
		Natural Gas -> Raw Iron (Heating)	GJ/t Raw iron	No gas is used for heating in the baseline case.
		Natural Gas -> Raw Iron (Reducing)	GJ/t Raw iron	Not included in base cases. Note that there is 2.3GJ/tDRI involved in heating that is excluded from this figure as heating is done electrically in all cases.[340]
		Life	years	L/H = +/- 10%.[341]
		Unit Opex	mA$/tph	Based on US$12.93 inflated from USD2015 to AUD2024 figure from Duke University report.[342]
		Unit Capex	mA$/tph	[Multiple sources]. [Explainer]. In lieu of commercial-scale plant CAPEX estimates for Zesty, a 20 per cent increase has been applied to the Midrex estimate for M.
		Water -> Post-Processed Iron	t Raw iron/t water	
	Post-processing	Electricity -> Post-Processed Iron	MWh/t Post-processed iron	Briquetting is required for the Eyre Peninsula. Smelting is required for Pilbara.[343]
		Hydrogen -> Post-Processed Iron	t H2/t Post-processed iron	No H2 required for smelting or briquetting.

[337] Wilmoth et al., 'Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future', 31.
[338] Millner et al., 'MIDREX H2 – The Road to CO2-Free Direct Reduction', 5; Pollard and Buckley, 'Green Metal Statecraft: Forging Australia's Green Iron Industry', 73; Calix, 'Calix Zesty Technology Zero Emissions Iron and Steel', 12.
[339] Gordon, 'Understanding of Rising and Failure of Gas Based Direct Reduction Processes'; Millner et al., 'MIDREX H2 – The Road to CO2-Free Direct Reduction'.
[340] Gordon, 'Understanding of Rising and Failure of Gas Based Direct Reduction Processes' slide 25; Elliott et al., 'Considerations for the Use of Hydrogen-Based DRI in Electric Steelmaking'.
[341] IEA, 'Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking', 108.
[342] Midrex O&M: Baig, 'Cost Effectiveness Analysis of HYL and Midrex DRI Technologies for the Iron and Steel-Making Industry', 19–20.
[343] Briquetting: Wilmoth et al., 'Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future', 31; Smelting: Paymooni et al., 'Simulations of DRI Integrated with EAF and ESF Processes Using Beneficiated and Direct Shipment Ores', 20.

Group	Sub-group	Item	Units	Description
		Water -> Post-Processed Iron	t water/t Post-processed iron	Small amounts of water is required for ESF cooling.[344]
		Raw Iron -> Post-Processed Iron	t Raw iron/t Post-processed iron	[Calc]. [Explainer]. Requirements to realise Fe content in benchmark products. L/H = -/+ 10%.
		Natural Gas -> Post-Processed Iron	GJ/t Post-processed iron	No natural gas is used in post-processing.
		Unit Opex	mA$/tph	Base 3% Capex assumption.
		Unit Capex	mA$/tph	[Calc] Briquetting for Eyre scenarios and ESF for others.[345]
		Life	years	Assumed
		Upstream Iron Ore Emissions	t CO2e/t iron ore	Assumed. Not including mining or transport emissions.
Costs & Finance		Iron Ore Unit Cost	A$/t	[Calc]. 2030 price forecast, China CFR. WA: 2030 price forecast, China CFR. Average of 62 and 58% fines. In 2024 AUD. SA: Adjusted based on the price forecast of 65% Fe sinter fines. In 2024 AUD. Includes transport and handling costs for respective ports where relevant to the envisaged scenario. Capesize for Gladstone and Handysize for Kwinana.
		Natural Gas Unit Cost	A$/GJ	[Calc]. Industrial gas price forecasts for 2030 by state from 2024 ACIL Allen (supporting material for AEMO 2025 Gas Statement of Opportunities).[346] Pipeline costs from various sources as they relate to the location of proposed green iron plants.
		Capital Costs Multiplier	None	[Calc]. [Explainer]. Location cost factors are comprised of equipment costs, installation costs, fuel connection costs, cost of land and development, and O&M costs. GHD provides a summary of the variation across locations for each of the above components. AEMO's location factors are taken from the GHD report from 2018, with adjustments applied based on regional development studies and feedback. AEMO's breakdown of component costs was used for our calculations. To increase accuracy, we split the cost factor for renewables (large-scale solar, wind, and batteries) and other facilities, as the proportions of the cost breakdown are different for renewables compared with standard industrial generation plants.
		Capital Costs Multiplier	None	[Calc]. [Explainer].

[344] Paymooni et al., 'Simulations of DRI Integrated with EAF and ESF Processes Using Beneficiated and Direct Shipment Ores'.
[345] Wilmoth et al., 'Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future', 31.
[346] AEMO, "Gas Statement of Opportunities."

Group	Sub-group	Item	Units	Description
				Same exercise as in capexCostsFactor, but this time splits for RE technologies are taken at face value.
		Operating Costs Proportion of CAPEX	% (fraction)	Base model assumption
		WACC (Renewables)	% (fraction)	As per the bi-annual IPART WACC February 2025 update. Middle reflects long-term post-tax real WACC, low reflects lower bound post-tax real WACC, and high reflects middle 10% market risk premium (upgraded from market rate of 6.25%)[347].
		WACC (Other)	% (fraction)	As per the bi-annual IPART WACC February 2025 update. Middle reflects long-term post-tax real WACC, low reflects lower bound post-tax real WACC, and high reflects middle 10% market risk premium (upgraded from market rate of 6.25%).[348]

Table 15: Baseline model input descriptions

Notes: For variables with [Calc], [Multiple Resources] or otherwise missing a referencing footnote without explicit assumption stated, check the background working on TSI's website.

Sub-group	Item	Units	Eyre Peninsula, inflexible	Eyre Peninsula, flexible	Geraldton, inflexible	Geraldton, flexible
Grid	Network Variable Charge	A$/kWh	0.0220	0.0220	0.0220	0.0220
	Loss Factor	% (fraction)	0.0500	0.0500	0.0500	0.0500
	Life	years	30.0000	30.0000	30.0000	30.0000
	Unit Opex	mA$/MW	0.0123	0.0123	0.0123	0.0123
Solar PV	Unit Capex	mA$/MW	1.1830	1.1830	1.1830	1.1830
	Loss Factor	% (fraction)	0.0500	0.0500	0.0500	0.0500
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/MW	0.0233	0.0233	0.0233	0.0233
Wind Turbines	Unit Capex	mA$/MW	2.5330	2.5330	2.5330	2.5330
	Distance	km	50.0000	50.0000	168.8000	168.8000
	Loss Factor	% (fraction) / 100 km	0.0100	0.0100	0.0100	0.0100
	Life	years	48.1000	48.1000	48.1000	48.1000
BTM Transmission	Unit Capex	mA$/(km GW)	1.6298	1.6298	1.6298	1.6298
	Hour 1 Level	% (fraction)	0.5000	0.5000	0.5000	0.5000
	Max Charge Rate	% (fraction)	0.1250	0.1250	0.1250	0.1250
	Max Depth of Discharge	% (fraction)	0.8000	0.8000	0.8000	0.8000
	Round trip efficiency	% (fraction)	0.8500	0.8500	0.8500	0.8500
	Life	years	15.8200	15.8200	15.8200	15.8200
	Unit Opex	mA$/MWh	0.0023	0.0023	0.0023	0.0023

Battery

347 IPART, 'Market Update'.
348 IPART.

Sub-group	Item	Units	Eyre Peninsula, inflexible	Eyre Peninsula, flexible	Geraldton, inflexible	Geraldton, flexible
	Unit Capex	mA$/MWh	0.2630	0.2630	0.2630	0.2630
Electricity distribution (between facilities)	Life	years	40.0000	40.0000	40.0000	40.0000
	Unit Capex	mA$/MW	0.2590	0.2590	0.2590	0.2590
Gas Turbines	Capacity	MW	0.0000	0.0000	0.0000	0.0000
	Natural Gas -> Electricity	GJ/MWh	11.7500	11.7500	11.7500	11.7500
	Natural Gas -> Emissions	GJ/tCO2e	19.6100	19.6100	19.6100	19.6100
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/MW	0.0309	0.0309	0.0309	0.0309
	Unit Capex	mA$/MW	1.3020	1.3020	1.3020	1.3020
Water production	Electricity -> Water	MWh/t	0.0035	0.0035	0.0035	0.0035
	Life	years	27.5000	27.5000	27.5000	27.5000
	Unit Opex		0.0004	0.0004	0.0004	0.0004
	Unit Capex	mA$/tph	0.0188	0.0188	0.0188	0.0188
Water storage	Hour 1 Level	% (fraction)	0.5000	0.5000	0.5000	0.5000
	Life	years	30.0000	30.0000	30.0000	30.0000
	Unit Capex	mA$/t	0.0019	0.0019	0.0019	0.0019
Water distribution	Life	years	30.0000	30.0000	30.0000	30.0000
	Unit Capex	mA$/tph	0.0009	0.0009	0.0009	0.0009
Hydrogen production	Electricity -> Hydrogen	MWh/t H2	55.0000	55.0000	55.0000	55.0000
	Water -> Hydrogen	t water/t H2	31.5000	31.5000	31.5000	31.5000
	Life	years	10.0000	10.0000	10.0000	10.0000
	Unit Opex	mA$/tph	2.2632	2.2632	2.2632	2.2632
	Unit Capex	mA$/tph	114.0200	114.0200	114.0200	114.0200
	H2 Emissions Intensity Limit	t CO2e / t H2	0.6000	0.6000	0.6000	0.6000
Hydrogen storage	Hour 1 Level	% (fraction)	0.5000	0.5000	0.5000	0.5000
	Max Charge Rate	% (fraction)	1.0000	1.0000	1.0000	1.0000
	Life	years	35.0000	35.0000	35.0000	35.0000
	Unit Opex	mA$/t	0.0467	0.0467	0.0467	0.0467
	Unit Capex	mA$/t	2.1900	2.1900	2.1900	2.1900
Hydrogen distribution (between facilities)	Life	years	42.0000	42.0000	42.0000	42.0000
	Unit Capex	mA$/tph	0.4451	0.4451	0.4451	0.4451

Sub-group	Item	Units	Eyre Peninsula, inflexible	Eyre Peninsula, flexible	Geraldton, inflexible	Geraldton, flexible
Ironmaking pre-processing	Iron Ore -> Pre-processed Iron	t iron ore/t Pre-processed iron	1.0526	1.0000	1.0526	1.0000
	Hydrogen -> Pre-processed Iron	t H2/t Pre-processed iron	0.0000	0.0000	0.0000	0.0000
	Electricity -> Pre-processed Iron	MWh/t Pre-processed iron	0.0337	0.0000	0.0337	0.0000
	Natural Gas -> Pre-processed Iron	GJ/t Pre-processed iron	0.4260	0.0000	0.4260	0.0000
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/tph	0.0793	0.0000	0.0793	0.0000
	Unit Capex	mA$/tph	2.6420	0.0000	2.6420	0.0000
Ironmaking reduction	Pre-Processed Iron -> Raw Iron	t Pre-processed iron/t Raw iron	1.3998	1.3778	1.3598	1.3384
	Hydrogen -> Raw Iron	t H2/t Raw iron	0.0540	0.0540	0.0540	0.0540
	Electricity -> Raw Iron	MWh/t Raw iron	1.3016	1.1000	1.3016	1.1000
	Water -> Raw Iron	t water/t Raw iron	1.2500	0.0000	1.2500	0.0000
	Natural Gas -> Raw Iron (Heating)	GJ/t Raw iron	0.0000	0.0000	0.0000	0.0000
	Natural Gas -> Raw Iron (Reducing)	GJ/t Raw iron	7.7000	7.7000	7.7000	7.7000
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/tph	0.2168	0.2168	0.2168	0.2168
	Unit Capex	mA$/tph	5.4111	6.4933	5.4111	6.4933
	Water -> Post-Processed Iron	t Raw iron/t water	0.0000	0.0000	0.0000	0.0000
Ironmaking post-processing	Electricity -> Post-Processed Iron	MWh/t Post-processed iron	0.0100	0.0100	0.0100	0.0100
	Hydrogen -> Post-Processed Iron	t H2/t Post-processed iron	0.0000	0.0000	0.0000	0.0000
	Water -> Post-Processed Iron	t water/t Post-processed iron	0.0000	0.0000	0.0000	0.0000
	Raw Iron -> Post-Processed Iron	t Raw iron/t Post-processed iron	1.0000	1.0000	1.0000	1.0000

Sub-group	Item	Units	Eyre Peninsula, inflexible	Eyre Peninsula, flexible	Geraldton, inflexible	Geraldton, flexible
	Natural Gas -> Post-Processed Iron	GJ/t Post-processed iron	0.0000	0.0000	0.0000	0.0000
	Unit Opex	mA$/tph	0.0030	0.0030	0.0030	0.0030
	Unit Capex	mA$/tph	0.1000	0.1000	0.1000	0.1000
	Life	years	25.0000	25.0000	25.0000	25.0000
	Upstream Iron Ore Emissions	t CO2e/t iron ore	0.0000	0.0000	0.0000	0.0000
Costs & Finance	Iron Ore Unit Cost	A$/t	153.7372	153.7372	158.6449	158.6449
	Natural Gas Unit Cost	A$/GJ	12.8882	12.8882	9.0507	9.0507
	Capital Costs Multiplier	None	1.0800	1.0800	1.2400	1.2400
	Capital Costs Multiplier	None	1.0800	1.0800	1.2300	1.2300
	Operating Costs Proportion of CAPEX	% (fraction)	0.0300	0.0300	0.0300	0.0300
	WACC (Renewables)	% (fraction)	0.0450	0.0450	0.0450	0.0450
	WACC (Other)	% (fraction)	0.0450	0.0450	0.0450	0.0450

Table 16: Baseline model inputs for Eyre Peninsula and Geraldton

Sub-group	Item	Units	Pilbara, inflexible	Pilbara, flexible	Gladstone, inflexible	Gladstone, flexible
Grid	Network Variable Charge	A$/kWh	1.0000	1.0000	0.0220	0.0220
Solar PV	Loss Factor	% (fraction)	0.0500	0.0500	0.0500	0.0500
	Life	years	30.0000	30.0000	30.0000	30.0000
	Unit Opex	mA$/MW	0.0123	0.0123	0.0123	0.0123
	Unit Capex	mA$/MW	1.1830	1.1830	1.1830	1.1830
Wind Turbines	Loss Factor	% (fraction)	0.0500	0.0500	0.0500	0.0500
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/MW	0.0233	0.0233	0.0233	0.0233
	Unit Capex	mA$/MW	2.5330	2.5330	2.5330	2.5330
BTM Transmission	Distance	km	50.0000	50.0000	152.0000	152.0000
	Loss Factor	% (fraction) / 100 km	0.0100	0.0100	0.0100	0.0100
	Life	years	48.1000	48.1000	48.1000	48.1000
	Unit Capex	mA$/(km GW)	1.6298	1.6298	1.6298	1.6298

Sub-group	Item	Units	Pilbara, inflexible	Pilbara, flexible	Gladstone, inflexible	Gladstone, flexible
Battery	Hour 1 Level	% (fraction)	0.5000	0.5000	0.5000	0.5000
	Max Charge Rate	% (fraction)	0.1250	0.1250	0.1250	0.1250
	Max Depth of Discharge	% (fraction)	0.8000	0.8000	0.8000	0.8000
	Round trip efficiency	% (fraction)	0.8500	0.8500	0.8500	0.8500
	Life	years	15.8200	15.8200	15.8200	15.8200
	Unit Opex	mA$/MWh	0.0023	0.0023	0.0023	0.0023
	Unit Capex	mA$/MWh	0.2630	0.2630	0.2630	0.2630
Electricity distribution (between facilities)	Life	years	40.0000	40.0000	40.0000	40.0000
	Unit Capex	mA$/MW	0.2590	0.2590	0.2590	0.2590
Gas Turbines	Capacity	MW	0.0000	0.0000	0.0000	0.0000
	Natural Gas -> Electricity	GJ/MWh	11.7500	11.7500	11.7500	11.7500
	Natural Gas -> Emissions	GJ/tCO2e	19.6100	19.6100	19.6100	19.6100
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/MW	0.0309	0.0309	0.0309	0.0309
	Unit Capex	mA$/MW	1.3020	1.3020	1.3020	1.3020
Water production	Electricity -> Water	MWh/t	0.0035	0.0035	0.0035	0.0035
	Life	years	27.5000	27.5000	27.5000	27.5000
	Unit Opex		0.0004	0.0004	0.0004	0.0004
	Unit Capex	mA$/tph	0.0188	0.0188	0.0188	0.0188
Water storage	Hour 1 Level	% (fraction)	0.5000	0.5000	0.5000	0.5000
	Life	years	30.0000	30.0000	30.0000	30.0000
	Unit Capex	mA$/t	0.0019	0.0019	0.0019	0.0019
Water distribution	Life	years	30.0000	30.0000	30.0000	30.0000
	Unit Capex	mA$/tph	0.0009	0.0009	0.0009	0.0009
Hydrogen production	Electricity -> Hydrogen	MWh/t H2	55.0000	55.0000	55.0000	55.0000
	Water -> Hydrogen	t water/t H2	31.5000	31.5000	31.5000	31.5000
	Life	years	10.0000	10.0000	10.0000	10.0000
	Unit Opex	mA$/tph	2.2632	2.2632	2.2632	2.2632
	Unit Capex	mA$/tph	114.0200	114.0200	114.0200	114.0200
	H2 Emissions Intensity Limit	t CO2e / t H2	0.6000	0.6000	0.6000	0.6000
Hydrogen storage	Hour 1 Level	% (fraction)	0.5000	0.5000	0.5000	0.5000
	Max Charge	% (fraction)	1.0000	1.0000	1.0000	1.0000

Sub-group	Item	Units	Pilbara, inflexible	Pilbara, flexible	Gladstone, inflexible	Gladstone, flexible
	Rate					
	Life	years	35.0000	35.0000	35.0000	35.0000
	Unit Opex	mA$/t	0.0467	0.0467	0.0467	0.0467
	Unit Capex	mA$/t	2.1900	2.1900	2.1900	2.1900
Hydrogen distribution (between facilities)	Life	years	42.0000	42.0000	42.0000	42.0000
	Unit Capex	mA$/tph	0.4451	0.4451	0.4451	0.4451
Ironmaking pre-processing	Iron Ore -> Pre-processed Iron	t iron ore/t Pre-processed iron	1.0526	1.0000	1.0526	1.0000
	Hydrogen -> Pre-processed Iron	t H2/t Pre-processed iron	0.0000	0.0000	0.0000	0.0000
	Electricity -> Pre-processed Iron	MWh/t Pre-processed iron	0.0337	0.0000	0.0337	0.0000
	Natural Gas -> Pre-processed Iron	GJ/t Pre-processed iron	1.0650	0.0000	1.0650	0.0000
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/tph	0.0793	0.0000	0.0793	0.0000
	Unit Capex	mA$/tph	2.6420	0.0000	2.6420	0.0000
Ironmaking reduction	Pre-Processed Iron -> Raw Iron	t Pre-processed iron/t Raw iron	1.3727	1.4222	1.3727	1.4222
	Hydrogen -> Raw Iron	t H2/t Raw iron	0.0540	0.0540	0.0540	0.0540
	Electricity -> Raw Iron	MWh/t Raw iron	1.3016	1.1000	1.3016	1.1000
	Water -> Raw Iron	t water/t Raw iron	1.2500	0.0000	1.2500	0.0000
	Natural Gas -> Raw Iron (Heating)	GJ/t Raw iron	0.0000	0.0000	0.0000	0.0000
	Natural Gas -> Raw Iron (Reducing)	GJ/t Raw iron	7.7000	7.7000	7.7000	7.7000
	Life	years	25.0000	25.0000	25.0000	25.0000
	Unit Opex	mA$/tph	0.2168	0.2168	0.2168	0.2168
	Unit Capex	mA$/tph	5.4111	6.4933	5.4111	6.4933
	Water -> Post-Processed Iron	t Raw iron/t water	0.0000	0.0000	0.0000	0.0000
Ironmaking post-processing	Electricity -> Post-Processed Iron	MWh/t Post-processed iron	0.6679	0.6679	0.6679	0.6679

Sub-group	Item	Units	Pilbara, inflexible	Pilbara, flexible	Gladstone, inflexible	Gladstone, flexible
	Hydrogen -> Post-Processed Iron	t H2/t Post-processed iron	0.0000	0.0000	0.0000	0.0000
	Water -> Post-Processed Iron	t water/t Post-processed iron	0.0000	0.0000	0.0000	0.0000
	Raw Iron -> Post-Processed Iron	t Raw iron/t Post-processed iron	1.0109	1.0239	1.0109	1.0239
	Natural Gas -> Post-Processed Iron	GJ/t Post-processed iron	0.0000	0.0000	0.0000	0.0000
	Unit Opex	mA$/tph	0.1150	0.1150	0.1150	0.1150
	Unit Capex	mA$/tph	3.8344	3.8344	3.8344	3.8344
	Life	years	25.0000	25.0000	25.0000	25.0000
	Upstream Iron Ore Emissions	t CO2e/t iron ore	0.0000	0.0000	0.0000	0.0000
Costs & Finance	Iron Ore Unit Cost	A$/t	105.0507	105.0507	124.7372	124.7372
	Natural Gas Unit Cost	A$/GJ	9.1521	9.1521	13.4159	13.4159
	Capital Costs Multiplier	None	1.3600	1.3600	1.1100	1.1100
	Capital Costs Multiplier	None	1.3400	1.3400	1.1000	1.1000
	Operating Costs Proportion of CAPEX	% (fraction)	0.0300	0.0300	0.0300	0.0300
	WACC (Renewables)	% (fraction)	0.0450	0.0450	0.0450	0.0450
	WACC (Other)	% (fraction)	0.0450	0.0450	0.0450	0.0450

Table 17: Baseline model inputs for Pilbara and Gladstone

Sub-group	Item	Units	Kwinana, inflexible	Kwinana, flexible
Grid	Network Variable Charge	A$/kWh	0.0220	0.0220
Solar PV	Loss Factor	% (fraction)	0.0500	0.0500
	Life	years	30.0000	30.0000
	Unit Opex	mA$/MW	0.0123	0.0123
	Unit Capex	mA$/MW	1.1830	1.1830
Wind Turbines	Loss Factor	% (fraction)	0.0500	0.0500
	Life	years	25.0000	25.0000
	Unit Opex	mA$/MW	0.0233	0.0233

Sub-group	Item	Units	Kwinana, inflexible	Kwinana, flexible
	Unit Capex	mA$/MW	2.5330	2.5330
BTM Transmission	Distance	km	272.0000	272.0000
	Loss Factor	% (fraction) / 100 km	0.0100	0.0100
	Life	years	48.1000	48.1000
	Unit Capex	mA$/(km GW)	1.6298	1.6298
Battery	Hour 1 Level	% (fraction)	0.5000	0.5000
	Max Charge Rate	% (fraction)	0.1250	0.1250
	Max Depth of Discharge	% (fraction)	0.8000	0.8000
	Round trip efficiency	% (fraction)	0.8500	0.8500
	Life	years	15.8200	15.8200
	Unit Opex	mA$/MWh	0.0023	0.0023
	Unit Capex	mA$/MWh	0.2630	0.2630
Electricity distribution (between facilities)	Life	years	40.0000	40.0000
	Unit Capex	mA$/MW	0.2590	0.2590
Gas Turbines	Capacity	MW	0.0000	0.0000
	Natural Gas -> Electricity	GJ/MWh	11.7500	11.7500
	Natural Gas -> Emissions	GJ/tCO2e	19.6100	19.6100
	Life	years	25.0000	25.0000
	Unit Opex	mA$/MW	0.0309	0.0309
	Unit Capex	mA$/MW	1.3020	1.3020
Water production	Electricity -> Water	MWh/t	0.0035	0.0035
	Life	years	27.5000	27.5000
	Unit Opex		0.0004	0.0004
	Unit Capex	mA$/tph	0.0188	0.0188
Water storage	Hour 1 Level	% (fraction)	0.5000	0.5000
	Life	years	30.0000	30.0000
	Unit Capex	mA$/t	0.0019	0.0019
Water distribution	Life	years	30.0000	30.0000
	Unit Capex	mA$/tph	0.0009	0.0009
Hydrogen production	Electricity -> Hydrogen	MWh/t H2	55.0000	55.0000
	Water -> Hydrogen	t water/t H2	31.5000	31.5000
	Life	years	10.0000	10.0000

Sub-group	Item	Units	Kwinana, inflexible	Kwinana, flexible
	Unit Opex	mA$/tph	2.2632	2.2632
	Unit Capex	mA$/tph	114.0200	114.0200
	H2 Emissions Intensity Limit	t CO2e / t H2	0.6000	0.6000
Hydrogen storage	Hour 1 Level	% (fraction)	0.5000	0.5000
	Max Charge Rate	% (fraction)	1.0000	1.0000
	Life	years	35.0000	35.0000
	Unit Opex	mA$/t	0.0467	0.0467
	Unit Capex	mA$/t	2.1900	2.1900
Hydrogen distribution (between facilities)	Life	years	42.0000	42.0000
	Unit Capex	mA$/tph	0.4451	0.4451
Ironmaking pre-processing	Iron Ore -> Pre-processed Iron	t iron ore/t Pre-processed iron	1.0526	1.0000
	Hydrogen -> Pre-processed Iron	t H2/t Pre-processed iron	0.0000	0.0000
	Electricity -> Pre-processed Iron	MWh/t Pre-processed iron	0.0337	0.0000
	Natural Gas -> Pre-processed Iron	GJ/t Pre-processed iron	1.0650	0.0000
	Life	years	25.0000	25.0000
	Unit Opex	mA$/tph	0.0793	0.0000
	Unit Capex	mA$/tph	2.6420	0.0000
Ironmaking reduction	Pre-Processed Iron -> Raw Iron	t Pre-processed iron/t Raw iron	1.3727	1.4222
	Hydrogen -> Raw Iron	t H2/t Raw iron	0.0540	0.0540
	Electricity -> Raw Iron	MWh/t Raw iron	1.3016	1.1000
	Water -> Raw Iron	t water/t Raw iron	1.2500	0.0000
	Natural Gas -> Raw Iron (Heating)	GJ/t Raw iron	0.0000	0.0000
	Natural Gas -> Raw Iron (Reducing)	GJ/t Raw iron	7.7000	7.7000
	Life	years	25.0000	25.0000
	Unit Opex	mA$/tph	0.2168	0.2168

Sub-group	Item	Units	Kwinana, inflexible	Kwinana, flexible
	Unit Capex	mA$/tph	5.4111	6.4933
	Water -> Post-Processed Iron	t Raw iron/t water	0.0000	0.0000
Ironmaking post-processing	Electricity -> Post-Processed Iron	MWh/t Post-processed iron	0.6679	0.6679
	Hydrogen -> Post-Processed Iron	t H2/t Post-processed iron	0.0000	0.0000
	Water -> Post-Processed Iron	t water/t Post-processed iron	0.0000	0.0000
	Raw Iron -> Post-Processed Iron	t Raw iron/t Post-processed iron	1.0109	1.0239
	Natural Gas -> Post-Processed Iron	GJ/t Post-processed iron	0.0000	0.0000
	Unit Opex	mA$/tph	0.1150	0.1150
	Unit Capex	mA$/tph	3.8344	3.8344
	Life	years	25.0000	25.0000
	Upstream Iron Ore Emissions	t CO2e/t iron ore	0.0000	0.0000
Costs & Finance	Iron Ore Unit Cost	A$/t	118.9403	118.9403
	Natural Gas Unit Cost	A$/GJ	9.4479	9.4479
	Capital Costs Multiplier	None	1.1200	1.1200
	Capital Costs Multiplier	None	1.1100	1.1100
	Operating Costs Proportion of CAPEX	% (fraction)	0.0300	0.0300
	WACC (Renewables)	% (fraction)	0.0450	0.0450
	WACC (Other)	% (fraction)	0.0450	0.0450

Table 18: Baseline model inputs for Kwinana

Appendix 8: Other LCOI estimates

Source	Estimated cost/tonne (AUD)	Notes/assumptions
Calix[349]	~AUD$630–800 DRI	30,000 tonne/annum HBI from hematite LCOH $5.5 - $6.2 AUD per kg
Western Australia and South Australia (Monash)[350]	AUD 565-800 DRI	
Western Australia and South Australia (Monash)[351]	AUD 585-780 DRI	
SA (Monash)[352]	AUD 678-862 HBI	
WA (MRIWA)[353]	DRI $612 (hematite) $712 (magnetite)	Based on $7/kg green hydrogen

Table 19: Summary of estimated costs of producing Australian green iron using different modelling frameworks and assumptions

[349] Walsh, 'Calix's ZESTY Study Finds High Potential for Economic Green Iron'.

[350] Wang et al., 'From Australian Iron Ore to Green Steel: The Opportunity for Technology-Driven Decarbonisation', 3.USD/AUD = 1.45. This study estimates the Levelized Cost of Steel (LCOS) rather than the Levelized Cost of Iron (LCOI). To approximate the iron-specific cost, we calculated the LCOI as 65% of the LCOS as described in Appendix 5 Table 11.

[351] Wang et al., 'Green Steel: Synergies between the Australian Iron Ore Industry and the Production of Green Hydrogen'. We use 2030 values. The LCOI is approximated to be 65% of the LCOS.

[352] Wang and Walsh, 'South Australian Green Iron Supply Chain Study'.

[353] MRIWA, 'Western Australia's Green Steel Opportunity'.

Appendix 9: Country and company commitments

Country	Net-zero target	Current interim target (unconditional)	The absolute emissions level in 2030	Climate Action Tracker: target rating
US	2050	GHG 50–52% below 2005 levels by 2030 (incl. LULUCF)	3,790–4,131 MtCO2e	Almost sufficient
EU	2050Note German and some other members 2045XXX	GHG 55% below 1990 levels by 2030 (incl. LULUCF and international aviation) GHG 90% below 1990 levels by 2040	2320 MtCO2e	Insufficient
China	2060	- Peaking carbon dioxide emissions before 2030 - Lower carbon intensity by “over 65%” in 2030 from the 2005 level - Share of non-fossil fuels in primary energy consumption to “around 25%” in 2030 - Increase forest stock volume by around 6 billion cubic metres in 2030 from the 2005 level (previously 4.5 billion cubic metres). - Increase the installed capacity of wind and solar power to over 1,200 GW by 2030	14.0 GtCO2e	Highly insufficient
Japan	2050	GHG 46% below 2013 levels in 2030 (including LULUCF credits)	813 MtCO2e	Insufficient
South Korea	2050	GHG 40% below 2018 by 2030	501 MtCO2e	Insufficient
India	2070	Emissions intensity of 45% below 2005 levels by 2030	4.6 GtCO2e	Highly insufficient

Table 20: Summary of countries’ decarbonisation commitments

Source: Climate Action Tracker[354]

[354] CAT, ‘Climate Action Tracker’.

Company	Country	Annual Production (Mt)	Net-zero target	Intermediate target
China Baowu Group	China	130.77	2050	30% emissions reduction by 2035 (2020 baseline)
Ansteel Group	China	55.89	2050	None stated. Note: Ansteel is in the process of integration into Baosteel.
Nippon Steel Group	Japan	43.66	2050	30% emissions reduction by 2030 (2013 baseline)
HBIS Group	China	41.34	2050	30% emissions reduction by 2030 (2022 baseline)
Shagang Group	China	40.54	None stated	None stated
POSCO Holdings	South Korea	38.44	2050	37% emissions reduction by 2030 (2021 baseline)
Jianlong Group	China	36.99	2060	20% emissions reduction by 2033 (2025 baseline)
Shougang Group	China	33.58	None stated	30 percent emissions reduction by 2030 (undefined baseline)
Delong steel	China	28.26	None stated	None stated
JFE Steel	Japan	25.09	2050	30% emissions reduction by 2030 (2013 baseline)
Hunan Steel	China	24.8	None stated	None stated
Hyundai Steel	South Korea	19.24	2050	12% reduction by 2030 (baseline 2018)
Kobe Steel	Japan	6.03	2050	30 to 40% reduction by 2030 (baseline 2013)
Dongkuk Steel	South Korea	3.77	2050	10% reduction by 2030

Table 21: Only some companies in major steelmaking trade partners have timely, ambitious decarbonisation targets

Notes: Companies are listed in order of total annual production. Companies headquartered outside of China, Japan and South Korea are not included.
Sources: Worldsteel[355]; Greensteel Tracker[356]; company annual reports; https://poscointl.com/eng/carbonNeutral.html

[355] World Steel Association, 'Top Steel-Producing Companies 2023/2022'.
[356] Leadit, 'Green Steel Tracker'.

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