WESTERN AUSTRALIA'S GREEN STEEL OPPORTUNITY

mriwa
Minerals Research Institute of Western Australia

minerals research advancing WA

Report collaborators

This report addresses the MRIWA focus area of Green Steel and our commitment to the use of minerals research to benefit Western Australia. We thank specialist consultants GHD and ACIL Allen for their detailed insights and analysis.

The Minerals Research Institute of Western Australia (MRIWA or the Institute) is a statutory body established by the Western Australian Government in 2013 under the Minerals Research Institute of Western Australia Act 2013 (WA) (the MRIWA Act).

We support applied minerals research projects to create capability and deliver economic and social benefit for Western Australia.

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ACIL Allen is a leading independent economics, policy and strategy advisory firm, dedicated to helping clients solve complex issues.

REFERENCE
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MRIWA

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Wood Mackenzie

Minister's Foreword

Western Australia is well placed to play an important role in decarbonising the world's steelmaking industry accounting for 38% of the global supply of iron ore.

With the steel industry generating more than 7% of global carbon emissions, there is a significant focus on the development of Green Steel technology and the low emission value chain starting with iron ore in Western Australia.

The ongoing success and growth in the industry will require a transition to lower emission technologies and there is a reasonable prospect that further processing of iron ore for lower carbon steelmaking is possible for Western Australia.

Western Australia is seen to have advantages which could help the industry move towards new technologies in steelmaking. It has natural gas and potential hydrogen networks available to help the transition. It has processing knowledge and extensive renewable energy opportunities close to the ore supply in each region.

The iron ore industry is working closely with its steelmaking customers in Australia and overseas. These strong partnerships can allow Western Australia to support the steel industry's transition by providing a stable investment environment, robust and transparent regulatory approvals system, access to export markets and low barriers to international trade.

The Minerals Research Institute of Western Australia's assessment of the Green Steel opportunity has examined low emission scenarios around magnetite and hematite iron ores including a range of energy solutions and iron ore qualities.

The findings increase the knowledge and technical understanding of the challenges facing the steel industry to reduce its emissions and can inform future discussions.

I look forward to potential opportunities for the Western Australia iron ore sector, in collaboration with their steelmaking customers, to progress further along the iron ore mining to steelmaking value chain.

Hon. Bill Johnston MLA

Minister for Mines and Petroleum, Energy

Contents

Contents

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Executive Summary

The Green Steel Challenge

Green Steel – the question is not 'is it possible', but rather 'how to make it possible'.

Understanding the pathways to enable Western Australia to maximise use of its hematite and magnetite iron ore resources, and to maximise emerging hydrogen and renewable energy potential are key to supporting global Green Steel ambitions and creating new markets for Western Australian iron ores.

This challenge aligns with the Western Australian Government's State Climate Policy: *Western Australian Climate Policy*: A plan to position Western Australia for a prosperous and resilient low-carbon future, which was released in November 2020. Specifically, the Policy includes a key focus on "clean manufacturing and future industries", with MRIWA's Green Steel Challenge one of the primary actions.

On 1 November 2021, the Minister for Mines and Petroleum announced an investigation into Green Steel had commenced, to inform the viability of sustainably processing Western Australian iron ore to Green Steel, or the inputs necessary to create Green Steel, with MRIWA engaging GHD and ACIL Allen to undertake a Green Steel Value Chain Assessment.

This report, summarises the findings of the work undertaken by GHD and ACIL Allen to:

- Map the iron ore-to-steel value chain to confirm scenarios against which further assessments will be undertaken related to infrastructure needs and market dynamics.
- Assess the existing and required regional attributes to identify the comparative advantages of the Mid West and Pilbara regions and future investment needs to enable delivery of the various scenarios.
- Assess the future iron ore mining, ironmaking and steel market dynamics to evaluate the potential opportunity and risk to Western Australia from action or inaction for each scenario.

It seeks to answer the question, *can the State competitively deliver across the various stages of the Green Steel value chain?*

A range of challenges and opportunities in developing a Green Steel industry are investigated through different scenarios which are described as pathways.

The Pathways Examined

Iron ore, ironmaking and steelmaking pathways are examined as part of the Western Australia's Green Steel Opportunity report. These are the key prospective scenarios considered as part of the market, technical and economic analysis undertaken.

The steelmaking value chain creates value by processing iron ore minerals into usable steel, removing impurities and other mineral contaminates through the use of energy and reductants.

The Green Steel model allows the pathways to be compared using a common basis, either a fixed volume of iron ore processed or as a set tonnage of steel product.

Five pathways, summarised in Table ES1, are examined separately in detail and then compared in terms of emissions, costs and other required inputs.

Table ES1 Iron ore to Green Steel development pathways

Pathway		Description
1	**Green Iron Ore Mining**	The export of hematite and magnetite concentrate from Western Australia, using renewable energy.
2	**Green Pellets**	The production and export of green pellets using renewable hydrogen.
3	**Iron-making – Hot Briquetted Iron (HBI) from Green Pellets using Fossil Fuels**	Producing HBI from Green Pellets, using renewable hydrogen to produce the pellets and a natural gas-based production process to produce the HBI.
4	**Iron-making – HBI from Green Pellets using Renewable Hydrogen**	Producing HBI from Green Pellets, using renewable hydrogen to produce both the pellets and the HBI. The product from this pathway is assumed in the modelling for this report to be Green Iron in the form of HBI.
5	**Green Steel**	Domestic production of Green Steel, with full renewable energy solutions.

Steelmaking infrastructure value drivers

In a general sense there are two primary technologies used to convert iron into steel: blast furnace (BF) and electric arc furnace (EAF).

It is estimated between 70% and 80% of steel produced today is through a BF pathway, an approach which has been refined over centuries, relying on the use of coking coal. Almost all of the remaining steel is made via an EAF, using an electrical current.

One of the critical challenges to overcome in moving towards lower emissions technologies in the medium term is the installed capital base of the steel industry being heavily weighted towards the BF pathway.

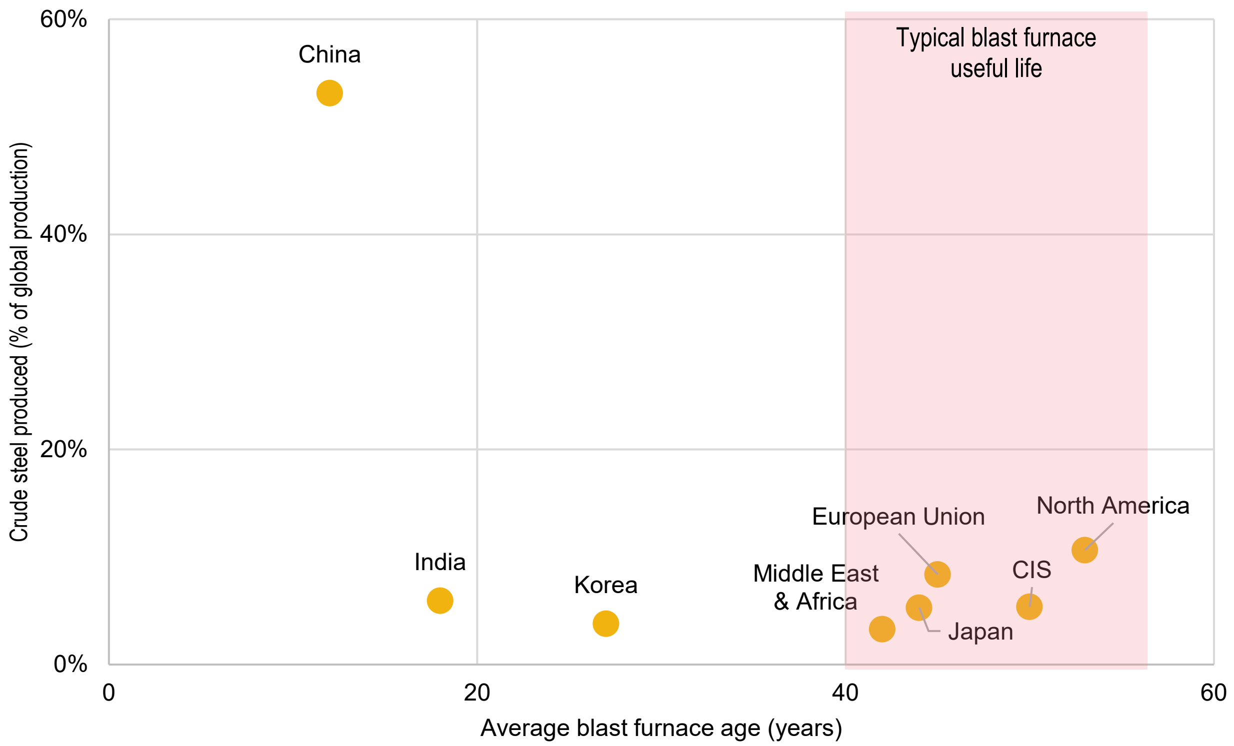
The current focus of steel decarbonisation is on the EAF pathway due to the capacity to utilise renewable electricity generation as an energy source.

Traditional integrated BF-based steel production assets are a large, expensive, and complex class of infrastructure. Modern BFs are designed to last for more than half a century. Therefore, the timing of when these capital investments were made will significantly influence the timing of their replacement, with some likely to remain operational well into the foreseeable future.

The average age of BFs by country is outlined in Figure ES1.

Given the long useful life of BFs, countries are now faced with the difficult decision to either retire BFs early to transition to greener production methods or extract the normal service life from existing facilities and focus on other strategies to reduce emissions such as carbon capture use and storage. This presents both an opportunity, and a challenge, for steel industry decarbonisation.

Figure ES1 Average BF age and share of global crude steel production



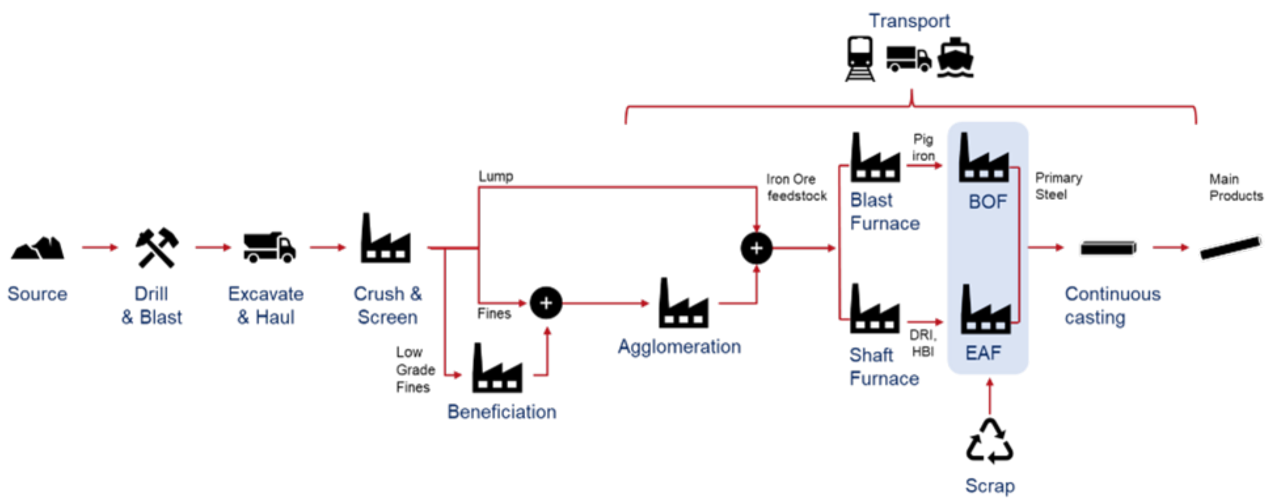
Source: BHP Pathways to decarbonisation episode two summary

Defining the Green Steel value chain

Although iron and steelmaking processes have changed substantially from the development of the first forges through the industrial revolution, the fundamentals remain the same.

A stylised example of the process to produce steel from iron ore is provided below at Figure ES2.

Figure ES2 Iron ore to steelmaking process

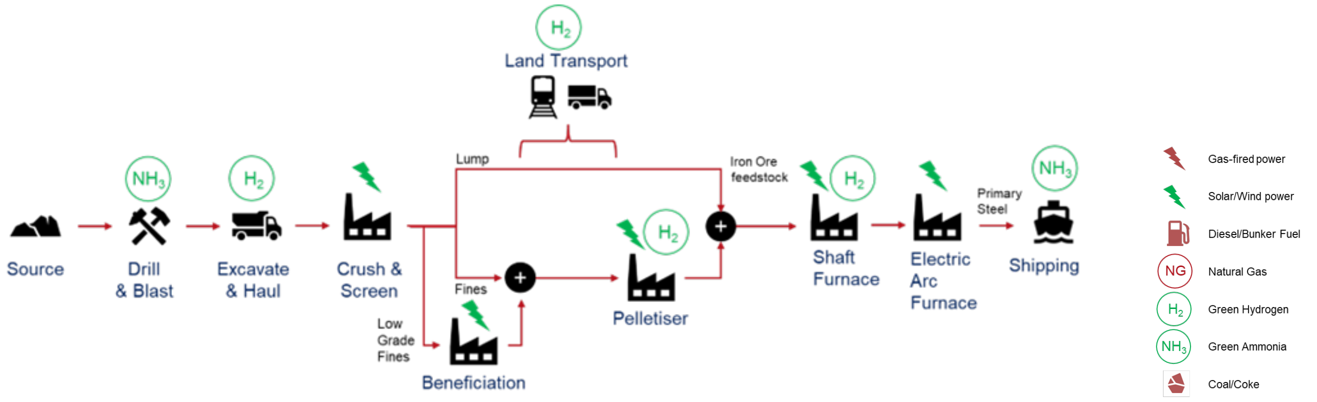


The term 'Green Steel' typically describes any process whereby steel is produced with renewable energy sources, thereby reducing or eliminating the use of fossil fuels such as coking coal, oil, diesel, or natural gas.

For the purposes of this study, and to explore as many opportunities as possible for Western Australia, a broader definition of Green Steel is adopted to include any opportunity to decarbonise (either using lower carbon sources or renewables) any stage of the entire process chain of steelmaking.

A notional, fully decarbonised steel value chain is presented below in Figure ES3.

Figure ES3 Green Steel - Fully decarbonised iron ore to steelmaking pathway



The progressive decarbonisation of each step, through adoption of new technologies, new production methods, and new energy sources, presents an opportunity and a challenge for Western Australia to engage in the decarbonisation efforts of the steel industry.

Western Australia has many attributes which position it strongly. The State's existing iron ore comparative advantage, abundance of reserves, established infrastructure, political and regulatory stability, and existing energy and emerging renewable energy advantages, can combine to provide a platform to meaningfully contribute to the decarbonisation of steelmaking, and continued economic development.

Making Green Steel and Green Steel products in Western Australia

To understand the extent to which Western Australia can benefit from the move to decarbonise the production of steel, a value chain model was developed by GHD to analyse opportunities and key obstacles to a formation of a Western Australian Green Steel industry.

The value chain model assists in understanding the capital requirements, costs, and emissions for expanding beyond the current iron ore mining and switching from fossil fuels to renewable energy sources.

The model considers all steps of the value chain from mining, processing, transport, agglomeration, iron and steelmaking, to shipping. It takes as inputs infrastructure and technology, consumables, costs, geographic factors, power use, operational scale and ore properties, and models current and potential future extended value chains.

Pathway 1: Green Iron Ore Mining

The Green Iron Ore Mining Pathway outlined in Figure ES4 considers the export of hematite and magnetite concentrate from Western Australia, using renewable energy. This pathway would see any new mines transition to the use of renewable energy sources and existing mine infrastructure progressively replaced. Green Iron Ore Mining would reduce emissions by 0.07 tCO_2 per tonne of steel produced.

The levelised costs for fossil fuel and Green Iron Ore Mining pathways are similar for both hematite and magnetite (Figure ES5). The higher costs for magnetite ore type relate to the higher rates of beneficiation required to remove the impurities naturally occurring with this ore type.

The indicative capital and other resource requirements for Green Iron Ore Mining are outlined in Table ES2.

Figure ES4 Green Iron Ore Mining pathway

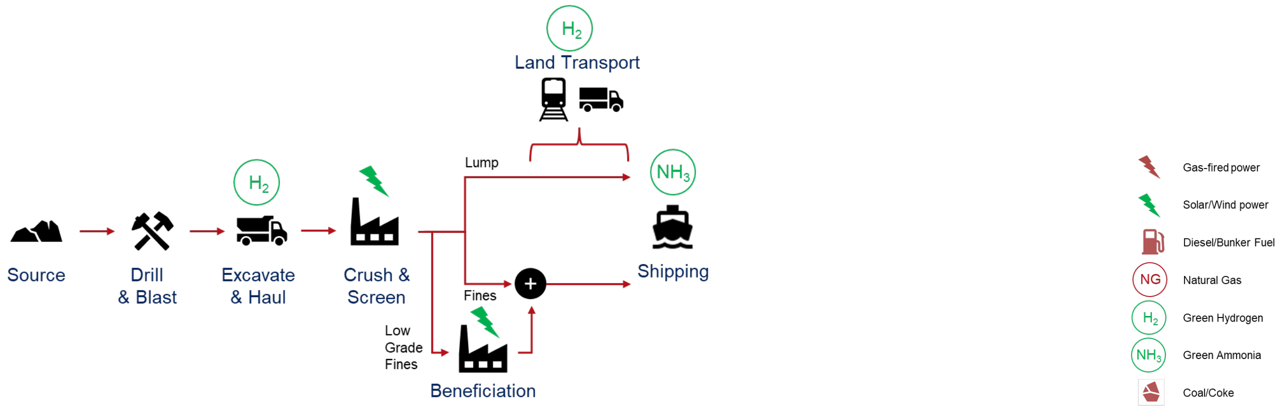
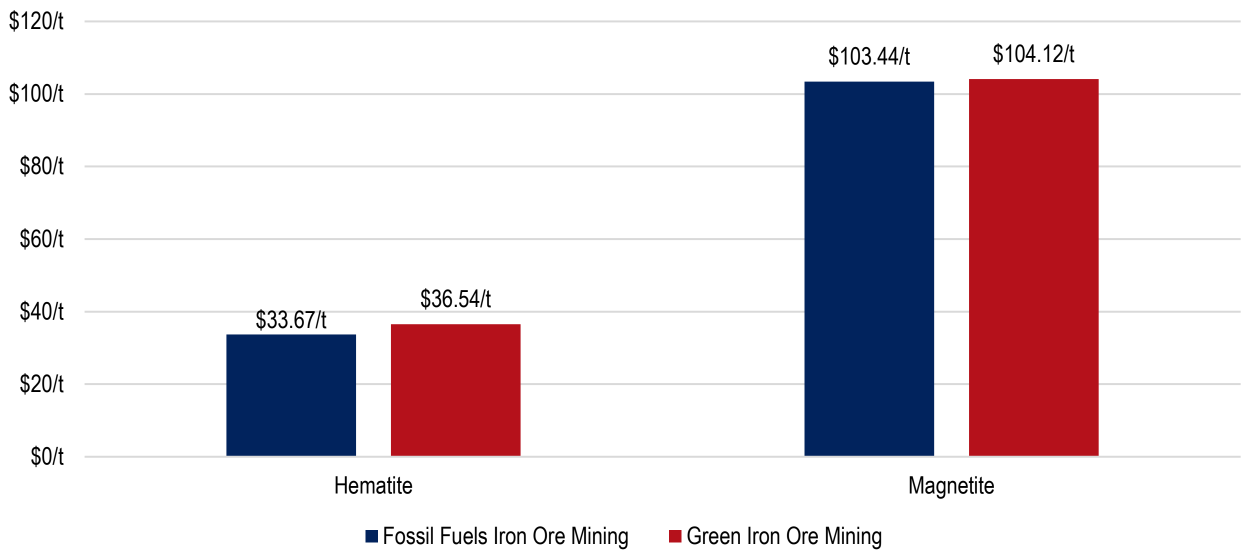


Figure ES5 Levelised Cost of Production (AUD/tonne), Green Iron Ore Mining vs Fossil Fuels Iron Ore Mining, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (1c and 2a), Magnetite (1f and 2a1))
Notes: For H_2 cost of $7 AUD/kg

Table ES2 Indicative capital and other resource requirements for Green Iron Ore Mining

Indicative Requirements for:	1Mtpa Shipped Green Iron Ore		50Mtpa Mined Ore Shipped as Green Iron Ore		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Sustained power required	16	38	787	565	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$138	$332	$6,948	$4,986	M AUD	Capex
Renewable facility land use	80	200	4,325	3,104	Hectares	
Annual hydrogen required	2	3	109	46	Ktpa	
Hydrogen facility	$24	$34	$1,228	$514	M AUD	Capex
Ammonia facility	$0.8	$0.8	$13	$6	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$1,097	$366	M AUD	Capex
Water required	132	742	6,602	11,131	ML p.a.	
Mined ore required	1.01	3.3	50	50	Mtpa	
Shipped product	1	1	49.85	15	Mtpa	

Source: GHD Model Value Chain (Scenarios: Hematite (2b and 2a), Magnetite (2b1 and 2a1)); MRIWA

Pathway 2: Green Pellets

The Green Pellets pathway, outlined in Figure ES6, upgrades and value-adds to iron ore to produce a new product to supply into the ironmaking and steelmaking markets, resulting in a greener value chain.

Current iron and steelmaking technologies rely on being fed with iron ore feedstock above a characteristic size (diameter). Lump hematite is ore of sufficient quality, and after screening, of a sufficient diameter to enable it to be directly fed to an ironmaking furnace. All other finer ores must first be agglomerated before the ore can be used.

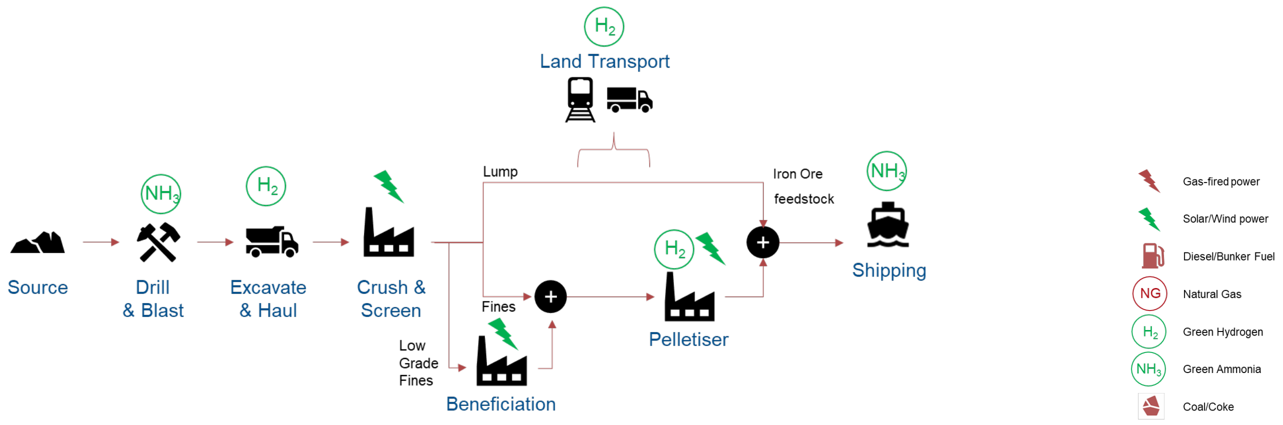
This process can be decarbonised through the process of pelletisation which uses a hydrogen indium furnace to help form the pellets.

The production of Green Pellets provides an avenue for Western Australia to go to the next step in the value chain beyond supply of hematite ore or magnetite concentrate made without the use of fossil fuels.

This pathway would not see any change to the export of lump or high-grade fines from the State. Rather it would focus on the development of a new product using either low-grade fines or through the opening of new mines to add to the suite of iron ore export products supplied by Western Australia.

Use of Green Pellets in steelmaking would see the reduction of emissions by 0.12 tCO_2 per tonne of steel produced.

Figure ES6 Green Pellets pathway



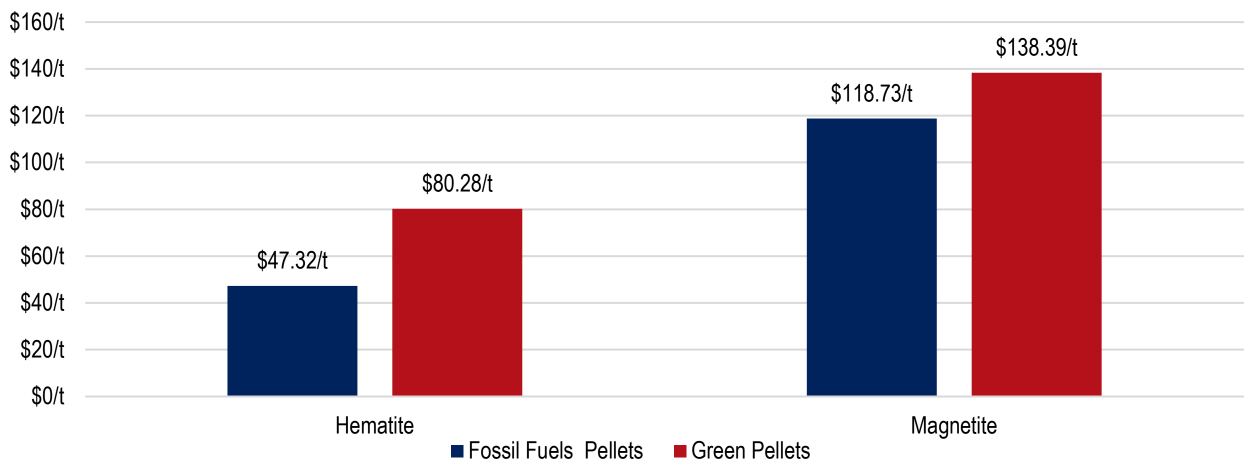
The levelised cost of production for the Green Pellet pathway is both higher for hematite and magnetite ores as outlined in Figure ES7.

In the case of hematite this is $32.96 AUD/tonne higher against only $19.66 AUD/tonne higher for magnetite.

The higher cost for hematite is due to more energy being required to process hematite ores to pellets. Magnetite is exothermic and releases energy requiring less energy for processing at this stage.

The indicative capital and other resource requirements for Green Pellets are outlined in Table ES3.

Figure ES7 Levelised Cost of Production (AUD/tonne), Green Pellets versus Fossil Fuels Pellets, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain Scenarios: Hematite (3 and 4), Magnetite (3a and 4a))
Notes: For H_2 cost of $7 AUD/kg

Table ES3 Indicative capital and other resource requirements for Green Pellets

Indicative Requirements for:	1 Mtpa Shipped Green Pellets		50 Mtpa Mined Ore Shipped as Green Pellets		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$100	$140	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 pellet plants
Processing facility land use	40	40	400	200	Hectares	H:1 M:1 / H:5 M:3 pellet plants
Sustained power required	48	60	2,426	902	MW	Ongoing 24 hr load
50/50 mixed solar/wind + batteries	$430	$530	$21,412	$7,957	M AUD	Capex
Renewable facility land use	266	330	13,330	4,954	Hectares	
Annual hydrogen required	7	6	338	89	Ktpa	
Hydrogen facility	$76	$67	$3,820	$1,009	M AUD	Capex
Ammonia facility	$0.8	$0.4	$13	$6	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$1,097	$366	M AUD	Capex
Water required	407	917	20,363	13,759	ML p.a.	
Mined ore required	1.01	3.3	50	50	Mtpa	
Shipped product	1	1	49.85	15	Mtpa	

Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (4b and 6a), Magnetite (4c and 6a1)); MRIWA

Pathway 3: Iron-making: HBI from Green Pellets using Fossil Fuels

This pathway considers producing hot briquetted (HBI) from Green Pellets, using renewable hydrogen to produce the pellets and a natural gas-based production process to produce the HBI (refer Figure ES8).

Production of HBI from Green Pellets is a technically feasible option today and utilises the existing access to natural gas available in Western Australia while the steel industry invests into further research to increase the use of hydrogen in its processes.

While using Green Pellets to make HBI with fossil fuels will reduce the steel industry's emissions, it will increase Western Australia's emissions. This is discussed further below.

The levelised cost of production for Green Pellets converted to HBI using fossil fuels are significantly lower than using fossil fuels to make pig iron due to the efficiency of reduction using natural gas as compared to using coke in a BF to make pig iron as demonstrated in Figure ES9.

The indicative capital and other resource requirements for HBI from Green Pellets using Fossil Fuels are outlined in Table ES4.

Figure ES8 HBI from Green Pellets using Fossil Fuels pathway

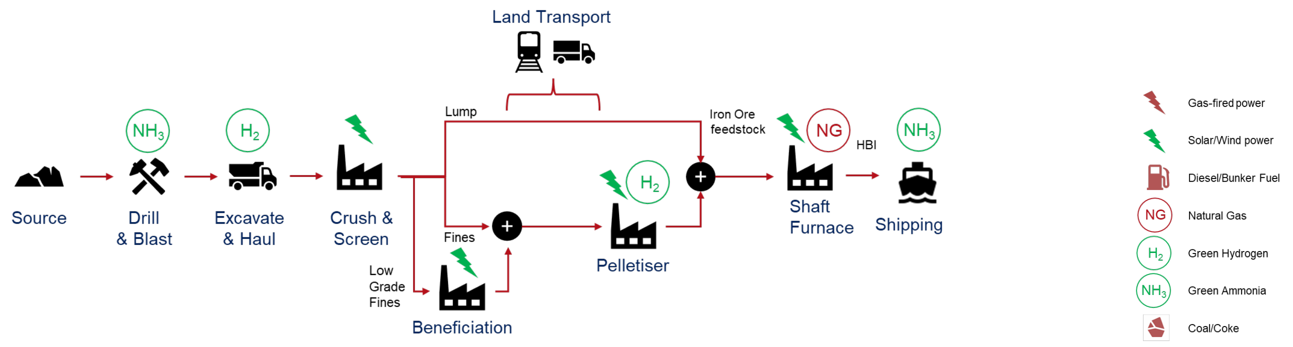
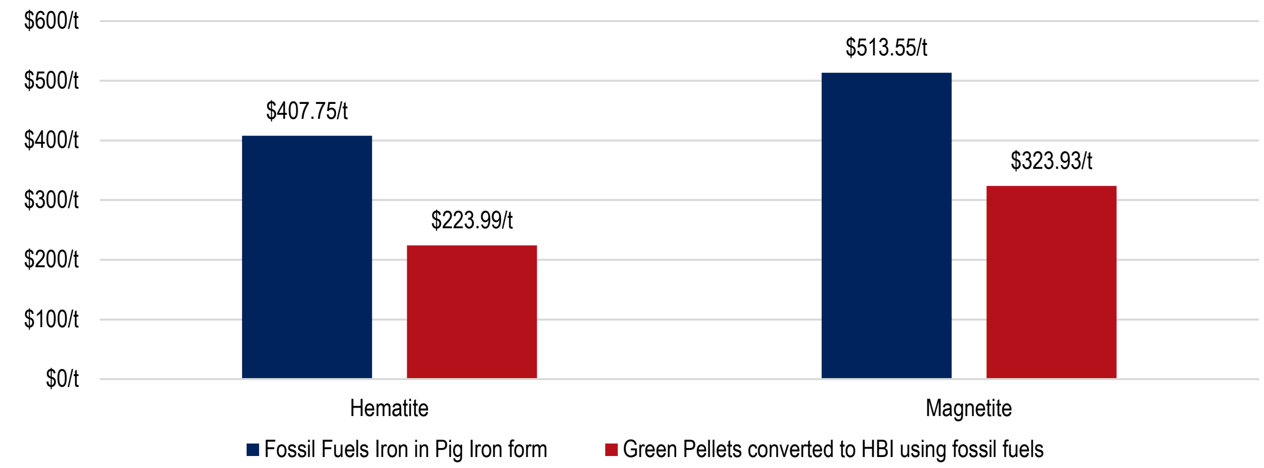


Table ES4 Indicative capital and other resource requirements for HBI from Green Pellets using Fossil Fuels pathway

Indicative Requirements for:	1 Mtpa Shipped HBI from Natural Gas		50 Mtpa Mined Ore Shipped as HBI from Natural Gas		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$145	$198	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 x pellet plants
Shaft furnace	$1,400	$1,400	$14,230	$6,720	M AUD	Capex - H:1 M:1 / H:10 M:3 x shaft furnaces
Processing facility land use	140	140	1,400	500	Hectares	H:1 M:1 / H:5 M:3 x pellet plants H:1 M:1 / H:10 M:3 x shaft furnaces
Sustained power required	105	120	3,307	1,197	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$926	$1,050	$29,192	$10,566	M AUD	Capex
Renewable facility land use	576	657	18,173	6,577	Hectares	
Annual hydrogen required	10	8	315	83	Ktpa	
Hydrogen facility	$112	$94	$3,559	$942	M AUD	Capex
Ammonia facility	$0.8	$0.4	$10	$4	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$731	$244	M AUD	Capex
Water required	602	1,340	18,981	13,399	ML p.a.	
Natural gas	182	182	5,720	1,857	Ktpa	For use in shaft furnace
Mined ore required	1.59	4.88	50	50	Mtpa	
Shipped product	1	1	31	10	Mtpa	

Source: GHD Model Value Chain (Scenarios: Hematite (6a2 and 6a), Magnetite (6a3 and 6a1)); MRIWA

Figure ES9 Levelised Cost of Production (AUD/tonne), HBI from Green Pellets using Fossil Fuels versus Fossil Fuels in Iron in Pig Iron form, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain Scenarios: Hematite (5 and 6a), Magnetite (5b and 6a1))
Notes: For H_2 cost of $7 AUD/kg

Pathway 4: Iron-making – HBI from Green Pellets using Renewable Hydrogen

This pathway considers producing HBI in a fully vertically integrated domestic supply chain, powered by 100% renewable hydrogen and renewable electricity as demonstrated in Figure ES10.

The product from this pathway is assumed in the modelling for this report to be Green Iron in the form of HBI. Other green iron ore products however would give similar results.

A large portion of emissions from steelmaking occur during the ironmaking phase of the process. In HBI pathway this is 65% and in the BF pathway up to 90% of emissions.

For the steel industry to succeed at significantly reducing their emissions, using renewable hydrogen will be critical at this stage of the process.

Significant technical hurdles exist in achieving this.

The use of 100% hydrogen to produce HBI is more expensive than making pig iron from fossil fuels for both type of ores, as demonstrated in Figure ES11, due to the cost of hydrogen.

Replacement of natural gas with hydrogen is only likely to occur as the input hydrogen cost gets closer to the natural gas costs.

The indicative capital and other resource requirements for HBI from Green Pellets using Renewable Hydrogen are outlined in Table ES5.

Figure ES10 HBI from Green Pellets using Renewable Hydrogen pathway

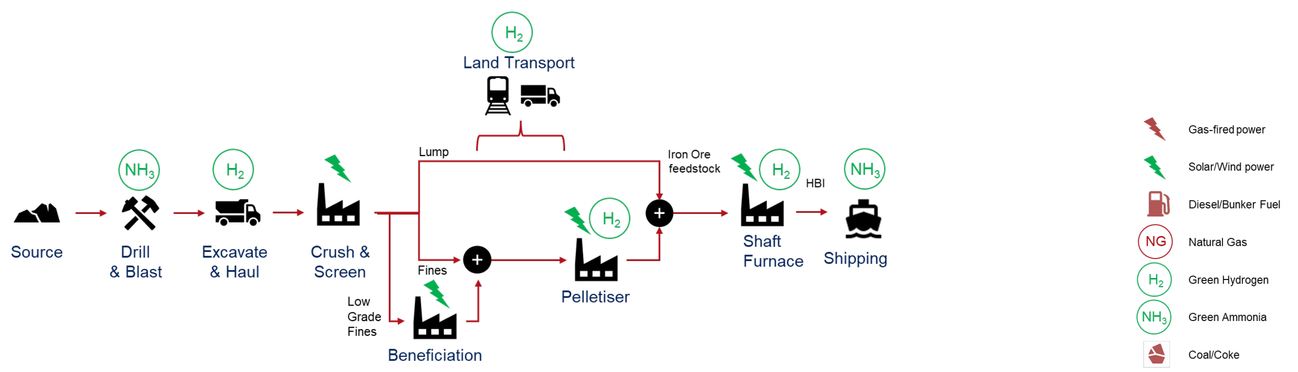
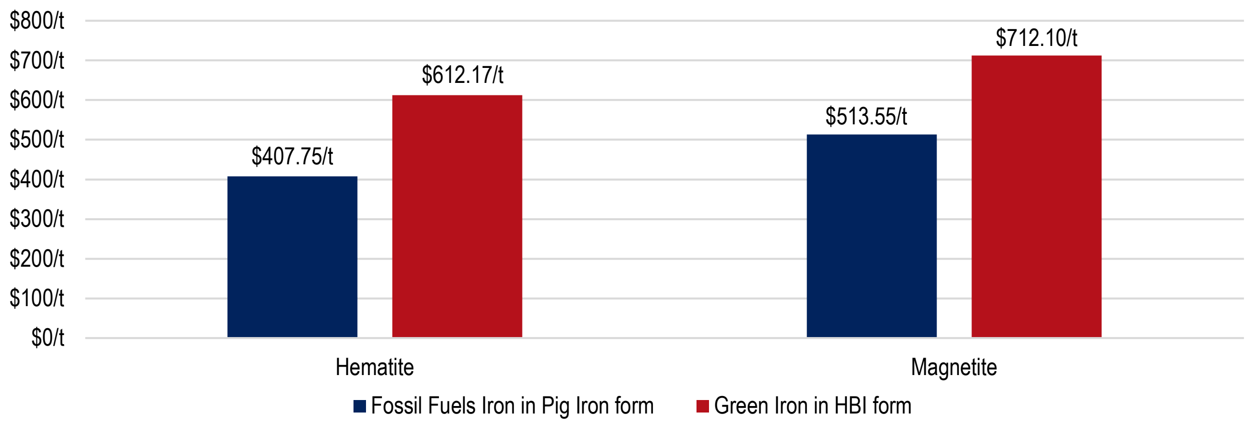


Table ES5 Indicative capital and other resource requirements for HBI from Green Pellets using Renewable Hydrogen pathway

Indicative Requirements for:	1 Mtpa Shipped 100% Green Iron in the form of HBI		50 Mtpa Mined Ore Shipped as 100% Green Iron in the form of HBI		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$145	$198	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 x pellet plants
Shaft furnace	$1,400	$1,400	$14,230	$6,720	M AUD	Capex – H:1 M:1 / H:10 M:3 x shaft furnaces
Processing facility land use	140	140	1,400	500	Hectares	H:1 M:1 / H:5 M:3 x pellet plants H:1 M:1 / H:10 M:3 x shaft furnaces
Sustained power required	477	500	15,039	5,006	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$4,200	$4,300	132,738	44,186	M AUD	Capex
Renewable facility land use	2,600	2,700	82,633	27,507	Hectares	
Annual hydrogen required	69	69	2,183	690	Ktpa	
Hydrogen facility	$783	$779	24,676	7,798	M AUD	Capex
Ammonia facility	$0.8	$0.4	10	4	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$731	$244	M AUD	Capex
Water required	4,000	5,000	131,093	49,800	ML p.a.	
Mined ore required	1.59	4.88	50	50	Mtpa	
Shipped product	1	1	31.43	10.21	Mtpa	

Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (6c and 6), Magnetite (6d and 6b)); MRIWA

Figure ES11 Levelised Cost of Production (AUD/tonne) Green Iron in the form of HBI using Renewable Hydrogen versus Fossil Fuels Iron in Pig Iron form, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (5 and 6), Magnetite (5b and 6b))

Pathway 5: Producing Green Steel in Western Australia

This pathway utilises an EAF, in a fully vertically integrated domestic supply chain, powered by 100% renewable hydrogen and renewable electricity to produce Green Steel as visualised in Figure ES12.

The levelised costs of Green Steel compared to fossil fuel steel is significantly higher.

In a market with competitive margins, Western Australian Green Steel would need to see lowering of the hydrogen production costs and the renewable power price to be competitive.

The amount of power required for EAF steelmaking has a strong relationship to the iron ore gangue content.

Whilst magnetite Green Steel costs are currently higher, as demonstrated in Figure ES13, there is the potential to lower costs to the same level as hematite, given the ability to remove more impurities during the beneficiation process.

The indicative capital and other resource requirements for Green Steel are outlined in Table ES6.

Figure ES12 Green Steel - Fully decarbonised iron ore to steelmaking pathway

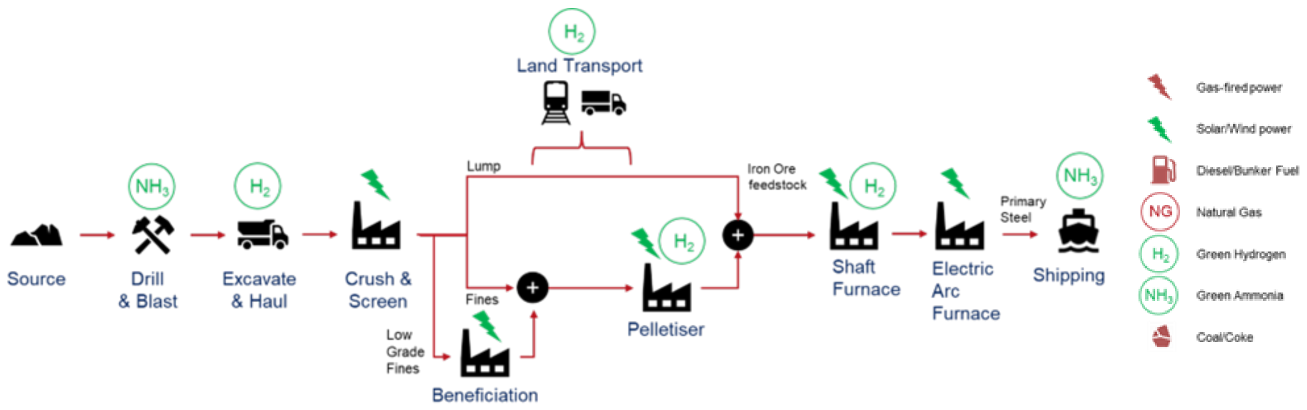
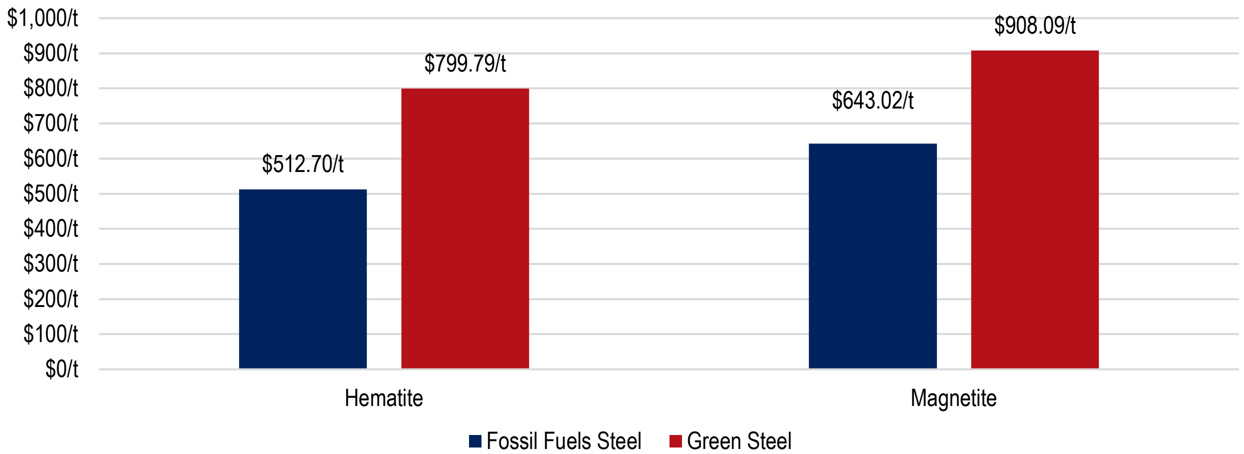


Figure ES13 Levelised Cost of Production (AUD/tonne), Green Steel versus Fossil Fuels Steel, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain Scenarios: Hematite (9c and 10a), Magnetite (9c1 and 10b))
Notes: For H_2 cost of $7 AUD/kg

Table ES6 Indicative capital and other resource requirements for Green Steel pathway

Indicative Requirements for:	1 Mtpa Shipped Green Steel		50 Mtpa Mined Ore Shipped as Green Steel		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$162	$216	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 x pellet plants
Shaft furnace	$1,500	$1,500	$14,230	$6,720	M AUD	Capex - H:1 M:1 / H:10 M:3 x shaft furnaces
EAF facility	$240	$240	$2,200	$1,035	M AUD	H:1x M:1 / H:15 M:5x x EAF
Processing facility land use	230	230	1,550	680	Hectares	H:1 M:1 / H:5 M:3 x pellet plants H:1 M:1 / H:10 M:3 x shaft furnaces H:1 M1x / H:15 M:x3 EAF
Sustained power required	638	638	17,554	5,743	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$5,600	$5,600	$154,937	$50,693	M AUD	Capex
Renewable facility land use	3,500	3,500	96,452	31,557	Hectares	
Annual hydrogen required	79	76	2,179	688	Ktpa	
Hydrogen facility	$895	$864	$24,620	$7,780	M AUD	Capex
Ammonia facility	$0.8	$0.4	$9	$4	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$609	$244	M AUD	Capex
Water requirements	4,700	5,500	130,795	49,704	ML p.a.	Capex
Mined ore required	1.82	5.89	50	50	Mtpa	
Shipped product	1	1	27.47	8.92	Mtpa	

Source: GHD Analysis (Model Value Chain Scenarios: Hematite (10a1 and 10a), Magnetite (10b1 and 10b)); MRIWA

Assessing the opportunities

Greening today's iron ore is economic now

Decarbonising the Western Australian iron ore industry sees existing and new iron ore mines become emissions-free by using renewable power supplied by solar and wind facilities.

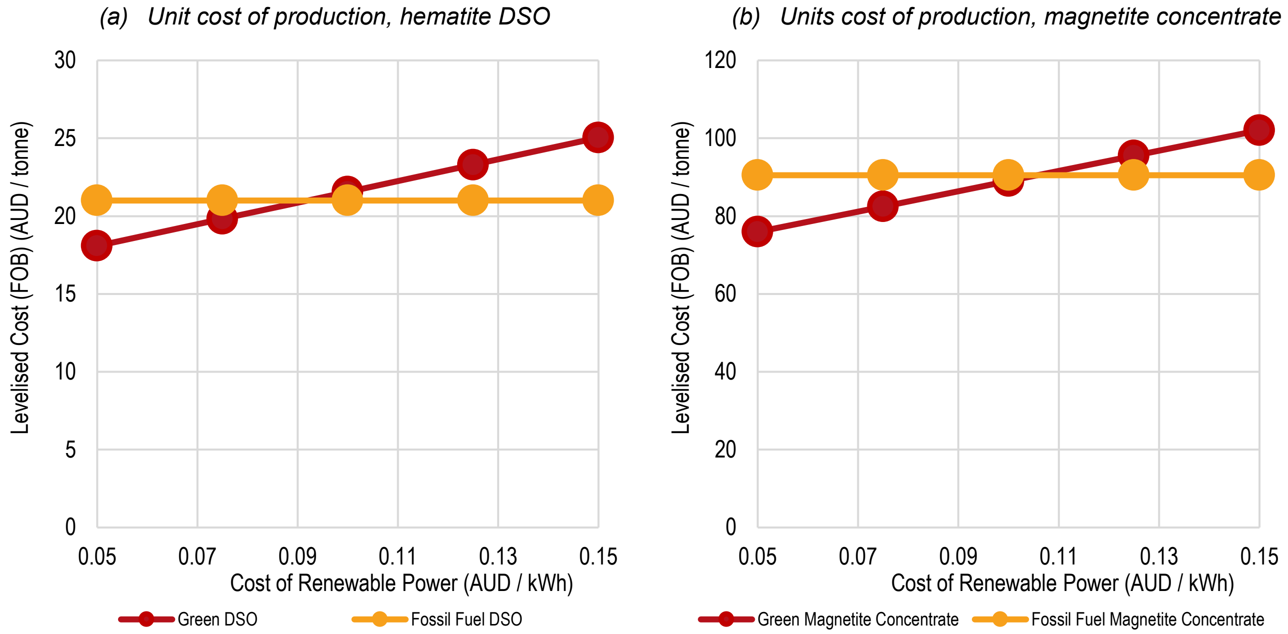
The value chain modelling indicates transitioning the production of iron ores to green power delivers a broadly similar, or slightly improved, unit cost of production on today's costs.

This pathway, for hematite and magnetite ores, is cost competitive compared to the prevailing practice at today's benchmark cost of $0.1 AUD/kWh for mixed solar/wind generated power, refer Figure ES14 for unit cost comparisons.

Establishing renewable power infrastructure will not only support the existing industry but also reduce iron ore production costs in the long run as the price of renewable power decreases.

Starting the Pilbara's and Mid West's electrification journey here could be a catalyst for further electricity infrastructure investments, fostering downstream and alternative industry developments like renewable hydrogen.

Figure ES14 Unit cost economics, iron ore mining by energy scenario, $/tonne output product



Source: GHD Analysis (Model Value Chain Scenarios: Hematite 1c,2a,, Magnetite 1f,2a1)
Note: Excludes shipping

Natural gas-based DRI in the form of HBI can be transformative, but domestic emissions would increase

Natural gas-based value adding has been shown by the technical analysis to be substantially cheaper than even today's BF-based iron reduction production processes, refer Figure ES9. Using a conservative long term domestic gas price of approximately $4 per gigajoule (GJ) yields a highly competitive direct reduced iron (DRI) product in the form of HBI in Western Australia.

Natural gas-based produced DRI in the form of HBI is around $200 per tonne cheaper than coal-fired pig iron produced in a traditional BF. Low natural gas prices will favour the production of DRI in the form of HBI in Western Australia, even accounting for the higher gangue contents which remains in the HBI.

This includes provision for hydrogen-based pelletising, which could also be done using natural gas to lower the cost of supply even further.

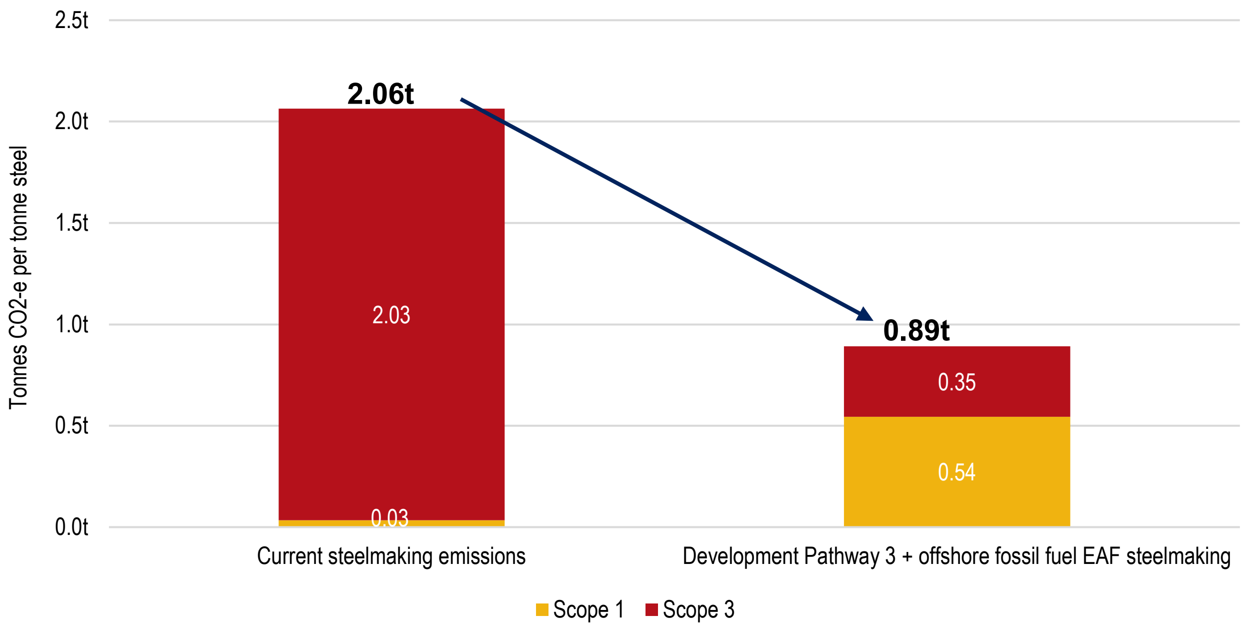
By using natural gas, the whole-of-supply-chain carbon emissions of primary steel made through this production process are significantly lower, at around 0.86-0.89 tCO_2 per tonne of steel (against 2.06-2.11 tCO_2 per tonne of steel in the similarly modelled coal-based pig iron supply chain).

The challenge with this version of the steelmaking value chain is the domestic emissions associated with Western Australia's participation increase sharply, from around 0.03-0.16 tCO_2 per tonne of steel to 0.54 tCO_2 per tonne of steel for a typical hematite and magnetite value chain as demonstrated in Figures ES15 and ES16.

In effect, there is a five-fold increase in domestic emissions to realise an overall net reduction in global steelmaking emissions of around 56-59%.

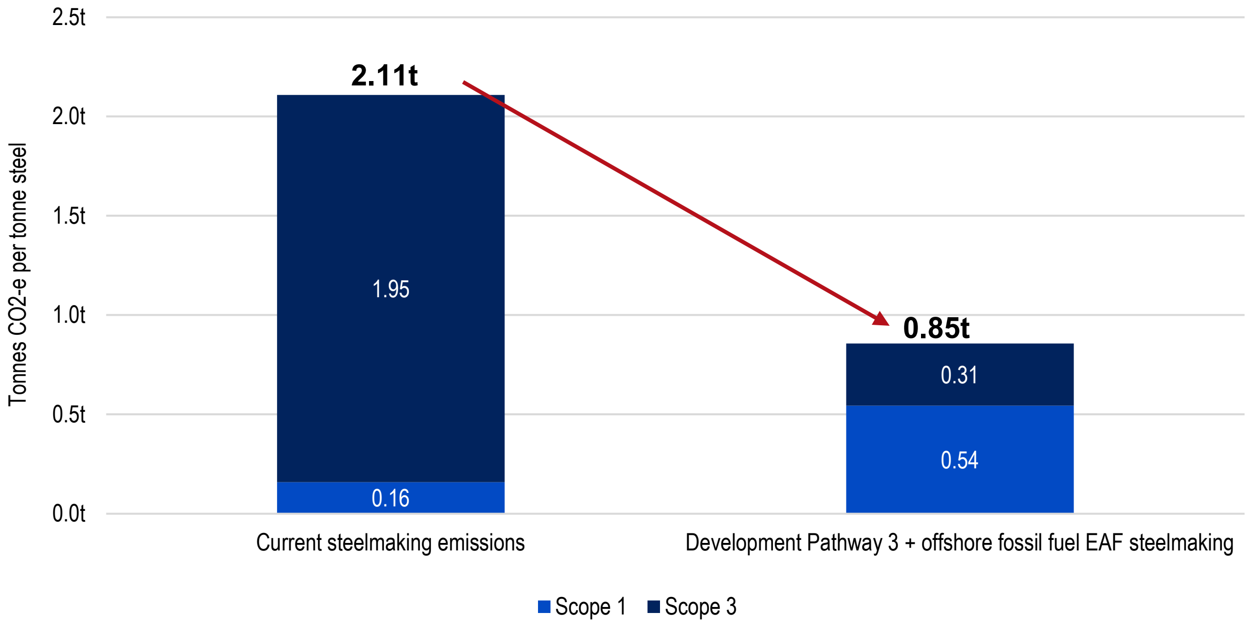
This reduction in emissions for the steel industry is potentially increased if lower gangue Western Australian ores are used due to the lower impurities in the HBI requiring lower energy use in steelmaking.

*Figure ES15 Steelmaking emissions, Hematite: Fossil fuels steelmaking value chain vs HBI from Green Pellets usings Fossil Fuels with offshore fossil fuels based EAF, tonnes per tonne of steel, domestic (Scope 1) vs offshore (Scope 3)**



Source: GHD Analysis (Model Value Chain Scenarios: 9c, 9f)
Notes: Excludes shipping.
** Sensitive to iron ore gangue content both on scope 1 and scope 3 emissions saving*

*Figure ES16 Steelmaking emissions, Magnetite: Fossil fuels steelmaking value chain vs HBI from Green Pellets usings Fossil Fuels with offshore fossil fuels based EAF, tonnes per tonne of steel, domestic (Scope 1) vs offshore (Scope 3)**



Source: GHD Analysis (Model Value Chain Scenarios: 9c1, 9g)
Notes: Excludes shipping
** Sensitive to iron ore gangue content both on scope 1 and scope 3 emissions saving*

Opportunities exist in domestically produced green iron products

The analysis in this study shows green hydrogen-based HBI, a feedstock in EAFs, is expected to reach cost parity with its fossil fuel counterpart sooner than production of Green Steel.

This creates an opportunity for Western Australia, alongside the expected continuation of levelised cost reductions in the production of green hydrogen. In the medium term, fully Green Iron in the form of HBI production can be an aspirational target for Western Australia.

As it stands, green hydrogen is not yet available at an economic price point for widespread adoption of renewable energy in the ironmaking process in place of fossil fuels. But instead of waiting for the price to fall, opportunity exists for the State in the above "transition strategy".

HBI can be produced at a highly competitive cost of production using natural gas, which has lower emissions than coking coal, as a fuel in the initial phase before transitioning to green hydrogen once costs become economic.

Substitution of hydrogen for the natural gas is also possible using current direct reduction technologies. This will have the effect of reducing emissions towards that of fully Green Iron in the form of HBI, based on the cost competitiveness of hydrogen to natural gas. Substitution of hydrogen could be based on availability.

HBI can be a feedstock for existing EAFs but can also replace the supply of iron ore to existing fossil fuel steelmaking in a BF or BOF. In this transformation therefore, HBI would not have to wait for Green Steelmaking technologies to evolve before having a good market.

For 100% hydrogen-based HBI production to be economic, analysis in this study shows infrastructure for renewable power fuelled hydrogen production plants must be developed to realise or support the price of hydrogen reaching $4 AUD/kg (in today's dollars). The assessment for current delivered price of electrolytic green hydrogen in Western Australia is approximately $7 AUD/kg.

As development of hydrogen production facilities continue, the costs of hydrogen should fall, which will incentivise the replacement of natural gas with hydrogen in shaft furnaces.

Replacement of hydrogen in shaft furnaces is not all-or-nothing but can be a staged process where the gas blend can be varied over time. Once hydrogen prices reach $4 AUD/kg, fully Green Iron in the form of HBI with 100% hydrogen feed would become cost competitive against coal-fired pig iron.

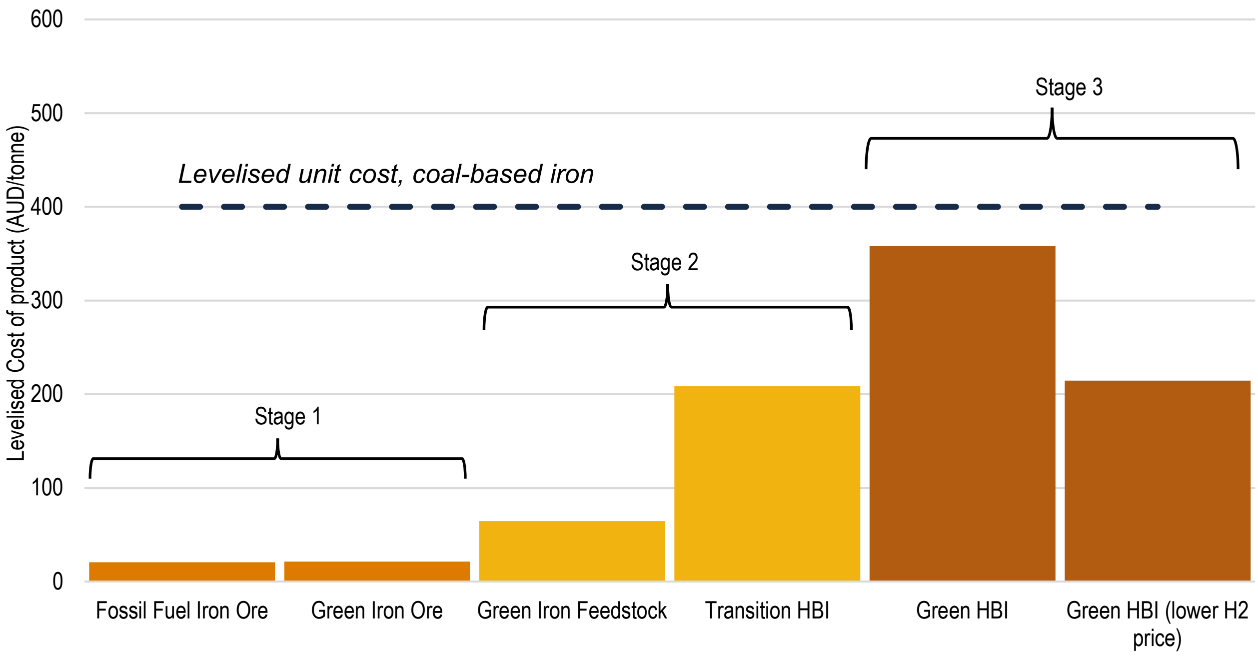
The second transition comes when hydrogen reaches below $1.50 AUD/kg, when it becomes more cost effective to use in shaft furnaces rather than natural gas – incentivising Green Iron in the form of HBI as the most economical way to make iron.

At this stage of development, robust renewable power infrastructure will exist to supply the 0.07 tonne of H_2 per tonne of HBI required across the value chain. Access to hydrogen at this scale also opens other opportunities in the form of an exportable energy market.

The levelised cost across the different pathways of the value chain are shown in Figures ES17 and ES18. Of note is the substantial step-up requirements in cost in going to fully Green Iron in the form of HBI.

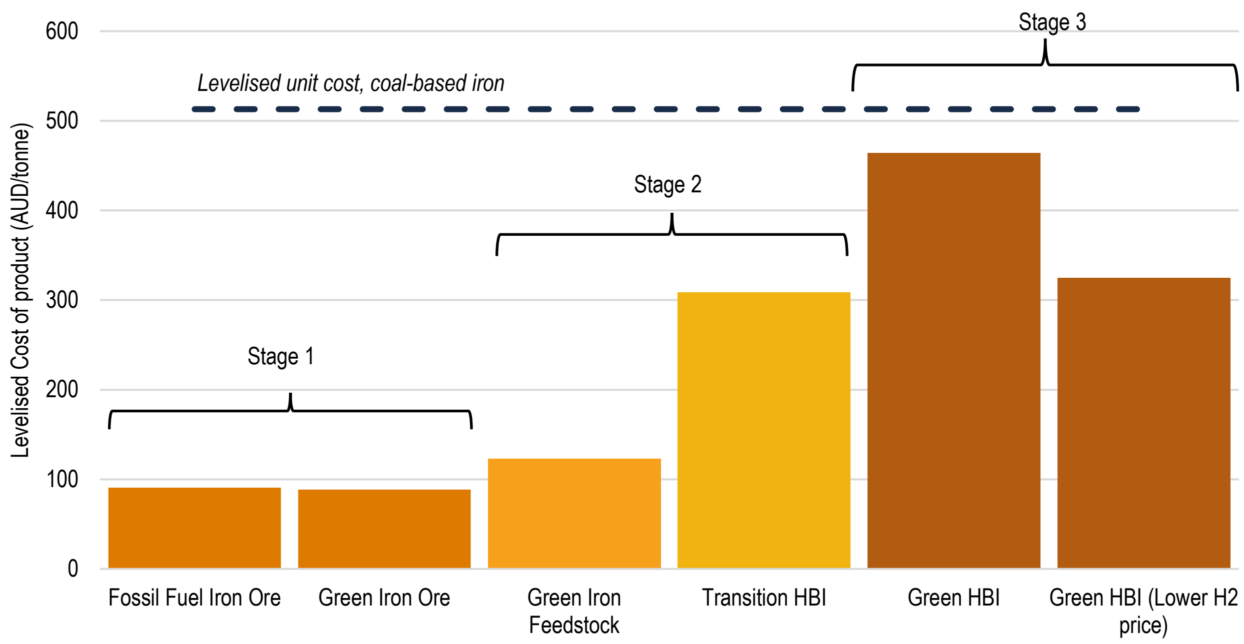
Hydrogen and sustained power required are considered below in figures ES21 and ES22.

Figure ES17 Levelised cost of production for Green Iron in the form of HBI transition strategies using hematite ores



Source: GHD Analysis
Notes: Iron ore feedstock is Pilbara hematite DSO, produced at 50 Mtpa. Input hydrogen price of $7/kg, falling to $3.50 at to Stage 3a, and then to $1.40/kg in Stage 3b. Input product equivalent unit cost represents conversion of cost of production into unit cost per tonne of fossil fuel pig iron produced through coal-based BOF pathway.

Figure ES18 Levelised cost of production for Green Iron in the form of HBI transition strategies using magnetite ores



Source: GHD Analysis
Notes: Iron ore is magnetite mined on a 50 Mtpa basis. Input hydrogen price of $7/kg, falling to $3.50 at to Stage 3a, and then to $1.40/kg in Stage 3b. Input product equivalent unit cost represents conversion of cost of production into unit cost per tonne of fossil fuel pig iron produced through coal-based BOF pathway.

In the long run, Green Steel may be possible subject to the price of hydrogen

While it may be feasible for Western Australia to produce Green Steel at a cost of supply not materially below current market prices, this requires the cost of hydrogen to reduce significantly.

As the cost of renewable electricity decreases, bringing the cost of green hydrogen down with it, there is an opportunity to move up the value chain and manufacture green value-added steel products. However, for Green Steel to be economic in Western Australia, the price of hydrogen must reach the so-called "stretch" target of approximately US$2/kg or $3 AUD/kg. Analysis of the breakeven price points for a variety of iron products is provided in Table ES7 and Figure ES19 for hematite ores and Figure ES20 for magnetite ores.

The replacement of over 60% of the world's fossil fuel BFs is unlikely in the near term due to their age, so offshore foreign environmental factors must change before Green Steel in Western Australia can be cost competitive with the export steel markets.

New Green Steel technologies involving other pathways to convert iron are also being explored by researchers and these technologies in the future may require less prohibitive investment or involve more economic feedstock (such as low impurity pig iron).

Currently much of the research is at pilot scale, and still involves green iron production rather than direct Green Steel production because of the large emissions from ironmaking.

Table ES7 Rounded required H_2 price for each pathway to break-even in cost against fossil-fuels equivalent

Breakeven H_2 prices (AUD/kg)	Green Pellets	Green Iron in the form of HBI	Green Steel
Hematite	$1.50	$4.00	$3.50
Magnetite	$2.80	$4.00	$3.50

Source: GHD Analysis

The energy investment task ahead is significant

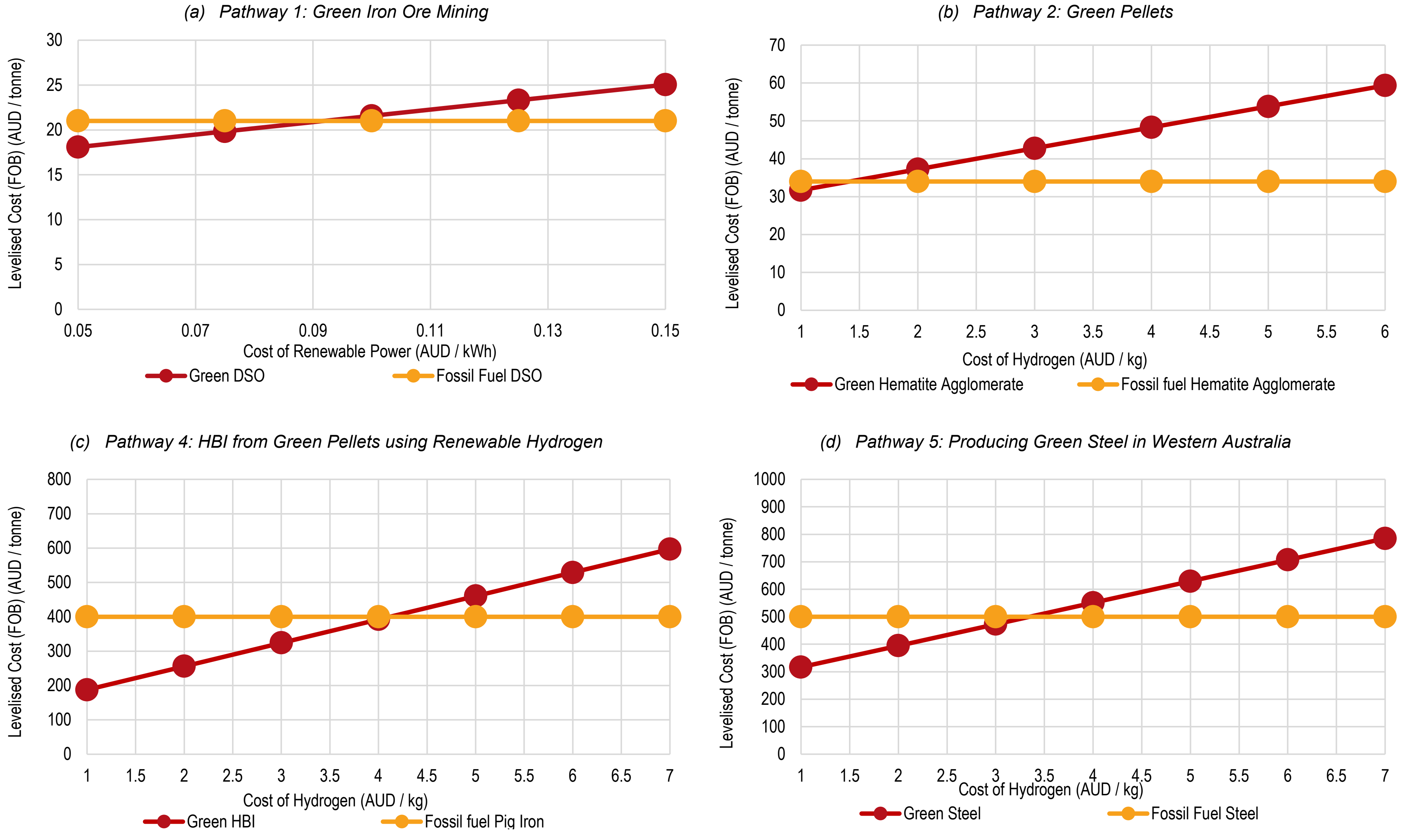
While the focus of the assessment is on the economics of iron ore, iron and steel, the interplay between this and Western Australia's emerging renewable electricity and renewable hydrogen industry figures strongly.

Decarbonisation of the steel industry will require large scale development of renewable hydrogen, regardless of where that hydrogen is used. Development of a renewable energy-powered iron ore, iron and / or steel projects in Western Australia will inextricably require large scale simultaneous investments.

To develop at-scale projects in Western Australia, the value chain model indicates the renewable energy infrastructure required to produce various iron ore, iron and steel products.

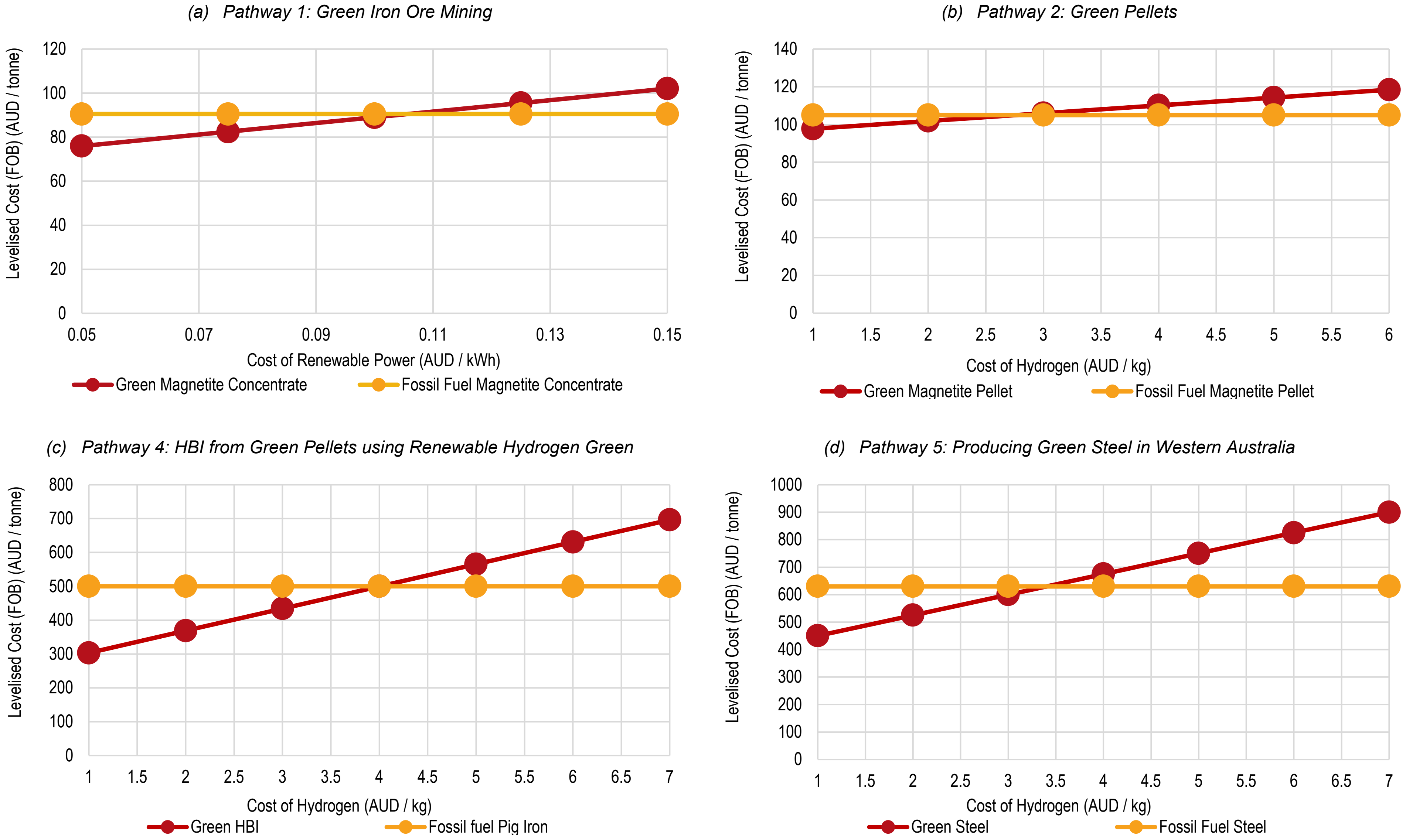
Figure ES21 demonstrates the installed energy consumption comparisons for 1 Mtpa of shipped product using hematite and magnetite ores and Figure ES22, the installed energy consumption comparisons for 50 Mtpa of mined hematite ore and magnetite ore.

Figure ES19 Breakeven hydrogen / electricity input costs, hematite ore based products, $/kg or $/MWh



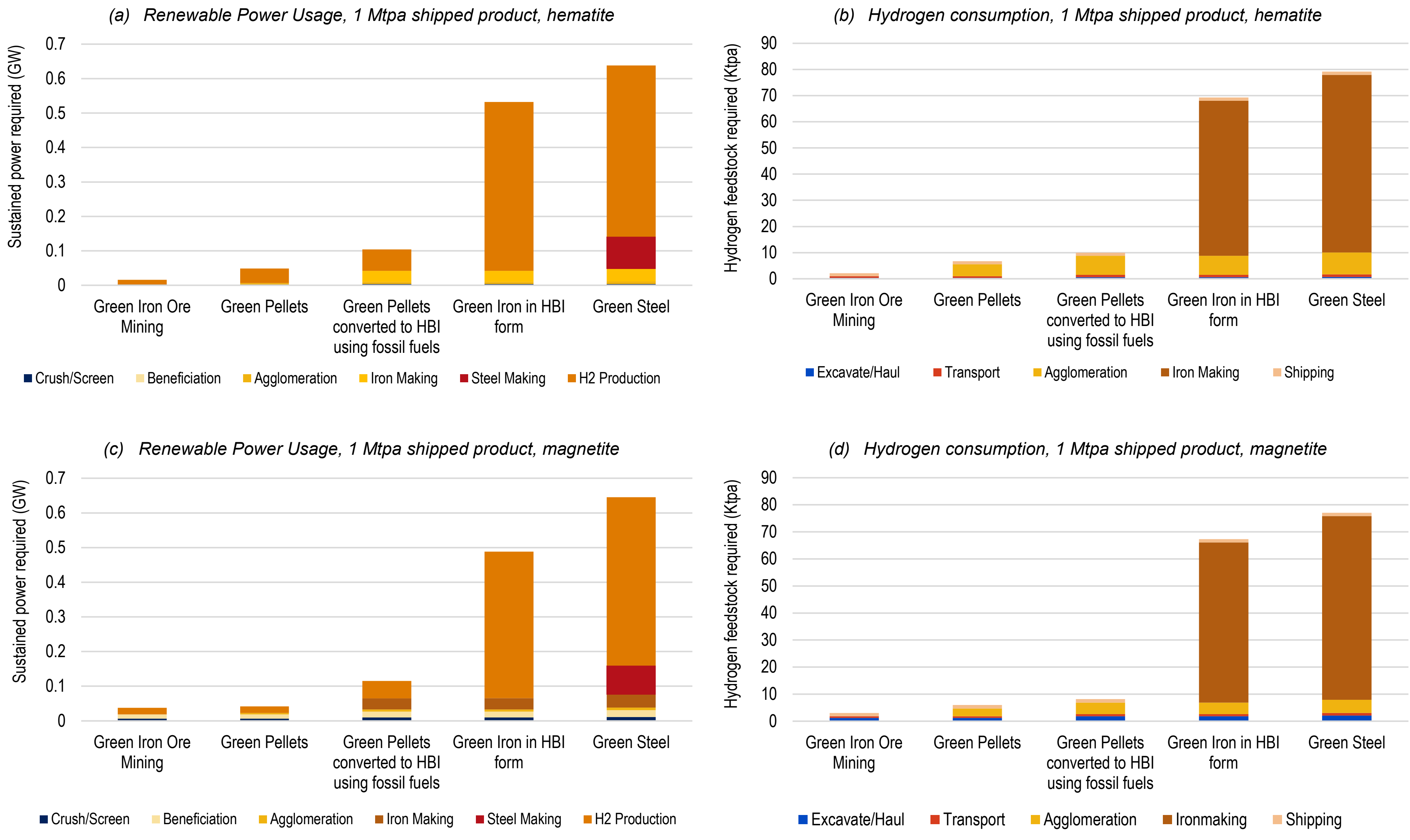
Source: GHD Analysis GHD Analysis (Model Value Chain Scenarios: Hematite (2b,4b,6a1,10a1))

Figure ES20 Breakeven hydrogen / electricity input costs, magnetite ore-based products, $/kg or $/MWh



Source: GHD Analysis (Model Value Chain Scenarios Magnetite (2b1,4c,6d,10b1))

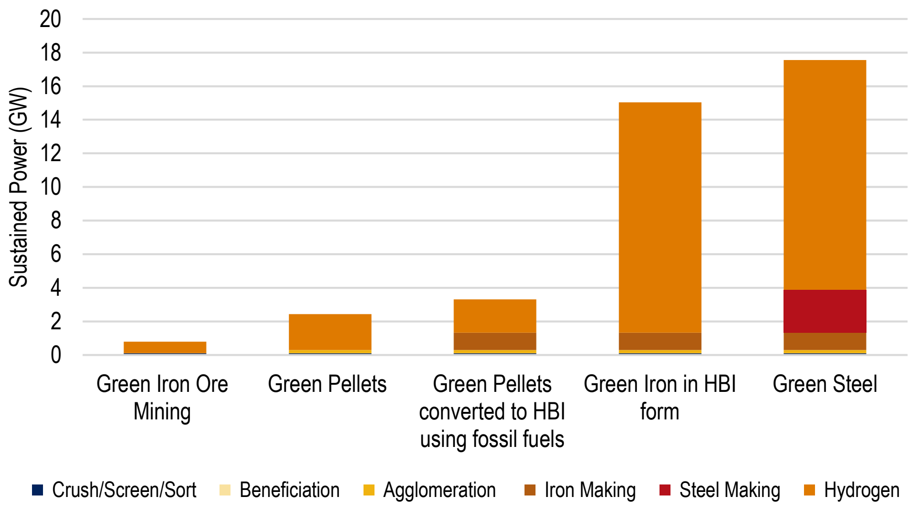
Figure ES21 Installed energy consumption comparisons for 1 Mtpa of shipped product using hematite and magnetite ores



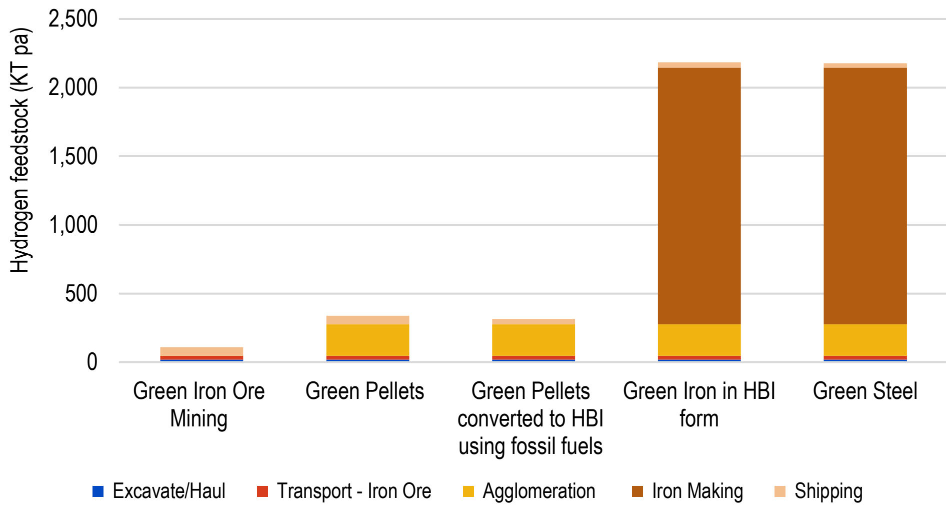
Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (2b,4b,6a1,6a2,10a1), Magnetite (2b1,4c,6a3,6d,10b1))

Figure ES22 Installed energy consumption comparisons for 50 Mtpa of mined hematite ore and magnetite ore

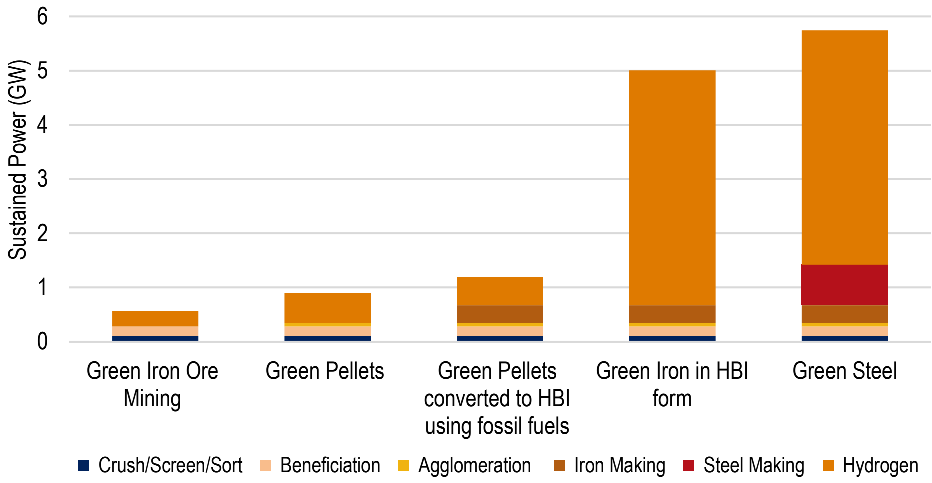
(a) Renewable Power Usage, 50 Mtpa mined ore by shipped product, hematite



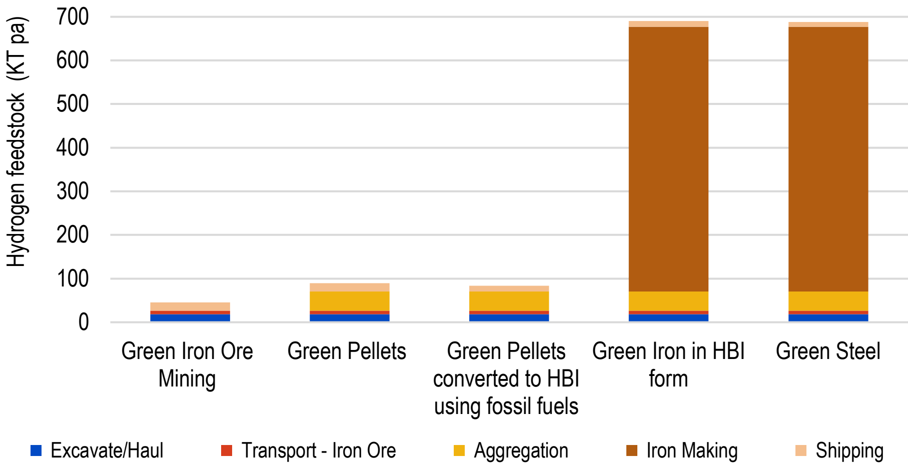
(b) Hydrogen consumption, 50 Mtpa mined ore by shipped product, hematite



(c) Renewable Power Usage, 50 Mtpa mined ore by shipped product, magnetite



(d) Hydrogen consumption, 50 Mtpa mined ore by shipped product, magnetite



Source: Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (2a,4,6,10a), Magnetite (2a1,4a,6b,10b))

The power requirements for producing 1 Mtpa of HBI using hematite or magnetite are similar. The extra energy used to beneficiate the magnetite ore are largely offset by lower energy use to make pellets.

In addition, the land needs for the processing infrastructure are significant and well beyond the scale of the majority of renewable energy infrastructure projects currently operating or planned in Western Australia, refer Table ES8.

The development and delivery of this scale of processing facilities and renewable energy infrastructure presents both a challenge and an opportunity for Western Australia.

Development of projects, from Green Iron Ore Mining through to Green Steel, can function as a critical catalyst for Western Australia's renewable electricity and renewable hydrogen ambitions.

However, the capital investment, construction and logistical challenges associated with this task should not be underestimated.

Table ES8 Indicative land area required to facilitate processing facilities for Green Steel projects vs available strategic industrial areas, hectares of land area

Facility type / land parcel	Area available / required
Pelletising facility – 1 Mtpa shipped product	40 hectares
Pelletising facility – 50 Mtpa mined ore	400 hectares (hematite), 200 hectares (magnetite)
Iron making – HBI form – 1 Mtpa shipped product	140 hectares
Iron making – HBI form – 50 Mtpa mined ore	1,400 hectares (hematite), 500 hectares (magnetite)
Green Steel – 1 Mtpa shipped product	230 hectares
Green Steel – 50 Mtpa mined ore	1,550 hectares (hematite), 680 hectares (magnetite)
Oakajee	1,330 hectares
Ashburton	8,000 hectares
Anketell	1,250 hectares
Boodarie	3,743 hectares
Burrup SIA	1,000 hectares

Source: MRIWA; Department of Jobs Tourism, Science and Innovation

Sizing the Opportunity: Economic Impacts

To provide a quantified view of what this might look like for Western Australia at large, ACIL Allen undertook an economic impact assessment utilising a combination of the value chain model, desktop analysis and review of the outlook.

This facilitated the development of project economic models for standalone iron and steelmaking projects in Western Australia.

While assessing the potential future iron ore, iron and steel industry pathways for Western Australia, an adverse scenario is considered where current iron ore products supplied from the State are no longer the preferred feedstock for steelmaking. In this scenario, it is projected demand for Western Australia's iron ore declines in coming decades.

To mitigate against potential adverse economic outcomes from this scenario, evaluating opportunities to harness the State's resources and energy can be considered.

Under **Development Scenario 1: Green Iron in the form of HBI**, a fully vertically integrated HBI plant is developed in the Pilbara region of Western Australia. The HBI plant uses green hydrogen-based direct reduced iron (DRI) production technologies, with beneficiated magnetite iron ore feedstock. Magnetite was considered in this scenario due to the focus on this as a feedstock in a Western Australian context and the existing place of hematite ores in the value chain. In addition, current hematite ores mined in Western Australia have gangue levels not as favourable for current steelmaking technologies and the HBI market more generally.

Under **Development Scenario 2: Green Steel**, an opportunity to produce fully green primary steel for export is identified and actioned in the Pilbara region. This would take the form of a fully integrated magnetite-based DRI-HBI pathway, with an EAF used to produce the primary steel for export. Similar to the Green Iron development, a magnetite pathway was used due to the focus on DRI-HBI as a product. It is noted magnetite ores exhibit a higher cost in DRI pathways than hematite ores, but in this context these costs can be recovered in the EAF steelmaking process due to lower energy input requirements.

The **final scenario for analysis** is to consider a future where demand for Western Australian iron ore as a steelmaking feedstock declines over coming decades. While an extreme scenario, this represents a view of the future where the State's most important industry contracts over time, as other global suppliers of iron ore and iron feedstock better position to succeed in a Green Steel world. New steelmaking technologies may develop to make Green Steel from current hematite direct shipping ores but if this technology is delayed then this final scenario becomes more likely.

Development Scenario 1: Green Iron in the form of HBI

Under this Development Scenario, the project:

— generates an additional $85 billion to Australia's GDP during construction and over a 24-year operational life through to 2050, or $3 billion per annum. The vast majority of this would be realised in the Pilbara region, with $83.5 billion in GRP ($2.98 billion per annum), with the remainder generated across Western Australia ($1.9 billion, $69.4 million per annum).

— generates an additional $66.5 billion in real income across the local, State and national economies during construction and over a 24-year operational life through to 2050, or $2.4 billion per annum. The majority of the income gain accrues to the Rest of Australia, on account of the Commonwealth taxation revenue generated by the project.

— creates on average 1,540 FTE jobs over the study period, of which 1,347 FTE jobs are created in the region where the project takes place. The employment outcomes associated with this project are a demonstration of the significant benefits a value-adding project can have to a regional economy.

— generates significant taxation benefits, with an estimated $31.7 billion in Commonwealth and State taxation benefits during the construction and operations through to 2050, or $1.1 billion per annum. The taxation payment includes the royalties payable to the State Government associated with the extraction of iron ore resources, as well as other applicable income and inputs taxation. The vast majority of the taxation benefits accrue to the Commonwealth, raising $29.1 billion across company income tax, excises and international trade taxation, and consumption taxes. Western Australia Government revenue streams include payroll tax ($381.8 million, $13.6 million per annum) and royalties ($2.3 billion, $81.4 million per annum).

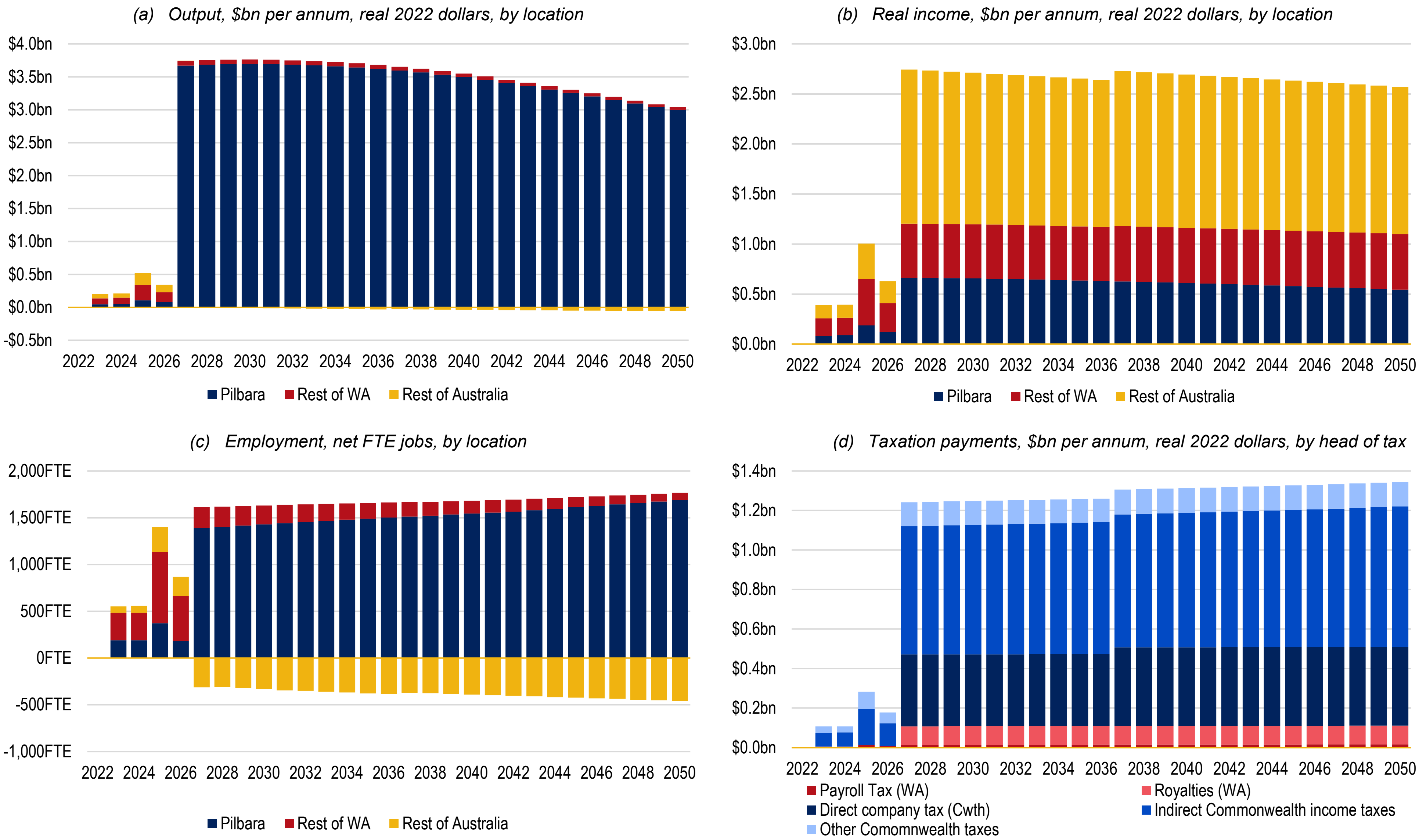
A summary of the indicative capital and other resource requirements is provided in Table ES9 and the impacts of a green iron development on the Pilbara and Western Australian economies is presented in Figure ES23.

Table ES9 Indicative capital and other resource requirements for 4.8 Mtpa of Green Iron HBI from Magnetite, Pilbara

Indicative requirements for:	4.8 Mtpa Shipped as Green Iron in the form of HBI	Units	Comments
	Magnetite		
Mining facility (crush, screen, beneficiation)	$2,100	M AUD	Capex
Pelletisation facility	$733	M AUD	Capex
Shaft furnace	$4,070	M AUD	Capex
Processing facility land use	672	Hectares	
Sustained power required	2,356	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	20,793	M AUD	Capex
Renewable facility land use	12,944	Hectares	
Annual hydrogen required	325	Ktpa	
Hydrogen facility	$3,670	M AUD	Capex
Ammonia facility	$3	M AUD	Capex
H_2 rail trains	$72	M AUD	Capex - 1 train
Ammonia-powered vessels	$122	M AUD	Capex - 1 ship
Water required	23,436	ML p.a.	
Mined ore required	23.5	Mtpa	
Shipped product	4.8	Mtpa	

Source: GHD Analysis (Model Value Chain Scenario Magnetite 6b1); MRIWA

Figure ES23 Economic Impact Assessment Results Summary: Green Iron in the form of HBI Development, Pilbara



Source: ACIL Allen Analysis

Development Scenario 2: Green Steel

Under Development Scenario 2, the project:

- generates an additional $56.2 billion to Australia's GDP during construction and over a 24-year operational life through to 2050, or $2 billion per annum. The vast majority of this would be realised in the Pilbara region, with $56 billion in Gross Regional Product ($2 billion per annum), with the remainder generated across Western Australia ($0.9 billion, $33.8 million per annum).
- generate an additional $45.6 billion in real income across the local, State and national economies during construction and over a 24-year operational life through to 2050, or $1.6 billion per annum. In the Green Steel project, Western Australia realises $22.6 billion of real income gains (about 50% of the total), while the Rest of Australia realises $23 billion.
- creates on average 1,434.2 FTE jobs, of which 1,285 FTE jobs are created in the region where the project takes place. The modelling shows the employment impact of the project on a per-unit of production basis is substantially higher in the Green Steel project (512.2 FTE per MT) compared to the green iron project (320 FTE per MT), on account of the additional processing step and associated need for more jobs.
- generates a total of $19.4 billion in Commonwealth and State taxation benefits during the construction and operations through to 2050, or $692.5 million per annum. The majority of the taxation benefits accrue to the Commonwealth, with $17.5 billion across company income tax, excises and international trade taxation, and consumption taxes. Western Australia Government revenue streams include payroll tax ($348.2 million, $12.4 million per annum) and royalties ($1.5 billion, $53.9 million per annum).

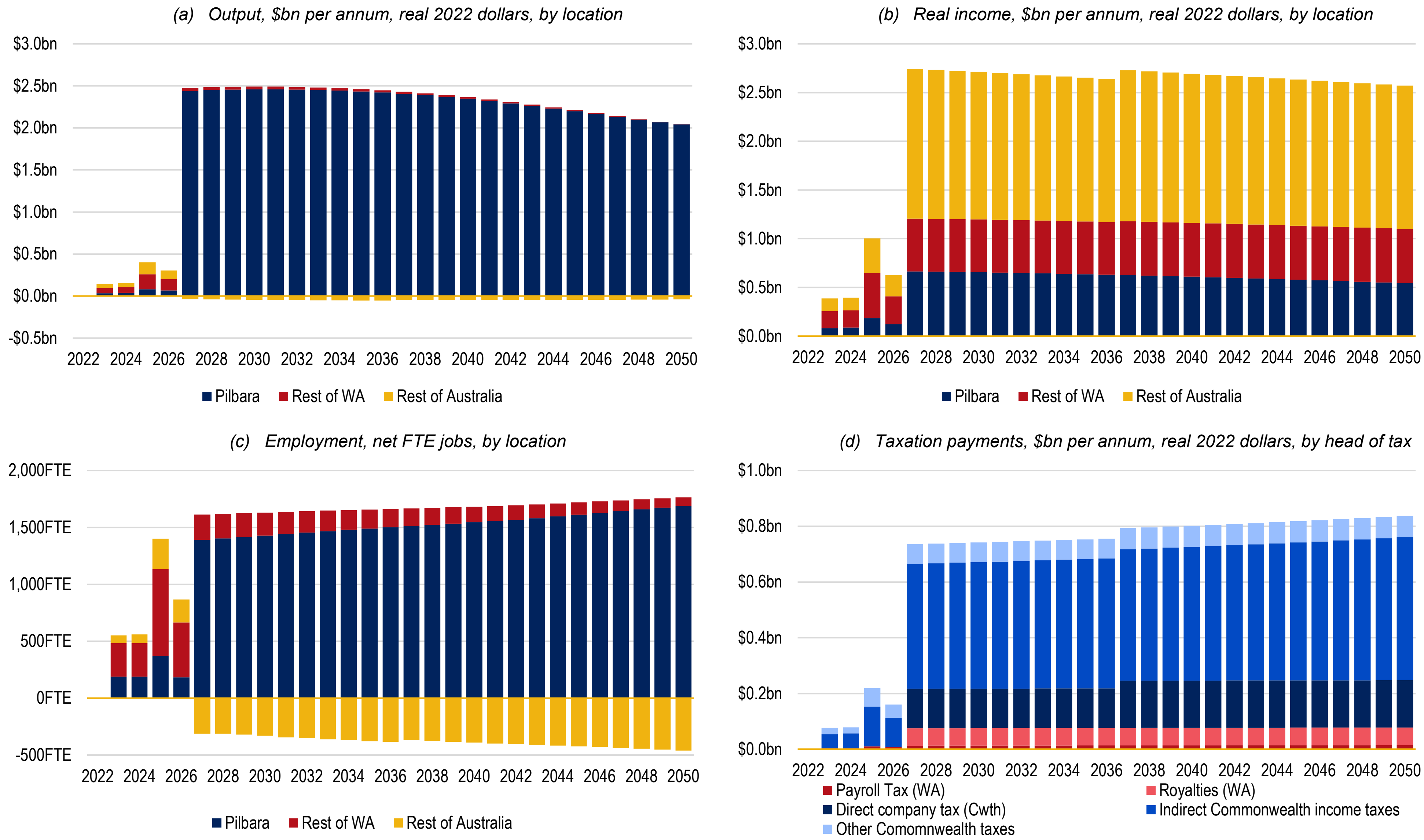
A summary of the indicative capital and other resource requirements is provided in Table ES10 and the impacts of a Green Steel development on the Pilbara and Western Australian economies is presented in Figure ES24.

Table ES10 Indicative capital and other resource requirements for 2.8 Mtpa of Green Steel from Magnetite.

Indicative requirements for:	2.8 Mtpa Shipped as Green Steel	Units	Comments
	Magnetite		
Mining facility (crush, screen, beneficiation)	$1,513	M AUD	Capex
Pelletisation facility	$517	M AUD	Capex
Shaft furnace	$3,107	M AUD	Capex
EAF facility	$479	M AUD	Capex
Processing facility land use	672	Hectares	
Sustained power required	1,802	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$15,904	M AUD	Capex
Renewable facility land use	9,900	Hectares	
Annual hydrogen required	216	Ktpa	
Hydrogen facility	$2,441	M AUD	Capex
Ammonia facility	$2	M AUD	Capex
H_2 rail trains	$43	M AUD	Capex
Ammonia-powered vessels	$61	M AUD	Capex
Water requirements	15,594	ML p.a.	Capex
Mined ore required	15.7	Mtpa	
Shipped product	2.8	Mtpa	

Source: GHD Analysis (Model Value Chain Scenario 10b2); MRIWA

Figure ES24 Economic Impact Assessment Results Summary: Green Steel Development, Pilbara



Source: ACIL Allen Analysis

Decline scenario: What's at risk?

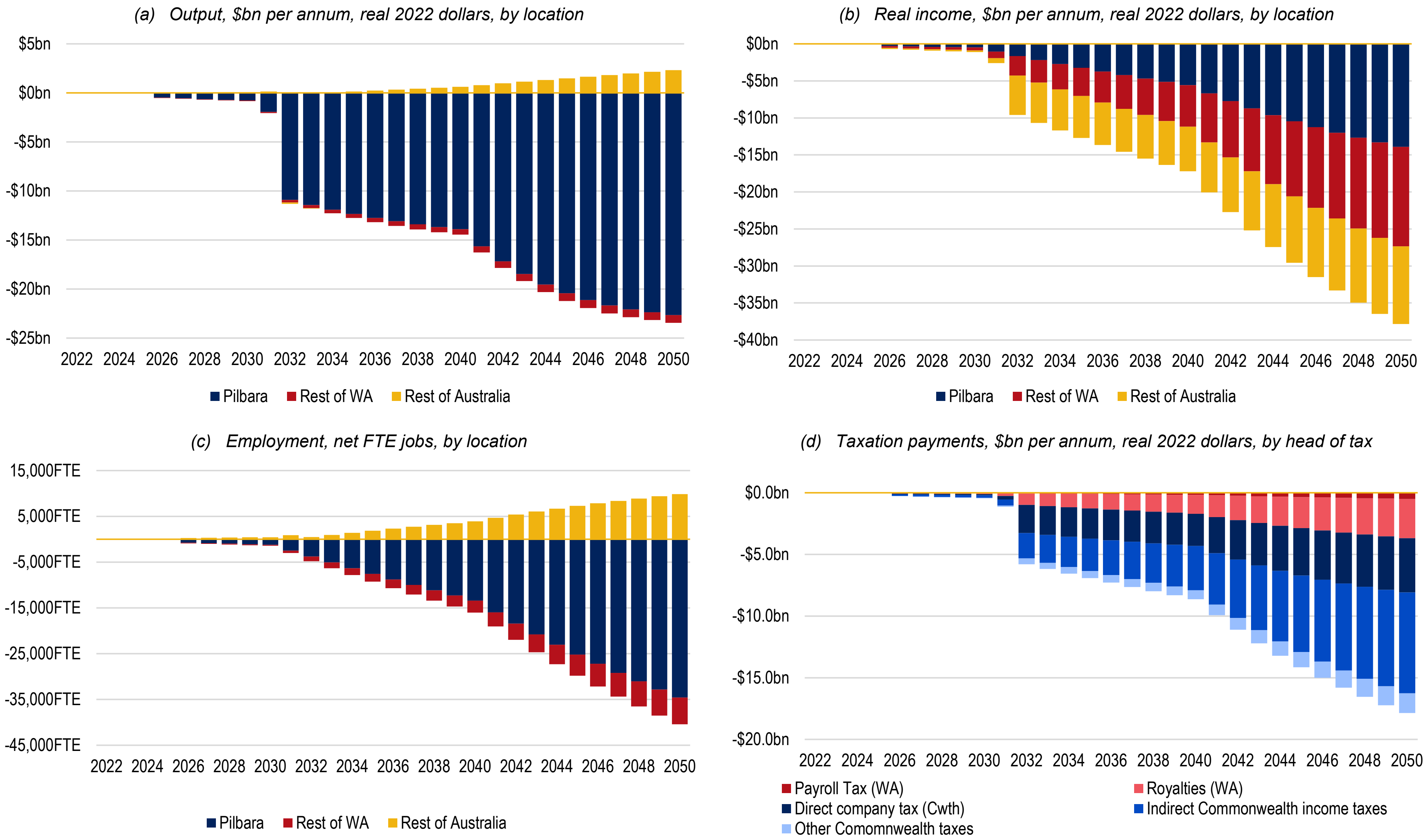
The modelling shows the decline scenario (refer Figure ES25) would have greatly impact on the Pilbara region's economy, with an associated decline in Commonwealth and State Government income tax receipts and royalty payments.

In this scenario, the industry's decline:

- creates a cumulative reduction in Australia's GDP is estimated to be $313.3 billion over 25 years between 2026 and 2050. This impact occurs almost wholly in the Pilbara region, as this is where the projects which would be expected to feel the effects of the decline in volumes and prices are based. By 2050, the annual average impact on the Pilbara region's economy is equivalent to one third of the size of the economy today.
- reduces employment in the Pilbara region by 34,570 FTE by 2050, equivalent to more than one out of every two jobs today. This would be expected to have a compound impact on the region's population given the substantial role employment plays in regional population growth and stability.
- slashes Western Australia's royalty income by $37.2 billion, or $1.3 billion per annum. As with the other metrics, the scale increases over time. By 2050 the State's royalty income stream would be $3.2 billion lower on an annual basis – or one-third of today's royalties.
- reduces Commonwealth taxes by $169.5 billion over the modelling period, on account of a significantly lower level of company income tax receipts.

This scenario is not expected to be realised; however the modelling provides insights into the potential risks to both the State and Commonwealth in-light of a declining iron ore sector in Western Australia. This is outlined in Figure ES25.

Figure ES25 Economic Impact Assessment Results Summary: Decline scenario, Pilbara



Source: ACIL Allen Analysis

Critical success factors

There are four critical success factors which position the State to capture its share of the Green Steel opportunity. These are:

- **Resources**: Access to the physical iron ore resources required to produce the steelmaking feedstock which will be demanded by the Green Steel value chain. Western Australia has an abundance of iron ore, providing the platform for this opportunity.
- **Energy**: Access to renewable energy resources and having the capacity to convert these into renewable hydrogen, is central to the development of Green Steel opportunities. Progressing through a natural gas based DRI pathway also required access to natural gas.
- **Infrastructure**: Access to infrastructure to connect resources to processing plants, and to global markets, is a critical enabler of all industries. In Green Steel, the sheer scale of renewable energy infrastructure required makes this critical to success.
- **Technology and enterprise**: The technologies and processes required to produce greener iron and steel continue to evolve. Securing access to research, and the capacity to drive commercial outcomes, is expected to be central to Western Australia's Green Steel opportunity.

Key Findings

Western Australia has played a central role in the growth of the global steel industry for over 60 years. Global demand for finished steel products is expected to remain robust, albeit without the same levels of compound growth experienced over the past 20 years.

Technologies are emerging which can, and will, begin to reduce the energy and emissions intensity of BF based steelmaking. There are multiple pathways to progress beyond energy and emissions intense reduction and the development of net zero emissions steelmaking.

Throughout this report, and over the course of the engagement, MRIWA, GHD and ACIL Allen have identified Green Steel production globally is not only possible, but inevitable. Changing market dynamics, and the race to reduce carbon emissions across industry and government, will take time to fully revolutionise the global steel industry. As technologies change, and renewable energy costs fall, a shift towards a Green Steel future will begin.

This will not be a sudden, dramatic change as has been experienced in a range of other industries in recent years. The complexity, interconnectedness, and capital investment in today's steelmaking value chains means the process will take time.

There is a future for Western Australia in the production of iron ore and supply of alternative iron products to the market.

Existing iron ore exports remain relevant for the largest steelmaking value chains, albeit customer preferences are shifting towards higher grade feedstock.

This presents the State with an emerging advantage due to the vast reserves of magnetite, and capacity to beneficiate the ores produced and shipped today. The value chain modelling shows this can be done using increasingly green energy.

The real Green Steel prize for Western Australia lies in further value-adding, to build new projects centred on production of intermediate iron products like HBI and pig iron. The State's existing natural gas energy advantages suggest this can be done on an economic basis, so long as a market for it emerges.

Progressing down the value chain to produce intermediate iron brings with it the potential for a significant domestic demand base for renewable hydrogen as technologies improve and the cost of production falls.

Co-industry development of this nature could compound the benefits for Western Australia, while bringing forward the renewable hydrogen future the State is committed to realising.

The final step towards steelmaking looks the most difficult part of the Green Steel challenge for Western Australia, on account of the truly global marketplace for this product and the dominance of major steelmakers within it. But the journey towards domestic steel begins with iron, where the opportunity is clear.

Industry announcements show a commitment to investment in a greener future, with Western Australia's major iron ore players all having a strong focus on opportunities to decarbonise both their own operations and assist in meeting their customers' ambitions.

Business is exploring value-adding to Western Australia's iron ore, because of the economic and climate outcomes which can be achieved.

Hosting the iron ore resources and a renewable energy advantage are necessary but not sufficient to meet the Green Steel challenge.

Alongside these two critical success factors sit infrastructure, and technology and enterprise. Building the connection of resources to infrastructure, services and paths to market is critical.

It is the same for technology and enterprise, where Western Australia has an opportunity to tap into its enormous mineral wealth as a funding source to become a global leader in research, development and commercialisation.

Western Australia should be the home of a world class centre for research and development into the Green Steel value chain.

This report is the first step towards Western Australia's Green Steel future with the key findings summarised below.

Finding 1 Significance of the iron ore industry

Western Australia is the largest iron ore supplier in the world, accounting for 38% of global supply, which is more than double the next largest iron ore supplier, Brazil which supplies 17% of global supply. The iron ore industry is the State's largest and most important industry, providing direct and indirect economic and social contributions which are greater than any other industry to the State. Through the royalties it pays, it is also the largest contributor to State Government finances, generating $11.35 billion which represented 28% of general government revenues in 2020-21.

Finding 2 The long-term outlook for steel

The long-term outlook for global steel demand is expected to remain robust through to the middle of the century. However, there are a range of scenarios which could eventuate regarding the type of feedstock most in demand, and the production processes used to produce steel, which have several implications for Western Australia's existing iron ore industry.

Moreover, given the size of the investments and the time taken to make investment decisions, there is a need to begin positioning in the short term.

Overall, it is considered likely Western Australian iron ore will remain a valued commodity in the global steel industry through to the middle of the century. However, there are clearly opportunities for development of new kinds of iron products to meet the emissions and energy reduction task facing customer countries.

Finding 3 Increasing focus on the quality of ore used by steelmakers is driving change

There is increasing focus on the quality of iron ore feedstock being used by steelmakers. This is increasingly observed through the price penalties received on lower grade ores, which has implications for Western Australia.

This provides a strong incentive for iron ore producers to pursue opportunities to improve the average grade of their product, through beneficiation or investment in new kinds of steelmaking feedstock products, but also a renewed interest in magnetite iron ore projects throughout Western Australia.

Finding 4 Lack of liquid markets and benchmark prices for intermediate iron products

There is currently limited or no benchmark products and associated prices available for intermediate iron products such as pig iron, HBI and even for iron ore pellet indexes they are often referenced to local sources of pellets which is not a true benchmark. This creates complexity for project development and project economic assessment as there is no commonly understood definition of products, of benchmark attributes or product quality, or market worth. The lack of benchmark products and associated prices contrasts strongly with iron ore where there is an abundance of these.

Finding 5 Economics of steelmaking is significantly more challenging than iron ore mining

The market for steel is fundamentally different to iron ore. While both industries are highly capital intensive, they have vastly different rates of profit. It is estimated the gross margin for steelmakers over the past 20 years has been 13.6%, which is in stark contrast to iron ore miners which regularly report gross margins of many multiples of the levels achieved by steelmakers. Western Australia's three largest iron ore miners have delivered an average gross margin on sales of 61.1% over the past six years where data on Western Australian specific operations is available.

Given the capital intensity of iron ore is substantially lower than in the steel industry, an iron ore mine can deliver a substantially higher rate of gross profit for a much smaller initial capital outlay.

Finding 6 Overcapacity in steelmaking

The current glut of capacity in global steelmaking results in a situation where it is challenging for new entrants to compete on price and deliver a return on capital to justify a new investment. This is because existing entrants have sunk capital and significant incentives to increase plant utilisation.

Finding 7 Age of BFs will influence rate of change

Given the long useful life of BFs, countries will progressively face a decision to either retire BFs early to transition to greener production methods or operate existing carbon-intensive steelmaking infrastructure for a regular life, and focus on other strategies to reduce emissions such as carbon capture use and storage.

Finding 8 Increasing potential for scrap steel will drive change in the industry

Future investment in EAF steelmaking is expected due to the sheer increase in availability of scrap steel as a feedstock from the growth in steel production; a lower hurdle of entry to construct a production facility such as a 'close-to-source' modular EAF; and consumption over the past two decades.

Finding 9 The decarbonisation of the global steel industry is a significant challenge

The global steel industry is one of the largest carbon emitters in the world, but also one of the hardest to abate. Recognising the challenges to decarbonising existing production, hydrogen-based steelmaking has emerged as a potential pathway to producing Green Steel. However, the production of green hydrogen needed for Green Steel is not yet available at a commercial scale.

Finding 10 Value chain modelling: Green Iron Ore Mining

Conversion of existing iron ore mines, and development of new iron ore mines to be emissions-free based on renewable power supplied by mixed solar/wind facilities is cost-competitive at today's cost rates, largely due to low cost and effective renewable power.

Green Iron Ore Mining, including ore upgrading through beneficiation, provides opportunity to marginally reduce emissions in the steelmaking value chain.

Potential cost savings is a natural incentive for industry to switch to renewable power and fuels in existing mining operations.

There are substantial power requirements to adopt Green Iron Ore Mining at scale.

The established power infrastructure will not only support existing industry but will also reduce ore production costs in the long run as the price of power decreases leading to substantial savings and allow energy intensive ore beneficiation to be done at lower cost.

Including hydrogen and ammonia facilities for long distance transport initiates the industrial base required for further downstream processing of iron ore.

Finding 11 Value chain modelling: Green Pellets

Green Pellets are a necessary product to have fully Green Steel, however hydrogen costs are too expensive at this point to produce them competitively against the equivalent fossil fuel process.

Magnetite concentrates are more economic to turn into Green Pellets, as they do not require as much heat to form pellets as hematite fines.

Finding 12 Value chain modelling: HBI from Green Pellets using Fossil Fuels

Green Pellets converted to HBI using fossil fuels are a cost competitive product when compared to pig iron produced with BFs, the dominant process for ironmaking today.

This approach will onshore Scope 3 emissions. However, it also has the potential to reduce overall emissions from ironmaking when compared to the pig iron BF route.

Shaft furnaces running on natural gas may be transitioned to hydrogen feedstock over time to produce fully Green Steel.

Finding 13 Value chain modelling: HBI from Green Pellets using Renewable Hydrogen (Green Iron in the form of HBI)

Green Iron in the form of HBI produced from shaft furnaces can potentially replace coke and natural gas for ironmaking, eliminating emissions from this carbon intensive stage.

Green Iron in the form of HBI can be economically produced when compared to BF produced pig iron when the hydrogen price reaches $4 AUD/kg.

Finding 14 Value chain modelling: Hydrogen cost and implications

The dominant costs in traditional steelmaking are those which arise from blast furnacing.

The price of hydrogen, which replaces coke as a reductant in the creation of Green Steel, is critical in ensuring price parity of Green Steel with blast furnacing.

Green Steel (SF-EAF) can be economically produced when compared to fossil fuels (BF-BOF) steel when the hydrogen price reaches $3.20 AUD/kg.

There are increased costs for processing high gangue HBI/DRI through electric arc furnacing, so higher quality or more refined ore is preferred. Though most cost benefit will accrue to whomever owns most of the value chain, including the steelmaking step.

Finding 15 Green Steel industry capital costs are expected to be substantial

To decarbonise or lower emissions in Western Australia's current mining sector and potential future steelmaking value chain, infrastructure for renewable power generation and for hydrogen-based iron/steelmaking plants must be developed. The capital costs are substantial for renewable power production at scale.

Finding 16 Western Australia's Green Steel value chain opportunities and pathways

Overall, the assessment suggests of the options considered, pathways which involve the development of intermediate iron products, such as HBI, are the most prospective for Western Australia.

These products are a natural extension of the State's current place in the value chain and make best use of both current and emerging advantages in energy. HBI and other intermediate products allow the State to continue to capture significant value in the steelmaking value chain without the high capital costs and low margins associated with steel itself.

The export steel product market will be slower to adjust to environmental factors than drivers for the use of Western Australian HBI, particularly in a market for an increasing global demand for lower emission HBI.

Finding 17 A significant common user infrastructure build is required

This report has highlighted the critical role of infrastructure in development and delivery of future iron ore, value-added iron and steel project opportunities in Western Australia. This, combined with the similar challenges associated with large-scale renewable energy development projects, suggests a significant common user infrastructure build program in the years and decades ahead is required.

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Part I: Setting the Scene

Introduction 1

This section provides a brief introduction and context behind the development of this report along with an overview its structure.

1.1 "The Green Steel Challenge"

Green Steel – the question is not 'is it possible', but rather 'how to make it possible'.

Understanding the pathway to enable Western Australia to maximise use of its hematite and magnetite iron ore resources, and to maximise emerging hydrogen and renewable energy potential are key to supporting global Green Steel ambitions and creating new markets for Western Australian iron ores.

This challenge aligns with the Western Australian Government's State Climate Policy, *Western Australian Climate Policy: A plan to position Western Australia for a prosperous and resilient low-carbon future*, which was released in November 2020. Specifically, the Policy includes a key focus on "clean manufacturing and future industries", with MRIWA's Green Steel Challenge one of the actions.

On 1 November 2021, the Minister for Mines and Petroleum announced an investigation into Green Steel had commenced, to inform the viability of sustainably processing Western Australian iron ore to Green Steel, or the inputs necessary to create Green Steel with MRIWA engaging GHD and ACIL Allen to undertake a Green Steel Value Chain Assessment.

This report summarises the work undertaken by GHD and ACIL Allen to:

1. Map the iron ore-to-steel value chain to confirm scenarios against which further assessments will be undertaken related to infrastructure needs, market dynamics and policy frameworks.
2. Assess existing and required regional attributes to identify the comparative advantages of the Mid West and Pilbara regions and future investment needs to enable delivery of the various scenarios.
3. Assess future iron ore mining, ironmaking and steel market dynamics to evaluate the potential opportunity and risk to Western Australia from action or inaction for each scenario.

1.2 Report Structure

This report has been structured into two main Parts.

Part I, **Setting the Scene**, presents a detailed examination of the global steel industry and its decarbonisation challenge, and the emerging opportunities, challenges and risks that present for the industry and more specifically for Western Australia. Chapters include:

- **Western Australia's role in the steel industry**

  The steel industry is one of the world's largest, most significant industries, providing input into almost every sector of the economy. Western Australia has been at the forefront of the growth and development of the steel industry over the past 60 years, following the development of the first large-scale iron ore production and export supply chains in the Pilbara region. But the steel industry is changing, as a global push to reduce carbon emissions shakes up the established order and creates new opportunities and risks.

- **From Iron Ore to Steel**

  Although iron and steelmaking processes have changed substantially since the development of the first furnaces and throughout the industrial revolution to the point where the process is now very internationalised, the fundamentals remain the same. This section of the report provides an overview of the iron ore mining to steelmaking value chain.

- **Global Steel Industry State of Play**

  Steel is an indispensable part of everyday life. Yet it is also one of the highest emitting among all industrial activities. This section of the report provides an overview of energy use and emissions along the value chain, critical drivers in the market for iron ore and steel from a Western Australian perspective, and how the outlook for steel production and consumption could evolve in the future.

- **Market dynamics and attributes**

  Steelmakers face a challenging industrial ecosystem, with low margins and a high exposure to volatile commodity prices at both the supply and output end of their production processes. This section considers several dynamic changes occurring in the global steel industry and the associated market for iron ore and intermediate iron products. This has important implications for Western Australia's current iron ore supply, and the potential future opportunities to supply new iron ore products into emerging Green Steel value chain.

Part II, **Seizing the Opportunity**, presents the key insights emerging from the research, analysis and modelling undertaken by GHD and ACIL Allen. Chapters include:

- **Decarbonising the iron ore to steelmaking value chain**

  This section provides an overview of decarbonisation in the iron and steelmaking process. It first provides a working definition of 'Green Steel', then explores the technology required to produce Green Steel, followed by discussions on the use of hydrogen, and low carbon inputs and renewable energy.

- **Green Steel in Western Australia**

  To evaluate where Western Australia could participate in the iron ore to steelmaking value chain a quantitative value chain model was developed to examine technology, fuel types, inputs costs, transport, and emissions and understand the relative investment costs and benefits from emissions reductions can be gleaned for the State. The section considers the value chain and the results from selected scenarios.

- **Sizing the Opportunity for Western Australia**

  The previous section, and first part of the report, explore a number of aspects of the future outlook for iron ore and steel in a net zero emissions world. This section of the report analyses the critical economic impacts of Western Australia’s future place in the Green Steel value chain, through the lens of economy-wide modelling of new Green Steel-inspired development projects and an exploration of what’s at stake if there is no response to the changing world.

- **Regionalising the Green Steel Challenge**

  This section provides a more detailed assessment of the capacity for three key regions in Western Australia to potentially host Green Steel opportunities now and into the future. This assessment has been based on ACIL Allen’s 2021 Multi-criteria Assessment which informed Infrastructure Western Australia’s State Infrastructure Strategy as well as the critical success factors defined in the previous section of this report which were identified as necessary to enable Green Steel opportunities to be realised.

- **Moving Towards Green Steel**

  This section presents a summary of the findings presented throughout this report, which together provide the foundation for Western Australian to understand the challenges and opportunities to moving towards downstream processing of iron ore in this State.

1.3 Glossary of Terms and Abbreviations

Throughout this report technical terms for reference have been defined in the table below.

Term	Definition
Agglomeration	The processing of fine iron ores to make a sizing suitable for use as a feed for ironmaking shaft and BFs, including processing by sintering or pelletising.
Beneficiation	Any process that improves the economic value of iron ore by removing the gangue content and increasing its iron concentration.
Biofuels	Fuels derived immediately (over a short time span) from living matter (biomass).
Biomass	Organic matter used as a fuel or feedstock, commonly used for heat or power generation.
Blue hydrogen	Hydrogen produced using a process called 'steam reforming', which uses steam to separate hydrogen from natural gas. Greenhouse gases are produced during the process but carbon capture, utilisation, and storage technologies capture and store those emissions.
Carbon Intensity	The amount of carbon dioxide produced per tonne of primary steel. Term used interchangeably with the amount of carbon produced per tonne of crude steel and for the purposes of this study is identical.
Crude steel	A type of steel product produced by feeding molten pig iron into a basic oxygen furnace with a small amount of scrap steel. Term used interchangeably with Primary Steel.
Direct reduction	A process where the oxygen is removed from iron ore by direct chemical reduction without the need to melt the iron.
Direct Shipping Ore (DSO)	High-grade hematite or goethite ores that are crushed and screened without beneficiation before being exported to an iron or steelmaking facility overseas.
Fines	Undersized ores.
Free on Board	The cost of transporting goods to the nearest port and loading onto a ship is included in the price.
Gangue	Minerals contained in the iron ore which are commercially valueless in the processing of iron. They include minerals such as silica, alumina and mineralised water.
Goethite	A form of iron ore containing a majority of the mineral Goethite (FeOOH).
Green hydrogen	Hydrogen extracted using a method that does not produce greenhouse gas emissions, commonly produced using an electrolyser.
Green iron ore	Iron ore mined using a method, technology or fuel source that does not produce greenhouse gas emissions.
Grey hydrogen	Hydrogen produced using a process called 'steam reforming', which uses steam to separate hydrogen from natural gas. Greenhouse gases are produced during the process and is not captured or stored.
Hematite	A form of iron ore containing a majority of the iron mineral Hematite (Fe_2O_3).
Horizontal Fiscal Equalisation	The distribution of the GST by the Commonwealth Government amongst the States and Territories.
Hot Briquetted Iron (HBI)	A compacted form of Direct Reduced Iron (DRI) that is manufactured for ease of transportation, and typically used as a feedstock to make steel in an EAF
Levelised cost	A metric for the average net present cost – for energy or hydrogen in the context of this report – over an assumed time period to depict operational lifespan.
Magnetite	A form of iron ore containing a majority of the iron mineral Magnetite (Fe_3O_4).
Pig iron	An iron metal product from reduction of iron ore in the BF. It typically contains 3-4% Carbon.
Pellets	Spheres of agglomerated iron ore fines that are typically used as raw material in steel-producing BFs.

Term	Definition
Present value	The current value of a future sum of expenditure or stream of cash flows given a specified rate of return (such as the discount rate or Weighted Average Cost of Capital).
Royalty revenue	A royalty is a payment made to the Government to compensate for the extraction of a resource – iron ore in the context of this report - owned by the community. In Western Australia royalty revenue is collected by the Government as State Revenue.
Scope 1 emissions	Emissions in the source country.
Scope 2 emissions	Emissions associated with transport, shipping and movement of energy.
Scope 3 emissions	Emissions which occur downstream of the source country owing to the use of their exports and output.
Sinter	Agglomerated iron ore formed using the sintering process, whereby fine iron ores and concentrates are mixed with fluxes, a solid fuel (typically coke breeze) and water in a mixing device then partially melted on a sintering machine then cooled to form a coarse porous solid.
Value chain	A concept describing the full chain or sequence. of an activity with an emphasis on cost or monetary value at each step of the chain.

A list of acronyms used throughout this report is also presented for reference.

Acronym	
°C	Degrees Celsius
$	Unless indicated, refers to Australian Dollar
ACAS	Adiabatic Compressed Air Storage
AUD	Australian Dollar
BAU	Business As Usual
BESS	Battery Energy Storage System
BF	Blast Furnace
BOF	Blast Oxygen Furnace
C.I.	Carbon Intensity
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture Use and Storage
CGE	Computable General Equilibrium
CIS	Commonwealth of Independent States
CMIEC	China Metallurgical Import and Export Corporation
CO_2	Carbon dioxide
COG	Coke Oven Gas
COP26	UN Climate Change Conference
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DMIRS	Department of Mines, Industry Regulation and Safety
DRI	Direct Reduced Iron
DSO	Direct Shipping Ore
DTWD	Department of Training and Workforce Development
DWER	Department of Water and Environmental Regulation
EAF	Electric Arc Furnace

Acronym	
EBITDA	Earnings Before Interest, Tax, Depreciation and Amortisation
EIA	Environmental Impact Assessment
EPA	Environmental Protection Authority
ESCAP	Energy Saving CO_2 Absorption Process
ESG	Environmental, Social and Governance
EU	European Union
Fe	Iron
FHRI	Future Health Research and Innovation Fund
FIFO	Fly-In-Fly-Out
FOB	Free On Board
FTE	Full-Time Equivalent
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIA	General Industrial Area
GJ	Gigajoule
GL	Gigalitre
GOU	Governance and Oversight Unit
GSP	Gross State Product
Gt	Giga Tonnes
GTE	Government Trading Enterprise
GW	Gigawatt
H_2	Hydrogen
HBI	Hot Briquetted Iron
HFE	Horizontal Fiscal Equalisation
IEA	International Energy Agency
JTSI	Department of Jobs, Tourism, Science and Innovation
kWh	Kilowatt Hour
Ktpa	Kilo Tonnes Per Annum
kWh/tonne	Kilowatt Hour per tonne of product
LCOP	Levelised cost of product
LNG	Liquefied Natural Gas
METS	Mining Equipment, Technology and Services
MRIWA	Minerals Research Institute of Western Australia'
MT	Million Tonnes
Mtce	Million Tonnes of Coal Equivalent
Mtoe	Million Tonnes of Oil Equivalent
Mtpa	Million Tonnes Per Annum
MoU	Memorandum of Understanding
MRRA	Mineral Royalty Rate Analysis
MWh/tonne	Mega Watt Hours Per Tonne

Acronym	
OECD	Organisation of Economic Cooperation and Development
PCI	Pulverised Coal Injection
PEM	Polymer Electrolyte Membrane
PV	Photovoltaic
SECWA	State Energy Commission of Western Australia
SIA	Strategic Industrial Area
SPOL	State Priority Occupation List
SWIS	South West Interconnected System
tCO_2	Tonnes of Carbon Dioxide
tCO_2-e	Tonnes of Carbon Dioxide Equivalent
tH_2	Tonnes of Hydrogen
TRL	Technology Readiness Level
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US$ / USD	United States Dollar
WACC	Weighted Average Cost of Capital
WASMOL	Western Australian Skilled Migration Occupation List

Western Australia's role in the steel industry

2

The steel industry is one of the world's largest, most significant industries, providing input into almost every sector of the economy. Western Australia has been at the forefront of the growth and development of the steel industry over the past 60 years, following the development of the first large-scale iron ore production and export supply chains in the Pilbara region. But the steel industry is changing, as a global push to reduce carbon emissions shakes up the established order and creates new opportunities and risks.

2.1 The global role of steel and steelmaking

Steel is used across almost every sector of the economy, either directly as an input into production or to support the activities of services sectors.

Most modern economies have some steelmaking capacity, due to the importance of steel in providing a critical input for economic growth and development.

Despite several manufacturing industries exiting Australia over the past two decades, the country maintains an estimated 5.5 million tonnes (MT) of steelmaking capacity, spread across New South Wales and South Australia, to service the domestic market for residential construction, commercial construction and public infrastructure sectors.

With the rapid industrialisation and resultant economic growth worldwide, the steel industry has largely benefitted as production volumes of primary steel reached an all-time high in 2021.

At a global level, total primary steel production has increased from 855 MT in 2001 to just shy of 2,000 MT in 2021[1], principally on account of a surge in steel production in China, India and the Rest of Asia.

The main production route for steel is through the processing of iron ore into iron and then into steel, using a BF and BOF. These production processes have been progressively refined over the past 200 years to the point where the supply chain for steel is now global and integrated.

[1] World Steel Association. 2022. *World Steel Association Short Range Outlook, January 2022*. Accessed online at http://www.worldsteel.org/

2.2 Western Australia's context

The Western Australian Government has announced its aspiration to achieve net zero emissions for the state by 2050.[2] This announcement came with a commitment to working with all sectors of the economy to achieve this ambition, including the iron ore industry that is Western Australia's single largest source of economic activity, employment, and taxation revenue for the State Government.

Before looking forward, it is important to consider the current climate policy context as it relates to the iron ore industry, the history of the iron ore sector in Western Australia, and the contribution of the iron ore industry to Western Australia today, to inform the discussion on future opportunities.

2.2.1 Iron ore in Western Australia

The iron ore industry is Western Australia's single largest source of economic activity, employment, and taxation revenue for the State Government. Its direct and indirect contribution to Western Australia's economy and society has been built through over 100 years of exploration, investment and production, to the point where the industry is now one of the most productive and successful singular industry clusters in the world.

Until the 1990s, mineral extraction activity in the Pilbara focussed on raw commodities rather than downstream processing and value adding.

Whilst hematite and goethite ores are beneficiated with low energy and low cost processing in some cases for managing the shipping grades of lower grade resources, this has largely been the extent of value adding for the vast majority of Western Australian iron ore production.

Between 2011 and 2021, Western Australia's iron ore supply increased by 443 MT, which was greater than the total increase in global iron ore supply over the same period, as supply in China and other countries fell.

The extent of current further downstream processing in the State includes two operating magnetite mines – Karara Mining and Sino Iron - which differ from the hematite and goethite ore producers that predominate the Western Australia iron ore sector, in that the ores are processed into a value-added product using a higher energy and cost intensive process. This results in a higher iron content prior to shipping.

Previous attempts at downstream processing of iron ore in the State are canvassed below.

[2] Government of Western Australia. 2020. Western Australian Climate Policy. Pg. 5.

Boodarie Iron Plant

The Boodarie Iron Plant was located approximately 20 kilometres south of Port Hedland, in the Pilbara region of Western Australia. The construction of the Boodarie Iron Plant commenced in 1996, with completion three years later in 1999.

The design of the Boodarie Iron Plant was based on FINMET direct reduction technology. The FINMET process produces DRI by reacting fine iron ore with reformed natural gas in a series of fluid bed reactors and then hot briquetting into HBI. Over 6 MT of HBI was shipped to BF and EAF steelmakers.

In May 2004, an explosion occurred during maintenance. The incident resulted in the death of one employee and serious injuries to two others. In August 2005, BHP announced it would permanently close the Boodarie Iron Plant, with the plant demolished in October 2011.

HIsmelt Process Plant

HIsmelt Corporation, a wholly owned subsidiary of Rio Tinto, commenced developing the HIsmelt process in 1981. The HIsmelt Process Plant at Kwinana was the first large-scale commercial application of the HIsmelt process. It was anticipated proving the viability of the HIsmelt process at a commercial scale would provide the global iron and steel industry with an alternative to the conventional BF ironmaking route.

The HIsmelt process does not require coke ovens, sinter plants or pellet plants, which helps to generate a significant improvement in environmental performance compared to the BF ironmaking process. The HIsmelt Process Plant used iron ore fines which are not suitable for BF feed due to their high phosphorous content. The iron ore fines were shipped to Kwinana from Dampier and railed from Koolyanobbing.

Operations at the HIsmelt Process Plant were suspended in late 2008 in the wake of the global financial crisis with the facility put into care and maintenance mode. In 2011, it was decided the HIsmelt Process Plant would permanently close. However, Rio Tinto was able to reclaim some value from its investment in the HIsmelt process through licensing it to other groups.

In 2017, the intellectual property of HIsmelt technology was sold to Molong Petroleum Machinery Limited.

2.2.2 Western Australia's iron ore industry today

As of February 2022, Western Australia is the largest iron ore supplier in the world, accounting for 38% of global supply, followed by Brazil (17%).[3]

Since 2020, there have been seven major iron ore projects in Western Australia that have commenced operations, including South Flank (BHP), Eliwana (FMG) and Western Turner Syncline 2 (Rio Tinto). Cumulatively, the seven major iron ore projects had a total capital expenditure of approximately $8.5 billion. The largest of these projects was South Flank which had total capital expenditure of approximately $4.7 billion and a production capacity of 80 Mtpa. A number of the major iron ore projects that have recently commenced operations will replace production from mines which will enter decommissioning phase. This includes the South Flank mine which will replace production from the Yandi mine, and Eliwana which will replace production from the Firetail mine.

There are four major iron ore projects currently under construction or committed in Western Australia (as of February 2022). Cumulatively, the four major iron ore projects have total capital expenditure of approximately $9.8 billion. The largest of these projects is Iron Bridge (FMG) which has total capital expenditure of approximately $4.6 billion.

[3] WA Department of Jobs, Tourism, Science and Innovation: Western Australia Iron Ore Profile – February 2022

2.2.3 Economic contribution

Iron ore projects create both financial and social value for the stakeholders and communities where they operate, as well as the State and Commonwealth more broadly. Value is delivered at each stage of the operating model, from exploration and acquisition through to closure and rehabilitation.

Projects provide employment, purchase goods and services, pay taxes, royalties and other payments to government and make contributions (such as donations and grants) to communities where they operate. In most instances, value is also created by operators of projects for shareholders, lenders and investors, including pension and superannuation funds, through paying dividends, interest and making other financial returns.

In the development and mining stage, jobs are created both directly in construction and indirectly through the provision of goods and services to the mining site. Capital expenditure on the construction of facilities and supporting infrastructure generates payments to suppliers and contractors, as well as payments to government in the form of indirect taxes (such as goods and services tax).

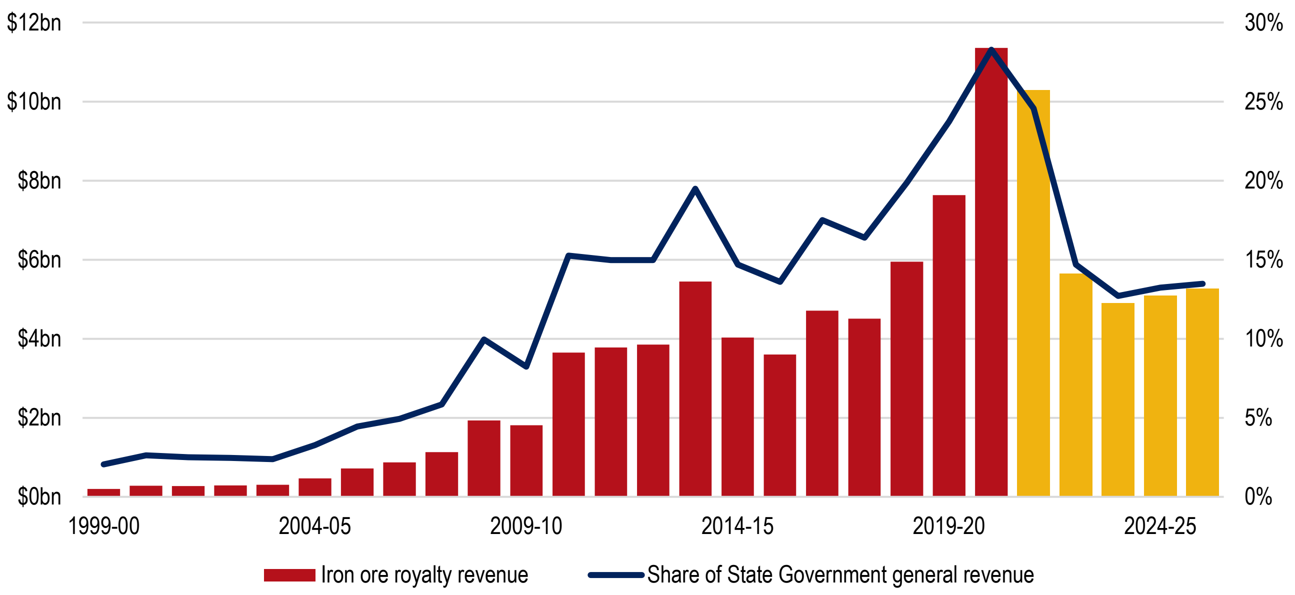
In the process and logistics stage, once extraction begins, royalties begin to be paid. Employment taxes increase as the operating workforce commences. Community contributions will generally continue throughout the operating life of a project, while payments to shareholders, lenders and investors increase as income from operations is generated.

2.2.4 Taxation and Royalties

In 2020-21, iron ore royalty revenue increased by 49% to $11.35 billion, which equated to approximately 28% of State Government general revenue.

As presented in Figure 2.1, from the start of the reference period through to 2020-21, the share of State Government general revenue accounted for by iron ore royalty revenue increased sharply from 2.1% to 28.3%. Over a short period from 2013-14 to 2015-16, the share of State Government general revenue accounted for by iron ore royalty revenue declined from 19.5% to 13.6%.

Figure 2.1 Iron ore royalty revenue as a share of State Government general revenue



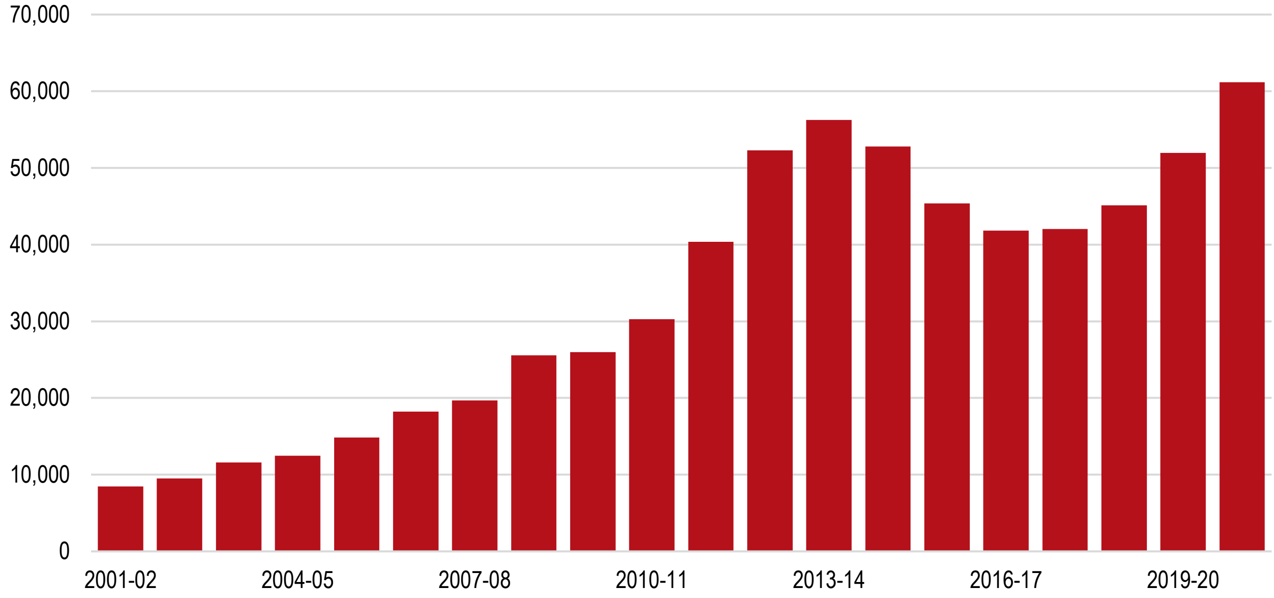
Source: Department of Mines, Industry Regulation and Safety, 2021

2.2.5 Employment

In 2020-21, direct full-time equivalent (FTE) employment in Western Australia's iron ore industry was 61,172, which equated to 52.7% of direct FTE employment in Western Australia's minerals mining industry (excluding exploration). The second largest commodity in Western Australia's minerals mining industry on the basis of direct FTE employment in 2020-21 was gold (29,413), which was less than half of employment in iron ore.

Direct FTE employment in iron ore rose sharply over the period from 2001-02 to 2013-14, before experiencing a period of contraction over the following three years. From 2016-17 to 2020-21, there was a recovery in direct FTE employment in iron ore with a 46% increase recorded over this period. Direct FTE employment as a share of Western Australia's minerals mining industry peaked at 57.4% in 2013-14.

Figure 2.2 Western Australia's iron ore industry employment



Source: Department of Mines, Industry Regulation and Safety, 2021

Box 2.1 Western Australian Iron Ore by the numbers

- In 2020-21, Western Australia produced 838.69Mt of iron ores, for a commercial value of over $154 billion.
- Western Australia produced more than twice the quantity of iron ore in 2020-21 than it did 10 years earlier in 2010-11 (397.60Mt).
- Western Australia accounts for 99% of Australia's iron ore production.
- Western Australia is the largest iron ore supplier in the world, accounting for 38% of global supply in 2022, followed by Brazil (17%).
- Western Australia accounts for one third of global iron ore exports.
- Western Australia exported more than $150 billion of iron ore in 2020-2021.
- Western Australia exports approximately 97% of its mined iron ore, in terms of value.
- China consumes 81.7% of Western Australia's iron ore exports, with Japan (5.9%) and South Korea (5.7%) the second and third largest customers.
- Australia supplies 59.6% of China's iron ore demand, more than twice the proportion of their second largest foreign supplier (Brazil).

Source: ACIL Allen from various sources (primarily DMIRS)

Finding 1 Significance of the iron ore industry

Western Australia is the largest iron ore supplier in the world, accounting for 38% of global supply, which is more than double the next largest iron ore supplier, Brazil which supplies 17% of global supply. The iron ore industry is the State's largest and most important industry, providing direct and indirect economic and social contributions which are greater than any other industry to the State. Through the royalties that pays, it is also the largest contributor to State Government finances, generating $11.35 billion which represented 28% of general government revenues in 2020-21.

From Iron Ore to Steel 3

Although iron and steelmaking processes have changed substantially since the development of the first furnaces and throughout the industrial revolution to the point where the process is now very internationalised, the fundamentals remain the same. This section of the report provides an overview of the iron ore mining to steelmaking value chain.

3.1 How steel is made using fossil fuels

In the first stage of the steelmaking process, iron ore is extracted from the ground. In Western Australia, which is the world's largest iron ore exporting region[4], this is typically done through open cut mining.[5] Here, iron ore bearing rock is blasted with explosives before being extracted and transported to facilities where it is crushed and screened to achieve a grade by size.[6]

Mined iron ores may then undergo a process of 'beneficiation' which 'upgrades' the ore.[7] Next, processed ore is typically transported by rail or road to bulk ports to be exported to iron and steelmaking facilities.

The two key products by size are undersized iron ore known as 'fines' (95% under 6.3 mm) or 'lump' (95% over 6.3 mm).

At the iron and steelmaking facilities, fines will undergo an agglomeration process such as sintering or pelletising, before being made into iron.[8]

This is either done using a BF, which produces molten pig iron[9], or through a direct reduction technique such as a fluidised bed, rotary kiln, or shaft furnace, which will produce metallic iron.[10]

Larger or oversized pre-screened 'lump' ores do not need to undergo this process before being fed into ironmaking furnaces, and so they attract a price premium relative to fines.

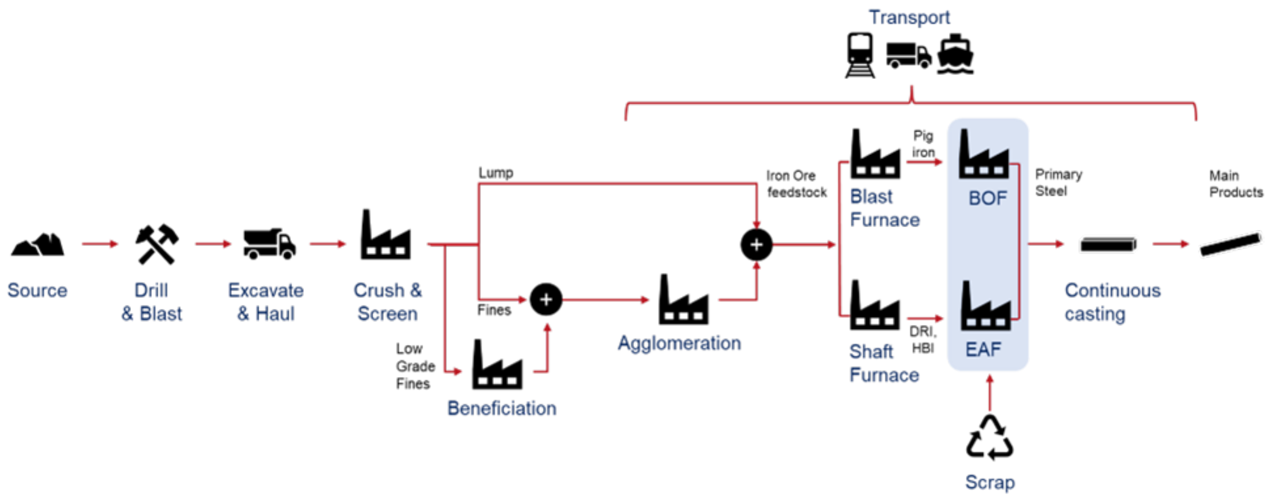
The majority of primary steel is made using molten pig iron from a BF as an input into a BOF (knowns as the BF-BOF process).[11]

In the alternative case of DRI, it is typically mixed with a significant quantity of scrap steel and fed into an EAF to produce the desired final product.[12] As Australia produces only a small amount of steel domestically, the vast majority of the 'value adding' iron and steel processes occur overseas.

[4] Department of Mines, Industry Regulation and Safety, 2021, *Mineral and petroleum review 2021*.
[5] Stace, R, 2015, 'Iron ore extraction techniques', in *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (Cambridge: Woodhead Publishing). Chapter 7.4: Modern-day surface mining: the Pilbara deposit.
[6] Metso, n.d., *Basics in Minerals Processing*. Chapter 4: Size Control.
[7] SGS Minerals Services, 2009, *Beneficiation*.
[8] Yang, Y, Raipala, K, and Holappa, L, 2014, 'Ironmaking', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).
[9] González, J, González, D, and González, L, 2020, *Operations and Basic Processes in Ironmaking* (Cham: Springer Nature Switzerland). Chapter 6: Production of Iron in the Blast Furnace.
[10] Battle, T, Srivastava, U, Kopfle, J, Hunter, R, and McClelland, J, 2014, 'The Direct Reduction of Iron', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).
[11] González, J, González, D, and González, L, 2020, *Operations and Basic Processes in Ironmaking* (Cham: Springer Nature Switzerland). Chapter 1: The Basic Oxygen Furnace to Obtain Steel.
[12] Madias, J, 2014, 'Electric Furnace Steelmaking', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).

Figure 3.1 depicts the general process from iron ore mining to steelmaking. While the process for making steel follows the same general steps, a significant variance exists between the manufacturing techniques, supply chains used, production processes, material feedstock, and capital equipment used by steelmakers.

Figure 3.1 Iron ore to steelmaking process



3.2 Iron ore mining

This section provides an overview of how iron ore is mined and the key characteristics which then influence options for processing and emissions reduction opportunities.

3.2.1 Orebody, ore types, ore grades, and gangue

An iron ore resource refers to a connected mass of material distinguishable in character and form from its enclosing host rocks and has reasonable prospects of being commercially extracted.[13]

Western Australia is home to the largest indicated iron resource – banded iron formation – in the world. It is closely followed in this regard by Brazil, which is also a significant iron ore producer and exporter. Large iron orebody reserves also exist in Russia, China and Africa.[14] Further information about the drivers behind iron ore markets can be found in Section 5.

Iron ore resources are not homogeneous as they vary in their characteristics and will be comprised of different iron oxide minerals, the most common of which are hematite, goethite and magnetite. These different ore types require different processing techniques.

Since the early 1960s, the dominant iron ore mined in Australia has been hematite and its related goethite ore. Pure hematite mineral (Fe2O3) contains 69.9% iron (Fe) by weight, although the commercial deposits in Western Australia contain an average of between 56% to 62% Fe.[15]

Importantly, high-grade hematite such as deposits from the Brockman Iron Formation make up a large portion of Australia's iron ore exports, often referred to as direct shipping ores (DSO), with the vast majority coming from Western Australia's Pilbara region.

Hematite is non-magnetic, and ranges in colour from reddish brown to silver.[16]

Goethite is a mineral formed from hematite but contains higher amounts of mineralised water in its structure in the form of FeOOH. In Western Australia, goethite is often co-located with hematite deposits and found throughout the Pilbara and Mid West regions.[17]

Magnetite mining is an emerging industry in Australia. In contrast to hematite, the mineral magnetite (Fe3O4) is magnetic with resources containing lower iron content despite the pure underlying mineral having a higher iron content than hematite.

Magnetite ore is deposited with a significant portion of waste minerals, and requires substantial beneficiation before further use, meaning it is more costly to process for shipment. Current commercial deposits in Western Australia are generally in the order of 30% to 35% Fe which through beneficiation typically become above 65% Fe as a concentrate. Magnetite is predominantly found in the Mid West and Pilbara regions of Western Australia, as well as in South Australia and Tasmania.[18]

Impurities in iron ore are known as gangue. The main gangues are alumina, silica, phosphorous, and sulphur, with different gangue associated with different types of ore. The level of gangue in an iron ore product directly affects negotiated prices with customers due to the negative impact gangue can have during processing.

[13] Gandhi, S, and Sarkar, B, 2016, *Essentials of Mineral Exploration and Evaluation* (Amsterdam: Elsevier). Chapter 2.5: Ore body.
[14] United States Geological Survey, 2021, *Iron Ore*.
[15] Brazil's average grade, which can average more than 66%, is higher than Western Australia. An example of high-grade direct shipping ore from Western Australia is from Koolan Island, a hematite mine operated by Mount Gibson Iron with an average grade of 65.3%.
[16] Geoscience Australia, 2013, *Australia's Mineral Resource Assessment 2013*, Chapter 3 Resources: Iron Ore.
[17] Hudson Institute of Mineralogy. n.d. *Goethite from Western Australia, Australia*. Content accessed via: https://www.mindat.org/locentries.php?p=15624&m=1719
[18] Geoscience Australia, 2013, *Australia's Mineral Resource Assessment 2013*, Chapter 3 Resources: Iron Ore.

Higher levels of gangue such as alumina and silica typically incur price penalties relative to 'indexed' (e.g., 62% Fe Fines) products. Western Australia iron ore producers in particular are facing resources with increasing levels of gangue and lower levels of Fe content as the best ores are depleted and not fully replaced by new mines. The impact of gangue for energy use further down the value chain is considered in Section 8.6.

Box 3.1 Why ore type, grade, and gangue matters

Ore type (e.g., hematite, goethite and magnetite) requires different processes and energy consumption in order to produce steel.

Grade refers to the iron unit (Fe) content of the iron ore, the main steelmaking input. Higher grade ore are more desirable as it requires less processing and hence energy costs. Conversely, lower grade ore requires beneficiation in order to improve its economic value and to lower the gangue content.

Gangue refers to non-Fe impurities in iron ore and requires removal during the iron and steelmaking processes. Higher gangue content increases the requirement of fluxes (including burnt lime), coke and energy usage in the Blast Furnace in turn increasing CO_2 emissions, costs and decreasing productivity.

3.2.2 Mining

Process

Most iron ore mines in Australia, and all the larger operations in Western Australia, are 'open cut'.[19] The open cut method of iron ore mining is drilling and blasting[20] using drilling rigs to obtain rock core samples in the area to be mined, before these holes are strategically detonated with explosives to access the ore body. Drilling and blasting ensure the iron ore bearing rock can be sized for transportation for further sizing and, if needed, subsequent beneficiation.

Following drilling and blasting, excavators, face shovels, or front-end loaders load the ore onto haul trucks[21] as run of mine – from the 'working face' of the mine to the crushing and screening facilities to be processed to size for shipment or beneficiation.[22]

Energy sources

The heavy machinery used in this process, such as the drill rigs, excavators, face shovels, front-end loaders, and haul trucks, typically require diesel fuel to operate, although several electrical and gas-powered models now exist and are being trialled.

[19] Stace, R, 2015, 'Iron ore extraction techniques', in *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (Cambridge: Woodhead Publishing). Chapter 7.4: Modern-day surface mining: the Pilbara deposit.
[20] BHP, n.d., *Iron ore*.
[21] Rio Tinto, n.d., *Iron Ore production in the Pilbara*.
[22] Stace, R, 2015, 'Iron ore extraction techniques', in *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (Cambridge: Woodhead Publishing). Chapter 7.4: Modern-day surface mining: the Pilbara deposit.

3.2.3 Processing and refining

Process

Following extraction, the run of mine iron ores will undergo a 'crushing' process. Crushing is where iron ore containing rock that has been blasted into material that varies substantially in size, is resized into more consistent sizes so it can be more easily transported and shipped, as well as used in later stages of the iron and steelmaking process.[23]

Mine sites typically have a primary crusher (such as a jaw or cone crusher) located as close as practically possible to the mine's working face. This ore will feed, via a system of conveyer belts, secondary and tertiary crushers used for further refinement.[24]

Because the technology and equipment used to make iron in a BF typically requires material of a certain diameter, crushed iron ores are also sorted into 'lump' that fits the size requirements (between 6.3mm and 31.5mm), and 'fines' that are less than the required diameter, which is typically up to 6.3mm.[25,26] Industrial screeners are used for this task.

Only a small amount of ore is beneficiated in Western Australia as the typical mined hematite is fit for purpose, i.e., of sufficiently high grade and sized for market enabling it to be directly exported – hence the term 'direct shipping ore' (DSO).

However, all magnetite ore undergoes beneficiation, as the natural processes that produce it mean there are large quantities of small magnetite particles buried with large quantities of other non-ferrous minerals. For magnetite, beneficiation separates the magnetite mineral particles from the surrounding and essentially valueless waste minerals it is embedded in.

Depending on the original ore quality, nature, and the requirements of the iron ore extracted during the mining phase, it may undergo any one of several beneficiation procedures including: scrubbing to remove impurities and potential oxidization, gravity separation, magnetic separation, floatation separation, or any other number of physical processes specific to a deposit.[27,28]

Energy sources

The heavy machinery involved in on-mine iron ore processing runs on a combination of diesel, electricity and natural gas depending on the model, specification, and set-up of the specific machinery and mine.

Box 3.2 Why size matters

Converting iron ore to iron can only be done effectively if the iron ore feed into reductive processes is of the correct sizing to suit the ironmaking process of each steelmaker.

Iron ore fines cannot be charged directly in significant quantities into the BFs or standard direct reduction shaft furnaces. These must first be agglomerated, generally by either sintering or by pelletising.

Fluidised Bed Direct Reduction (e.g., Finmet) and direct smelting (e.g., HIsmelt furnace) can use iron ore fines without agglomeration. These technologies which do not need agglomeration are not standard technology but are under development in order to simplify the ironmaking process.

[23] Rio Tinto, n.d., *Iron Ore production in the Pilbara*.
[24] Stace, R., 2015, 'Iron ore extraction techniques', in *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (Cambridge: Woodhead Publishing). Chapter 7.4: Modern-day surface mining: the Pilbara deposit.
[25] Metso, n.d., *Basics in Minerals Processing*. Chapter 4: Size Control.
[26] Resource Capital Research, 2010, *Industry Background and Analysis*.
[27] SGS Minerals Services, 2009, *Beneficiation*.
[28] Stace, R, 'Iron ore extraction techniques', in *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (Cambridge: Woodhead Publishing). Chapter 7.4: Modern-day surface mining: the Pilbara deposit.

3.2.4 Transportation and export

Process

After undergoing crushing and screening, and in some cases, beneficiation depending on the ore type, quality of the natural ore deposit and profitability of further upgrade, the ore will be transported to iron and steel manufacturing facilities, most commonly overseas.[29]

The Western Australian transport and export supply chain is relatively simplistic.[30] At large iron ore mines, such Rio Tinto's Yandicoogina and BHP's Mount Whaleback operations, the processed ore is first stockpiled in mine stockyards, and then transported directly from the mine by rail to bulk carrier ports such as those at Dampier and Port Hedland.[31] Conveyors then move the ore around the port.

At the port, the product maybe again stockpiled using stackers and sometimes rescreened to further separate undersized ore from the lump product, before being loaded onto bulk carriers using reclaimers and shipped to iron and steel production facilities.[32] For smaller mines where ore volumes do not commercially justify dedicated rail connections, ore is transported on road via specialist road trains, or via a conveyer/pipeline, to either nearby rail infrastructure, or to a port directly.[33]

The supply of iron ore to Australia's small domestic steelmaking operations, such as the BlueScope facility in Port Kembla, also proceeds in this way, with ores shipped out of Western Australia and around the coast.[34]

Furthermore, the 'blending' of ores of different quality is frequently necessary to meet the specifications of iron and steel producers who purchase the material. This is typically undertaken at the port itself, but can occur earlier in the supply chain, depending on the commercial viability of each option for producers.[35]

Energy sources

The bulk transport machinery involved in the domestic transportation and then export of iron ore overseas, including the transport trains, trucks and bulk carrier ships, will typically run off diesel in the case of trains, bunker fuel in the case of ships and diesel or liquified natural gas (LNG) in the case of trucking. At the stockyards next to the export jetty, the stackers and reclaimers are powered using electricity.

[29] Department of Mines, Industry Regulation and Safety, 2021, *Mineral and petroleum review 2021*.
[30] Department of Infrastructure and Regional Development, 2014, *Freightline 2 – Australian iron ore freight transport*.
[31] Brent, A, 2021, *Best in Class: Australia's Bulk Commodity Giants* (Canberra: Minerals Council of Australia).
[32] ibid
[33] Department of Infrastructure and Regional Development, 2014, *Freightline 2 – Australian iron ore freight transport*.
[34] ibid.
[35] ibid.

3.3 Ironmaking

Ironmaking refers to the process of converting iron ore and associated feedstock into a purer form of iron, prior to the commencement of the steelmaking process.

3.3.1 Agglomeration

Process

Once the ore arrives at an iron and steel manufacturing facility, it may undergo further processing depending on its quality, and the product specifications of the facility.

Ore that does not meet the size specifications of an iron furnace is agglomerated into the larger usable sizing, most commonly through the sintering process.

Sintering facilities heat iron ore fines to partially melt the ores, and cause fines to fuse into larger, and commercially usable, agglomerate called sinter. Typically, coke, which is made by heating coking coal to between 1000-1100°C in the absence of oxygen, is used to generate the necessary heat which is drawn through the ore blend during the sintering process. The blended iron ore fines are mixed with water and fluxes such as lime or dolomite to aid in the procedure.[36]

Several of the beneficiation processes outlined in Section 3.2.3 can leave processed ore in the form of a fine concentrate. This concentrate is not only too small (fine) to be used in most commercial ironmaking processes, but also too small to agglomerate in large amounts through the sintering method.

For this reason, fine concentrates may undergo the process of 'pelletising'. This is where concentrated ore is first moistened with water and then fed, along with 'binders' such as bentonite and hydrated lime, into what is typically a rotating steel drum or rotary disk. This process creates soft 'pellets' of an appropriate size for use in iron and steelmaking, and that are then allowed to dry out before being hardened in a rotary kiln or shaft furnace at approximately 1200°C.[37] Often, this form of agglomeration, unlike sintering, will occur at the loading port or closer to the mine site.[38]

Energy sources

Typically, sintering and pelletising will run on either natural gas, fuel oil or electricity, depending on the availability of energy. Furthermore, traditionally, high grade coals blended with the ores, has also been utilised to generate heat for both sintering and pelletising in the process.

[36] Lu, L, and Ishiyama, O, 2015, 'Iron ore sintering', in *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (Cambridge: Woodhead Publishing). Chapter 14.1: Introduction.

[37] González, J, González, D, and González, L, 2020, *Operations and Basic Processes in Ironmaking* (Cham: Springer Nature Switzerland). Chapter 3: Pelletizing.

[38] Brent, A, 2021, *Best in Class: Australia's Bulk Commodity Giants* (Canberra: Minerals Council of Australia).

3.3.2 Blast furnace method

Process

The most common method of ironmaking, as a precursor to commercial steelmaking, involves the utilisation of a BF[39] with approximately 70% of steel being produced in coal-fire based BFs globally.[40]

The median historic BF campaign life is around 17 years, with each BF capable of having up to three campaigns.[41] At the end of each campaign a BF is relined, which extends their service life.

In the BF process, coke is first produced in coke ovens by heating coking coal, in the absence of oxygen, using coke oven gas (COG). Once it has been produced, the coke is then quenched with water to cool it before it is screened into lumps of coke for the BF. The COG is also cleaned and used in other parts of the steelmaking process, including power generation for the facility.

The BF is then charged with lump ore or sinter ores, coke, and usually extra fluxes such as lime and dolomite used to collect impurities. Pressurised hot air, at a temperature of 1200°C, is injected in the lower section of the BF, with BF gas (BFG) typically used to heat this air.

The hot air injected into the BF reacts with the lump coke forming carbon monoxide gases and the heat required to start the reduction of the iron ore and eventually from molten iron droplets to descend to the base of the furnace.[42]

This reaction is called iron ore reduction to the desired iron metal (hot metal) and causes it to melt, while also producing the by-product 'slag', which is typically a mixture of lime, silicates, and aluminates that develops as the iron ore reduces.[43]

Once the process is complete, the molten iron is drained from the bottom of the BF through a 'taphole' and the hot metal produced is then often called pig iron (when solid often cast into small ingots called pigs).[44] Slag is separated from the molten iron by gravity and is removed from the top of the BF to be used as a by-product in other industries.[45]

The preference to use coal is not simply driven by cost considerations as there are also practical reasons for using coal. To produce commercial grade steel, other elements are usually added following direct reduction, since steel is relatively weak at this stage.

One of the elements is carbon as increasing the carbon content makes the steel harder and stronger. This makes the transition away from coal complex, given the reliance upon the carbon content of coal and applicability across the integral parts of the steelmaking process.

Further information about the global steel industry can be found in Section 4.

Energy sources

Coking coal to make the necessary coke, various (natural) gasses including COG and BFG to provide heat to deoxidise the iron ore, and oil for ancillary processes.

[39] Yang, Y, Raipala, K, and Holappa, L, 2014, 'Ironmaking', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).
[40] Toto, D, 2021, *Steel could be made with almost no carbon emissions through 2050*
[41] Vogl, V, Olsson, O and Nykvist, B, 2021, *Phasing out the blast furnace to meet global climate targets*.
[42] Cameron, I, Sukhram, M, Lefebvre, K, and Davenport, W, 2019, *Blast furnace ironmaking: analysis, control, and optimisation* (Amsterdam: Elsevier). *Chapter 1: The Iron Blast Furnace Process.*
[43] Australasian (iron & steel) Slag Association, n.d., *Blast Furnace Slag (BFS)*.
[44] Cameron, I, Sukhram, M, Lefebvre, K, and Davenport, W, 2019, *Blast furnace ironmaking: analysis, control, and optimisation* (Amsterdam: Elsevier). *Chapter 1.3.1: Molten Iron*.
[45] Australasian (iron & steel) Slag Association, n.d., *Blast Furnace Slag (BFS)*.

Box 3.3 Why age of BFs matter

Blast furnaces are a significant capital cost and have a significant operating life of 50-60 years.

Manufacturers have a high incentive to keep newer BFs running due to the sunk capital costs, whereas it is easier to economically justify replacing ageing BFs reaching their end-of-life (refer to Section 5.5 for more detail).

Box 3.4 Why it is difficult to move away from coal

Coal-based ironmaking and steelmaking, where coal is used as a reductant to convert iron from the oxide forms and as an energy source, is a well-established process with established supporting supply chains for supply of metallurgical coking coal.

Sunk capital costs in ironmaking technologies that rely on metallurgical coking coal, specifically BFs, means there is little economic incentive to move away from the use of coal in the short term.

3.3.3 Direct Reduced Iron (DRI) / Hot Briquette Iron (HBI)

Iron ore, which is the most common raw material for steelmaking, is fundamentally an iron oxide mineral.

To produce iron, carbon or hydrogen is used to strip the oxygen from the iron ore via reaction processes called direct reduction.

Process

Although the BF method is the most common way of commercially producing iron, it is not the only way. Iron ore can also be directly reduced to form metallic iron in a solid state, in only one step, without the production of pig iron in molten form. The resultant product of this process is known as DRI,[46] which can be made into HBI if it is briquetted under high pressure and heat to make it less porous and reactive.[47]

There are three main methods through which DRI is created. The first of this is a 'fluidised bed'. In this process, ores are fed into a typical fluidised bed reactor, which is then heated, typically using natural gas, to reduce the ore into metallic iron.[48] Although the fluidised bed process can utilise fine ores, without the need for agglomeration techniques such as sintering and pelletising, only a handful of commercial fluidised bed plants exist globally.[49]

Another method of commercially producing DRI involves ore being heated for several hours in an inclined rotary kiln, where heat is typically provided by the burning of coal. The final product is then cooled, and the resultant metallic iron is magnetically separated from unwanted non-magnetic impurities (the gangue).

Although this method is somewhat common around the world, and especially in developing nations such as India because it is relatively cheap, there are mechanical constraints limiting the ability to 'scale up' this carbon intensive process, meaning most facilities are small in comparison to the average BF.[50]

Lastly, DRI can also be produced in a shaft furnace. In shaft furnace methods, such as the MIDREX process,[51] the necessary reactants used to reduce iron ore pellets or lump ore is provided by a 'reducing gas', which is typically a

[46] International Iron Metallics Association, 2018, *Direct Reduced Iron (DRI)*.
[47] Carbones, 2020, *HBI & DRI*.
[48] Kinaci, E, Lichtenegger, T, and Schneiderbauer, S, 2018, 'Direct Reduction of Iron-Ore in Fluidized Beds'. *Computer Aided Chemical Engineering* 43(1): 217-222.
[49] Battle, T, Srivastava, U, Kopfle, J, Hunter, R, and McClelland, J, 2014, 'The Direct Reduction of Iron', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).
[50] Battle, T, Srivastava, U, Kopfle, J, Hunter, R, and McClelland, J, 2014, 'The Direct Reduction of Iron', in Treatise on Process Metallurgy Volume 3: Industrial Processes (Oxford: Elsevier).
[51] Midrex Technologies, 2021, *MIDREX® Process*.

mix of reactive gases made from a source of natural gas such as methane.

Like all direct reduction processes, because they do not melt the ore, the temperatures reached in a shaft furnace are less than those achieved in a BF, and typically lie in the range of 900°C.[52]

Energy sources

Natural gas to provide heat and reductant in a fluidised bed or shaft furnace, coal to provide heat and reductant in a rotary kiln, and oil for ancillary processes.

Box 3.5 Direct Reduction Technology: A Primer

In a direct reduction process, iron ores are reduced by a reducing gas to produce DRI via a gas based or coal/oil-based process.

In the gas based direct reduction process, the reducing gas is produced by reforming a mix of natural gas and off-gas from the furnace to create a reducing gas rich in hydrogen and carbon monoxide. In the coal/oil based direct reduction process, the reducing gas is generated from hydrocarbons, primarily from coal and occasionally using oil and natural gas, in the reduction zone of the furnace.[53] Alternatively, hydrogen may partially or fully replace carbon dioxide as the reducing agent.

One of the most common direct reduction technologies currently utilised is the MIDREX gas-based process for steelmaking where natural gas is processed and reformed into a commercially usable reducing gas with high hydrogen and carbon monoxide content. MIDREX NG™, operated by Japanese company Kobe Steel, through use of the patented MIDREX® Reformer, cost effectively makes reducing gas for the iron ore reduction reactions that take place in the MIDREX® Shaft Furnace, which produces DRI such as HBI.

The MIDREX® Reformer externally generates reducing gas and further optimizes the MIDREX Shaft Furnace performance by converting recycled gas (from the iron reduction reactions) along with fresh natural gas into hydrogen and carbon monoxide, to produce additional reducing gas. The company's future ambition is to switch from natural gas feed to 100% green hydrogen, which is to be produced by an electrolyser plan, powered by renewable energy.

Other examples of direct reduction technology for iron and steelmaking include the Energiron HYL process by Tenova and Danieli, the SL/RN process, and ACCAR process.

The Cleveland Cliffs Direct Reduction Plant is an example of a successful small scale steelmaking facility that has achieved full run-rate nameplate annual capacity shortly after commencing operations and integrated itself into the supply chain of steel producers in the local region. Cleveland Cliffs have also been successful in designing a facility that can adapt to developments in the commercialisation of emerging energy sources, such as hydrogen.

[52] Yang, Y, Raipala, K, and Holappa, L, 2014, 'Ironmaking', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).
[53] Lu, L, Pan, J, and Zhu, D, 2015, 'Quality requirements of iron ore for iron production', in *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (Cambridge: Woodhead Publishing). Chapter 16.3: Quality requirements of iron ore for alternative ironmaking processes.

3.4 Steelmaking

The final step in the iron ore to steelmaking process is conversion of iron into steel. This process is described below.

3.4.1 Basic oxygen furnace (BOF)

Process

The BOF method of steelmaking follows on directly from the BF method of ironmaking outlined in Section 3.3.2.[54] Iron from a BF is also typically fed immediately into a BOF after it has been produced.

Up to 15-25% of scrap steel is added[55] as well as small quantities of additives needed to give the final steel the specification required for commercial applications.

Fluxes such as lime and dolomite are also fed into the basic oxygen process to remove impurities.[56]

In the BOF process, high purity oxygen is injected onto the surface of a molten bath of pig iron through a water-cooled lance.[57]

This procedure causes dissolved carbon, silicon, manganese, phosphorus, and other impurities in the pig iron, to oxidise,[58] which liberates a large quantity of heat, melting the scrap and causing the temperature of the furnace to raise to approximately 1700°C. The carbon from the pig iron is a fuel for the BOF.

Energy sources

Carbon from the pig iron or hot metal, oxygen, natural gas injection.

3.4.2 Electric arc furnace

Process

Many modern steel plants, such as those in the United States,[59] use EAF. Presently, almost 30% of world steel is produced using an EAF.[60]

The main input into an EAF is scrap steel, as opposed to molten or pig iron as in a BOF. However, this method is frequently also used to convert HBI or DRI. Used as a low impurity source of iron, often for making higher grade steels, it relies on the EAF to remove the impurities such as gangue still present in the iron.[61]

In an EAF, electrical energy is used to run a current through large graphite electrodes.[62] The heat energy is necessary to turn the scrap, HBI or DRI into steel in the presence of carbons and fluxes such as lime and dolomite.[63] This reaction is accompanied by either oxygen injection or oxy-fuelled burners to aid in the refining process.

Energy sources

Electricity from various renewable and non-renewable sources, coal in the form of injection fines, coal or coke charged with the scrap, oxygen for reacting with the carbon sources as well as oil and natural gasses for ancillary processes.

[54] González, J, González, D, and González, L, 2020, *Operations and Basic Processes in Ironmaking* (Cham: Springer Nature Switzerland). Chapter 1: The Basic Oxygen Furnace to Obtain Steel.
[55] World Steel Association, 2021, *Scrap use in the steel industry*.
[56] Cameron, I, Sukhram, M, Lefebvre, K, and Davenport, W, 2019, *Blast furnace ironmaking: analysis, control, and optimisation* (Amsterdam: Elsevier). *Chapter 1: The Iron Blast Furnace Process*.
[57] Southeast Asian Iron and Steel Institute, n.d., *The Making of Iron and Steel*. Chapter 4.2: Basic Oxygen Steelmaking.
[58] Southeast Asian Iron and Steel Institute, n.d., *The Making of Iron and Steel*. Chapter 4.2: Basic Oxygen Steelmaking.
[59] American Iron and Steel Institute, n.d., *Steel Production*.
[60] Karbowniczek, M, 2020, *Electric Arc Furnace Steelmaking* (Boca Raton: CRC Press). Chapter 1: Introduction.
[61] Madias, J, 2014, 'Electric Furnace Steelmaking', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).
[62] Karbowniczek, M, 2020, *Electric Arc Furnace Steelmaking* (Boca Raton: CRC Press). Chapter 1: Introduction.
[63] Madias, J, 2014, 'Electric Furnace Steelmaking', in *Treatise on Process Metallurgy Volume 3: Industrial Processes* (Oxford: Elsevier).

Box 3.6 Case Study 1: H_2 Green Steel Project, Sweden

H_2 Green Steel was founded in 2020 with the ambition to accelerate the decarbonisation of the steel industry, using green hydrogen. H_2 Green Steel have plans for a hydrogen-based integrated primary steel manufacturing plant located in Boden in northern Sweden. Boden is in close proximity to high-grade iron ore resources mined by LKAB and Kaunis Iron.

The total financing for the first phase of the project amounts to approximately €2.5 billion. This will be raised through a combination of equity and green project financing. H_2 Green Steel has qualified for the European Investment Bank's list of projects under consideration and is currently under appraisal.

H_2 Green Steel aim to have the plant entering the production phase in 2024, with a production capacity of 5MT achieved by 2030.

The northern region of Sweden offers unique opportunities for Green Steel production based on good access to fossil-free electricity, high quality iron ore and a specialised and innovative steel industry.

It is anticipated the outcoming steel will have a very low carbon content and will support the manufacturing of green high-quality flat carbon steel products for the automotive, construction, white goods, industrial equipment and energy sectors. As an example, luxury carmaker Mercedes-Benz plans to use H_2's steel in its vehicles from 2025 onwards and has an equity stake in H_2 Green Steel.

The H_2 Green Steel Project highlights the opportunity for Western Australia to support similar Green Steel projects given similarities to Sweden with respect to the three characteristics of good access to fossil-free technology, high quality iron ore and a specialised and innovative industry base. The H_2 Green Steel Project also provides evidence of the level of demand for low-carbon steel products from manufacturers in the automotive, construction, white goods, industrial equipment, and energy sectors. The level of demand associated with the H_2 Green Steel Project from these sectors is shown through both offtake agreements signed to date, as well as equity stakes in the project.

Source: ACIL Allen from various sources

Global Steel Industry State of Play 4

Steel is an indispensable part of everyday life. Yet it is also one of the highest emitting among all industrial activities. This section of the report provides an overview of energy use and emissions along the value chain, critical drivers in the market for iron ore and steel from a Western Australian perspective, and how the outlook for steel production and consumption could evolve in the future.

4.1 The steel industry today

Steel is a significant driver of global carbon emissions. Against the backdrop of renewed emphasis on achieving net zero emissions by 2050, the industry now needs to manage its carbon footprint. Following the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP26) in 2021, individual countries and some of the world's largest private sector companies are increasingly seeking ways to progress towards net zero emissions on some defined time scale.

These targets take in emissions across the value chain, considering scope 1 (emissions in the source country or country), scope 2 (emissions associated with transport, shipping and movement of energy), and scope 3 (emissions which occur downstream of the individual country or company, owing to the use of their exports and output).

Steel is a critical input into every modern or emerging economy. The relationship between a country's Gross Domestic Product per capita and primary steel demand is well documented and has been readily observed over time.[64] In general, there are four stages of an economy's long-term development and industrialisation that strongly correlate with demand for steel.

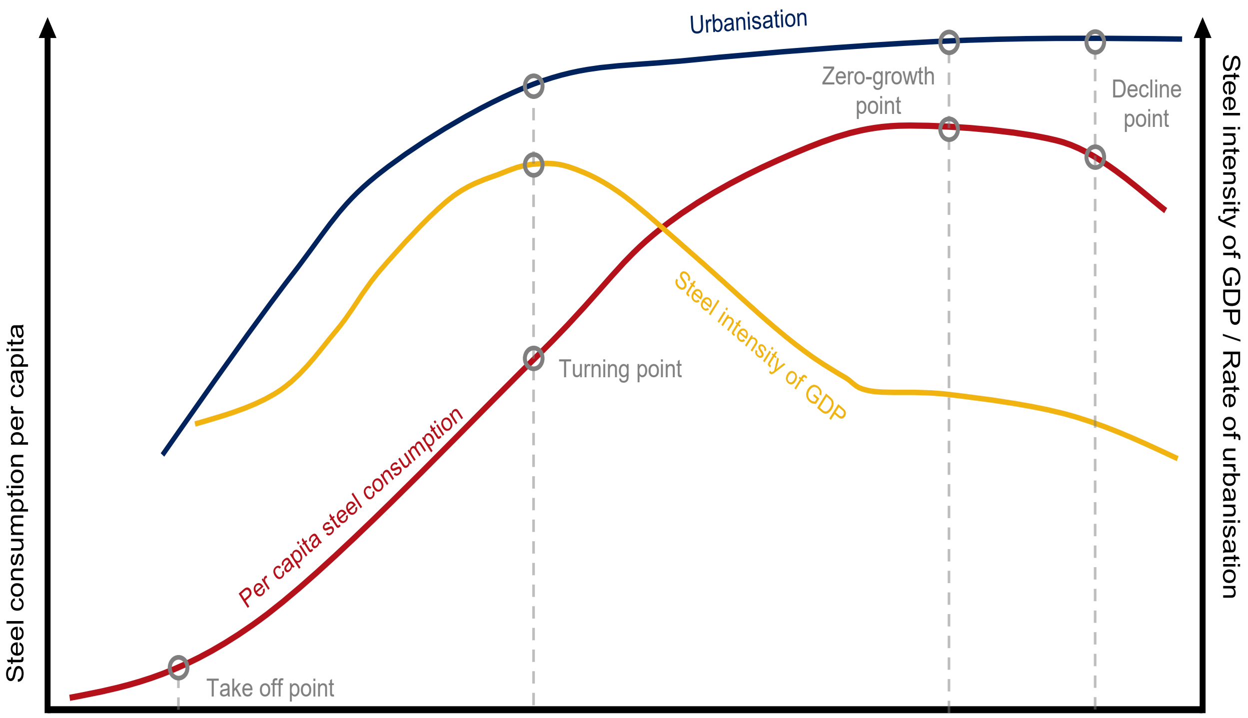
These are:

1. A "take off" point, where steel consumption grows rapidly in line with industrialisation and urbanisation of a previously deindustrialised or largely rural / agrarian population.
2. A "turning point", where steel consumption continues to grow but the absolute rate of growth slows as industrialisation and urbanisation begins to reach a critical mass.
3. A "zero growth" point, where steel consumption levels off relative to the size of the economy, which is typically at the point where the economy reaches a steady-state level of economic growth.
4. A "decline" point, where steel consumption begins to decline relative to the size of the economy, while occurs when services sectors become the dominant driver of economic activity – as is the case in modern economies.

This dynamic is often represented in a visualisation like the one reproduced in Figure 4.1.

[64] Gao, X., Wang, A., Liu, G. *et al*, 2019, Expanded S-Curve Model of a Relationship Between Crude Steel Consumption and Economic Development: Empiricism from Case Studies of Developed Economies. *Natural Resources Research* 28, 547–562. Available at: https://doi.org/10.1007/s11053-018-9406-3.

Figure 4.1 Global steel consumption and economic development curve



Source: Gao, X., Wang, A., Liu, G. et al, 2019, Expanded S-Curve Model of a Relationship Between Crude Steel Consumption and Economic Development

4.2 Energy and emissions in iron and steelmaking

4.2.1 Steel industry energy use and emissions today

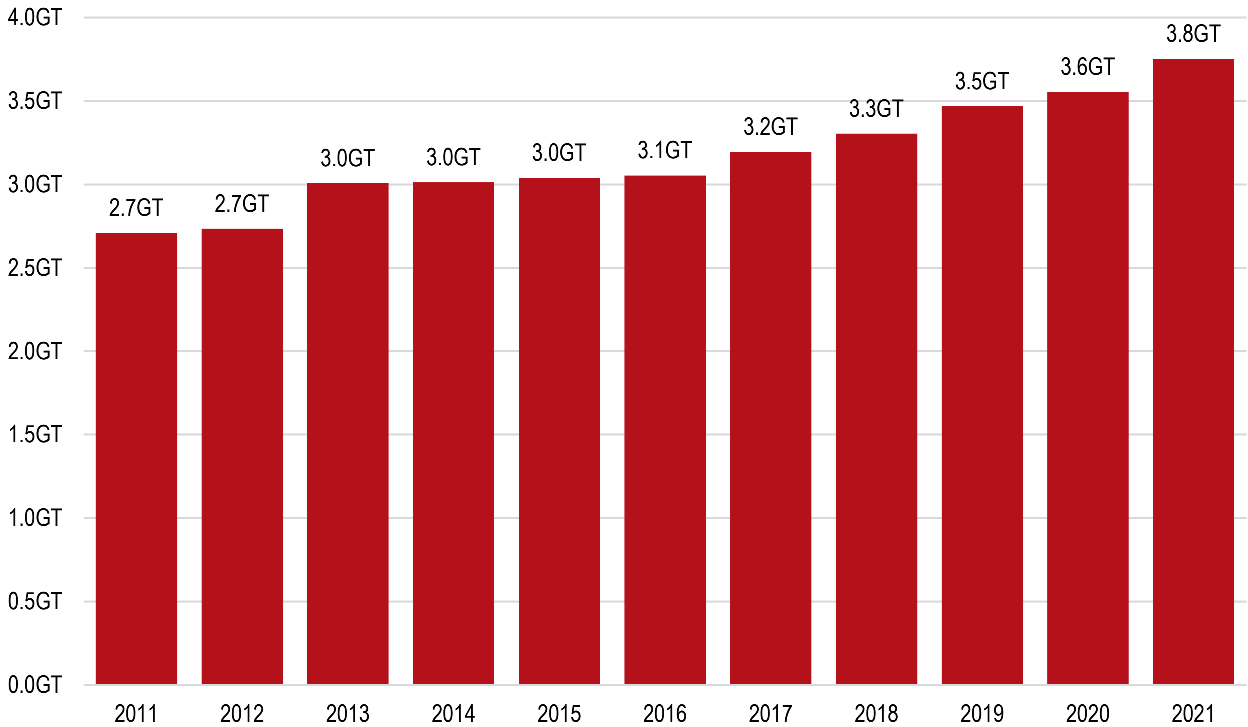
Steelmaking is a very energy intense process resulting in the global steel industry being one of the largest carbon emitters in the world, with annual emissions surpassing 3.6 giga tonnes of carbon dioxide (Gt CO_2) in 2020 (and an estimated 3.8 Gt CO_2 in 2021). If the global steelmaking industry were an independent 'country', then it would be the third largest in the world if ranked by carbon emissions, behind only China (10.7 Gt CO_2) and the United States (5.7 Gt CO_2).

Among other heavy industries, the steel industry is the world's second largest energy consumer, behind only chemical production at 1,050 million tonnes of oil equivalent per year (Mtoe/year). The third of the so-called "hard to abate" sectors, cement production, consumes just under 400 Mtoe/year.

The high reliance on metallurgical coking coal for traditional steelmaking processes has profound environmental implications. For every tonne of primary steel produced using coal, roughly 2.1 to 2.4 tonnes of carbon dioxide (tCO_2) is emitted.[65] Most newer furnaces are typically at the lower end of this range with the oldest at the higher end.

In 2020, the average global production of one tonne of primary steel produced 1.89 tCO_2.[66] Across the year, the iron and steel industry constituted 7.2% of all global emissions.[67]

Figure 4.2 Global steel industry's carbon emissions



Source: World Steel Association Global Steel Supply Chain Study, OECD, ACIL Allen analysis

[65] BHP, 2020, *Pathways to decarbonisation episode two: steelmaking technology*

[66] World Steel Association, 2021, *Sustainability Indicators: 2021 report*.

[67] Our World in Data, 2020, *Emissions by sector*.

The extensive carbon footprint of the steel industry is not solely attributable to rising steel production globally, as its emissions intensity (i.e., the amount of carbon dioxide released during steelmaking) has also increased. This is broadly reflective of the rapid industrialisation of various developing countries who not only require more steel, but also historically relied on more carbon-intensive production technologies.

These developing countries are improving the efficiency of new BFs but in most cases they are replacing EAF steelmaking with large coal fed BFs driven by the initial shortage of recycled scrap. Notwithstanding this, steelmaking is inherently an emissions-intensive industry as carbon is historically embedded into its production processes.

At a global level, the International Energy Agency estimates coal accounts for 75% of the energy used to produce steel across the supply chain as outlined in Figure 4.3.

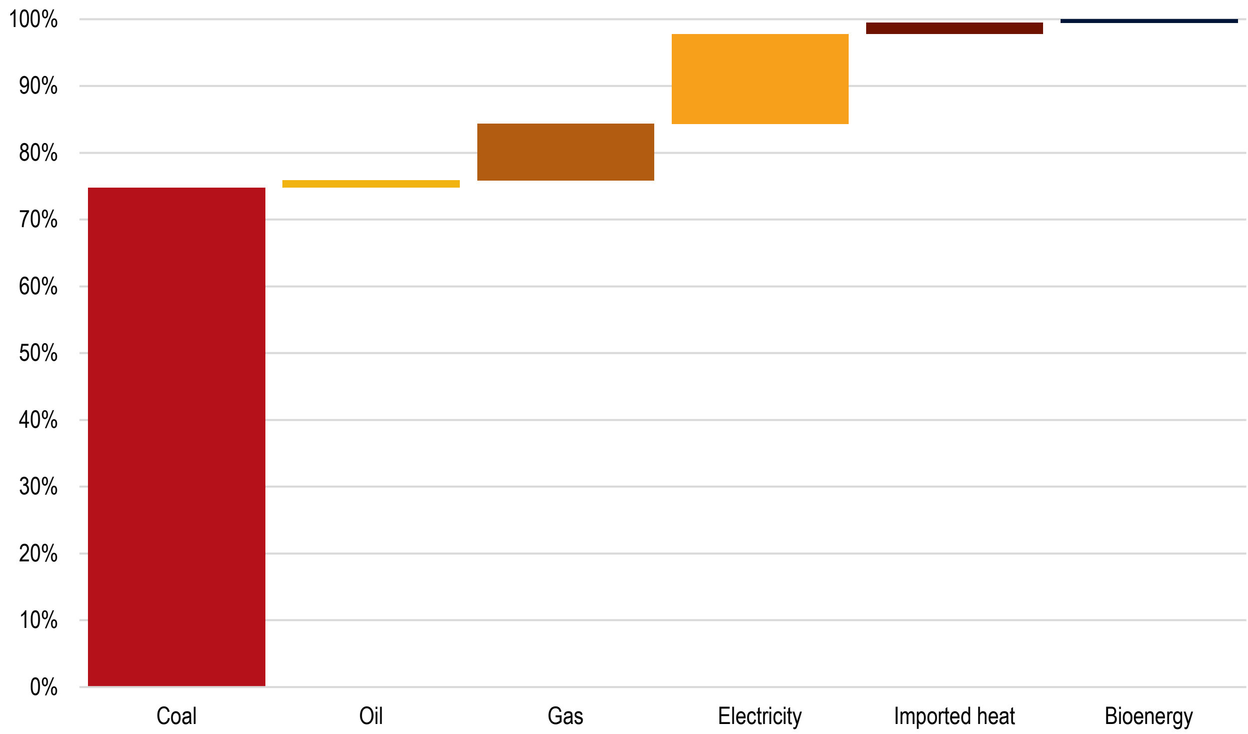
At all stages of its production, from the mining of iron ore to the finished product, a wide array of different fossil fuels sources are used including diesel, natural gas, coal, oil for three key purposes:

1. Transport fuel.
2. Energy source.
3. Reductant.

Each step of the steelmaking process produces different levels of emissions depending on the technology and energy source used.

Table 4.1 shows the emissions for a typical BF-BOF steelmaking process, by activity. This is also shown visually in Figure 4.4.

Figure 4.3 Energy use in global steelmaking, by consumed energy source, % of total energy



Source: International Energy Agency

During the mining phase, the main sources of emissions are from the heavy machinery used and transportation of ores within the mine site and in many cases power generation for site electricity. These commonly use diesel and natural gas, contributing to the relatively low emissions in comparison with other steelmaking steps.

In the iron and steelmaking phases, where most emissions are produced,[68] the use of coal, to make the necessary coke and as a heat and reductant source in and of itself, is utilised, as are natural gases resulting in the high emissions output making steel production a key contributor towards global emissions.

Direct reduction uses either carbon or carbon monoxide with hydrogen (often produced from converting natural gas processing) to strip the oxygen from the iron ore. The carbon or carbon monoxide releases carbon dioxide as a by-product once combined with the unwanted oxygen molecules in the iron ore. Notably, this partly explains the reliance on fossil fuels in ironmaking as the carbon is an effective reductant for removing oxygen.

In this direct reduction process, a large amount of heat energy is also applied to catalyse these chemical reactions as iron has a high reaction point. Consequently, the steel industry has extensive energy requirements, which the IEA estimated to be in excess of 900 million tonnes of coal equivalent (Mtce) in 2019.[69]

Table 4.1 Emissions output currently for a typical fossil fuel BF-BOF steelmaking process

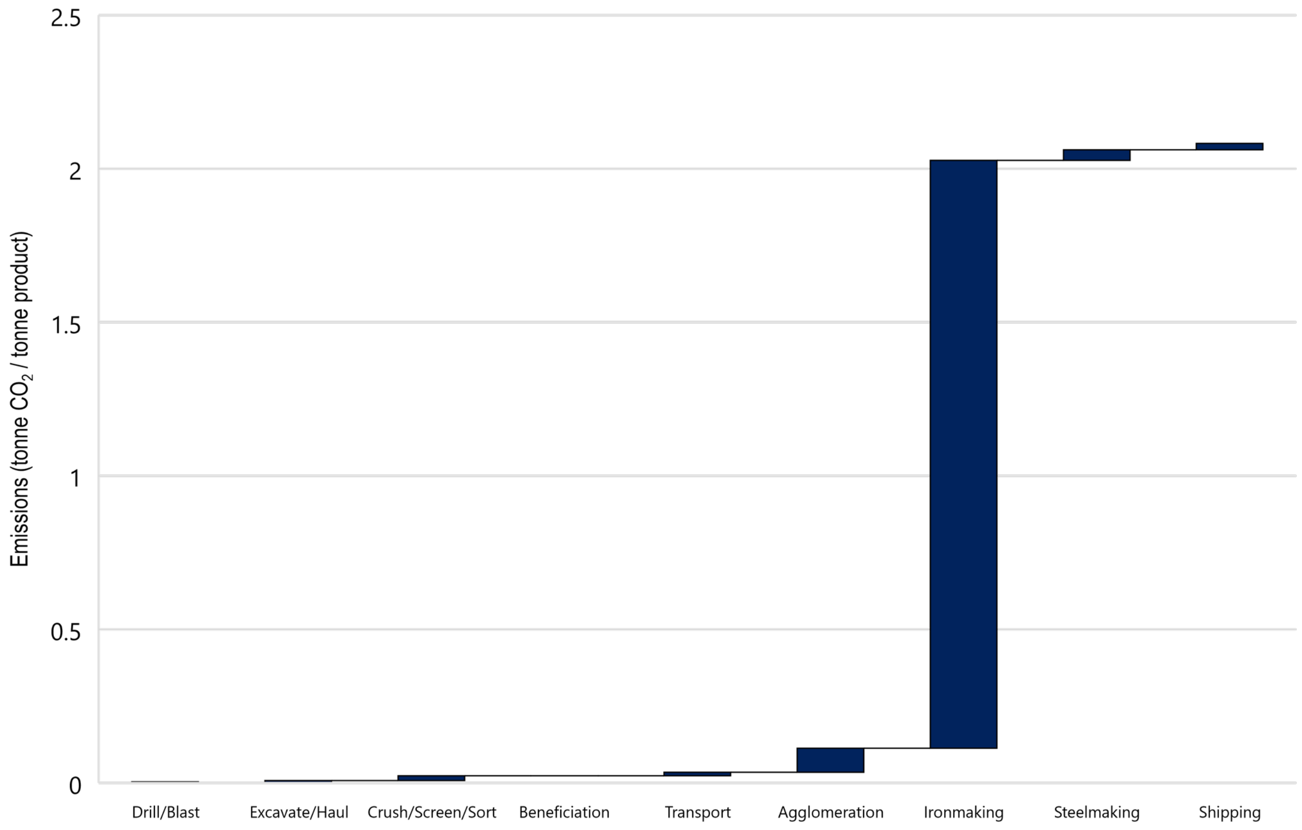
Steelmaking step (phase)	Current example sources of emissions	Emissions (tonne CO_2 / tonne product)	Percentage of total emissions
Drill & Blast*	– Diesel powered blasthole drill rigs – Explosives (such as ANFO, a mixture of ammonium nitrate and fuel oil)	0.00	0.00%
Excavate & Haul	– Fossil fuel (e.g., diesel) powered excavators, face shovels, front-end loaders and haul trucks	0.01 - 0.02	0.37% - 1.13%
Crush / Screen / Sort	– Industrial crushing equipment (such as a 'jaw' or 'cone' crusher) – Conveyor belts	0.01 - 0.05	0.71% - 2.16%
Beneficiation	– Industrial screens/sieves – Beneficiation equipment specific to the process employed (such as gravity, magnetic, or floatation separation)	0.00 - 0.08	0.02% - 3.70%
Transport – Iron Ore	– Diesel locomotives	0.01	0.51% - 0.56%
Agglomeration including Fines Post-Processing	– Travelling-grate machine (for sintering) – Disc pelletiser or rotary drum for pelletising) – Industrial crushing equipment – Conveyor belts – Industrial screens/sieves	0.06 - 0.09	2.92% - 4.20%
Iron Making	– Blast furnaces	1.85 - 1.91	86.98% - 91.48%
Steelmaking	– Basic oxygen furnace	0.03	1.62% - 1.65%
Shipping	– Bunker fuelled Cape size vessels	0.02	0.99% - 1.01%
Total		**1.99 -2.21**	**100%**

Source: GHD Analysis
*Note: * Drill and blast activities do emit residual emissions; however they are considered negligible in this analysis*

[68] This is also a function of rail distance and diesel consumption for locomotives. See levelised emissions buildup in the value chain model for fossil fuel based steel production.

[69] International Energy Agency, October 2020, *Iron and Steel Technology Roadmap: Towards more sustainable steelmaking*.

Figure 4.4 Total carbon emissions across currently existing steelmaking value chains



Source: GHD Analysis

4.2.2 The carbon intensity of steelmaking

The Carbon Intensity (C.I.) of steelmaking varies across the world and is dependent on the technologies, and the greenhouse gas intensity of the power, used at the steelmaking facility. The C.I. at facilities using EAFs is on average 0.6 tCO_2/tonne of primary steel lower than facilities using BOFs.

In locations such as India and China the C.I. ranges from between 2.4 and 2.8 tCO_2/tonne[70] of primary steel whereas in Brazil the C.I. is 2 tCO_2/tonne of primary steel due to the dominance of hydroelectric power. Moreover, in Mexico, the C.I. is 1.65 tCO_2/tonne[71] of primary steel due to higher EAF capacity.

Australian steelmaker BlueScope[72] has reported the greenhouse gas intensity for their steelmaking facilities was 1.823 tCO_2/tonne of raw steel in 2016, and 1.665 tCO_2 per tonne of raw steel in 2020. In the UK, the C.I. varies between 2.2 and 2.3 tCO_2/tonne of primary steel.[73]

[70] Global Efficiency Intelligence, September 2, 2020, *Cleanest and Dirtiest Countries for Primary Steel Production*.
[71] Global Efficiency Intelligence, September 2, 2020, *Cleanest and Dirtiest Countries for Primary Steel Production*.
[72] BlueScope Sustainability Report 2019/20.
[73] Bernstein, L, Roy, J, Delhotal, K, Harnisch, J, Matsuhashi, R, Price, L, Tanaka, K, Worrell, E, Yamba, F, and Fengqi, Z, 2007, *Climate Change 2007: Working Group III: Mitigation of Climate Change* (Geneva: IPCC). Chapter 7: Industry.

4.2.3 Gangue and the impact for energy use in iron and steelmaking

Even after undergoing processes of beneficiation, commercially valueless impurities known as gangue minerals are still attached to iron ores (refer to Section 3.2.1 for background overview of gangue). Importantly, gangue affects the quality of pre-treated agglomerates such as sinters and pellets, meaning ores with higher amounts of gangue lead to decreased yields and increased production costs, emissions, and waste.

Gangue and other small traces of unwanted metals require removal during the iron and steelmaking processes described in Sections 3.3 and 3.4 above, where it becomes unwanted by-products referred to as slag. Higher levels gangue in the iron ore:

- is directly related to the increase in production of iron and ironmaking slag in the BF and, in the case of HBI can add steelmaking slag, overwhelming the EAF process efficiency.
- increases the reducing agent ratio (coke usage) required and decreases the tapping ratio (pig iron amount) for a typical BF and greatly increases the energy use for EAF steelmaking using HBI.
- invariably increases energy consumption, CO_2 emissions, and iron production costs whilst decreasing the productivity of the ironmaking process.

Studies have shown the additional quantity of coke needed in the BF to account for various levels of gangue can be significant. As an example, an ore product with 5% gangue requires incrementally more coke relative to a product with 2.5% gangue.

This is because the higher the gangue the lower the tapping ratio (pig iron produced) for a typical BF process and therefore more iron ore is required as well as more reducing agent (coke). This ultimately increases the CO_2 emissions per tonne of steel produced.

The overall impacts of gangue reductions on emissions in the context of fossil fuel steelmaking is further explored in Section 7.6.

Market dynamics and attributes 5

Steelmakers face a challenging industrial ecosystem, with low margins and a high exposure to volatile commodity prices at both the supply and output end of their production processes. This section considers several dynamic changes occurring in the global steel industry and the associated market for iron ore and intermediate iron products. This has important implications for Western Australia's current iron ore supply, and the potential future opportunities to supply new iron ore products into emerging Green Steel value chain.

5.1 A long-term perspective on iron and steel demand[74]

Change is inevitable in the steel industry. This will impact Western Australia's existing iron ore industry in a number of ways. Notwithstanding, there is no suggestion steel, or steelmaking, is facing an existential risk due to climate change and the drive to reduce carbon emissions like other carbon-intensive industries and industrial processes. Indeed, quite the opposite is true.

Demand for steel is expected to continue rising in the future, with annual crude steel production approaching 2.3 billion tonnes by 2050, from two billion tonnes in 2022.

The sustained demand is unsurprising given the importance of steel in the modern-day economy. At present, there are no cost competitive substitutes for steel in its many end-use applications, such as construction and manufacturing.

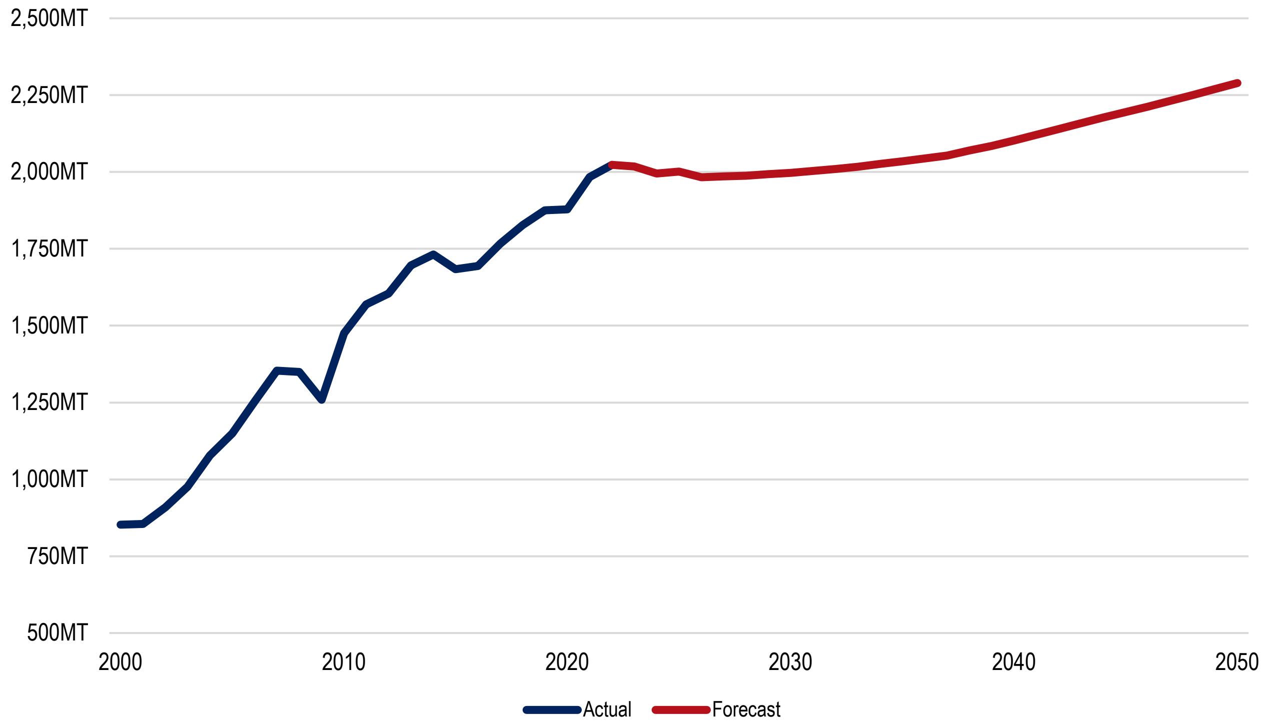
However, the pace of growth is considerably slower compared to historical levels. Over the past decade, steel production has grown by roughly 2.3% on a yearly basis. This is five times greater than the projected growth rate for the next 30 years.

In recent years, the global steel industry has largely benefitted from the economic development in China, which caused a surge in steel demand to fuel its rapid industrialisation.

However, as the Chinese economy matures, demand for steel will begin to tail off, coinciding with China's transition away from manufacturing to a service-oriented economy. The slowdown in Chinese economic growth is projected to dictate the near-term outlook of the global steel industry, as industry experts consider that steel demand may soften until 2026.

[74] ACIL Allen has relied upon a long term outlook publication from data services provider Wood Mackenzie. The below description and discussion is ACIL Allen's interpretation of the outlook and forecast prepared by Wood Mackenzie as provided by MRIWA. Refer Wood Mackenzie disclaimer at the beginning of this report.

Figure 5.1 Global Crude Steel Production, Actual and Forecast, Millions of Tonnes



Source: ACIL Allen Analysis, Wood Mackenzie[75]

In the longer term, China is expected to become a smaller part of the global steel industry from a consumption perspective.

Through to 2050, China's steel production, which predominately serves its domestic market, is forecast to contract by 224 Mtpa, or a decline of around 25%. This trend is not limited to China as many developed economies have already begun this transition, given their earlier economic development timelines.

However, the production of steel in a number of developed economies is forecast to grow over the coming 30 years, on account of the rise of the EAF steelmaking pathway, and the capacity of industry to use recycled steel and intermediate iron products as a feedstock.

Finding 2 The long-term outlook for steel

The long-term outlook for global steel demand is expected to remain robust through to the middle of the century. However, there are a range of scenarios which could eventuate regarding the type of feedstock most in demand, and the production processes used to produce steel, that have several implications for Western Australia's existing iron ore industry.

Moreover, given the size of the investments and the time taken to make investment decisions, there is a need to begin positioning in the short term.

Overall, it is considered likely Western Australian iron ore will remain a valued commodity in the global steel industry through to the middle of the century. However, there are clearly opportunities for development of new kinds of iron ore products to meet the emissions and energy reduction task facing customer countries.

[75] Refer Wood Mackenzie disclaimer at the beginning of this report.

5.2 The outlook for iron ore[76]

There is expected to be a robust demand for steel, and subsequently iron ore, well into the middle of the century. However, this future is not assured, as there is a risk policy actions by international governments drive a future where the transition to net zero emission steelmaking happens more rapidly and suddenly than is expected.

Wood Mackenzie's *Iron Ore Outlook Under Steel's Accelerated Energy Transition Two-Degree Scenario*[77] report, produced following the COP-26 summit in July 2021, provides one perspective of this future. The associated scenario analysis, suggests all of the following must occur for an accelerated transition case to occur in the steel industry:

- Scrap use in steelmaking needs to nearly double.
- DRI production, and use, must more than triple.
- Global average EAF emissions intensity must fall by 70%.
- BF-BOF emissions intensity needs to fall by 30% close to its theoretical minimum.
- 46% of the residual carbon emissions must be captured and stored or used (around 500 Mtpa).

Some of these technological solutions are not yet available to industry in its effort to decarbonise steelmaking despite work underway to achieve them. However, not all are expected to materialise at the same rate, nor contribute to the decarbonisation of steel at the same time.

Notwithstanding, if the above accelerated transition case were to materialise, it would represent a revolution in the market for steelmaking feedstock, which would place Western Australia's industry in a precarious position assuming no change to the current product mix.

5.2.1 Iron ore customers are increasingly demanding higher quality ores

While ore for the BF will remain as the primary source of iron units, the steel industry anticipates a gradual shift in demand towards the use of higher-grade pellet feed DRI. Indeed, although ores for the BF holds a dominant market share of 92% of total ore demand, this is expected to erode to 82% by 2050 as the alternative DRI ore market share grows to 18% in 2050, from 8% in 2022.[78]

This underlies a significant structural shift in the composition of ore-based feedstock as demonstrated in Figures 5.2 and 5.3.

In these circumstances, demand for iron ore fines (the primary product produced in Western Australia, consisting of undersized ore product that must be agglomerated before being fed into an ironmaking process) declines by 43%, and demand for iron ore lump (the secondary product produced in Western Australia, consisting of oversized ore that does not need to be agglomerated before being fed into an ironmaking process) declines by 24.7%. Demand for pelletised ores, the beneficiated product produced without undertaking any ironmaking process, increases by 40.6%.

This highlights the risks posed by the transition to net zero emissions steelmaking for Western Australia and the Commonwealth. While the change would not be expected to really gather pace until after 2030, a decline in the demand for iron ore of this magnitude would present a material, structural change to Western Australia's iron ore industry, and the economy

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[76] ACIL Allen has relied upon a long term outlook publication from data services provider Wood Mackenzie. The below description and discussion is ACIL Allen's interpretation of the outlook and forecast prepared by Wood Mackenzie as provided by MRIWA. Refer Wood Mackenzie disclaimer at the beginning of this report.

[77] Refer Wood Mackenzie disclaimer at the beginning of this report.

[78] Refer Wood Mackenzie disclaimer at the beginning of this report.

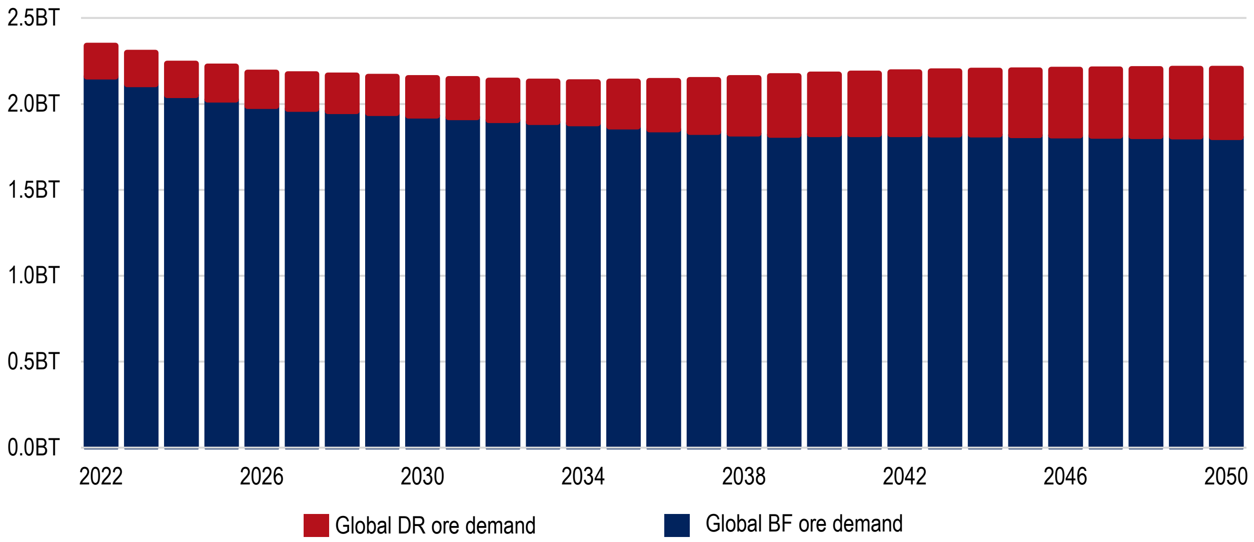
more broadly. The possible impacts of this scenario are explored in Section 8.3.

Ore demand is a proxy to represent industry efforts towards decarbonisation. This is because both are production inputs into separate manufacturing processes.

For instance, BF ore is as the name suggests, used in BFs conventionally powered by fossil fuels. On the other hand, direct reduced ore is increasingly deployed in EAFs, which may be powered by renewable energy.

The increasing uptake of direct reduced ore follows a (somewhat) stepped process, as the surge in demand is most prominent between 2034 and 2039 and will vary by jurisdiction subject to the age of their BFs. This is considered further below in Section 5.4.

Figure 5.2 Relationship between global demand for ores for the BF, and pellet feed for direct reduction



Source: ACIL Allen Analysis from Wood Mackenzie[79]

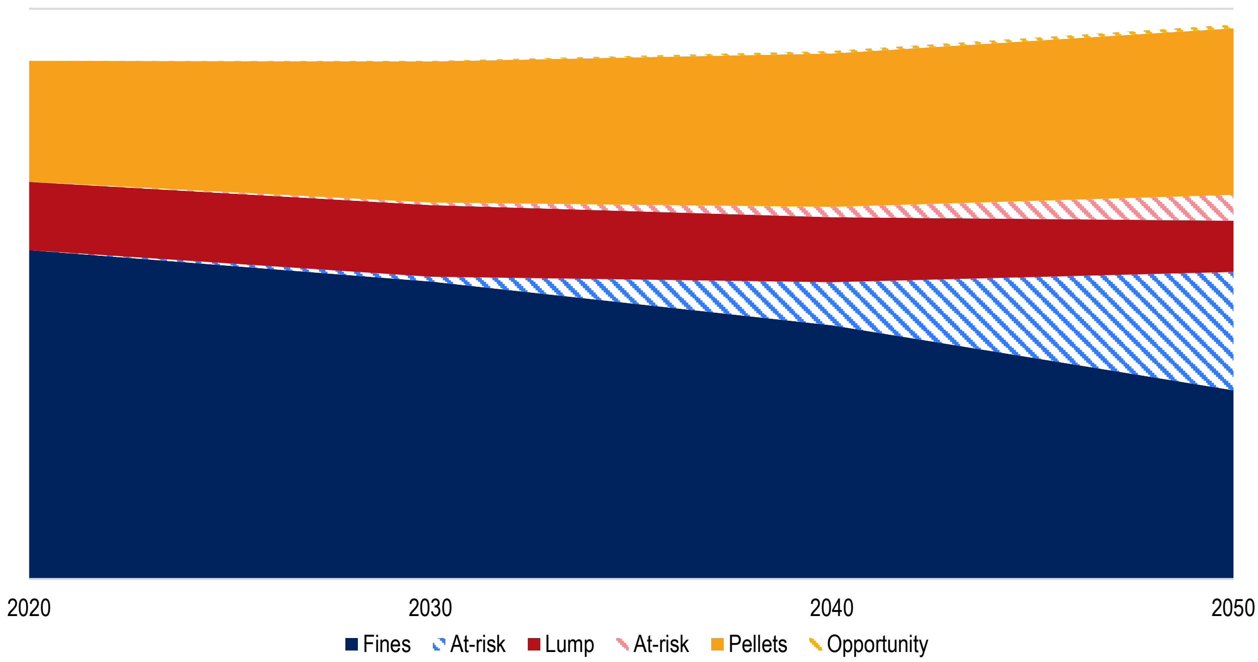
To standardise production inputs, iron ore is graded based on its iron content. Ore with higher concentrations of iron is typically more desirable as it implies lower levels of impurities. Importantly, this means steelmakers will require less energy to process it. Securing higher grade ores enables steelmakers to reduce emissions without significantly altering their production processes.

It follows iron ore with a relatively high grade or with low impurities will become more valuable relative to iron ore with relatively low grade or high impurities.

Steelmakers also prefer high grade ore when it comes to producing premium grade steel. This is because iron ore grade is the major determinant of the quality of the steel product. While it is possible to produce high quality steel with lower iron grade ore, the trade-off is significantly greater energy requirements. The high iron grade ores also tend to have less impurities and trace metals which can affect the final steel product.

[79] Refer Wood Mackenzie disclaimer at the beginning of this report.

Figure 5.3 Global iron ore demand, by product, base case versus accelerated transition scenario (highlighted area = ore consumption at risk by type of ore)



Source: Wood Mackenzie (absolute values removed)[80]

Sinter Fines Basis 65% Fe is the high iron content ore sold to China. It currently commands a price premium compared to the lower concentration alternative. While Figure 5.4 presents a relatively constant price premium, there will likely be greater price divergence over the next 30-years.

As the world progresses towards net zero emissions by 2050, high grade ore will become increasingly sought after due to its lower emissions intensity. Depleting supply of high-grade ore will also contribute to price appreciation, as ore with differing grades cannot be easily substituted.

The additional costs resulting from use of lower grade ores or ores with higher levels of impurities are pushed upstream by BF operators, under the premise they can blend with higher grades ores to offset these extra costs.

Between 2015 and 2020, the average price for a 58% Fe content fines ore was 14.7% below the 62% Fe benchmark price. By contrast, the premium for a 65% Fe content fines ore was 6.8% above the benchmark price (refer to Figure 5.4).[81]

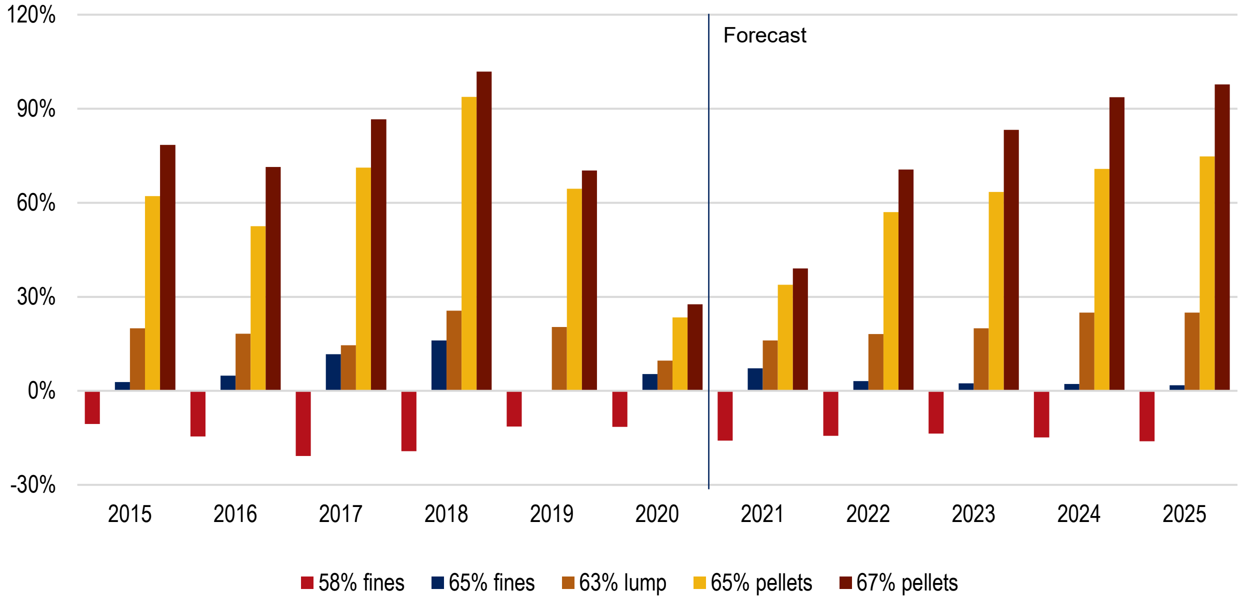
This trend plays out in terms of alternative product types as well. Lump ores have historically attracted a slight premium over higher grade fines (worth 18% against the benchmark) on account of the more limited intermediate sintering processing required for the ore to be used in steelmaking. Similarly, pelletised ore with 65% Fe content or 67% Fe content have attracted substantially higher premiums over 58 to 63% Fe Ores.[82]

[80] Refer Wood Mackenzie disclaimer at the beginning of this report.
[81] ACIL Allen has relied upon a long-term outlook publication from data services provider Wood Mackenzie. The below description and discussion is ACIL Allen's interpretation of the outlook and forecast prepared by Wood Mackenzie as provided by MRIWA. Refer Wood Mackenzie disclaimer at the beginning of this report.
[82] There is no directly available benchmark exclusively for magnetite concentrates, given the limited seaborne trade and fact magnetite mines tend to be part of vertically integrated operations. It can be assumed as price using the 65 daily price index's plus a small premium given the generally high grades and low gangue content.
At times the Fast Market 66% concentrate index is used as a pricing point but suffers from a poor number of transaction points and is only reported weekly. This is because magnetite ores are still subject to some processing prior to being used as a feedstock in steelmaking (such as pelletising).

However, at times of elevated steel prices, and associated increases in iron ore demand, the 'spread' between the high prices for premium products and the lower prices for lesser quality products tends to narrow. This is because steelmakers can look past the additional costs associated with processing lower quality ores due to higher prices and margins for their products.

This phenomenon played out in 2020, when all ore type prices lifted, but the prices for lower grade and benchmark ores increased by a larger nominal amount than higher grade feedstock – leading to a sharp reduction in premiums for higher grade products.

Figure 5.4 Price penalties and premia for iron ore grade and product type, US$/tonne FOB, actual & forecast



Source: ACIL Allen Analysis, from World Steel Association, Wood Mackenzie[83]

As indicated in Figure 5.4 the spread between lower and higher-grade product prices is expected to widen in the future.

This is because an increasing proportion of Western Australian hematite direct shipping ores are in the 'low' grade category, with grades below even the low benchmark. This increasing supply will further amplify the discount in any softer iron ore market demand conditions.

However, it also provides a strong incentive for producers to pursue opportunities to improve the average grade of their product, through beneficiation or investment in new kinds of steelmaking feedstock products.

In particular, the increasing drive towards quality ores is likely to spur a renewed interest in magnetite iron ore projects throughout Western Australia.

[83] Refer Wood Mackenzie disclaimer at the beginning of this report.

Finding 3 Increasing focus on the quality of ore used by steelmakers is driving change

There is increasing focus on the quality of iron ore feedstock being used by steelmakers. This is increasingly observed through the price penalties received on lower grade ores, which has implications for Western Australia.

This provides a strong incentive for iron ore producers to pursue opportunities to improve the average grade of their product, through beneficiation, or investment in new kinds of steelmaking feedstock products, but also a renewed interest in magnetite iron ore projects throughout Western Australia.

5.3 There are presently limited pricing benchmarks for intermediate iron products

One of the short-term challenges in the market for intermediate iron products, such as pig iron and HBI, is the lack of a recognised pricing benchmark for traded products.[84]

The lack of internationally recognised benchmark prices for iron products reflects the limited development of the market for these products as internationally traded commodities, given most intermediate iron products presently produced are part of vertically integrated supply chains.

Some metals data providers produce estimates of premiums based on a reference against iron ore or steel scrap markets, taking a similar approach to penalties and premia for higher or lower grades of iron ore.

Finding 4 Lack of liquid markets and benchmark prices for intermediate iron products

There is currently limited or no benchmark products and associated prices available for intermediate iron products such as pig iron, HBI and even for iron ore pellet indexes they are often referenced to local sources of pellets which is not a true benchmark.

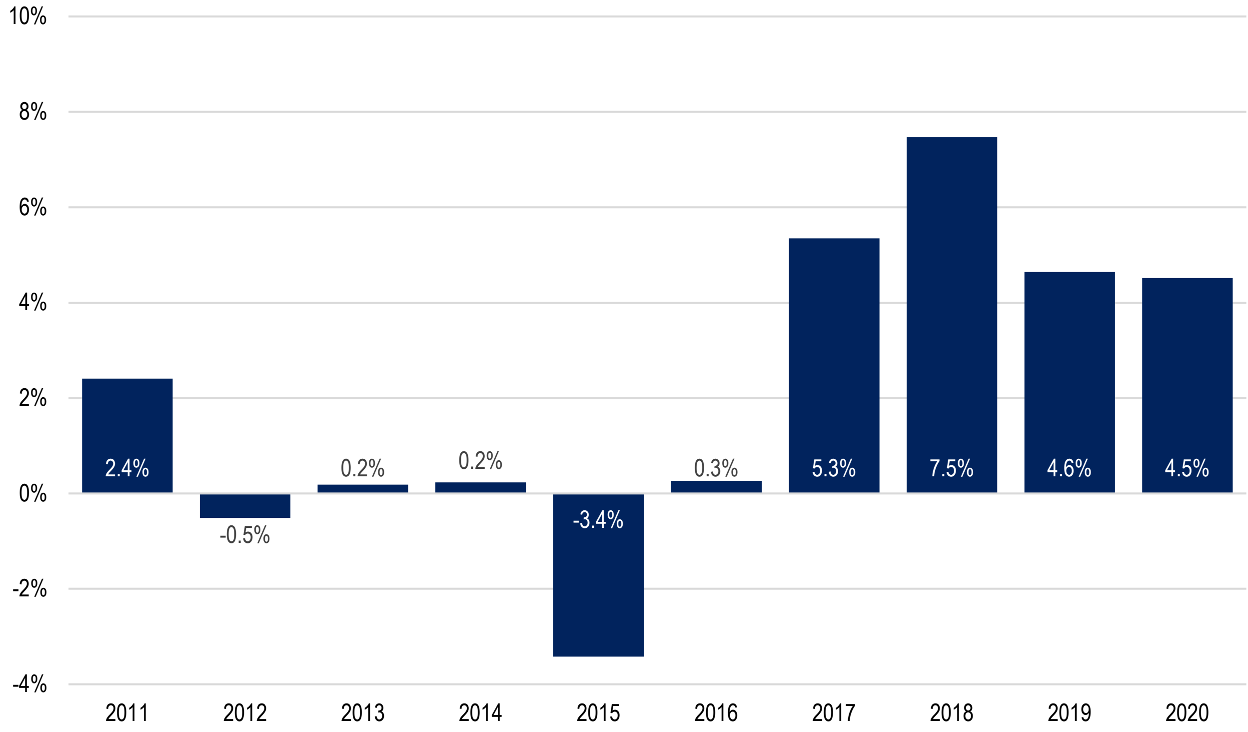
This creates complexity for project development and project economic assessment as there is no commonly understood definition of products, of benchmark attributes or product quality, or market worth. The lack of benchmark products and associated prices contrasts strongly with iron ore where there is an abundance of these.

[84] ACIL Allen engaged with data providers S&P Platts and Wood Mackenzie during the development of this report. The providers indicated there was no benchmark for HBI or pig iron presently prepared to the same standard or regularity of reporting as benchmarks for iron ore, coking coal, and steel products. Refer Wood Mackenzie disclaimer at the beginning of this report.

5.4 Steelmakers operate on substantially thinner margins than input providers

The average Earnings Before Interest, Tax, Depreciation and Ammortisation (EBITDA), or gross margin, for steelmakers over the past 20 years has been 13.6%.[85] Gross margins in China's steel industry have been substantially lower according to China's CEIC statistics agency, averaging just 2.4% over the past decade. In some years, China's steel industry operated at an operating loss in the aggregate, with extraordinarily thin margins between 2012 and 2016. This is demonstrated in Figure 5.5.[86]

Figure 5.5 China steel industry aggregate profit margin, % of gross sales revenue, by year



Source: CEIC. 2022. China Steel Industry Statistic Aggregates: Sales and Gross Operating Profit, 2011-2020

This level of profitability is broadly consistent with academic research and other sources, noting publicly available data on this issue is limited. There are examples of steelmakers in advanced economies delivering larger margins on sales: US Steel delivered an EBITDA margin of 28% in the 2021 calendar year, while ArcelorMittal generated a 22.1% EBITDA margin.[87]

Gross margins do not reflect the ability of a project to deliver a return on capital, or to repay the owners of capital.

All things being equal, this relatively low level of gross margin suggests steelmaking is a challenging industry to make a return on investment.

[85] OECD. 2021. *OECD Steel Market Developments Q4 2021*. Accessed online at http://www.oecd.org/

[86] CEIC. 2022. *China Steel Industry Statistic Aggregates: Sales and Gross Operating Profit, 2011-2020*. Accessed online at http://www.ceicdata.com/en/

[87] Relevant Annual Reports. It is worth noting both companies had delivered negative EBITDA margins at least once in the last three financial years. AccelorMittal is also a more diversified business than a typical steelmaker, operating iron ore mines, ports and other assets alongside steelmaking.

In stark contrast, iron ore miners regularly report gross margins of many multiples of the levels achieved by steelmakers.

Western Australia's three largest iron ore miners have delivered an average EBITDA margin on sales of 61.1% over the a six year period where data on Western Australia-specific operations is available.[88] At this level of profitability, a Western Australian iron ore miner is delivering $61 of gross profit for every $100 worth of iron ore sold.

Furthermore, the "capital intensity" of iron ore is substantially lower than in the steel industry. According to BHP, the capital cost of a typical four million tonne per annum integrated steelmaking facility is US$4 billion.[89] The capital cost to develop a greenfield direct shipping ore mine to service the iron ore requirements of a steelmaking facility of this size – approximately 7.7 Mtpa, according to GHD's value chain model – would be approximately US$340 million.[90]

In effect, an iron ore mine can deliver a substantially higher rate of gross profit for a much smaller initial capital outlay**.**

Using the values above, ACIL Allen estimates a gross "return on invested capital" for an integrated steelmaking facility running at 95% capacity utilisation with an EBITDA margin of 13.6% would be US$615.6 million per annum, or 15.4% return on invested capital. By contrast, the margin for the iron ore mine required to service this steelmaking facility, with an EBITDA margin of 61.1% would be $634.7 million per annum, or a 169.2% return on invested capital. The returns from the iron ore mine are an order of magnitude larger than the steelmaking facility.

Table 5.1 Return on Invested Capital Analysis, Steel vs Iron Ore

	Steelmaking facility	Iron ore mine
Capital cost of facility	US$4,000m	US$340m
Production capacity	4 Mtpa	7.7 Mtpa
Modelled utilisation	95%	95%
Product sales price	US$1,000/tonne	US$142/tonne
Gross revenue	US$3,800m	US$1,038m
EBITDA margin (as per above analysis)	16.2%	61.1%
Annual gross profit / return	US$615.6m	US$634.7m
Gross return on invested capital (%)	**15.4%**	**169.2%**

Source: ACIL Allen Analysis

[88] *Consecutive BHP, Rio Tinto and FMG Annual Reports, 2016 to 2021.* Underlying EBITDA is a common metric which measures the gross operating costs required to produce and sell iron ore at the point of export, inclusive of administrative costs. As such it is comparable to the EBITDA values derived for steelmakers.

[89] BHP, 2020, *Pathways to decarbonisation episode two: steelmaking technology*

[90] Estimate derived using GHD's value chain model, converted to US dollars at a rate of $1 = US$0.72.

Finding 5 Economics of steelmaking is significantly more challenging than iron ore mining

The market for steel is fundamentally different to iron ore. While both industries are highly capital intensive, they have vastly different rates of profit. It is estimated the gross margin for steelmakers over the past 20 years has been 13.6%, which is in stark contrast to iron ore miners which regularly report gross margins of many multiples of the levels achieved by steelmakers. Western Australia's three largest iron ore miners have delivered an average gross margin on sales of 61.1% over the past six years, where data on Western Australia-specific operations is available.

Given the capital intensity of iron ore is substantially lower than in the steel industry, an iron ore mine can deliver a substantially higher rate of gross profit for a much smaller initial capital outlay.

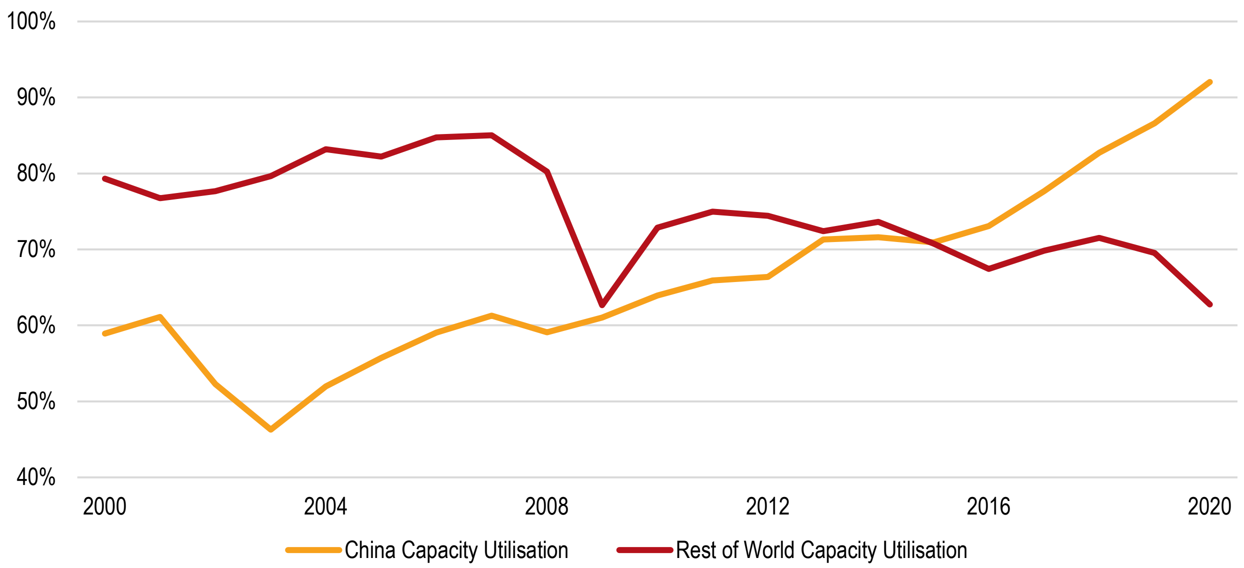
5.5 There is significant overcapacity in the global steel industry

According to the OECD, the global steel industry has operated at around 75% of its potential productive capacity for the past five years, with capacity utilisation increasing from less than 70% during the first half of the 2010s.[91]

High levels of underutilisation existed in China in particular, owing to the rapid build-up in steel production and consumption over the 2000s and 2010s. The Chinese Government introduced a "capacity swap" scheme in 2015 and has made a number of changes to it in recent years, in an effort to slow the growth and eventually reduce the installed capacity of steelmaking infrastructure in the country.[92]

This overcapacity creates challenges for new entrants into the steelmaking industry, due to the high capital costs associated with establishing new steelmaking capacity. The current level of overcapacity in the global steel industry provides, all things being equal, a "surge" production potential of 586 MT with its capital cost already sunk.

Figure 5.6 Global steelmaking production versus steelmaking capacity, % of capacity, China vs Rest of World



Source: OECD. 2021. OECD Steel Market Developments Q4 2021

Finding 6 Overcapacity in steelmaking

The current glut of capacity in global steelmaking results in a situation where it is challenging for new entrants to compete on price and deliver a return on capital to justify a new investment. This is because existing entrants have sunk capital and significant incentives to increase plant utilisation.

[91] OECD. 2022. *Latest developments in steelmaking capacity: 2021 report*. Accessed online at http://www.oecd.org/

[92] Ibid.

5.6 Age of steelmaking infrastructure

Traditional steel production assets (i.e., integrated BFs) are a large, expensive, and complex class of infrastructure. Steelmakers face a challenging industrial ecosystem, with low margins and a high exposure to volatile commodity prices at both the supply and output end of their production processes. A typical steel producer today will need to incur large capital costs to establish a pure hydrogen-based steel production facility, on top of managing hydrogen transport and storage requirements.

With most of global steel production concentrated in developing nations, decarbonising the steel industry is expected to be a long-term process.

Given the long useful life of BFs, developing countries are now faced with the difficult decision to either: retire BFs early to transition to greener production methods, or extract the normal lifetime from existing facilities.

A recent report by BHP estimates the full asset replacement cost for a typical traditional integrated ironmaking and steelmaking facility is roughly US$4 billion[93]. This compares with the cost of relining a BF to extend its useful life, which range from US$50 million and US$200 million and is only required every 15 years.

As such, it is simply uneconomical to overhaul existing facilities unless they are at the end of their service life.

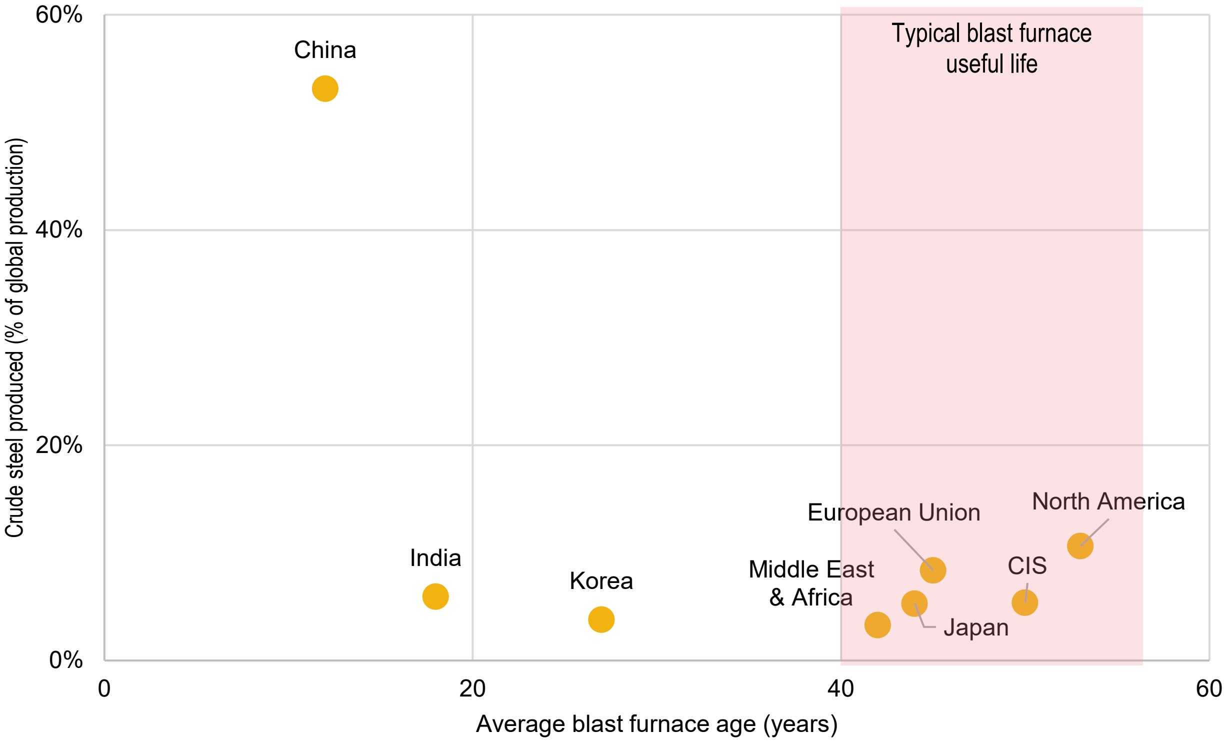
Steelmakers in Western countries, such as North America and Europe, are in an economic "sweet spot" as it relates to future decisions to invest in steelmaking capacity. By contrast, the BF fleet in China is only 12 years old on average, and India and South Korea have similarly young fleets.

Finding 7 Age of BFs will influence rate of change

Given the long useful life of BFs, countries will progressively face a decision to either retire BFs early to transition to greener production methods, or operate existing carbon-intensive steelmaking infrastructure for a regular life, and focus on other strategies to reduce emissions such as carbon capture use and storage.

[93] BHP, 2020, Pathways to decarbonisation episode two: steelmaking technology

Figure 5.7 Average BF age and share of global crude steel production



Source: BHP Pathways to decarbonisation episode two summary

5.7 Likelihood of a Green Steel market

The likelihood of Green Steel market development varies across the top iron and steel producing countries and will be driven by respective decarbonisation measures and their impacts. A summary of the various approaches being taken globally is summarised in Table 5.1.

With progressive government policies and several pilot projects in operation the EU presents the best opportunity for Green Steel in the short term.

With many of the BFs in Europe and North America approaching the end of their useful life by 2040, there will likely be heightened interest to switch to EAF-based steelmaking over this period.

In Japan, both government and industry are intent on decarbonising, and the Green Steel industry presents an opportunity to maintain its economic competitiveness through diversification. However, Japan is also resource constrained and will require a substantial amount of its hydrogen needs to be imported. Securing these supply chains is heavily reliant on other countries progressing in green hydrogen production.

China is increasingly intent on adaptation to maintain its dominance in supplying domestic and Western steel needs and have witnessed investments in decarbonisation. However, the rate of this adaptation will be the major risk for the development of a Green Steel market in China, given it has less incentive (in addition to major dependence on continued operation) to replace its relatively new BF-BOF infrastructure.

Given the young BF fleet in China and India, it is unsurprising the ore for the BF is projected to retain its dominant market share in 2050 as it is simply uneconomical to prematurely retire these furnaces in the short term.

Other countries in Asia, including South Korea, also have decarbonisation plans but have younger blast furnaces reducing the imperative for retiring these assets.

Importantly, this suggests there will likely be divergence in decarbonisation approaches over the coming years. The working hypothesis is developed nations will focus on replacing their existing production assets, while emerging economies will emphasise retrofitting existing facilities with carbon capture use and storage (CCUS) technologies.

Table 5.1 Summary of decarbonisation measures and their impacts

Signal	Rationale
Net zero targets	The steel industry is the largest heavy industry contributor to CO_2 emissions. Net zero targets are likely to prompt emissions reductions and drive the emergence of a Green Steel market. The more aspirational and relevant the target, the greater the likelihood of a Green Steel market emerging.[94]
Previous decarbonisation efforts	The scale and success of previous decarbonisation efforts will convey the level of certainty around achieving future decarbonisation targets. An example may include successfully meeting past industrial CO_2 emission reductions. Previous progress aimed to lower emissions in steelmaking provides a stronger indication – e.g., decarbonisation using CCUS/hydrogen vs. general efficiency gains in BOF operation.
Decarbonisation market mechanisms	Implemented and effective market mechanisms demonstrate a commitment to decarbonisation beyond signalling and intent. For example, an emissions trading scheme (ETS), through extension of the net zero policy, would encourage Green Steel markets to grow by providing the appropriate financial incentives.
Renewable Energy Targets (RET)	The emergence of a Green Steel market is highly dependent on the penetration and cost of variable renewable energy (VRE). Aspirational targets demonstrate a commitment to overcoming this barrier. The more aspirational and relevant the targets, the greater likelihood of Green Steel markets emerging.
Renewable energy, meeting previous targets	The scale and success of previous renewable progress will convey the level of certainty around achieving future RET. An example may include successfully meeting previous solar or wind growth targets. Previous progress that aligns with specific barriers to Green Steel emergence provides a stronger indication (i.e., growth of solar adoption and hydrogen systems).
Renewable Energy Market Mechanisms	Implemented and effective market mechanisms demonstrate a commitment to achieving RET beyond just policy. For example, direct subsidies would support the drive to make renewable electric arc furnace pathways competitive.
Hydrogen policy	A hydrogen policy demonstrates future commitment to developing the technical and commercial resources and infrastructure needed for Green Steel markets to emerge.
Hydrogen strategy	A hydrogen strategy demonstrates further and present commitment to development of the technical and commercial development of resources and infrastructure needed for Green Steel markets to emerge.
Hydrogen investment or implementation; R&D, funding, and activities (into Green Steel, industrial hydrogen, or decarbonisation in general).	Direct investment or implementation of hydrogen projects is a strong indicator for technical and commercial development of resources and infrastructure needed for Green Steel market emergence. Examples of this may include development of hydrogen production, storage, or transmission infrastructure. The more relevance to the steel industry and decarbonisation of heavy industry the stronger indicator for an emerging Green Steel market.
Pilot, demonstration, or commercial scale Green Steel production	Evidence of actual Green Steel operations is the strongest indicator for emergence of a nation or region's Green Steel industry and market.

Source: GHD Analysis
Notes:
**Enabler for other methods of decarbonisation*
***This maximum is only achieved if all BF feedstock produced with fossil-fuel energy (sinter and lump) are fully replaced with Green Iron from HBI*
****Proportional to availability of steel*

[94] The IEA sustainable development scenario demonstrates 34% cumulative direct emission reductions by between 2020 and 2050 via pursuing of green steel market strategies.

5.8 Scrap steel is increasingly used as a feedstock in primary steel production

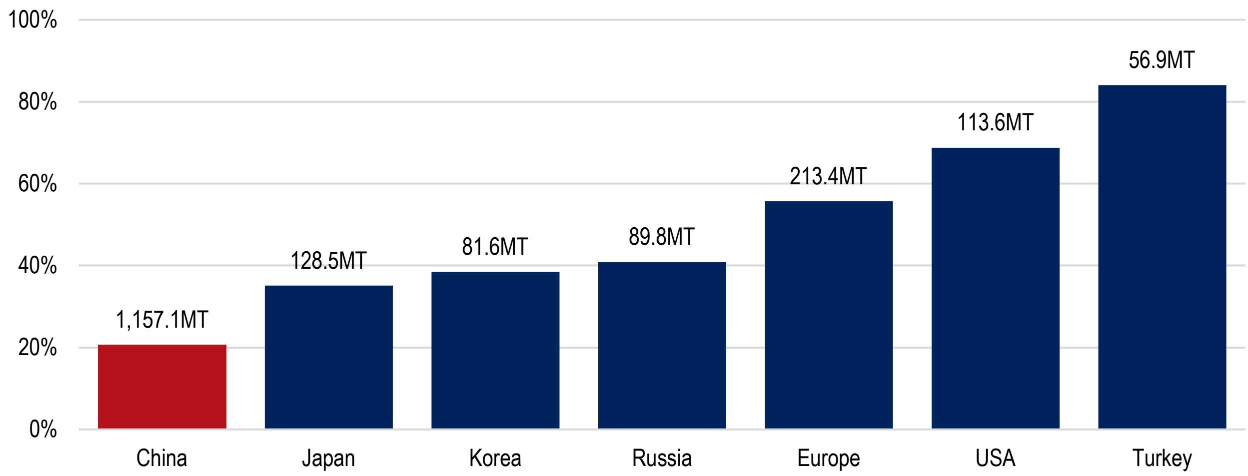
The final market trend considered is the rising use of recycled steel as a feedstock in primary steel production. Carbon steel can be utilised indefinitely once it is created. This, plus the rising prevalence of EAF steelmaking (which still requires some form of carbon as a feedstock alongside iron), is leading to strong growth in the rates of steel scrap recycling in the production of steel.

Use of recycled steel in the steelmaking process has increased by 28% between 2013 and 2020, or more than double the rate of overall primary steel production (13.3%) over the same period, with an estimated 220 MT of scrap steel used in China in 2020, up from 85.7 MT in 2013.[95][96]

Rates of steel recycling versus primary steel production range from 20% in China – on account of the country's established BF-based steelmaking infrastructure and associated industrial ecosystem – up to 84% in Turkey, the world's eighth largest steelmaking country. Turkey's high rates of scrap steel recycling are due to the utilisation of EAF technologies.[97]

Over time, these trends are expected to continue, with use of EAF steelmaking and the sheer increase in availability of scrap steel as a feedstock due to the growth in steel production and consumption over the past two decades. This is particularly true for China, which has been the largest source of growth in steel production, steel consumption, and steel production capacity over the past 20 years.

Figure 5.8 Use of scrap steel (scrap steel consumption as share of total primary steel production), major steelmaking countries, by percentage of recycling (value = total steelmaking capacity in 2020)



Source: BIR World Steel Recycling in Figures 2020

Finding 8 Increasing potential for scrap steel will drive change in the industry

Future investment in EAF steelmaking is expected due to the sheer increase in availability of scrap steel as a feedstock from the growth in steel production; a lower hurdle of entry to construct a production facility such as a 'close-to-source' modular EAF; and consumption over the past two decades.

[95] *BIR World Steel Recycling in Figures 2020*
[96] BHP, 2020, *Pathways to decarbonisation episode two: steelmaking technology*
[97] *BIR World Steel Recycling in Figures 2020s*

Part II: Seizing the Opportunity

Decarbonising the iron ore to steelmaking value chain

6

This section provides an overview of decarbonisation in the iron and steelmaking process. It first provides a working definition of 'Green Steel', then explores the technology required to produce Green Steel, followed by discussions on the use of hydrogen, and low carbon inputs and renewable energy.

6.1 Defining Green Steel

The term 'Green Steel' typically describes any process whereby steel is produced with renewable energy sources, i.e., with a reduced use or elimination of fossil fuels such as coking coal, oil, diesel, or natural gas.

For the purposes of this study, and to explore as many opportunities as possible for Western Australia, a broader definition is being used to include any opportunity to decarbonise (either using lower carbon sources or renewables) any stage of the entire iron ore mining to steelmaking process.

6.1.1 Use of technology to reduce steelmaking emissions

Among heavy industries, steelmaking is ranked second last to achieve the target of carbon neutrality, only ahead of the petrochemicals industry.[98] Without significant investment the steel industry will inevitably fail to reduce carbon emissions materially under the status quo.

Recognising the challenges to decarbonising existing production, hydrogen-based steelmaking has emerged as a potential pathway to producing Green Steel. Integrating hydrogen into steel production is technically possible, and with continual research and development, can reduce emissions in a number of ways, including hydrogen being used:

- in BFs, which minimises coal consumption by improving the efficiency of furnaces. However, this does not result in entirely Green Steel as coking coal is still required for the reduction process.
- as an alternative reductant to produce DRI, which will then be further processed into steel using an EAF.

  This is the ideal solution, assuming "green hydrogen" is used, the EAF process is powered by renewable electricity and the small amount of carbon which is still used are from fully green sources.

This integration, along with other methods for lowering emissions in steelmaking, is further discussed in Section 6.3.

[98] McKinsey Global Institute. 2022. *The net-zero transition: What it would cost, what it could bring*. Accessed online at: http://www.mckinsey.com/.

While it is possible to produce green hydrogen today, it is not yet available at a commercial scale.

A typical steel producer today will need to incur large capital costs to establish a pure hydrogen-based steel production facility, on top of managing hydrogen transport and storage requirements.

Currently, most of the global hydrogen production is "grey hydrogen", which is produced via the steam methane reforming process. Importantly, this process releases carbon dioxide as a by-product; hence, using grey hydrogen will not result in carbon-neutral steel. Alternatively, the prospects of "blue hydrogen" are increasingly being explored, though its success is largely conditional on innovations to CCUS technologies.

At present, there is an economic argument against using green hydrogen, as it is simply not price competitive relative to grey hydrogen. Historically, natural gas used for grey hydrogen production is cheaper than the renewable electricity for powering green hydrogen production.

That said, forward estimates released by the Hydrogen Council, indicate green hydrogen may achieve price parity by 2030[99], should the cost of renewable electricity and electrolysers continue to fall. With limited decarbonisation benefits to using grey hydrogen, hydrogen use has yet to gain traction in the steel industry.

More broadly, hydrogen-based steel is only economically viable if depreciation is not factored into asset renewal decisions, as traditional steel production assets (i.e., integrated plants) have largely been written off.

In its assessment of European steelmaking, McKinsey[100] anticipates the transition to pure hydrogen-based steel production will only be sensible between 2030 and 2040, while acknowledging the prospects of condensed timelines, given the large-scale innovation to produce green hydrogen in recent years.

Finding 9 The decarbonisation of the global steel industry is a significant challenge

The global steel industry is one of the largest carbon emitters in the world, but also one of the hardest to abate. Recognising the challenges to decarbonising existing production, hydrogen-based steelmaking has emerged as a potential pathway to producing Green Steel. However, the production of green hydrogen needed for Green Steel is not yet available at a commercial scale.

6.1.2 Technology required for the Green Steel challenge

At present, most stages of the iron ore mining to steelmaking value chain use technology and equipment run on fossil fuels. However, there are opportunities to use new technologies, which generate low or no carbon emissions, at some or all these stages, subject to technological readiness and cost constraints.

Indeed, to lower the carbon emissions of the steel industry, there are many technological developments of varying maturity that can work to replace traditional techniques with low or no emission alternatives.

A summary of the technology required to replace traditional high-emission methods, at the different stages of the value chain, is then outlined in Table 6.1.[101]

[99] Hydrogen for Net-Zero A critical cost-competitive energy vector November 2021, Hydrogen Council Intelligence. http://hydrogencouncil.com

[100] McKinsey Global Institute. 2022. *The net-zero transition: What it would cost, what it could bring*. Accessed online at: http://www.mckinsey.com/.

[101] This subsection only lists low or no emission technologies pertinent to different stages of the steel value chain.

Table 6.1 Summary of New Technology Requirements

Technology	Current Technology	Low Emission New Technology	Maturity of New Technology
Drill and Blast	Diesel power drill rigs Explosives derived from fossil fuels	Electric of H_2 drill rigs Explosives from green ammonia	**High** e.g. Komatsu,[102] Sandvik,[103] and Liebherr.[104]
Excavate and Haul	Fossil fuel (i.e., diesel) powered: Excavators, Face shovels, Front end loaders Haul trucks.	Battery electric or hydrogen-electric vehicles.	**High** e.g. Komatsu[105]and CAT[106] currently sell electric rope (or face) shovels BHP, Rio Tinto, and Vale 'to develop new concepts for electric haul trucks Anglo American develop a hydrogen mining truck.
Crushing and Screening	Industrial crushing Heavy grinding mills for magnetite production.	Current equipment, powered instead by renewable energy.	**High**. Most company have electric powered screens. Can be changed to renewables with no change in equipment
Beneficiation	Screens/sieves Beneficiation equipment specific to the processes employed (such as gravity, magnetic, or floatation separation).	Current equipment, powered instead by renewable energy.	**High**. Most company have electric powered screens. Can be changed to renewables with no change in equipment
Fines Post Processing	Grinding using dry ball mill or high pressure rolls.	Newer more efficient grinding technologies e.g. stirred milling, high pressure rolls	**Medium** (High 2050 for Pilbara)
Agglomeration[107]	Travelling grate sintering, disc or rotary drum pelletiser	Hydrogen or biofuels as a fuel source or extruded pellets with binders	**Low.** E.g. Swiss company Ferrexpo is currently electrifying its pellet facilities.[108]
Iron making	Blast furnaces (BF), Direct reduced iron (DRI) techniques employing fossil fuels such as coking coal	Fluidised bed using fine ore or/ shaft furnace using Green Pellets and hydrogen to make HBI	**Low. (**2050: High). There are only a few operational facilities globally using more than 30% green hydrogen e.g. HYBRIT[109].
Steelmaking	BOF, EAF powered by non-renewable source.	EAF powered by renewable energy. HBI used in EAF or a smelter	**Medium**. (2050: High). e.g. HYBRIT facility in Sweden (which is fed with green DRI),[110] and CMC's mill in Mesa, Arizona.[111]
Transport and Shipping	Diesel locomotives Bunker fuelled Cape size vessels.	Electric or hydrogen locomotives Ammonia fuelled Cape size vessels.	**Low** (expected high) e.g. Rio Tinto has purchased four 7MWh FLXdrive battery-electric locomotives from Wabtec Corporation, to be trailed in early 2024.[112] FFI have committed to convert the MMA Leveque, a 75m vessel to run on green ammonia by end of 2022[113]

Source: GHD Analysis

[102] Komatsu, n.d., *P&H 77XR Blasthole Drill*.
[103] Sandvik, n.d., *SANDVIK 1190E Electric Rotary Blasthole Drill*.
[104] Liebherr, n.d., *LB 16 unplugged*.
[105] Komatsu, n.d., *Electric rope shovels*.
[106] CAT, n.d., *Electric rope shovels*.
[107] Only pelletising has been considered in this study, rather than sintering, for the following reasons:
- Sinter process burns coke (reliant on fossil fuels), cannot eliminate emissions,
- Sinter product cannot be transported easily (it is weak and falls apart),
- Pellets are a superior feedstock (increased productivity in ironmaking processes),
- Pellets are compatible with shaft-based gas reduction processes (i.e., Midrex), unlike sinter,
- Pelletising can accommodate very fine particulate agglomeration.

[108] Gleeson, D, 2020, 'North sets Ferrexpo on a course for 'carbon neutrality'' *International Mining*.
[109] Soderpalm, H, 2021, 'Sweden's HYBRIT delivers world's first fossil-free steel', *Reuters*.
[110] Soderpalm, H, 2021, 'Sweden's HYBRIT delivers world's first fossil-free steel', *Reuters*.
[111] England, R, 2021, 'Solar to power CMC's new Arizona mill' *Fastmarkets*.
[112] Wabtec Corporation, 2020, *Rio Tinto Orders Wabtec FLXdrive Battery Locomotives to Reduce Emissions*.
[113] Fortescue Future Industries calls for net zero target for shipping by 2040 and announced a green ship at sea in 2022. Source: FFI, 2021, *Fortescue Future Industries calls for net zero target for shipping by 2040 and announced a green ship at sea in 2022*.

6.2 Use of green hydrogen in iron and steelmaking

The cycle for Green Steel production starts at the mine where iron ore is produced. Extraction, haulage, and processing steps, such as beneficiation and pelletising, can all use renewable energy (such as solar photovoltaic (PV), wind, or hydroelectric) or carbon neutral fuels such as green hydrogen and biomass.

New low carbon or carbon free technologies are emerging for steelmaking which will reduce the carbon emissions currently associated with traditional steelmaking processes. One such technology is based on the use of green hydrogen as a reductant with iron ore to produce DRI, which can then be pressed into HBI. HBI is further processed in an EAF, where it is typically mixed with scrap metal and additives, to produce liquid steel that can be cast as slabs.

Among the renewable/carbon neutral options available, green hydrogen stands to be the most likely option to decarbonise the steelmaking process and have the best prospects for Western Australia due to an abundant source of wind and solar resources, and a supportive government with a comprehensive Western Australian Renewable Hydrogen Roadmap.

As a summary of what is possible and what is being modelled in this work, a high-level process flow diagram of the green hydrogen Green Steelmaking process is provided in Figure 6.1.

Renewable power generated by solar, wind, or hydroelectric sources can be used to provide sufficient power to an electrolyser plant, where demineralised water is split into oxygen and commercially useful hydrogen. The electrolyser plant can be based on either alkaline or polymer electrolyte membrane (PEM) technology.[114]

Since solar PV and wind are not a reliable source of uninterrupted power, a storage facility is required to store the sufficient power needed to operate an EAF plant on a 24/7 basis.

A battery energy storage system (BESS) can be utilised for this purpose. However, if a storage system such as an adiabatic compressed air storage (ACAS) system is implemented, it is possible to provide all electrical power to the site inclusive of power required by the EAF. This eliminates the need for a separate hydrogen fuelled power plant.

In the Green Steelmaking process, as depicted in Figure 6.1, hydrogen produced by the electrolyser plant will be compressed and stored in a hydrogen storage tube bank at the steelmaking plant. To charge the hydrogen shaft, hydrogen is transferred from the storage facility through the condenser, where it is heated by the excess return of warm hydrogen from the shaft. More than the required quantity of hydrogen is sent to the lower section of the shaft as a reductant and excess hydrogen, containing hydrogen and water vapour, is removed from the upper section of the shaft, and is sent to a condenser.

In the condenser, water vapour in the excess return hydrogen stream is condensed and sent to the electrolyser plant where it is combined with make-up demineralised water before being delivered to the electrolysers. Dry excess return hydrogen from the condenser is delivered from the main hydrogen feed line to the shaft, where it is mixed with a new stream of hydrogen. From this point the combined hydrogen stream is delivered to a heat exchanger, where the temperature of hydrogen is raised to approximately 800°C.

Heat for this process is recovered from the heat in flue gas steams from the power generation plant and the EAF. In addition to these heat streams, a duct burner firing hydrogen will be used to raise the temperature of hydrogen, used as a reductant to the shaft, to the desired temperature. The rate of hydrogen use in this process will be approximately 51kg hydrogen/tonne steel produced[115].

[114] The efficiency of alkaline technology is between 60 and 62%, whereas for PEM an efficiency of approximately 65% can be expected. This level of efficiency is projected to improve as more PEM electrolysers are built.

[115] *Assessment of hydrogen direct reduction for fossil free steelmaking*, Valentin Vogl, Max Åhman, Lars J. Nilsson, March 2018, Department of Environmental and Energy Systems Studies, Lund University, Box 118, SE-221 00 Lund, Sweden.

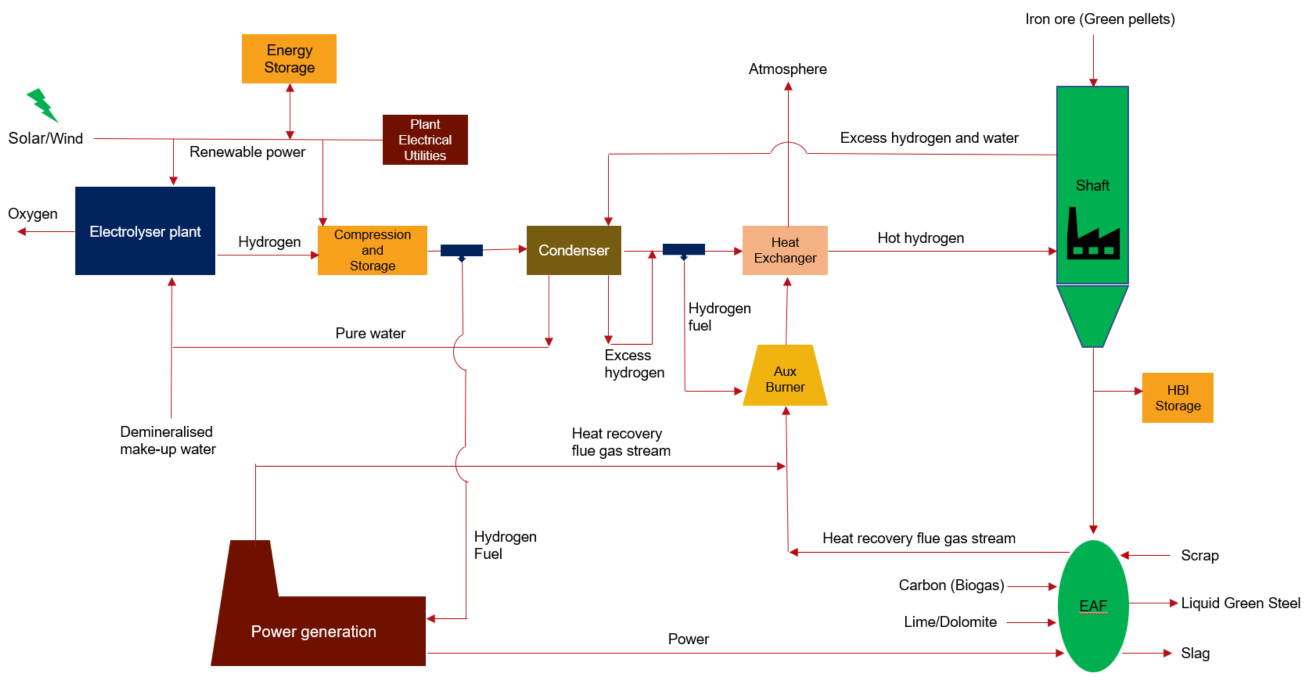
Adoption of hydrogen in the DRI process is the preferable route for decarbonisation, although in many countries most of the production is from BF-BOF, and steps can be taken to decarbonise this pathway also. Adoption of hydrogen as a fuel source and replacement reductant in this process face several challenges to implementation.

In BFs there is a continuous process of heating, reduction and melting and coke supports each of these as the reducing agent, source of heat, structural support, and ventilation for flow gases and as energy source for downstream steel processing.

Replacing coke with hydrogen reduces this operability. Moreover, a carbon source is required to make the steel and so options such as CCUS will be required to capture the outstanding emissions. The COURSE50 project in Japan is the furthest progressed demonstration of this for decarbonised BF-BOF pathway. The project follows the traditional BF-BOF process but with an increased hydrogen to coke ratio[116] and with a CCUS process and is known as the Energy Saving CO_2 Absorption Process (ESCAP).[117]

Similar challenges occur in the DRI-EAF process with increased hydrogen use leading to the requirement for higher energy input, the preheating of hydrogen before injection and inclusion of CCUS for remanent carbon emissions. The Hybrit project in Sweden is the most progressed example of a green DRI-EAF pathway with commercial operation being predicted for 2026.[118]

Figure 6.1 Representation of a hydrogen-based steelmaking process



Source: GHD Analysis

[116] COURSE50: CO_2 Ultimate Reduction System for Cool Earth 50 Project.
[117] ESCAP Technology developed under the NEDO-sponsored research project COURSE50. Source: Nippon Steel Engineering, n.d., *Energy-Saving CO_2 Absorption Process (ESCAP™).*
[118] The first fossil free steel production by 2026. Source: HYBRIT, n.d., *A fossil-free future*.

6.2.1 Energy use

The energy consumption of the hydrogen shaft steelmaking process is reported to be 3.48 megawatt hour per tonne (MWh/tonne of steel). [119] This is as opposed to a similar rated BF that consumes 3.68 megawatt hour per tonne (MWh/tonne steel) mainly in the form of coal and coke.[120]

In the hydrogen-based Green Steelmaking process, the electrolyser consumes approximately two thirds of the energy, with the EAF and the ore heating processes also large energy users. The energy consumption of the shaft is very small, which is explained by recovered heat from the condenser.

If scaled up to replace today's BF-BOF route, hydrogen-based steelmaking facilities would lead to a substantial increase in electricity demand. It is assumed power for the EAF is 0.816 MWh/tonne steel.[121] Power required for the remaining ancillary plant is 0.250 MWh/tonne steel.[122]

6.2.2 CO_2 emissions

As the green hydrogen-based steelmaking process is assumed to be entirely electrified, the emissions produced depend primarily on the emission intensity of the power source. However, even in the case of a 100% renewable energy source such as solar or wind, zero emission electricity is *not* sufficient for producing zero emission steel.

This is because CO_2 emissions are still embedded in, for example, the extraction and generation of iron ore and limestone, in lime calcination, and through the addition of carbon as an essential component of steel. Avoiding the process emissions from lime calcination would require CCUS in lime production.

Another option for further reducing emissions even with a 100% clean and renewable power source is with the substitution of lime with other materials that can provide the functions of lime in the EAF (namely slag foaming, sulphur removal, and slag basicity adjustment). Similarly, the iron ore will have embedded emissions unless it is extracted and processed in an emissions-free manner.

Furthermore, small amounts of carbon must be added to the EAF in the hydrogen direct reduction process to make steel from iron. When pure hydrogen is used as the reducing agent another carbon source instead of the natural gas (currently used) is needed. This could be done through the injection of pulverised coal, but also bio-methane or other sources of biogenic carbon could be used.

Even if the CO_2 emissions from carbon and lime are accounted for, hydrogen-based steelmaking would still result in much lower emission intensities than that of today's integrated steelmaking route. To put it into perspective, emissions from carbon and lime use, and consumption of the graphite electrodes, would result in emissions of 53 kg of CO_2 per tonne of steel[123], which is equal to only 2.8% of emissions from the traditional BF-BOF route.

[119] *Assessment of hydrogen direct reduction for fossil free steelmaking*, Valentin Vogl, Max Åhman, Lars J. Nilsson, March 2018, Department of Environmental and Energy Systems Studies, Lund University, Box 118, SE-221 00 Lund, Sweden.
[120] *Power-to-Steel: reducing CO_2 through the integration of renewable energy and hydrogen into the German steel industry*, Otto, M. Robinius, T. Grube, S. Schiebahn, A. Praktiknjo, D. Stolten.
[121] *Assessment of hydrogen direct reduction for fossil free steelmaking*, Valentin Vogl, Max Åhman, Lars J. Nilsson, March 2018, Department of Environmental and Energy Systems Studies, Lund University.
[122] *Assessment of hydrogen direct reduction for fossil free steelmaking*, Valentin Vogl, Max Åhman, Lars J. Nilsson, March 2018, Department of Environmental and Energy Systems Studies, Lund University.
[123] *Assessment of hydrogen direct reduction for fossil free steelmaking*, Valentin Vogl, Max Åhman, Lars J. Nilsson, March 2018, Department of Environmental and Energy Systems Studies, Lund University.

6.3 Opportunities to decarbonise the steel industry

Noting the limitations outlined regarding technology solutions in previous sections, opportunities to decarbonise steelmaking exist along the entire value chain, including:

1. Replacement of fossil fuel generated power.
2. Use of alternative fuels for transport
3. Upgrading ore using renewables and green hydrogen.
4. Replacement of sintering to produce Green Pellets.
5. Partial replacement of coal in BFs.
6. Blast furnace carbon capture.
7. Replacement of BF in steel production.
8. Using green iron in existing BF and BOFs.
9. Increased green EAF and scrap recycling.

These options are summarised in Table 6.2, along with a more detailed explanation and discussion of the options follows in Section 6.3.

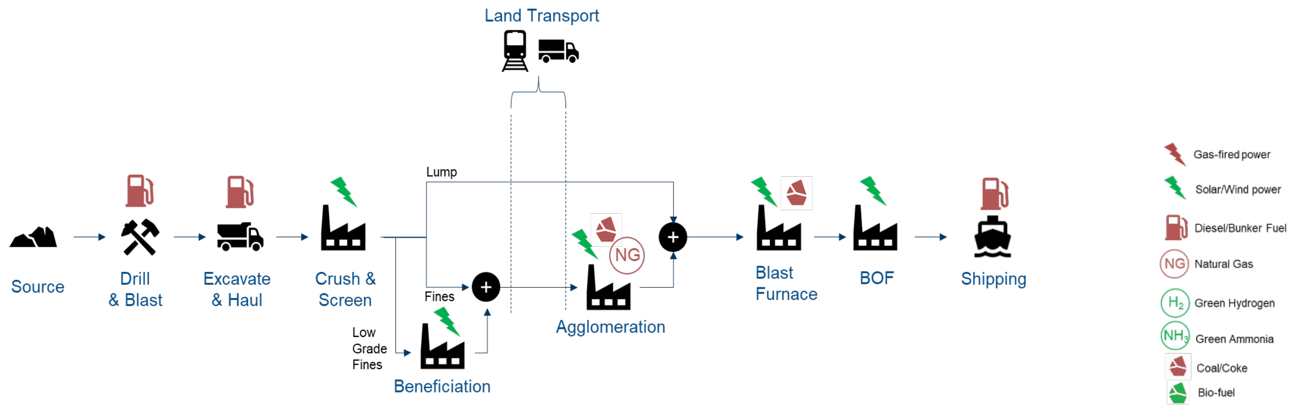
Table 6.2 Summary of decarbonisation measures and their impacts

Decarbonisation measure	Type	Use of green hydrogen?	Potential total % reduction in emissions from fossil fuel-based steelmaking
Replacement of fossil fuel generated power	Power		10%*
Use of alternative fuels for transport	Fuel	Yes	<5%
Upgrading ore using renewables and green hydrogen	Process, Power		<10%
Replacement of sintering to produce Green Pellets	Technology, feedstock	Yes	5% - 10%
Partial replacement of coal in BFs	Feedstock		5-10% with fossil fuels or hydrogen, or up to 50% with biomass
Blast furnace carbon capture	Technology		55 - 90%
Replacement of BF in steel production	Technology, Feedstock	Yes	60- 90%
Using green iron in existing BFs	Technology, Feedstock	Yes	40%**
Increased green EAF and scrap recycling	Process, Power, Social		100%***

Source: GHD Analysis
Notes:
**Enabler for other methods of decarbonisation*
***This maximum is only achieved if all BF feedstock produced with fossil-fuel energy (sinter and lump) are fully replaced with green iron*
****Proportional to availability of steel*

6.3.1 Replacement of fossil fuel generated power

Figure 6.2 Replacement of fossil fuel generated power in iron ore to steelmaking value chain



Plant processes across the steelmaking value chain require electrical energy which typically utilise coal or natural gas power sources. Replacement with renewable energy from solar, wind, or hydroelectric facilities can lead to emissions savings across the value chain or in specific parts of the value chain.

Overall replacement of fossil fuel power with renewable power in existing steelmaking value chain would lead to ~10% reduction in carbon emissions.

While this is only a modest decrease, renewable power is a critical enabler of other highly effective decarbonisation options. Therefore, its net importance to emissions reduction in steelmaking is greater than what is indicated from like-for-like replacement of fossil fuel sources in existing chains.

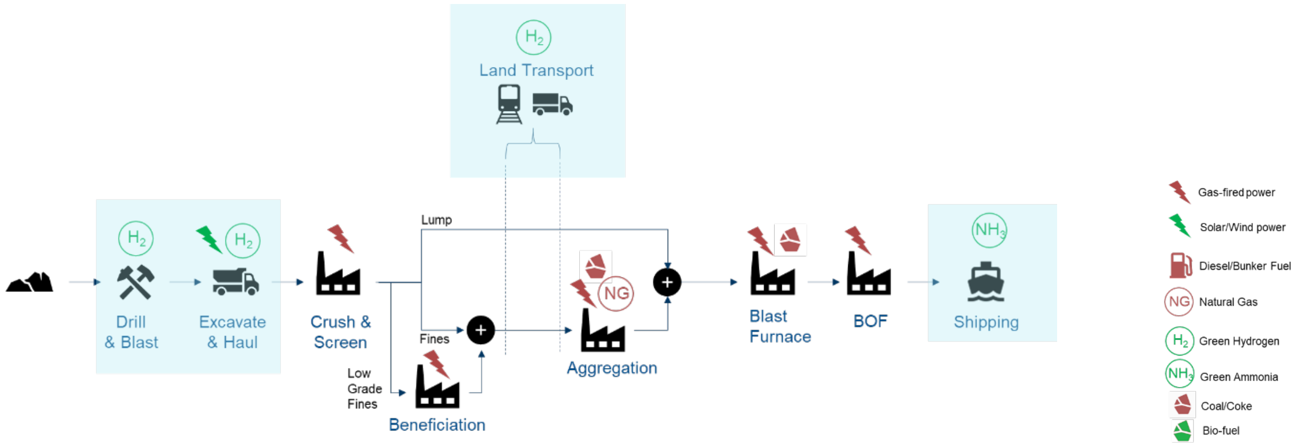
There are greater opportunities, around 5% extra, for emissions reductions in the context of the fossil-fuels powered magnetite ore to steel value chain. The power requirements to turn magnetite ore into 1 MT of steel are roughly 1.5 times higher than for making an equivalent quantity of steel from a hematite ore. This is due to the significant additional energy required for grinding, and to a lesser extent the beneficiation and the greater yield losses in going from a magnetite ore to steel.

Opportunity for Western Australia

- Direct role in replacing fossil fuels with renewable energy in its existing onshore mining process, starting immediately.
- Production of hydrogen using natural gas in the short term and renewable energy solutions in the medium term for use in further downstream processing of iron ore.
- Further potential beyond just the iron ore sector, as these technologies could be transformative to any energy intensive sector.
- Establishment of Western Australia as a world-class centre of excellence for renewable technology research.

6.3.2 Use of alternative fuels for transport

Figure 6.3 Use of alternative fuels for transport in the iron ore to steelmaking value chain



The logistics and transport components in steel value chains rely on fossil fuels to power transport of iron ores and end products. In-pit haul trucks, truck or train land transport rely on diesel and shipping relies on bunker fuel.

All these fuels may be replaced with either electrical battery engines for land vehicles, or green-derived hydrogen fuels. Initiatives such as the 'Charge on Innovation Challenge' are seeking to accelerate commercialisation of effective solutions for charging large electric haul trucks while simultaneously demonstrating there is an emerging market for these solutions in mining.[124]

Hydrogen fuel cell vehicle and locomotives are currently under trial[125] and green hydrogen converted to green ammonia to be used as a fuel source for ships.[126] This green ammonia may also be used to create blasting charges.

The decarbonisation gains from replacement of these fuel sources are at best 5% across the value chain.

Value chains using both hematite and magnetite benefit from this decarbonisation method, however mining operations with larger overburden quantities and higher gangue ores (such as magnetite) will benefit more on a per-tonnes of steel produced basis. This is because for these deposits more ore has to be mined, and more overburden removed, to produce a tonne of steel – hence there is greater excavate and haul fuel usage.

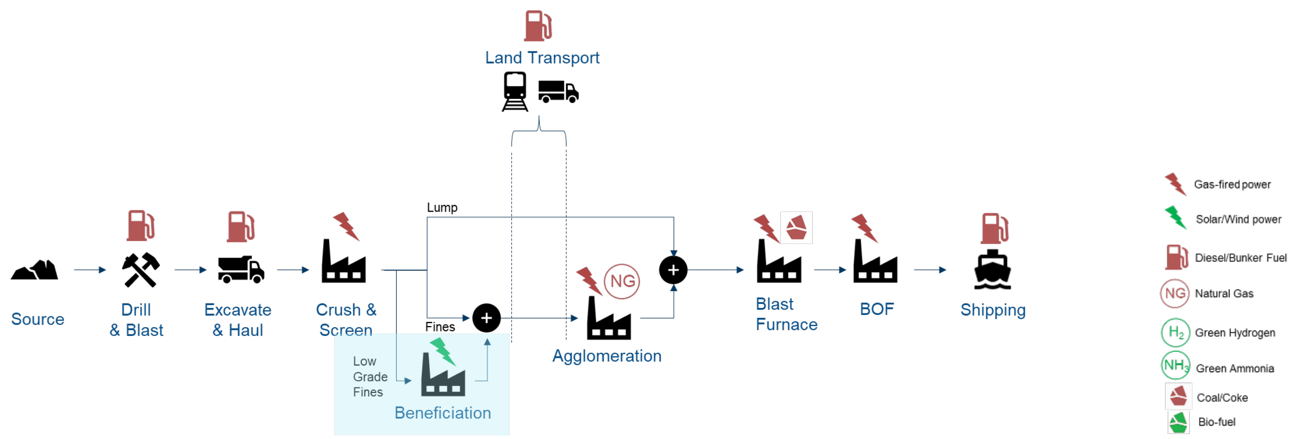
Opportunity for Western Australia

- Direct role in replacing fossil fuels with alternative fuel sources for transport purposes in its existing onshore mining process.
- Direct role in replacing fossil fuels with alternative fuel sources for transport purposes in its shipping contracts which depending on the destination market, are arranged by either the iron ore producers or steelmakers.
- Further potential beyond just the iron ore sector, as these technologies could be transformative to both general global shipping practices and domestic transport sectors.
- Pioneer trials for testing and deployment of new green fuelled transport technology.

[124] Further information available at: https://chargeoninnovation.com/.
[125] ARENAWIRE, 2021. *Hydrogen powered prime movers to roll into Townsville*.
[126] Gallucci, M, 2021 Why the shipping industry is betting big on ammonia, IEEE Spectrum.

6.3.3 Upgrading ore using renewables and green hydrogen

Figure 6.4 Upgrading of ores using renewables in the iron ore to steelmaking value chain



The amount of iron present in ores that undergo blast furnacing directly impacts the amount of metallurgical coke and other reductants used to generate iron and steel. Lower gangue quantities in the ore will lead to reductions in the carbon generating feedstock, and therefore lower emissions.

Additional removal of gangue, or upgrading low grade iron ore fines, with beneficiation processes using renewable power can lead to downstream emissions reductions in iron ore processing.

Increased beneficiation has the potential to reduce overall emissions in the value chain by at best ~10%. However, there are significant increased costs to miners for doing this with little corresponding increase in value of the product at this point in time.

Magnetite ores are upgraded to magnetite concentrate, and already undergo a high degree of beneficiation, as explained in Section 3. There is a more limited opportunity to realise gains in Scope 3 emissions by further improving high grade hematite iron ores. Emissions reductions from upgrading ore will more likely come from improving low grade hematite ores and goethite iron ores.

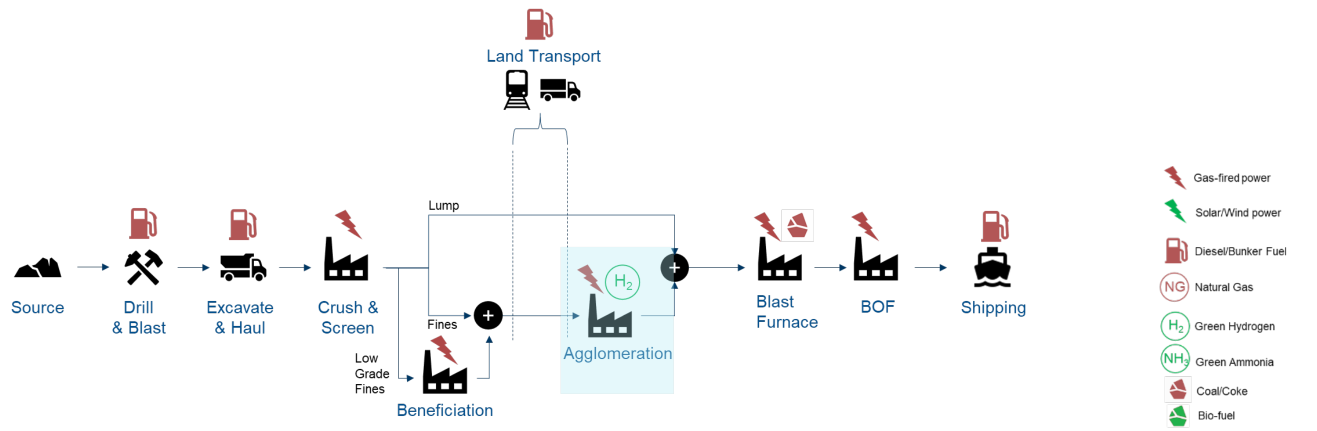
Western Australia has historically been recognised for its typically good quality ore (high grade and gangue less than 10%). However as discussed, this ore grade is declining requiring consideration of strategies to prevent loss of market share over the longer term.

Opportunity for Western Australia

Continuing to export lump and high-grade fines, while upgrading low grade fines through beneficiation with renewable power sources.

6.3.4 Replacement of sintering to produce Green Pellets

Figure 6.5 Green pellet value chain



Sintering occurs at the agglomeration phase and is the process of taking iron ore fines and sometimes a limited amount of magnetite concentrate and bonding it to form material of a suitable size for processing in a BF. Fine iron ores are mixed with coal fines and fluxes to form a sintered mass when fired from the top surface using gas or oil. The mass is fired by the strong draw of air from fans underneath the sinter mass. The sinter is then broken and sized for the required BF optimal sizing.

The contribution of this process to emissions can be up to 10% of the total from steelmaking[127].

The requirement for sintering can be eliminated by upgrading iron ore fines to Green Pellets for export, using natural gas in the short term and green hydrogen fired pelletisation over the longer term.

This involves taking the fines and running them through a rotating drum with a bentonite binder, whilst firing in an indurating furnace either as a rotary kiln or a shaft.

Pellet products can be transported easily, be formed by either grinding hematite or magnetite concentrate and can increase productivity in the steelmaking process as their size properties are well controlled.

This technology used with magnetite concentrate can take less energy to turn into pellets then hematite. Pellets with high strength for transport requires very fine ore size to properly form the ore into pellets. Magnetite concentrates are often of a suitable size and require no further processing to make into pellets.

Hematite fines mined in Western Australia may require further grinding to render them in a suitable form for pelletisation, and experimentation to determine if they will bind well into pellets of the necessary high temperature strength is needed to determine how to best convert hematite ores into the required pellets for BF or DRI use.

Opportunity for Western Australia

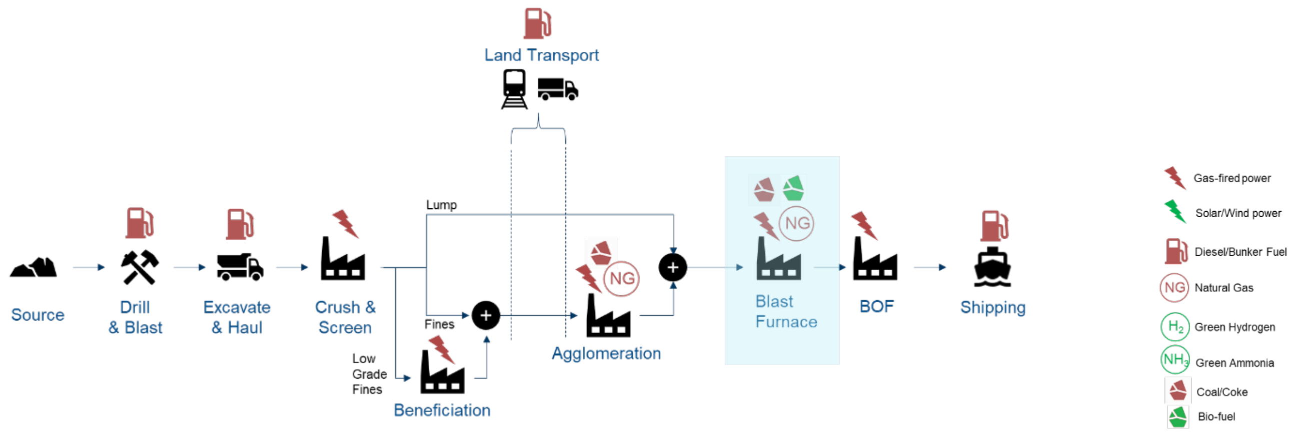
- Continuing to export lump and high-grade fines, while producing Green Pellets using low grade fines creating a new export product from the State.
- Development of new mines to produce Green Pellets using magnetite concentrates, creating a new export product from the State.

  Research into the feasibility of converting hematite and goethite iron ore fines into pellets with the required properties for ironmaking.

[127] Lu, L, Ooi, TC, Li, X, 2015, Sintering emissions and their mitigation technologies, in *Iron Ore: Mineralogy, Processing and Environmental Sustainability*. (Sawston: Woodhead Publishing).

6.3.5 Partial replacement of coal in BFs

Figure 6.6 Partial replacement of coal in BF



Iron-producing BFs primarily use metallurgical coke for several purposes. It acts as a reducing agent to turn iron oxide into iron; melts the metal; provides the structural support for this melting and chemical reduction. However, this same process also leads BFs to produce around 90% of the emissions in steelmaking.

Metallurgical coke (otherwise known as met coke) can be partially replaced by other feedstock such as pulverised coal (for pulverised coal injection (PCI)) and natural gas. This replacement is at best roughly 50% of the carbon mass[128], as the carbon load must still be in the form of met coke to provide the structural support for melting iron.

For the purposes of this report and typical now for a standard BF using fossil fuels, it is assumed coke consumption is minimised by using a high standard amount of injection carbon and natural gas as a replacement.

Another substitute for metallurgical coke is the use of biomass or biofuels.[129] Biomass[130] is considered a carbon neutral feedstock and is thus better in this regard than natural gas. Biomass can be gasified or made into a product like coal and injected into the BF. Assuming similar replacement levels to PCI or natural gas, this could halve the carbon burden of the BF, however it requires ongoing access to biofuel produced in a way which removes carbon from the atmosphere through new plant growth. However, there are substantial land-use requirements for producing biofuels at scale and this will potentially compete with land use for other purposes, such as for food production.

Unless demand for biofuels increases and consumers are willing to pay the premium required for these there is limited market opportunity for Western Australia to produce biofuels for use in the steelmaking process.

Partial replacement of coke in BFs is equally applicable to hematite and magnetite ore feeds.

Opportunity for Western Australia

- Potential for biofuel production and export to existing BF operators.
- Investigation into the feasibility of doing this, as well as biofuel production techniques.

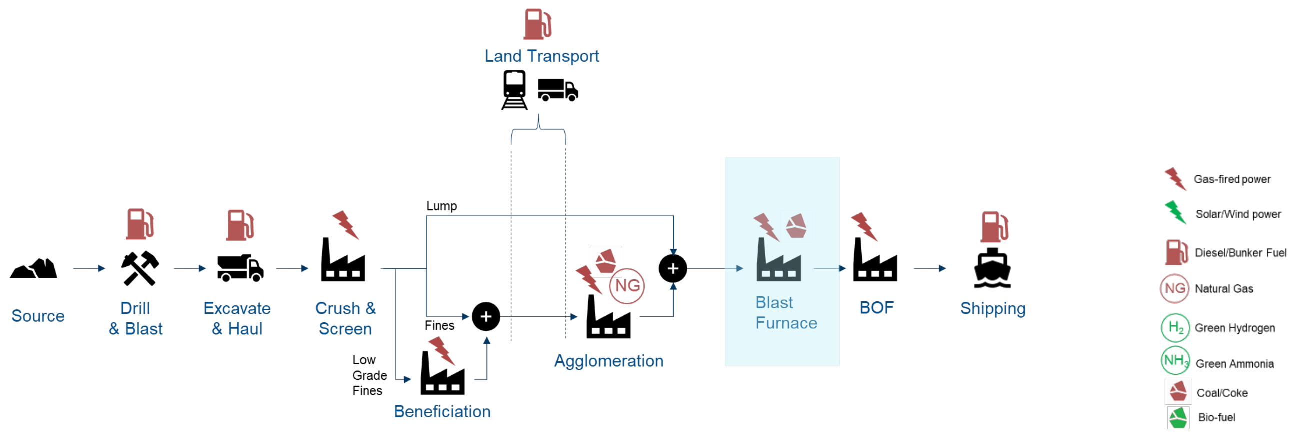
[128] Cameron, I. Sukhram, M. Lefebvre, K. Davenport, W, 2019, Blast Furnace Ironmaking: Analysis, Control and Optimization. (Amsterdam: Elsevier).

[129] *Improved Energy Efficiency and Fuel Substitution in the Iron and Steel Industry*, Maria T. Johansson, Linkoping University, April 2014

[130] Composed of wood waste, bagasse, plant waste, or deliberately grown plant product such as Mallee or cereal straw.

6.3.6 Blast furnace carbon capture

Figure 6.7 Blast furnace carbon capture



Carbon capture use and storage (CCUS) is recognised as a key climate change mitigation option for many users, including within the iron and steelmaking industry.

The post combustion carbon capture option involves a capture unit installed to collect and process exhaust gases emitted from the BF to separate carbon dioxide from other gases and remove particulate matter.

The carbon dioxide is absorbed by a liquid solvent, typically an aqueous amine solution, allowing other gases to be released into the atmosphere, whilst the captured carbon dioxide is stripped from the liquid solvent, compressed and cooled to liquid form for other uses, including regenerating the liquid solvent for reuse.[131] Alternatively, if not utilised, it must be stored in a highly pressurised fluid form deep beneath the earth.[132]

Carbon capture technology applied to BFs is equally applicable to both magnetite and hematite ore types.

Post combustion carbon capture with chemical absorption is the most proven technology for carbon dioxide removal from combustion exhaust gases due to its maturity and research work undertaken in its application.

Carbon capture technology could be applied to BF gases to remove between 55% to 90% of emissions.[133] [134] Removal of >90% carbon in emissions is technologically difficult.

Opportunity for Western Australia

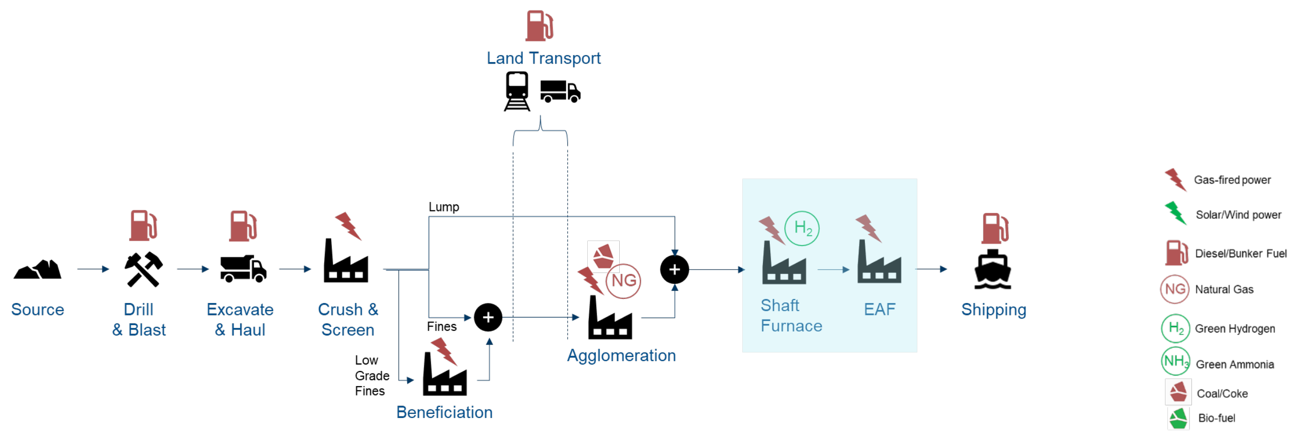
- While Western Australia does not have any existing BFs, and there is limited ability for Western Australia to influence the implementation of carbon capture technology on existing BFs outside of its jurisdiction, if natural gas is used as a transition fuel there will be a need to consider CCUS to offset emissions produced in other parts of the value chain.
- Use of mineral carbonation through direct air capture to sequester emissions produced in Western Australia from other parts of the value chain is being considered.

[131] Basile, A, Gugliuzza, A, Iulianelli, A, and Morrone, P, 2011, Membrane technology for carbon dioxide (CO_2) capture in power plants in *Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications* (Cambridge: Woodhead Publishing).
[132] Department of Energy, n.d., How to Store Carbon.

[133] Bailera, M, Lisbona, P, Peña, B, and Romeo L, 2021, A review on CO_2 mitigation in the Iron and Steel industry through Power to X processes in *Journal of CO_2 Utilization*, vol. 46 (Oxford: Elsevier)
[134] Moseman, A and Herzog, H, 2021, How efficient is carbon capture and storage?, MIT Climate Portal.

6.3.7 Replacement of the BF in steel production

Figure 6.8 Replacement of the BF in steel production



The best and most effective way to decarbonise the steelmaking process is to replace the traditional BF steelmaking route with direct reduction of iron utilising green hydrogen. Rather than use coke and coal, direct reduction uses gas products (either natural gas or hydrogen) to strip the oxygen from iron ore. This process leaves DRI, which can be melted in EAFs to produce steel.

Use of natural gas shaft furnaces can reduce the emissions from steelmaking by 60%. Utilising green derived hydrogen in shaft furnaces can decarbonise 90% of emissions in steelmaking.

Shaft furnaces can turn pellets or lump iron ore into HBI or DRI products. Furthermore, EAFs have lower power use requirements for HBI or DRI feedstock low in gangue. Magnetite concentrate and high-grade hematite lump fulfill both these requirements and so can be used in shaft furnaces.

Further investigation is needed to explore how best to turn Western Australian hematite ore fines into pellets.

Electric arc furnaces can turn higher gangue HBI/DRI into steel with greater use of power[135], this is explored in Section 8.6.

Opportunity for Western Australia

- Supply gas feedstock (natural gas or green hydrogen) to DRI steelmakers, utilising the state's abundant renewables and existing gas export industries.
- Supply new iron ore products suited to DRI steelmaking.
- Expand the onshore value chains to become a DRI producer or steelmaker onshore.

135 Anderson, S. *Educated use of DRI/HBI Improves EAF Efficiency and Yield and Downstream Operating Results.* Midrex Technologies Inc.

6.3.8 Using green iron in existing BF and BOFs

Figure 6.9 Use of green iron in the BF and BOF

Blast furnaces use iron ore-based feedstock (e.g. sinter) to produce pig iron or hot metal to be converted into steel via the BOF.

Green Iron in the form of HBI can partially replace iron ore in the BF. This allows reduction in the amount of coke used in the BF.

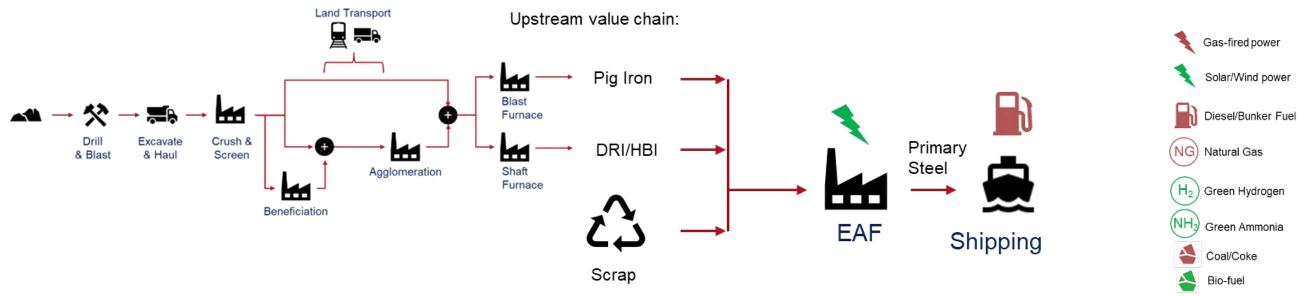
If Green Iron in the form of HBI were to completely replace other iron-ores being fed into the BF, it would allow an overall ~40% reduction to steelmaking emissions.

Opportunity for Western Australia

- Production and supply of Green Iron in the form of HBI and market to the existing customer base.

6.3.9 Increased green EAF and scrap recycling

Figure 6.10 Use of renewable energy and scrap in the EAF



Electric arc furnaces typically use electricity to melt scrap metal, along with other additives, to produce steel. The decarbonisation measure associated with this is to use renewable energy instead of fossil-fuel generated electricity in EAFs along with bypassing the entire dig-ship-reduce ironmaking value chain through the use of scrap.

Steel is one of the most recycled or recyclable materials. An increase in scrap adoption to produce steel via the (renewable) EAF route would contribute to lowering emissions from steelmaking globally. The only limitation on this measure is the availability of scrap to replace any iron created by the BF and shaft furnace processes.

Typically for most growing economies scrap will not act as a total replacement for steel and will vary from country to country. There is also a large social aspect to adoption of this measure with regards to recycling and reuse rather than sending ferrous materials to landfill.

Hot briquetted iron is used in EAFs to dilute the impurities in scrap, such as copper and zinc, which have detrimental impacts on the quality of the steel.

Opportunity for Western Australia

- Use of surplus scrap metal and the potential to generate scrap over time, particularly in the Pilbara region with steel-intensive industries such as the LNG sector (subsea pipes) and iron ore industry in EAF plants.[136]

[136] Australia exported 4.25 Mt of scrap in 2020-21 (Department of Agriculture, Water and the Environment, 2021).

Green Steel in Western Australia 7

To evaluate where Western Australia could participate in the iron ore to steelmaking process a quantitative value chain model was developed to examine technology, fuel types, inputs costs, transport, and emissions and understand the relative investment costs and benefits from emissions reductions can be gleaned for the State. The section considers the value chain and the results from selected scenarios.

7.1 Green Steel value chain model assessment

A value chain model has been constructed by GHD to analyse opportunities and key obstacles to a formation of a Western Australian Green Steel industry. Its main goal is to understand the capital requirements, costs and emissions for expanding beyond the business as usual (BAU) iron ore mining and switching from fossil fuels to renewable energy sources.

The Green Steel value chain model has been used to inform the various stages along which Western Australia can participate in the production of Green Steel.

7.1.1 Modelling framework

The model created for the analysis in this report maps the value chain of steel production in ten distinct blocks representing separate stages of the production process.

It begins with a source block containing the specifications of the iron orebody that is mined and ends with primary steel production and shipping for export. Input parameters are supplied for each process which utilise a fossil fuel production or processing option, as well as for a green (or lower carbon or renewable energy based) alternative.

By mapping the progression of iron ore through different fossil fuel or green blocks, inputting parameters, and calculating the mass flow of a product from ore to steel, the model provides a levelised cost estimate (as described in Box 7.1) of the product being produced at different stages of the value chain, and an emissions breakdown.

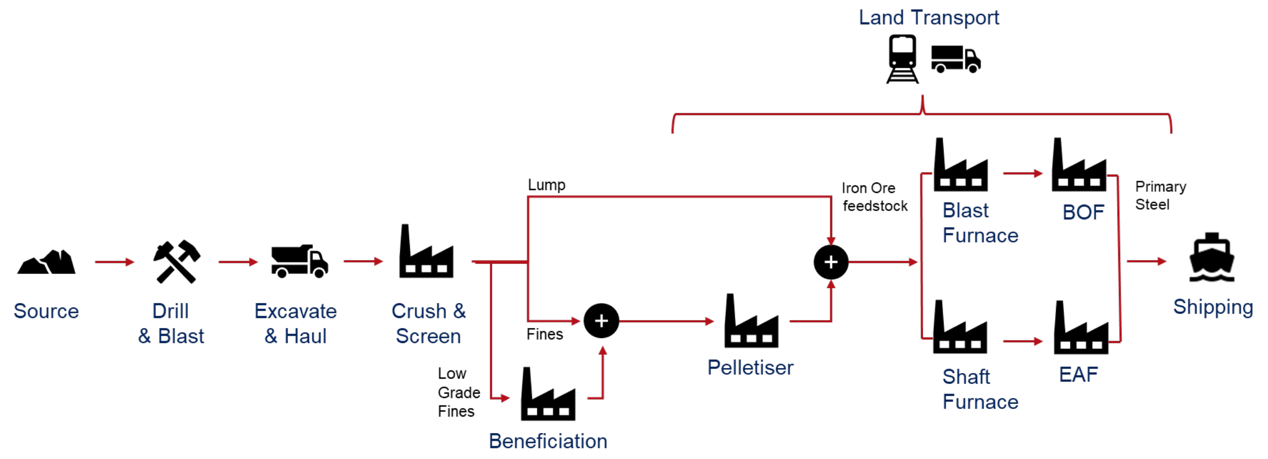
This provides a basis of comparison for cost and emissions to be identified and quantified for the traditional steelmaking process, and for possible green alternatives, where one or more of the blocks of the value chain is changed to represent the low-emission alternative.

This model takes into account all steps of the value chain from mining, processing, transport, agglomeration, iron and steelmaking, to shipping, as shown in Figure 7.1.

It takes as inputs infrastructure and technology, consumables, costs, geographic factors, power use, operational scale and ore properties, and models current and potential future extended value chains.

Intermediate stages between the end points of Green Iron Ore Mining and Green Steelmaking are also explored. These include green agglomeration (pelletisation) and ironmaking.

Figure 7.1 Steps in the steelmaking value chain model



Using the model, comparisons can be drawn between fossil fuels-driven processes and existing whole-value chain costs and emissions for steel. These costs are used to set a lower bound on current market values, and the breakeven costs for the green products are inferred for the key obstacle identified in this study, which is the price of green hydrogen.

An appropriate scale of raw material mined and representative costs (estimated at 2022 prices) are chosen to model the base case for different final products and to conduct supporting sensitivities.

Further details on the modelling methodology and assumptions may be found in Box 7.2 and the Model Basis Document.

Box 7.1 Levelised cost

Levelised cost of product (LCOP) is a measure of the average net present cost to produce an end-product in the value chain over its operational lifetime. It is used to compare the costs of production for a given product via several methods (i.e., fossil fuels-based value chain vs renewables powered value chain) on a like-for-like basis. It is the ratio between all discounted costs over the lifetime of the value chain, divided by the discounted sum of product delivered to market.

The costs included for each value chain component are:

- Capital expenditure.
- Operational expenditure.
- Feedstock and fuels.
- Power.
- Water.

Box 7.2 Additional assumptions

As a basis for comparison across the scenarios, several factors within the value chain model are held constant. The focus is on the two main iron ore producing regions in Western Australia – the Pilbara and the Mid West. Iron ore to process facility distance is selected to be 350 km by rail, a representative distance in Pilbara ore operations. As a shipping component is included in the model a shipping distance representative of Port Hedland, Pilbara to Tianjin, China, was selected reflecting the largest export market for iron-based products.

Unless otherwise stated the following assumptions are also made across cases to present a like-for-like comparison across scenarios:

- Assumed mixed solar/wind power price of $0.1 AUD/kWh.
- Lump/Fines/Low-Grade (requiring beneficiation) split for hematite ore of 35%/64%/1%; all magnetite ore requires beneficiation.
- Hematite gangue level of 9.8% on export, and 5.9% for magnetite concentrate.
- All processing beyond beneficiation is conducted close to port facilities.
- A conservative estimate of $7 AUD/kg for green hydrogen and $1.30 AUD/kg for ammonia.

Box 7.3 Economies of scale: 50 Mtpa

Many of the capital infrastructure items used in steelmaking benefit from economies of scale. That is, their cost per unit decreases as the overall facility becomes larger. The analysis in this report indicates operations which collectively mine at least 50 Mtpa of ore and make 15/31 Mtpa of steel (for magnetite and hematite ores respectively) obtain most of the benefits of this scale, and the analysis of levelised cost was done on this basis.

There are several key themes which emerge from the value chain assessment:

- Removal of fossil fuels from the raw material preparation and Green Iron Ore Mining is cost effective now and could lead to substantial savings for DSO and magnetite exporters, but requires investment in power, and land access for deployment of renewables at scale.
- Fully green *processed* products will all be cost-effective once hydrogen reaches the right price, which is expected to happen, but not in the short term.
- Green iron (HBI) as a processed product for Western Australia represents the greatest economic opportunity.
- Capital costs are substantial for renewable power production at scale and will likely require shared infrastructure between users.
- Ore upgrading is only economically viable for high gangue ores and provides the most cost savings to whomever controls more of the Green Steelmaking process.
- A staged transition strategy incorporating Green Iron Ore Mining, natural gas and scaling of power facilities can lead to a cost-effective green iron industry and lower net overall value chain emissions.

These themes will be explored in the rest of this section.

A high-level summary of the opportunities for green value chains (i.e., ones which produce a product with no or minimal carbon emissions) is presented in Table 7.1.

This outlines what is involved from a technological standpoint, required breakeven cost against equivalent fossil fuels value chain used today, and additional hurdles to uptake in Western Australia.

Table 7.1 Summary of green end points for the value chain

	Green Iron Ore	Green Pellets	Green Iron in the form of HBI	Green Steel
Price competitiveness vs traditional methods	Price competitive today	Hydrogen reaches ~$2.80/kg (magnetite) or ~$1.50/kg (hematite)	Hydrogen reaches $4/kg	Hydrogen reaches $3.20/kg
Markets	Iron/steel mills	Iron/steel mills	Steel mills	Fabrication companies, compete against existing mills
Technologies	Solar/Wind facilities, small scale H_2 electrolysis, H_2 fuel cell vehicles, ammonia fuelled shipping	Solar/Wind facilities, small scale H_2 electrolysis, H_2 fuel cell vehicles, pelletisation, grinding, ammonia fuelled shipping	Solar/Wind facilities, large scale H_2 electrolysis, H_2 fuel cell vehicles, pelletisation, grinding, shaft furnaces, ammonia fuelled shipping	Solar/Wind facilities, large scale H_2 electrolysis, H_2 fuel cell vehicles, pelletisation, grinding, shaft furnaces, EAFs, ammonia fuelled shipping
Hurdles	Initial investment in renewables	Typically done for low gangue or finely crushed ores. Makes most sense for magnetite/beneficiated ores.	Capital investment, no motivation for mining companies to invest, access to hydrogen at scale	Small domestic market, many types of steel grade and product

Source: GHD Analysis

There are two findings of note. Firstly, green iron ore production is competitive and feasible with today's technology, and there is a strong economic argument for immediate uptake by industry if questions around energy infrastructure can be addressed, and commercial technologies made available for haulage fleets that can run off battery or hydrogen.

Secondly, Green Iron in the form of HBI will be the next product to reach cost parity with coal-fired BF ironmaking once hydrogen is available for $4 AUD/kg. HBI is a bulk export product that can be distributed in a similar way to iron ore and sold to a variety of end-users, including domestic steelmakers.

The iron ore, ironmaking and steelmaking pathways examined in detail as part of the Green Steel Challenge are summarised in Table 7.2.

Table 7.2 Iron ore to Green Steel development pathways

	Pathway	Description
1	**Green Iron Ore Mining**	The export of hematite and magnetite concentrate from Western Australia, using renewable energy.
2	**Green Pellets**	The production and export of green pellets using renewable hydrogen.
3	**Iron-making – HBI from Green Pellets using fossil fuels**	Producing HBI from Green Pellets, using renewable hydrogen to produce the pellets and a natural gas-based production process to produce the HBI.
4	**Iron-making – HBI from Green Pellets using Renewable Hydrogen**	Producing HBI from Green Pellets, using renewable hydrogen to produce both the pellets and the HBI. The product from this pathway is assumed in the modelling for this report to be Green Iron in the form of HBI
5	**Green Steel**	Domestic production of Green Steel, with full renewable energy solutions.

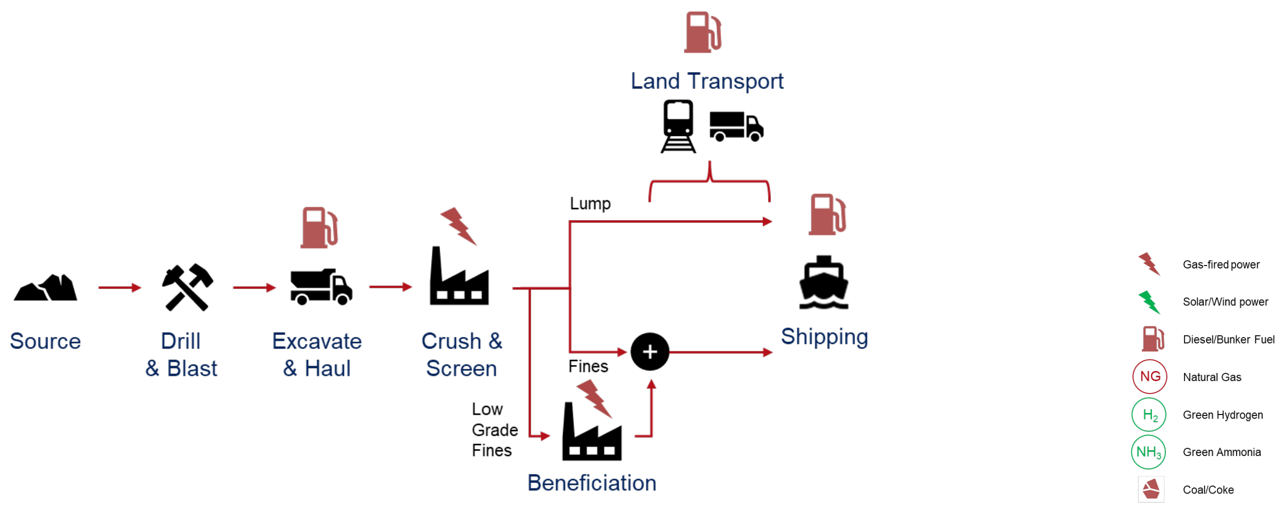
7.2 Pathway 1: Green Iron Ore Mining

The state's iron ore industry has historically relied on high margins from hematite DSO mining. This margin is due to the DSO directly competing with processed, lower grade ores that steel-producing countries such as China can obtain locally.

A schematic of the traditional mining value chain is shown in Figure 7.2.

Iron ore mining and export is currently the only existing iron-based value chain in Western Australia. It consists of blasting and drilling rock in open pit mines, hauling the material with diesel-based trucks, some crushing and grading of material, beneficiation of poor quality or magnetite ore, transport via train to port facilities and finally shipping overseas.

Figure 7.2 Existing (fossil fuel) mining value chain



The levelised cost of supplying hematite DSO (~$20 AUD/tonne free-on-board[137]) is around $70 AUD/tonne ore less than heavily processed magnetite concentrate (~$90 AUD/tonne free-on-board). This higher cost is due to the expense and material losses involved in fine grinding and beneficiation of the Western Australian magnetite iron ores.

The difference can be indicative of the additional margin hematite DSO miners currently obtain from sale of their ores. As any further processing steps require more expense, this creates a powerful disincentive to undertake further processing of hematite DSO.

Magnetite is abundant in Western Australia, particularly in the Mid West. It requires high degrees of energy-intensive beneficiation. This beneficiation accounts for around half the overall cost of magnetite production, with energy costs accounting for around one third of beneficiation costs.

Magnetite concentrate is valued as a high iron purity export product. As these products compete with both locally produced hematite DSO and internationally produced magnetite, any cost savings that can be realised will encourage further growth of this industry.

The levelised cost and emissions breakdown for typical fossil fuels hematite DSO and magnetite concentrate value chains are shown in Figure 7.3.

The iron ore sector in Western Australia can immediately support the transition pathways for steelmaking by removing the use of fossil fuels in iron ore mining through replacing fossil fuel

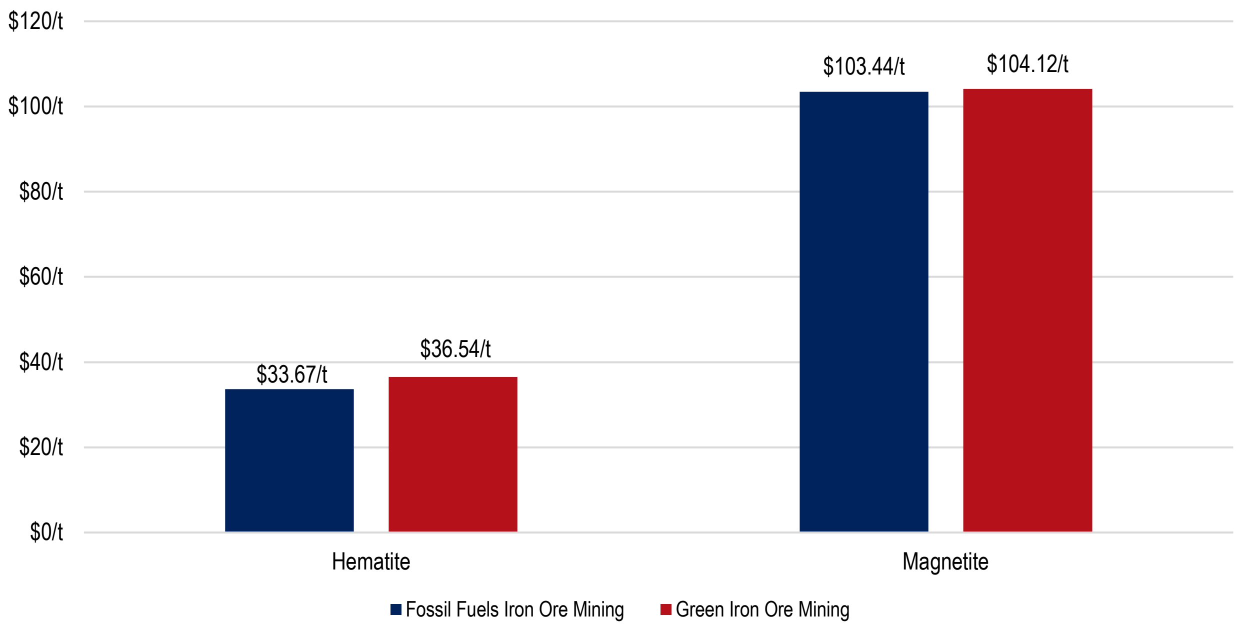
[137] Free-on-board costs exclude the cost of shipping the final product to customer.

generated power and use of alternative fuels for transport for both existing and new mines.

In doing so, it can remove scope 3 emissions for steelmakers and reduce emissions for Western Australia overall. This fully green value chain for iron ore mining is represented in Figure 7.4.

The levelised cost breakdown for the fully green iron ore mined hematite DSO and magnetite concentrate value chains are shown in Figure 7.5. The comparison of fossil fuel and Green Iron Ore Mining costs (inclusive of shipping) are shown in Figure 7.6.

Figure 7.3 Levelised Cost of Production (AUD/tonne), Green Iron Ore Mining versus Fossil Fuels Iron Ore Mining, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (1c and 2a), Magnetite (1f and 2a1))
Notes: For H_2 cost of $7 AUD/kg

Figure 7.4 Green Iron Ore Mining pathway

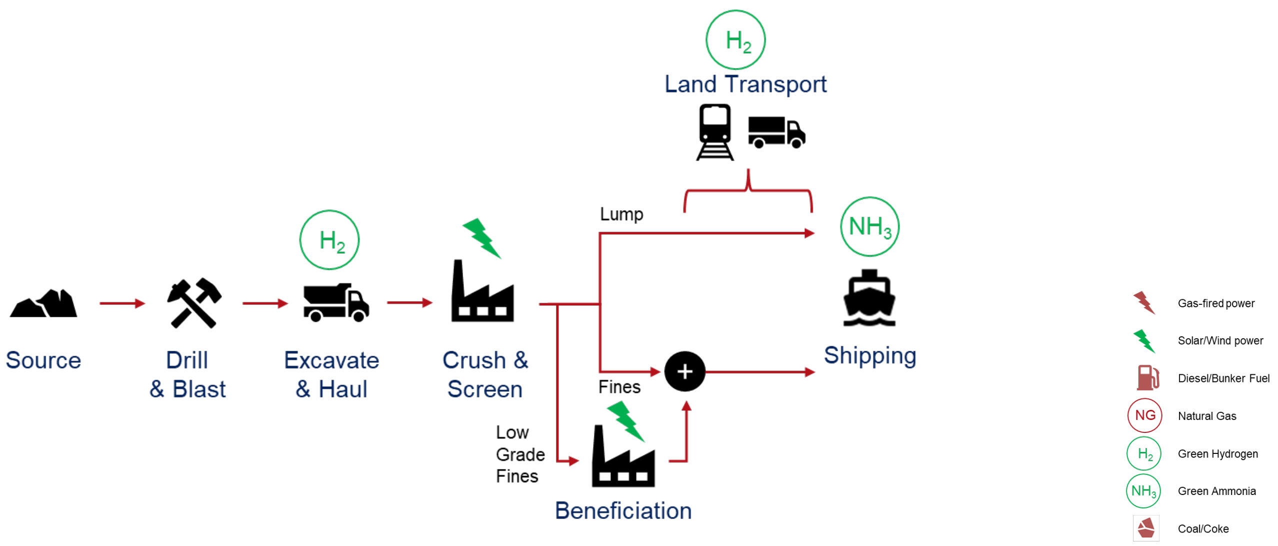
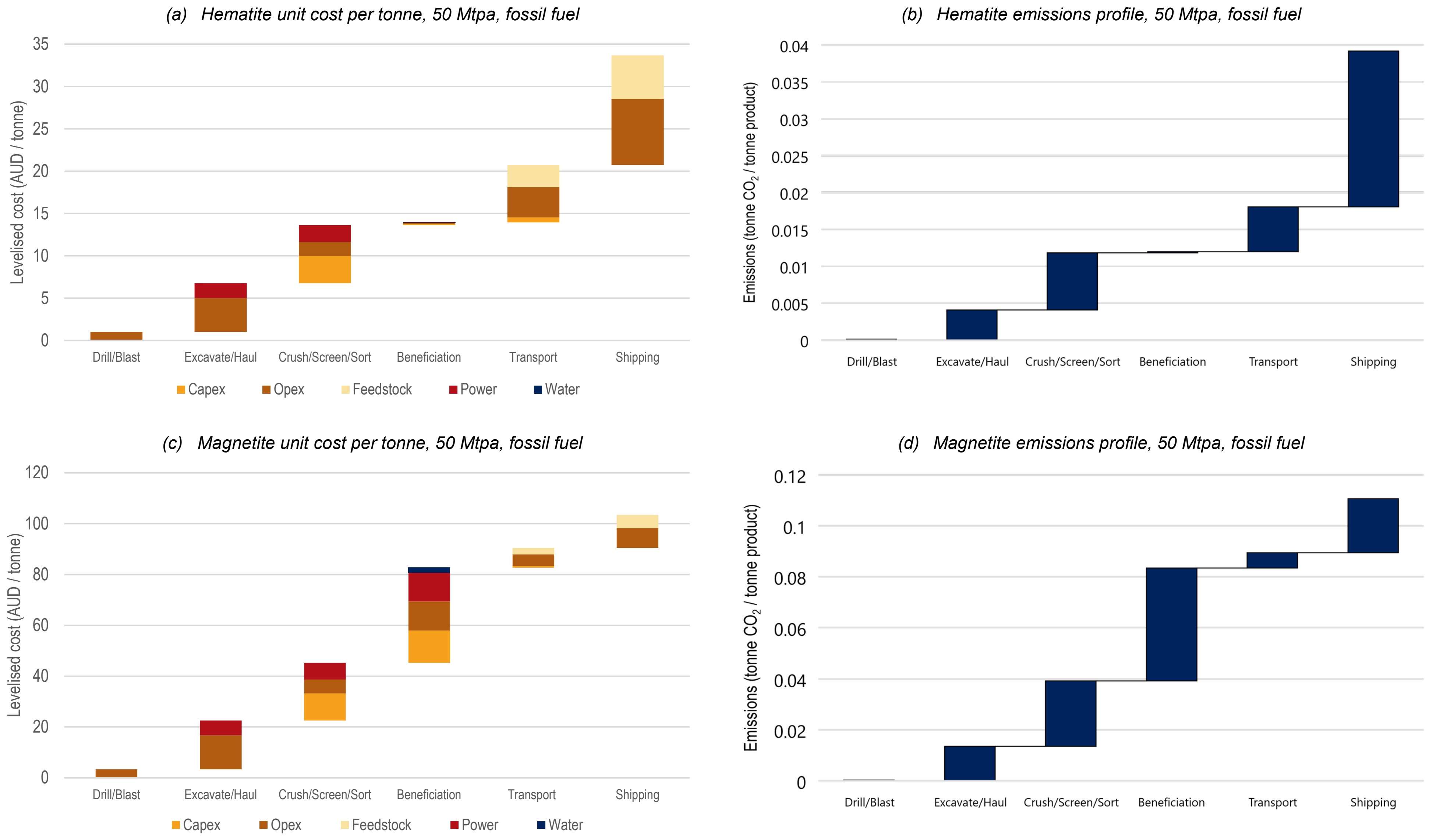


Figure 7.5 Value chain modelling output, base case fossil fuels iron ore mining value chain by ore type



Source: GHD Analysis (Model Value Chain Scenarios 1c and 1f)
Note: Analysis based on a fossil-fuels iron ore mining value chain, with assumptions as listed in the Model Basis Document.

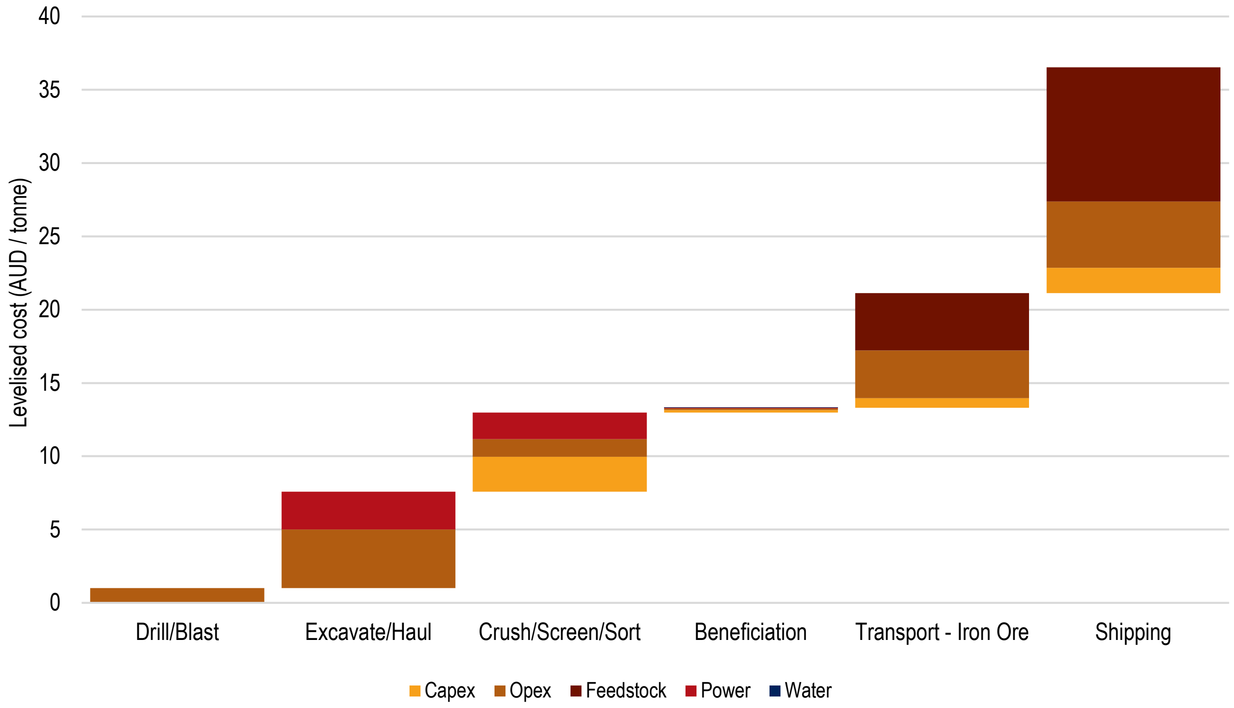
Table 7.3 Indicative capital and other resource requirements for Green Iron Ore Mining

Indicative Requirements for:	1 Mtpa Shipped Green Iron Ore		50 Mtpa Mined Ore Shipped as Green Iron Ore		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Sustained power required	16	38	787	565	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$138	$332	$6,948	$4,986	M AUD	Capex
Renewable facility land use	80	200	4,325	3,104	Hectares	
Annual hydrogen required	2	3	109	46	Ktpa	
Hydrogen facility	$24	$34	$1,228	$514	M AUD	Capex
Ammonia facility	$0.8	$0.8	$13	$6	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$1,097	$366	M AUD	Capex
Water required	132	742	6,602	11,131	ML p.a.	
Mined ore required	1.1	3.3	50	50	Mtpa	
Shipped product	1	1	49.85	15	Mtpa	

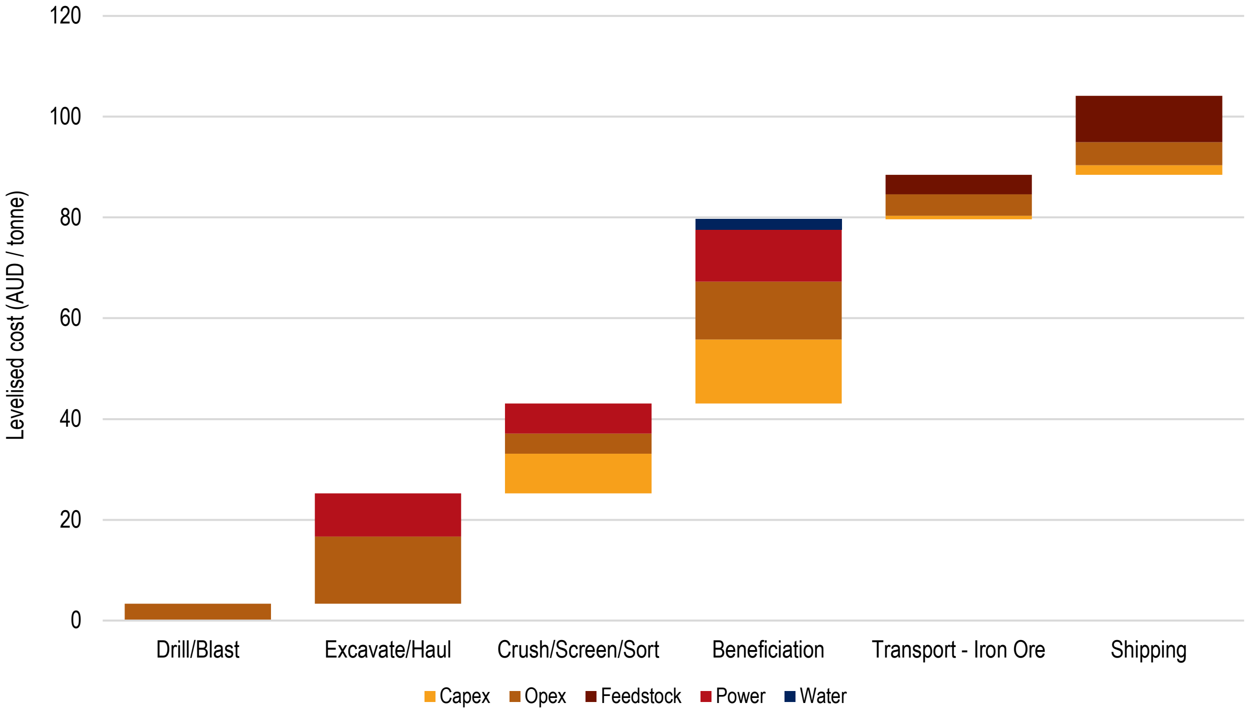
Source: GHD Analysis (Model Value Chain Scenarios: Hematite (2b and 2a), Magnetite (2b1 and 2a1)); MRIWA

Figure 7.6 Levelised cost, Green Iron Ore Mining value chain by ore type, 50 Mtpa mined basis

(a) Hematite unit cost per tonne



(b) Magnetite unit cost per tonne



Source: GHD Analysis (Model Value Chain Scenarios 2a and 2a1)
Note: Analysis based on a Green Iron Ore Mining value chain, with assumptions as listed in the Model Basis Document.

Renewable Energy Needs

Fundamental to removing fossil fuels in the supply of hematite ores and magnetite concentrate is the provision of renewable energy at comparable cost to existing solutions. The sector is currently highly reliant on gas fired power. Due to the high reliance on gas fired power, its replacement with renewable power offers an attractive path to lowering emissions in these existing value chains.

A benchmark power cost for today's renewable energy is based on a mixed 50/50 solar/wind facility, oversized with sufficient storage to supply uninterrupted power to the operation. This benchmark cost is around $0.1 AUD/kWh[138], and when compared with the breakeven cost for green iron ore suggests the entire existing Green Iron Ore Mining value chain can be run competitively.

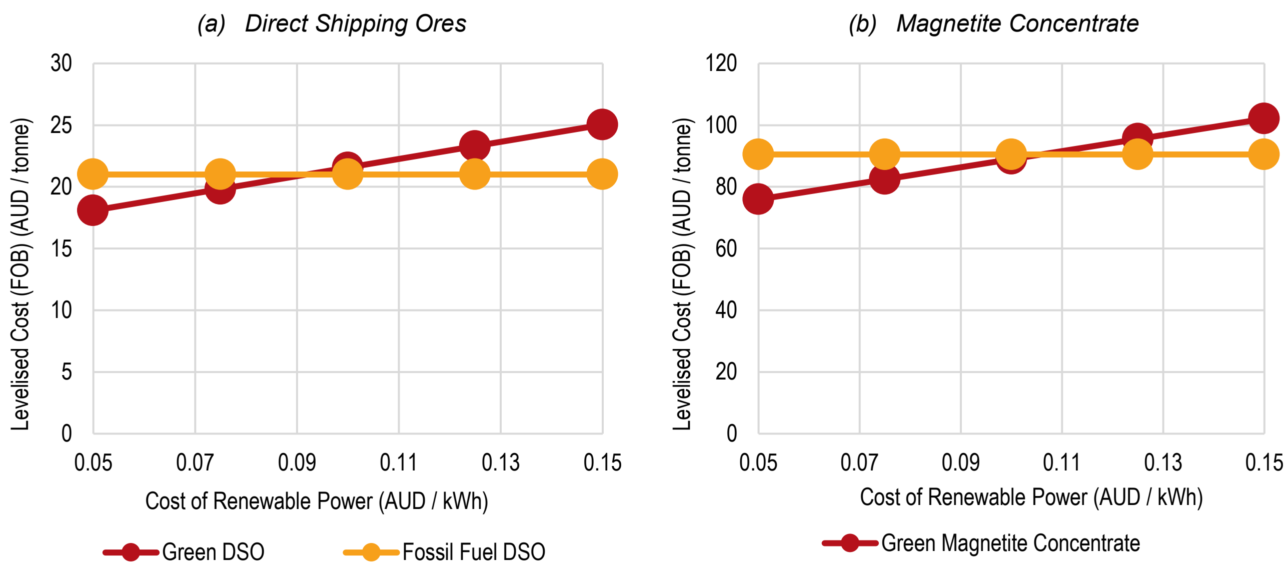
Further substantial savings can be realised for additional reductions in the price of power.

For example, if the cost of power is halved to $0.05 AUD/kWh, the levelised cost for the supply of magnetite concentrate is reduced to ~$75 AUD/tonne free-on-board, a $15 AUD/tonne reduction.

The relatively low cost of renewable power will allow savings to be realised by miners – particularly for energy intensive magnetite concentrate production. Furthermore, these cost savings should offset expenses from adoption of other green technologies (e.g. hydrogen fuel cell transport of ore), further reducing emissions. Early adoption of these hydrogen technologies also paves the way for more intensive use in future iron and steelmaking onshoring of process.

An analysis of the breakeven free-on-board costs for green hematite and magnetite concentrate against the cost of renewable power is shown in Figure 7.7.

Figure 7.7 Breakeven green power prices vs fossil fuels for BAU mining



Source: GHD Analysis
Notes: Excludes shipping

[138] Further details of this analysis is contained in Section 7.7.2.

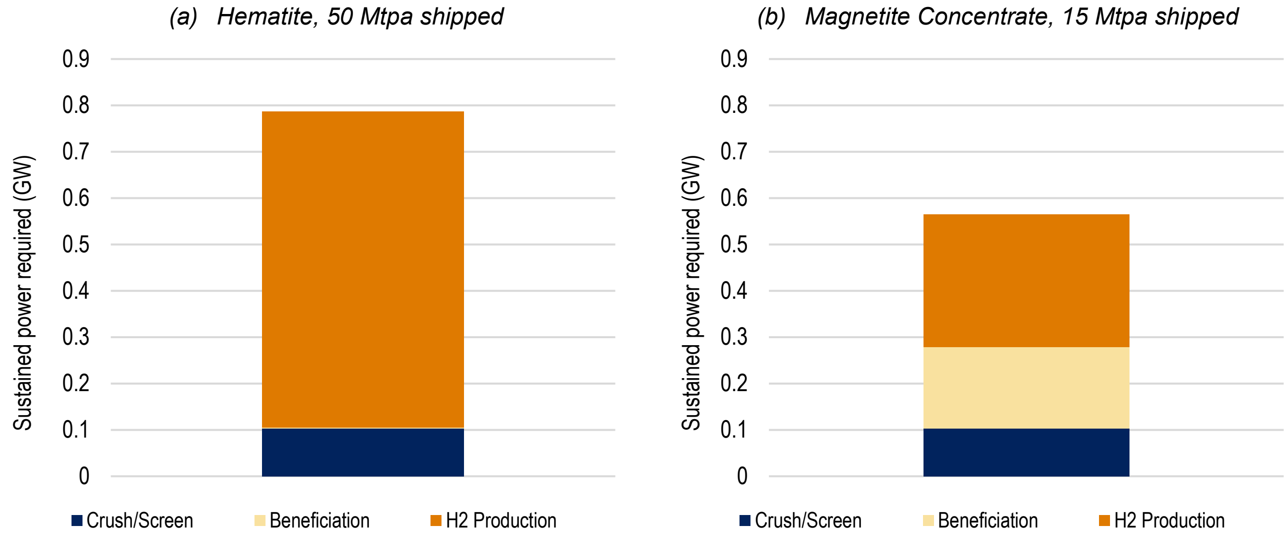
The typical power needs for supplying hematite ores and magnetite concentrate in a decarbonised way is shown in Figure 7.8.

Under a Green Iron Ore Mining pathway, the power requirements to mine 50 Mtpa of iron ore, including that required to produce hydrogen fuels but excluding shipping, are:

- around 70 kWh/tonne hematite ore
- around 260 kWh/tonne magnetite concentrate

The additional energy requirements to create the green ammonia shipping fuel are substantial and depend on the final destination. Approximately an additional 70kWh per tonne shipped product would be required with a one-way shipping distance of 6500km – roughly that from Port Hedland, Pilbara to Tianjin, China.

Figure 7.8 Renewable power requirements by ore type, Green Iron Ore Mining, 50 Mtpa iron ore mined operations, includes energy required to make H_2 fuel land vehicles and produce ammonia for ships



Source: GHD Analysis (Model Value Chain Scenarios 2a and 2a1)
Note: Analysis based on a Green Iron Ore Mining value chain, with assumptions as listed in the Model Basis Document.

Emissions reduction

The largest emissions contributions in iron ore mining and exporting the product come from crushing/grading and shipping for hematite ores, and beneficiation power supply for magnetite-based ores.

The Scope 1 emissions reduction potential from the Green Iron Ore Mining pathways is:

- around 0.04 tCO_2/tonne exported hematite ores, the majority (53%) due to shipping; and
- around 0.11 tCO_2/tonne exported magnetite concentrate, 40% due to the energy intensive beneficiation process and 19% due to shipping.

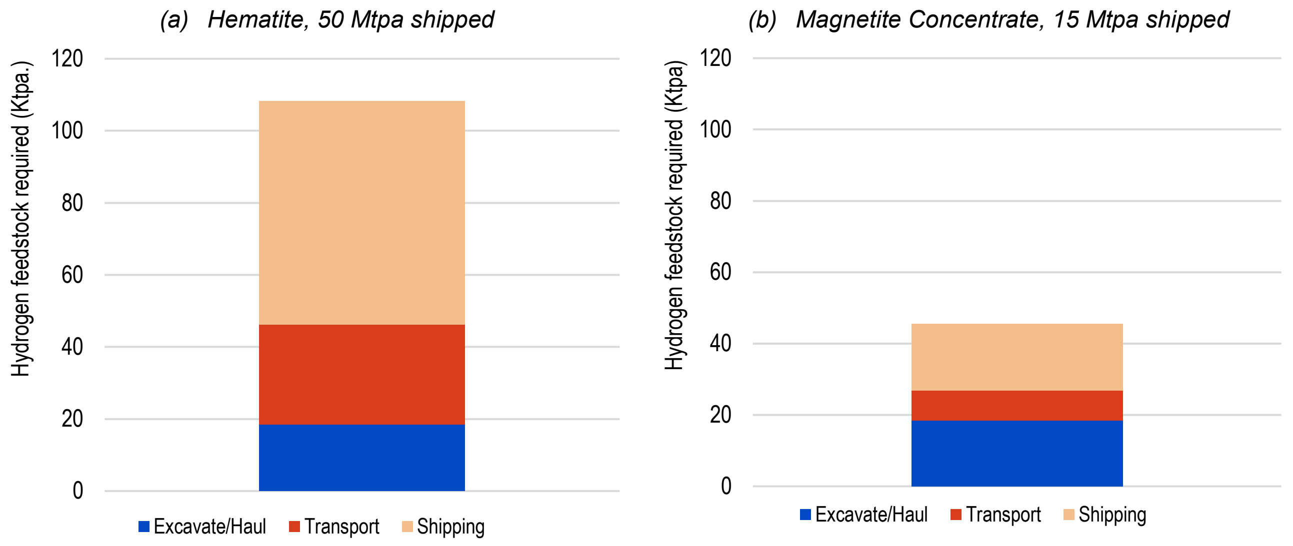
Though shipping may be considered to fall into Scope 3 emissions, the onus will fall on local suppliers to provide a green alternative for ship refuelling, such as green ammonia. The net change in supply chain costs amounts to an additional several dollars per shipped tonne of product.

Whilst this is not a significant additional cost and may be expected to improve over time, it does add substantially to the required energy to produce this ammonia onshore – approximately an additional 70kWh per tonne shipped product.

Green Iron Ore Mining has requirements for hydrogen and ammonia facilities for long distance transport, as shown in Figure 7.9.

Around 0.003 tonnes of H_2 are needed to support fully green export of one tonne of ore, mostly in producing green shipping fuel.

Figure 7.9 Value chain modelling output, hydrogen feedstock requirements by ore type, Green Iron Ore Mining, 50 Mtpa iron ore mined operations



Source: GHD Analysis (Model Value Chain Scenarios 2a and 2a1)
Note: Analysis based on hematite iron ore for a renewables value chain, with assumptions as listed in the Model Basis Document.

7.2.2 Role of beneficiation in reducing scope 3 emissions

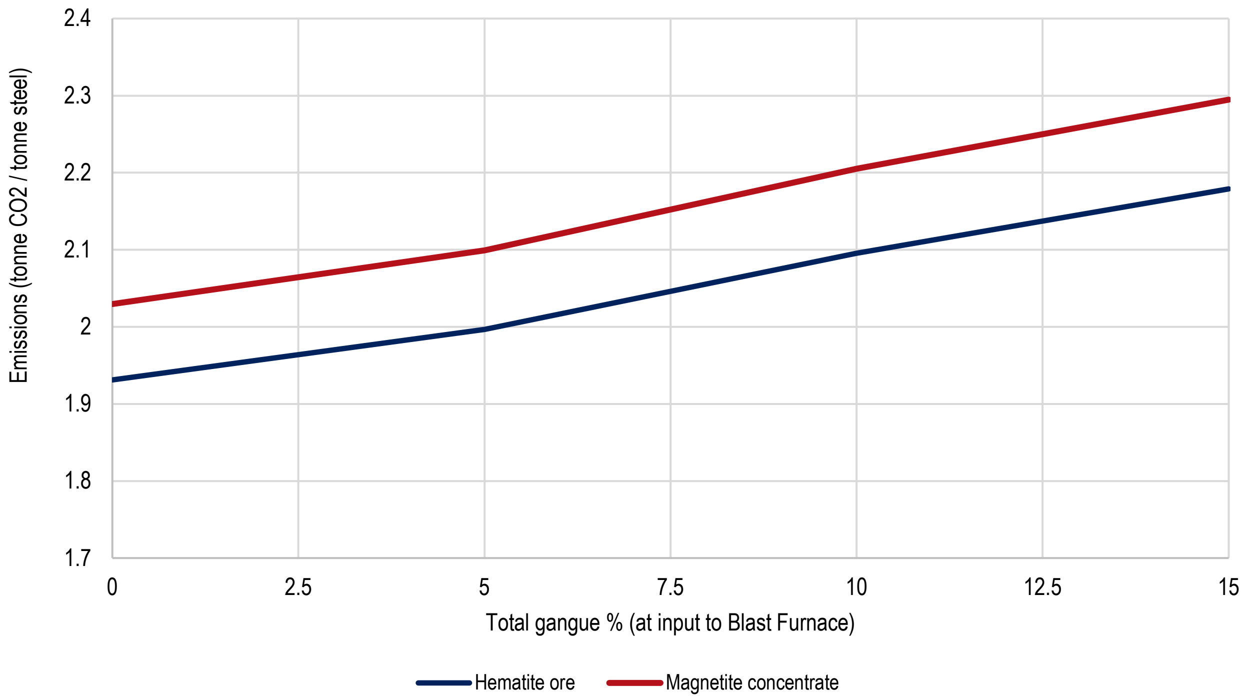
Supply of beneficiated ore to steelmakers has the potential to reduce Scope 3 emissions. Lowering the gangue content of ore, if done in a green way, reduces carbon feedstock used in BFs.

However as shown in Section 4.2.1 the vast majority of emissions occur in ironmaking. If all other emissions are eliminated (including onshore BAU iron ore mining) steelmaking would still be responsible for a carbon footprint of 1.9 tCO_2/tonne steel, or ~90% of the emissions in the value chain.

Gangue in iron ore leads to extra Scope 3 emissions in the value chain as extra coke/coal is needed in the BF process.

One pathway to address these emissions is to refine ores onshore to reduce global emissions. However, the net effect is a reduction of 0.17 tCO_2/tonne steel for every 10% reduction in gangue, as shown below. This is small compared to the baseline 1.9 tCO_2/tonne steel. Therefore, ore upgrading can only marginally improve emissions. The only truly effective way to reduce emissions in steelmaking, is to address the pollutants and current technology used in ironmaking.

Figure 7.10 Emissions in the fossil fuels steel value chain vs gangue content in ore supplied to BF



Source: GHD Analysis

Finding 10 Value chain modelling: Green Iron Ore Mining

Conversion of existing iron ore mines, and development of new iron ore mines to be emissions-free based on renewable power supplied by mixed solar/wind facilities is cost-competitive at today's cost rates, largely due to low cost and effective renewable power.

Green Iron Ore Mining, including ore upgrading through beneficiation, provides opportunity to marginally reduce emissions in the steelmaking value chain.

Potential cost savings is a natural incentive for industry to switch to renewable power and fuels in existing mining operations.

There are substantial power requirements to adopt Green Iron Ore Mining at scale.

The established power infrastructure will not only support existing industry but will also reduce ore production costs in the long run as the price of power decreases leading to substantial savings and allow energy intensive ore beneficiation to be done at lower cost.

Including hydrogen and ammonia facilities for long distance transport initiates the industrial base that will be required for further downstream processing of iron ore.

7.3 Pathway 2: Green Pellets

Current iron and steelmaking technologies rely on being fed with iron ore feedstock above a characteristic size (diameter). Lump hematite is ore of sufficient quality and mined rock diameter that can be directly fed to further processing stages. All other ore must first be agglomerated before it can be used**.**

This process can be decarbonised through the process of pelletisation which uses a hydrogen indium furnace to help form the pellets. Green pellets are a potential next step in the value chain beyond supply of green hematite ore or magnetite concentrate.

There are differing cost implications for pelletising hematite and magnetite concentrates without the use of fossil fuels due to the different energy needs involved for each ore type and additional energy supplied by oxidation processes in magnetite.

Pelletisation involves heating and binding fine iron ore into larger sized material. For the purposes of this study, pelletisation has been modelled rather than sintering as the key agglomerating technology for several reasons:

- Sinter process burns coke (is reliant on fossil fuels) and cannot be converted into a zero emissions process.
- Sinter product cannot be transported easily (it is weak and falls apart) and so cannot be used as an on-sellable standalone product. This is in comparison to pellets which are compatible with shaft-based gas reduction processes (e.g. MIDREX), unlike sinter.
- Pellets can be made from extremely finely ground product, and so is suitable technology to pelletise both magnetite concentrates and processed haematite fines.
- Pellets are a superior feedstock, increasing productivity in ironmaking processes.

The Green Pellet value chain is shown in Figure 7.11. A summary of the indicative capital and other resource requirements for Green Pellets is outlined in Table 7.4.

Figure 7.11 Green Pellets pathway

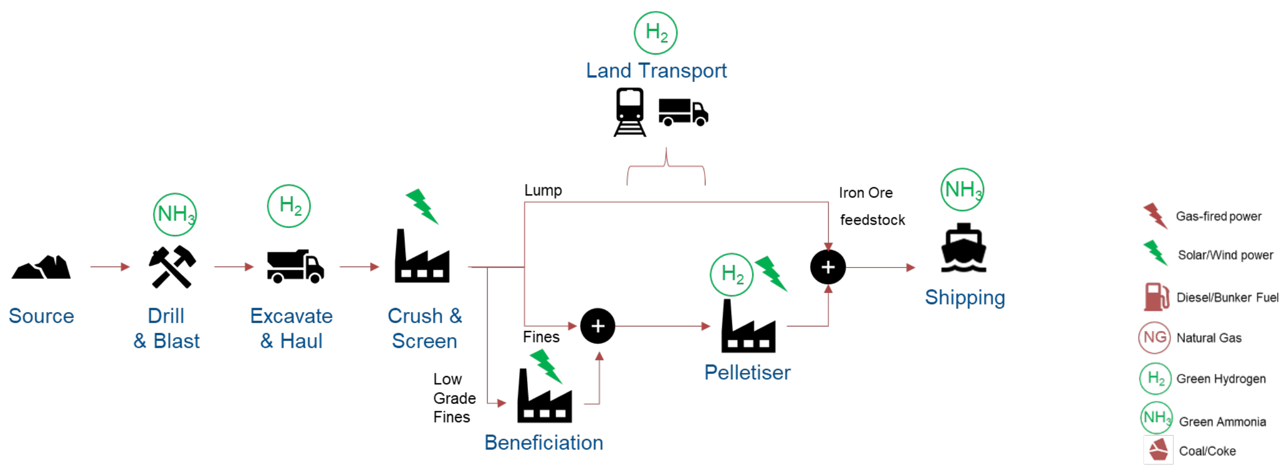


Table 7.4 *Indicative capital and other resource requirements for Green Pellets pathway*

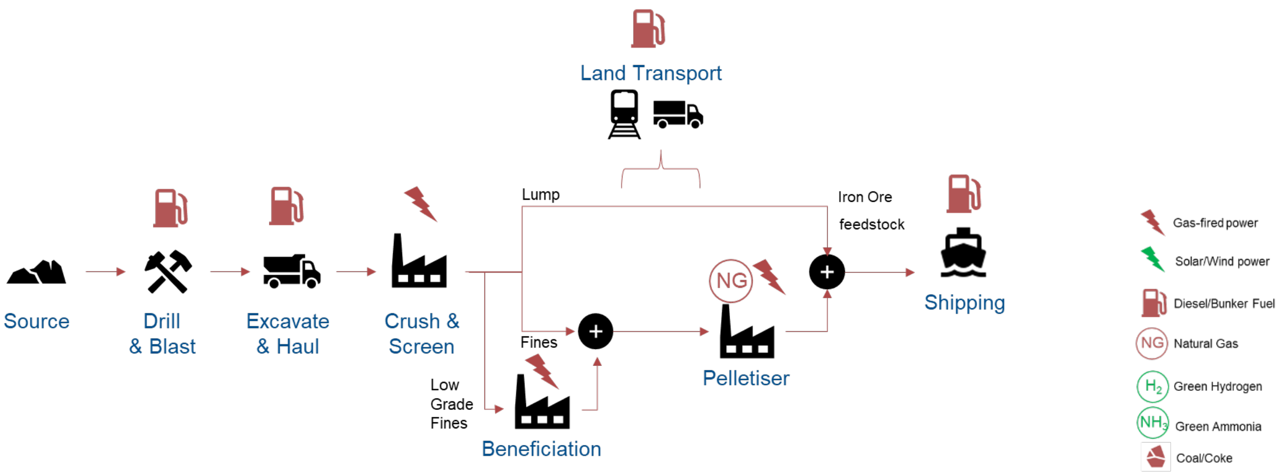
Indicative Requirements for:	1 Mtpa Shipped Green Pellets		50 Mtpa Mined Ore Shipped as Green Pellets		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$100	$140	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 pellet plants
Processing facility land use	40	40	400	200	Hectares	H:1 M:1 / H:5 M:3 pellet plants
Sustained power required	48	60	2,426	902	MW	Ongoing 24 hr load
50/50 mixed solar/wind + batteries	$430	$530	$21,412	$7,957	M AUD	Capex
Renewable facility land use	266	330	13,330	4,954	Hectares	
Annual hydrogen required	7	6	338	89	Ktpa	
Hydrogen facility	$76	$67	$3,820	$1,009	M AUD	Capex
Ammonia facility	$0.8	$0.4	$13	$6	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$1,097	$366	M AUD	Capex
Water required	407	917	20,363	13,759	ML p.a.	
Mined ore required	1.01	3.3	50	50	Mtpa	
Shipped product	1	1	49.85	15	Mtpa	

Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (4b and 6a), Magnetite (4c and 6a1))

Pelletisation of iron ore requires it be ground to a sufficiently fine size. Magnetite concentrate comes at a size suitable for pelletisation due to the beneficiation process while Western Australian hematite fines would require further grinding to make them suitable for pelletisation.

The cost build-up for pelletising magnetite concentrate with fossil fuels is presented in Figure 7.13. There is an additional cost to turn magnetite concentrate into pellets, using natural gas as a heating agent, of approximately $15 AUD/kg.

Figure 7.12 Fossil Fuel Pellets value chain

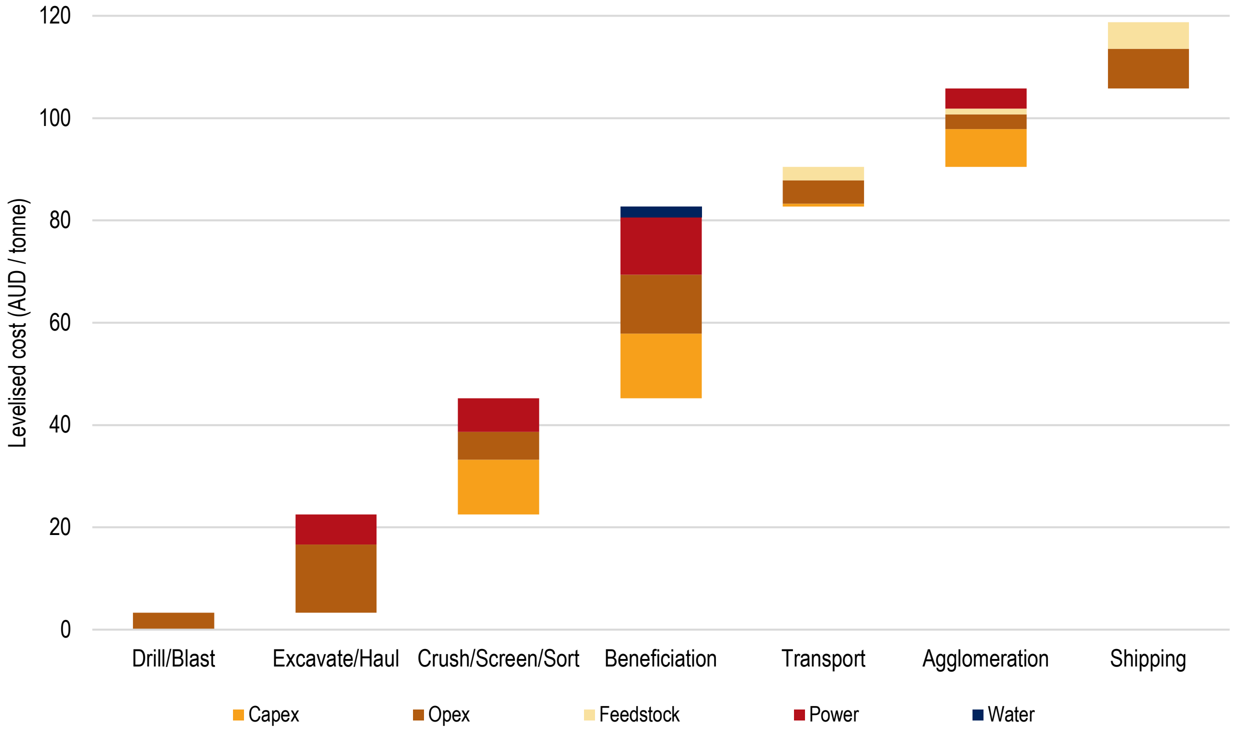


Due to the relatively small increase in costs from the iron ore baseline to pelletise magnetite, the high suitability of beneficiated magnetite pellets for use in shaft furnaces, and slimmer margins for magnetite ore (as compared to hematite) it presents a promising candidate for existing companies to expand their value chains.

Though agglomeration adds significant emissions, the largest contribution to emissions is still the electrical power used in the beneficiation step. This, combined with the reduction in cost of mixed solar/wind energy as compared to natural gas fired power plants, mean the best cost and emissions outcome for magnetite pelletisation is transitioning to renewable energy of sufficient scale.

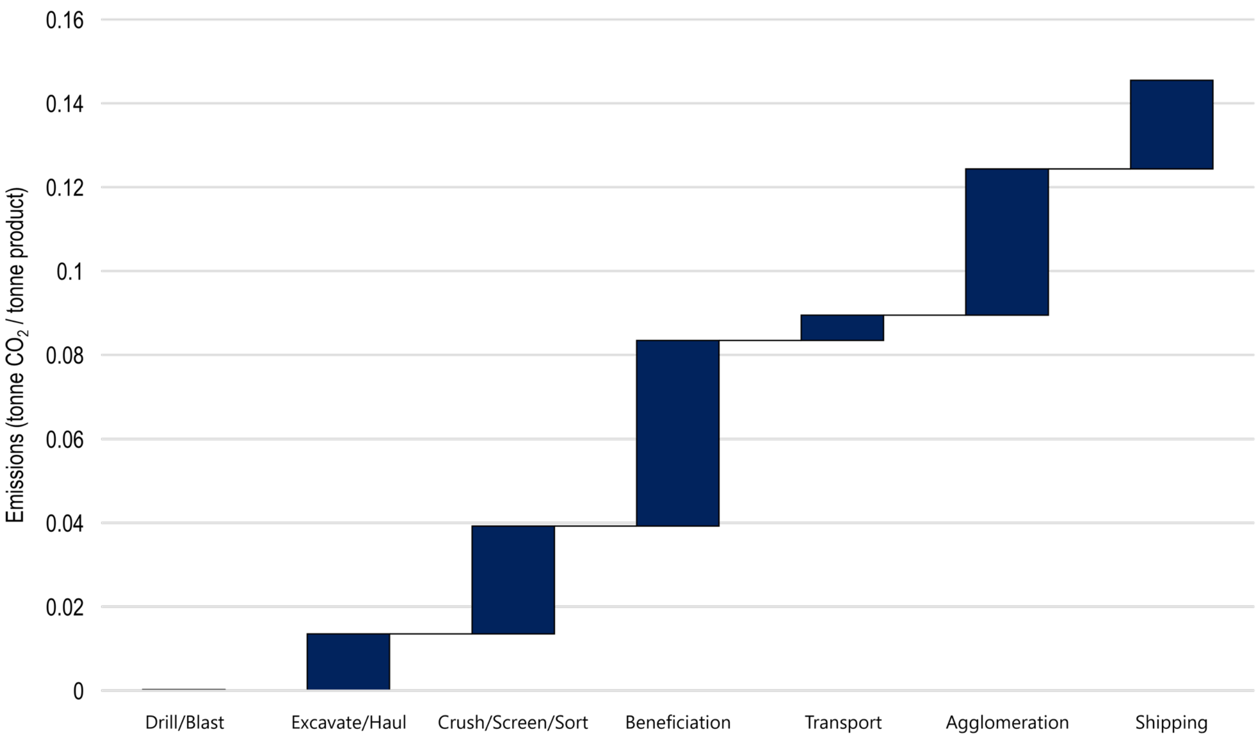
Figure 7.13 Levelised cost and emissions of magnetite pellets in a fossil fuels value chain

(a) Levelised cost build up



Source: GHD Analysis

(b) Emissions profile

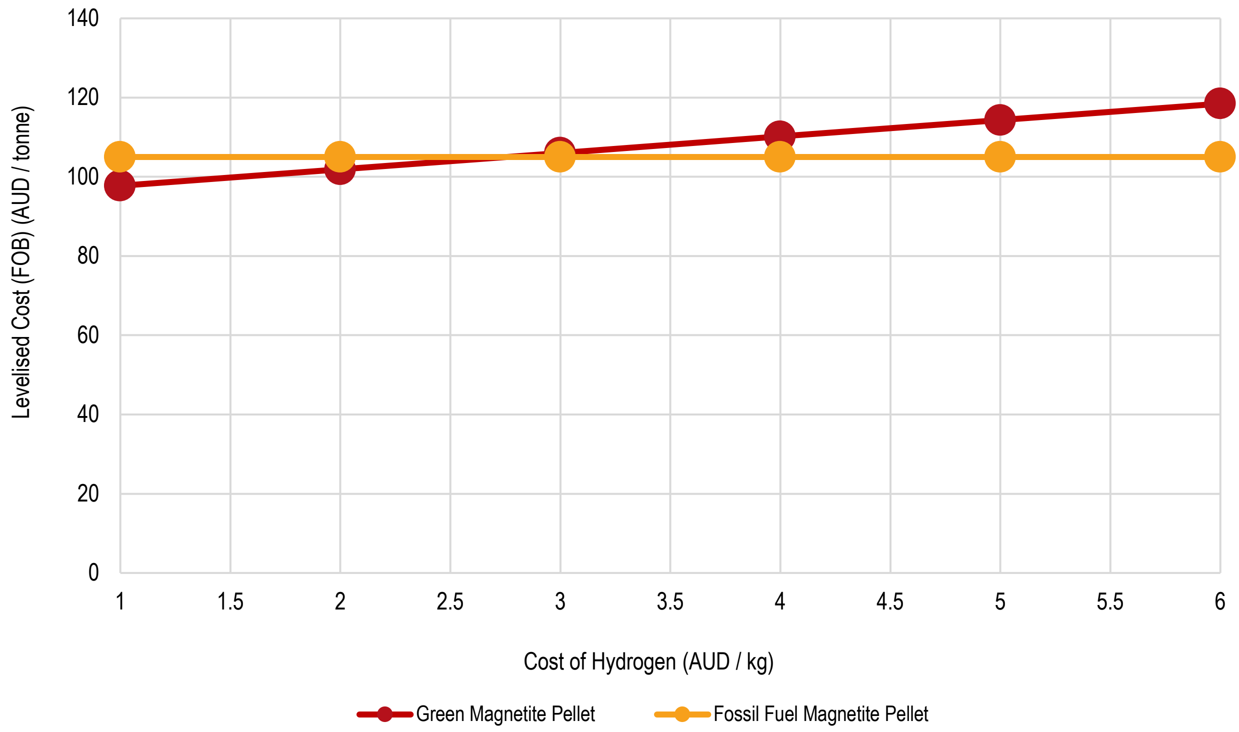


Source: GHD Analysis (Model Value Chain Scenario 3a)
Note: Analysis based on magnetite iron ore agglomerated feedstock for a fossil-fuels value chain, with assumptions as listed in the Model Basis Document.

To eliminate emissions from the magnetite agglomeration step means replacing natural gas heating in the pelletising facilities with hydrogen. This would increase the pelletising cost addition from approximately $15 AUD/tonne to $34 AUD/tonne at an assumed hydrogen price of $7 AUD/kg.

Whilst there still may be a positive cost margin at this price point, true price parity with the fossil fuels chain will be reached if renewable hydrogen costs drop below approximately $2.80 AUD/tonne as shown in Figure 7.14, assuming renewable energy is used across the value chain to derive saving from electrical energy intensive beneficiation.

Figure 7.14 Cost parity for green vs fossil fuels magnetite pellets and hydrogen price



Source: GHD Analysis
Note: Analysis based on magnetite iron ore agglomerated feedstock for a fossil-fuels value chain, with assumptions as listed in the Model Basis Document.

Although it is possible to pelletise hematite ores, typically further grinding is required in addition to the crushing it undergoes at earlier mining stages.

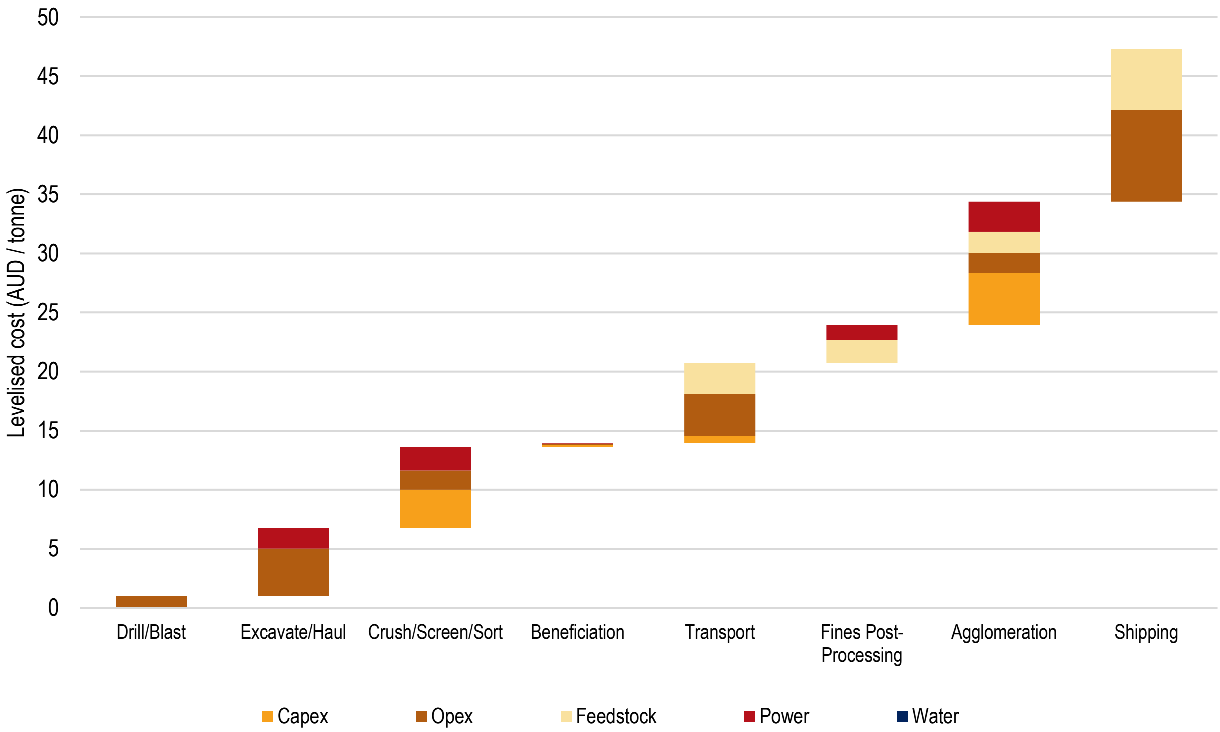
As such it is not a process currently done in the Pilbara/Mid West, however an allowance is made for this cost to estimate the agglomerated (or fully ready for ironmaking) hematite price.

The cost build-up and emissions profile for hematite ore fully agglomerated and ready for ironmaking is presented in Figure 7.15.

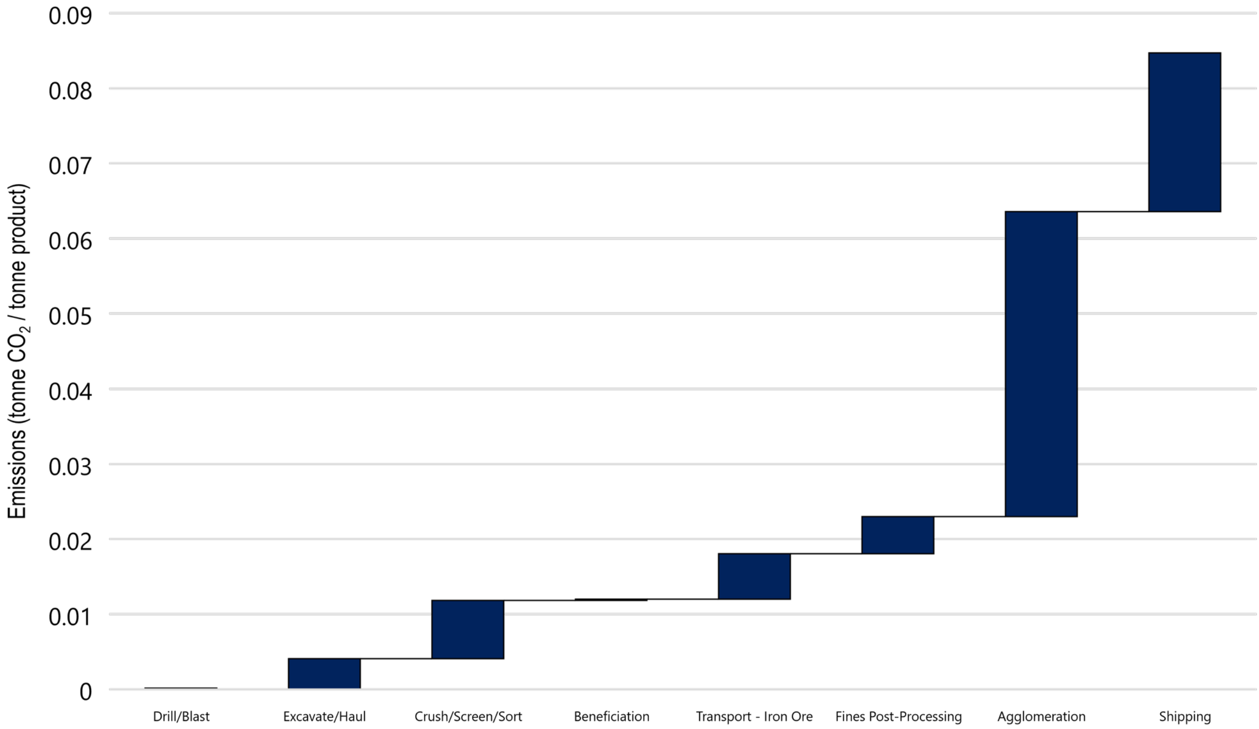
The additional processing step adds approximately $14 AUD/kg to the cost of product (inclusive of additional grinding and pelletising) and adds 0.04 tonnes CO_2 per tonne of iron ore to the value chain, representing a substantial increase.

Figure 7.15 Levelised cost and emissions of hematite pellets and lump in a fossil fuel value chain

(a) Levelised cost build up



(b) Emissions profile

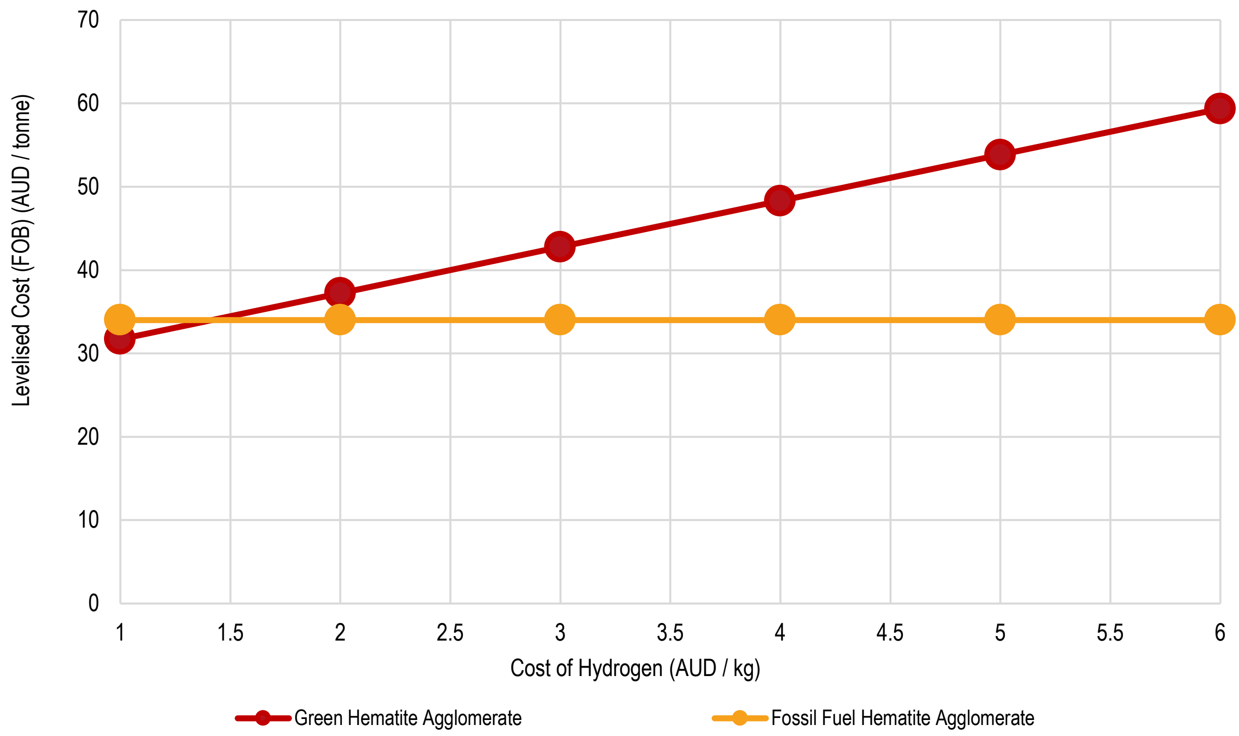


Source: GHD Analysis (Model Value Chain Scenario 3)
Note: Analysis based on hematite iron ore agglomerated feedstock for a fossil-fuels value chain, with assumptions as listed in the Model Basis Document.

If the pelletisation step were to use hydrogen instead of natural gas, the pelletisation costs for hematite jump from $14 AUD/tonne to $44 AUD/tonne at an assumed hydrogen price of $7 AUD/kg.

Due to the large energy cost of pelletising hematite, when comparing hydrogen fuelled hematite agglomeration against natural gas, the breakeven point is for hydrogen prices below $1.50 AUD/kg as shown in Figure 7.16. From this perspective, green magnetite pellets present a more economical development path than green hematite pellets.

Figure 7.16 Cost parity for green vs fossil fuels hematite pellets/lump and hydrogen price



Source: GHD Analysis
Note: Analysis based on hematite iron ore agglomerated feedstock for a fossil-fuels value chain, with assumptions as listed in the Model Basis Document.

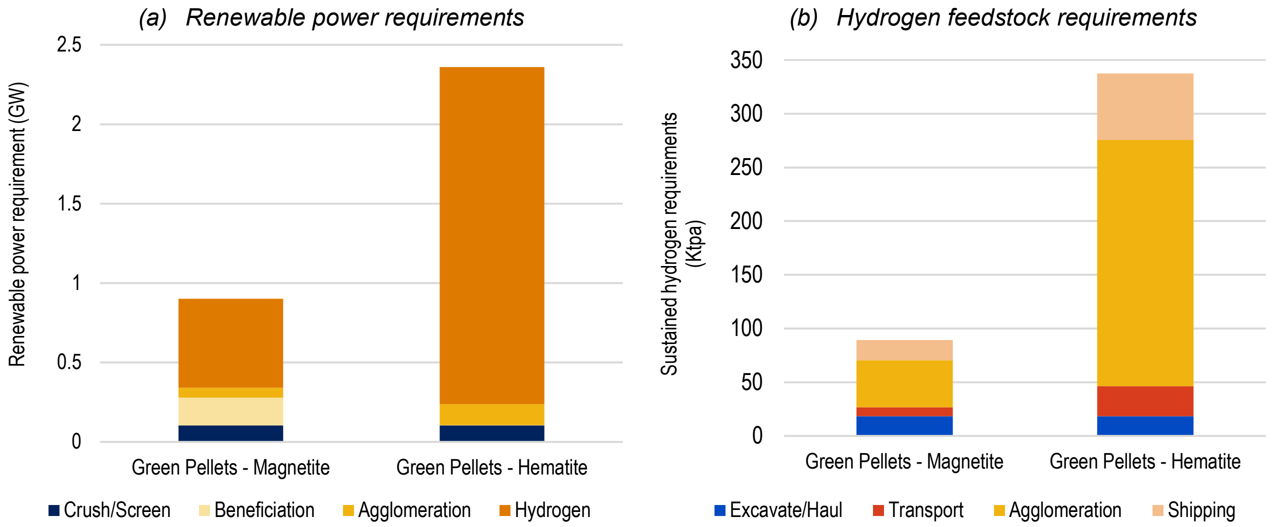
A summary of the full cost of present day pellet production (inclusive of shipping) for fossil fuels versus a green pellet value chain is shown in Figure 7.18. The levelised cost of production for the green development pathways are both higher. In the case of hematite, this is $32.96 AUD/tonne higher against only $19.66 AUD/tonne higher for magnetite. As noted, drops in the price of hydrogen will make the green pathway more competitive against fossil-fuels.

Sustained renewable power requirements for processing 50 Mtpa of ore into Green Pellets are between 1-3 GW, as shown in Figure 7.17.

The requirements are not as high for magnetite due to two factors. Firstly, yield losses in beneficiating magnetite ores mean there is around 70% less ore being fed into the pelletising process than for hematite. Secondly, the energy requirements to pelletise magnetite are less than for hematite.

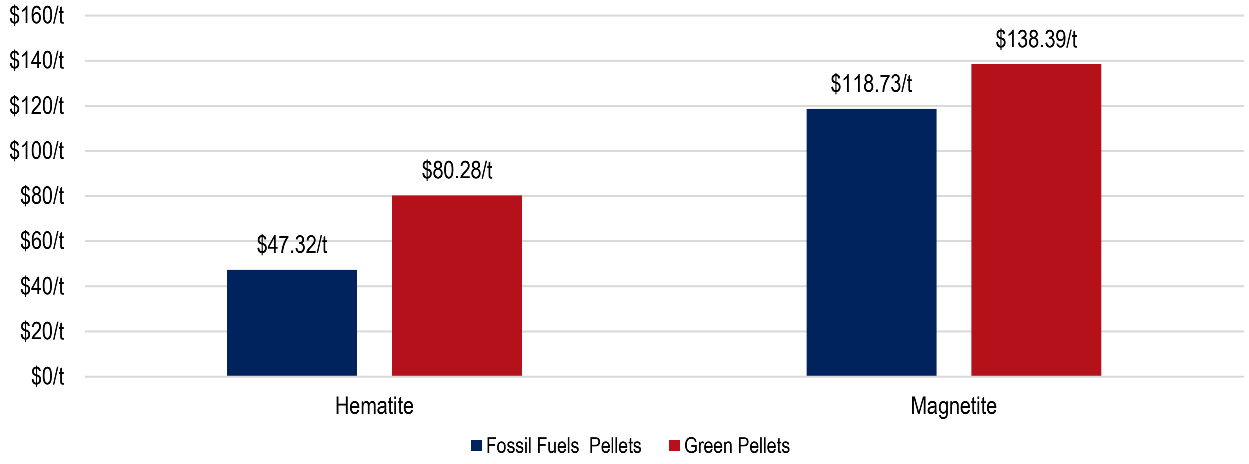
To support green pelletisation, substantial quantities of hydrogen are required to heat and form the pellets – between 50-200 Ktpa To have truly green onshore pelletising, hydrogen electrolysis capability is required to be built and scaled up.

Figure 7.17 Sustained renewable power and hydrogen feedstock requirements for 50 Mtpa mined iron ore into Green Pellets for hematite and magnetite



Source: GHD Analysis (Model Value Chain Scenarios: Hematite (3 and 4), Magnetite (3a and 4a))
Note: Analysis based on magnetite/hematite iron ore agglomerated feedstock for a renewables value chain, with assumptions as listed in the Model Basis Document.

Figure 7.18 Levelised Cost of Production (AUD/tonne), Green Pellets versus Fossil Fuels Pellets, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain Scenarios: Hematite (3 and 4), Magnetite (3a and 4a))
Notes: For H_2 cost of $7 AUD/kg

Finding 11 Value chain modelling: Green Pellets

Green Pellets are a necessary product to have fully Green Steel, however hydrogen costs are too expensive at this point to produce them competitively against the equivalent fossil fuel process.

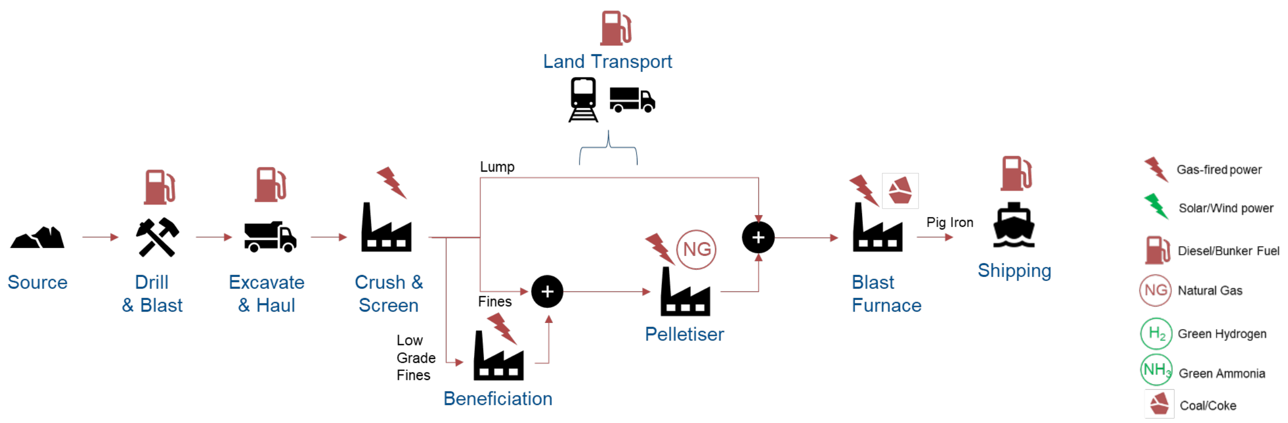
Magnetite concentrates are more economic to turn into Green Pellets, as they do not require as much heat to form pellets as hematite fines.

7.4 Pathway 3: HBI from Green Pellets using Fossil Fuels

The next value-adding process in the steelmaking value chain is to turn iron ore into iron. As discussed in Section 3, this is predominantly done through a process of putting iron ore agglomerate through a BF, as shown in Figure 7.19.

A summary of the indicative capital and other resource requirements for production of Green Pellets using fossil fuels is outlined in Table 7.5.

Figure 7.19 Brown Pellets converted to Pig Iron (BF) using fossil fuels.



One possibility for Western Australia is to take advantage of the state's abundant natural gas resources by creating Green Pellets and converting them to HBI using natural gas shaft furnaces as shown in Figure 7.20**.** All elements of this value chain use renewable energy or green fuel sources, except for the iron reduction that occurs in the shaft furnace.

Figure 7.21 shows the typical cost and emissions profile for pig iron produced with a BF route and a fully fossil fuels value chain, and Figure 7.22 shows the equivalent costs and emissions for Green Pellets converted to HBI using natural gas.

Due to the cost of natural gas, HBI can be produced for around $200/tonne cheaper than the equivalent pig iron product produced via the coal-fired BF route. This means this way of making HBI is highly competitive against existing iron production practices as shown in Figure 7.19, even with the additional expense of hydrogen use in pelletisation which is assumed to not come down in price from the base assumption cost.

Currently, every tonne of iron produces 1.7 t/CO_2 – all considered Scope 3 as they are produced by steelmaking countries overseas. The transition iron product can reduce overall emissions across the value chain by up to ~70%.

One of the consequences of this approach is the emissions from the shaft furnace will be brought onshore due to the conversion of natural gas to carbon dioxide. This amounts to around 0.5 tCO_2/t iron, however it is important to note this will reduce the overall emissions compared to existing ironmaking value chains that use BFs.

This reduction in emissions is potentially increased further if lower gangue Western Australian ores are used, the HBI impurities are a driver of still further Scope 3 steelmaking energy use, reducing emissions at a rate of ~0.01 tCO_2/tonne steel made with fossil-fuels EAF per 1% gangue removed.

The gangue contents of the current ores can be reduced by increase the beneficiation rate or by targeting higher grade reserves.

Figure 7.20 HBI from Green Pellets using Fossil Fuels pathway

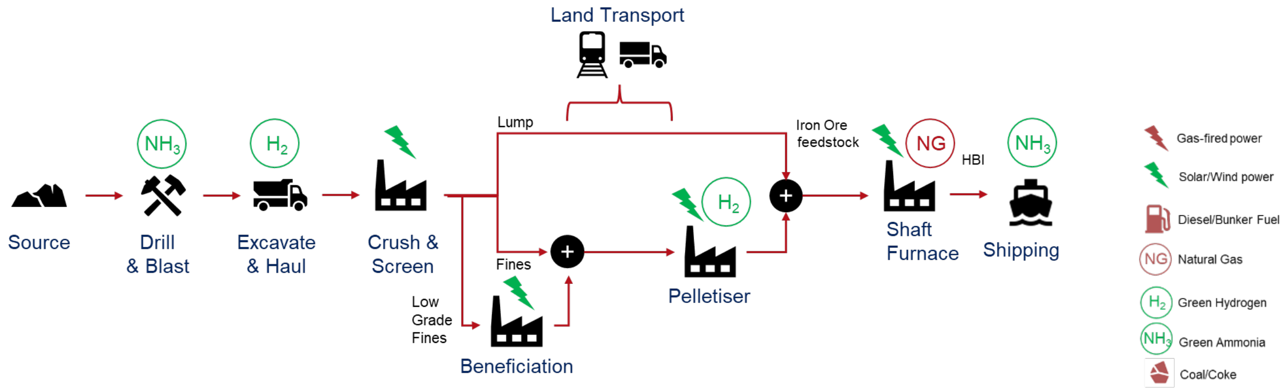
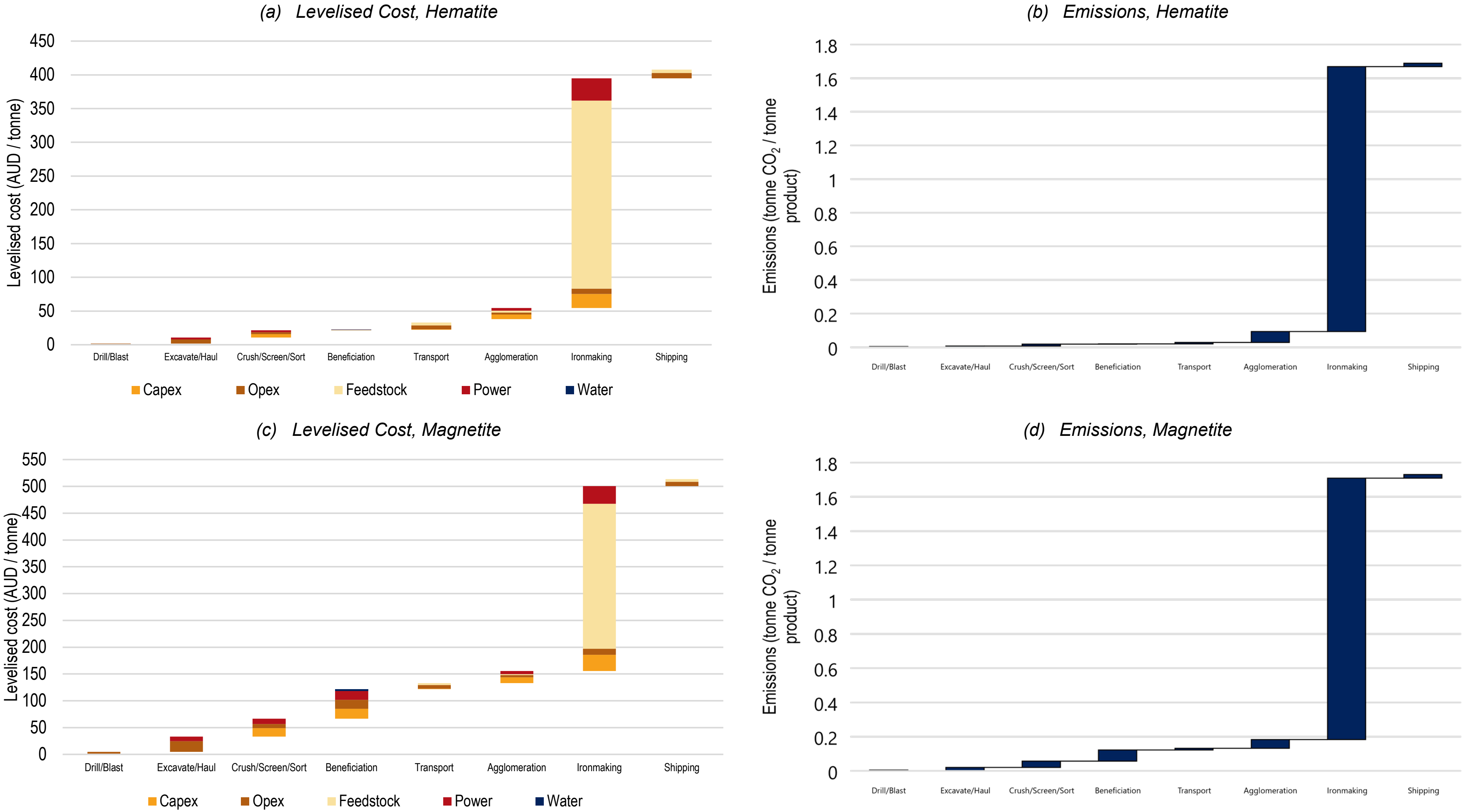


Table 7.5 Indicative capital and other resource requirements for HBI from Green Pellets using Fossil Fuels pathway

Indicative Requirements for:	1 Mtpa Shipped HBI from Natural Gas		50 Mtpa Mined Ore Shipped as HBI from Natural Gas		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$145	$198	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 x pellet plants
Shaft furnace	$1,400	$1,400	$14,230	$6,720	M AUD	Capex - H:1 M:1 / H:10 M:3 x shaft furnaces
Processing facility land use	140	140	1,400	500	Hectares	H:1 M:1 / H:5 M:3 x pellet plants H:1 M:1 / H:10 M:3 x shaft furnaces
Sustained power required	105	120	3,307	1,197	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$926	$1,050	$29,192	$10,566	M AUD	Capex
Renewable facility land use	576	657	18,173	6,577	Hectares	
Annual hydrogen required	10	8	315	83	Ktpa	
Hydrogen facility	$112	$94	$3,559	$942	M AUD	Capex
Ammonia facility	$0.8	$0.4	$10	$4	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$731	$244	M AUD	Capex
Water required	602	1,340	18,981	13,399	ML p.a.	
Natural gas	182	182	5,720	1,857	Ktpa	For use in shaft furnace
Mined ore required	1.59	4.88	50	50	Mtpa	
Shipped product	1	1	31	10	Mtpa	

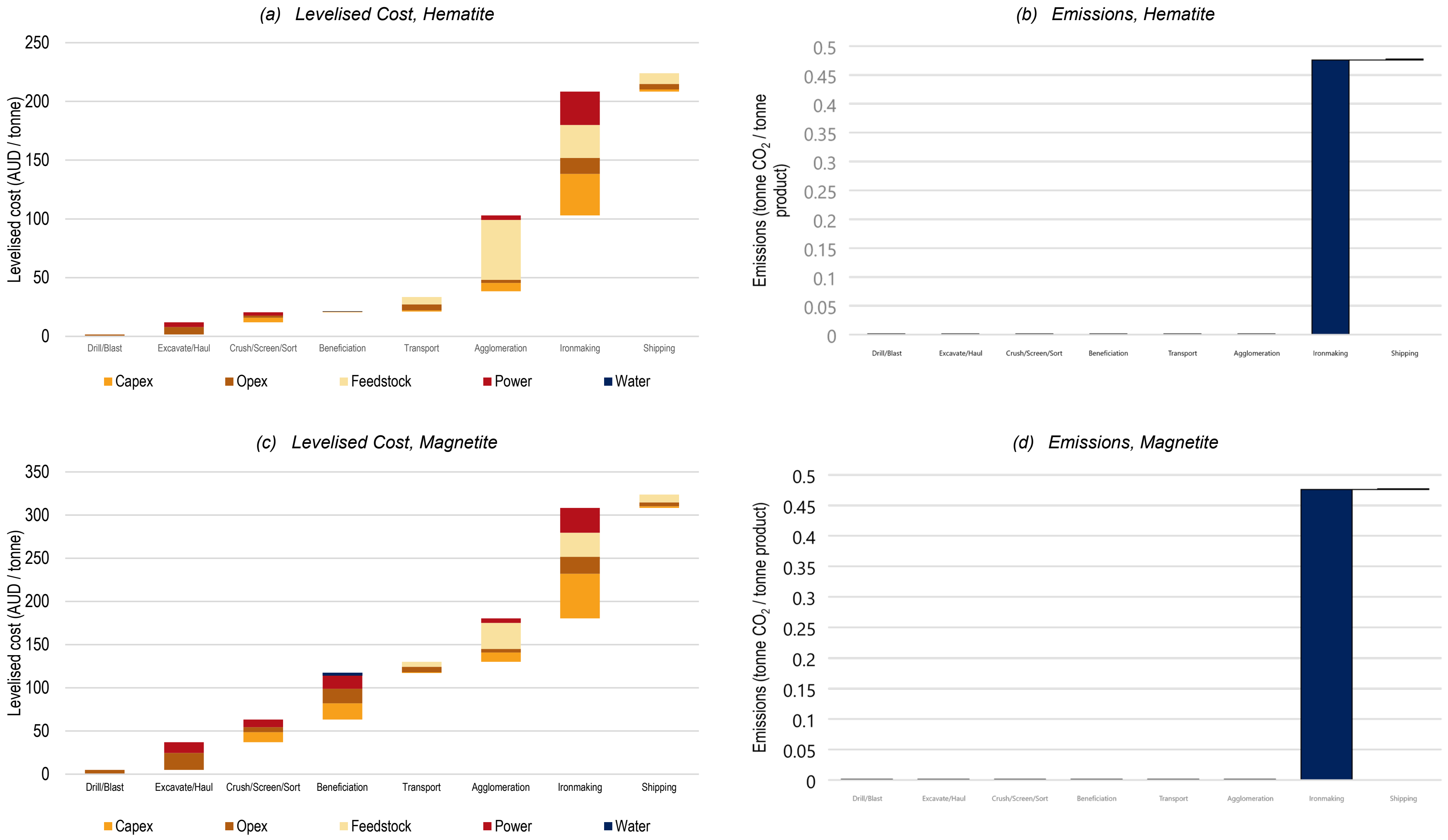
Source: GHD Model Value Chain (Scenarios: Hematite (6a2 and 6a), Magnetite (6a3 and 6a1)); MRIWA

Figure 7.21 Pig iron made with fossil fuels, cost and emissions, 50 Mtpa iron ore mined



Source: GHD Analysis (Model Value Chain Scenarios 5, and 5b)
Note: Analysis based on pig iron production for a fossil-fuels value chain, with assumptions as listed in the Model Basis Document.

Figure 7.22 Green Pellets converted to HBI using fossil fuels, cost and emissions, 50 Mtpa iron ore mined

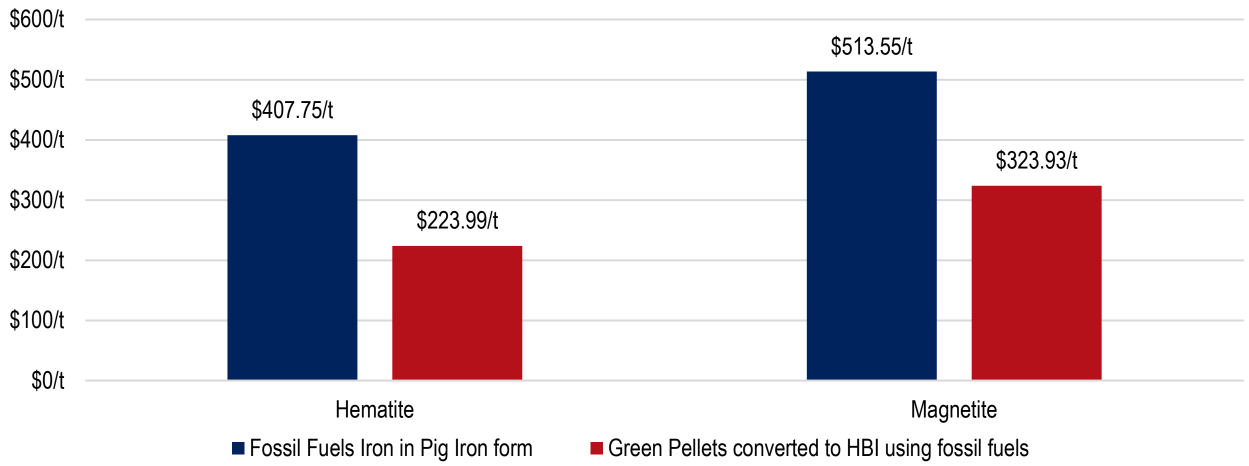


Source: GHD Analysis (Model Value Chain Scenario 6a, 6a1)
Note: Analysis based on Green Pellets and HBI produced with natural gas shaft furnaces value chain, with assumptions as listed in the Model Basis Document.

No additional hydrogen is needed for this value chain (per tonne mined) compared to the Green Pellet value chain, as the shaft furnace uses a natural gas feedstock. The shaft furnaces have an additional electrical energy requirement of ~0.28 MWh/tonne of HBI produced, to power the facility.

One final important consideration is replacement of hydrogen in shaft furnaces is not all-or-nothing but can be a staged process where the gas blend can be varied over time, and so use of natural gas to make HBI from Green Pellets may lend itself well to transitioning to a fully green iron industry.

Figure 7.23 Levelised Cost of Production (AUD/tonne), HBI from Green Pellets using Fossil Fuels versus Fossil Fuels Iron in Pig Iron form, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain Scenarios: Hematite (5 and 6a), Magnetite (5b and 6a1))
Notes: For H_2 cost of $7 AUD/kg

Finding 12 Value chain modelling: HBI from Green Pellets using Fossil Fuels

Green Pellets converted to HBI using fossil fuels are a cost competitive product when compared to pig iron produced with BFs, the dominant process for ironmaking today

This approach will onshore Scope 3 emissions. However, it has the potential to reduce overall emissions from ironmaking when compared to the pig iron BF route.

Shaft furnaces running on natural gas may be transitioned to hydrogen feedstock over time to produce fully Green Steel.

7.5 Pathway 4: Iron making – HBI from Green Pellets using Renewable Hydrogen

Iron-making via the traditional BF routes is incredibly carbon-intensive, with the value chain responsible for emitting up to 1.7 tCO2/tonne of pig iron produced as discussed above. To make truly Green Iron, such as HBI, the carbon use in blast furnacing must be fully replaced. The most promising way in which this could be done is to use shaft furnaces that fully utilise green hydrogen as a reductant and heating agent in the conversion of iron ore to iron.

The product from this pathway is assumed in the modelling for this report to be Green Iron in the form of HBI. Other green iron products however would give similar results.

This section considers a fully green iron product and is very similar to the value chain presented above, with the change to using fully green hydrogen in the shaft furnace as shown in Figure 7.24**.**

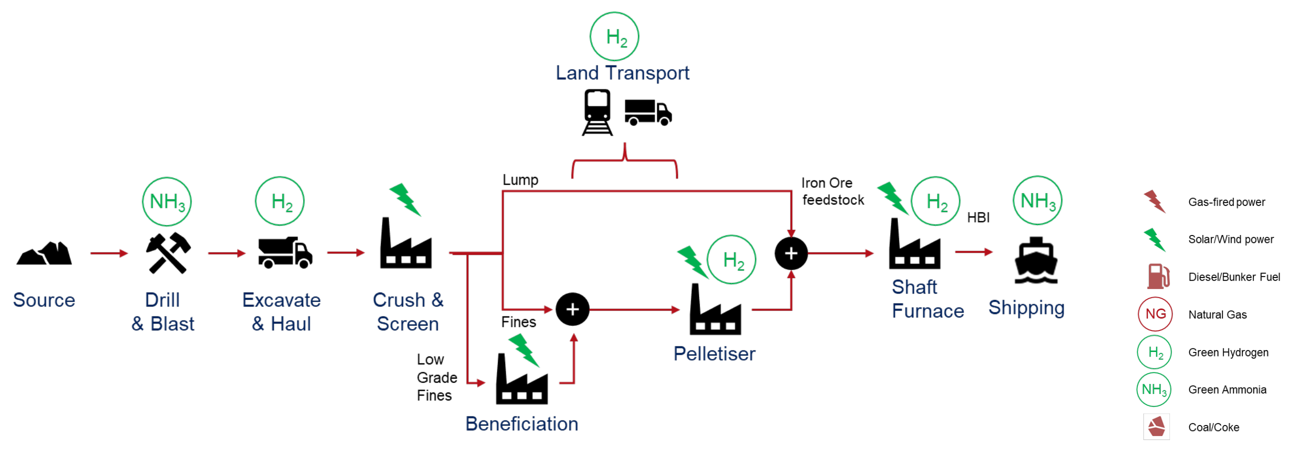
The biggest infrastructure changes in going to a fully green iron value chain are the substantial scale-up required of power facilities of around $4 billion AUD per Mt of HBI produced. Most of the power is required for hydrogen production, costing ~$780 million AUD per Mt of HBI, the full power requirements of this value chain are shown in Table 7.6 below.

When hydrogen fully replaces fossil-fuels based transport fuel, reduction and heating agents, and along with the use of renewable power, makes this value chain emissions free. Around 70 Ktpa of hydrogen is required to produce and ship 1 Mt of HBI, as shown in Table 7.6 below.

A comparison of the levelised costs of Green Iron in the form of HBI with the cost of fossil fuels pig iron in Figure 7.25 reveals a green premium of approximately $200 AUD/tonne. This largely stems from the relatively high cost of green hydrogen used in the modelling ($7 AUD/tonne), and its importance to the process of ironmaking.

The basis for this cost of hydrogen and what is required to reduce it is further discussed in Section 7.7.2.

Figure 7.24 HBI from Green Pellets using Renewable Hydrogen pathway



Given green hydrogen prices are expected to fall in the future and the key role it plays in setting the price of HBI and steel, a key question is how low would the price of hydrogen have to be to reach cost parity with BF (fossil fuels energy) pig iron production?

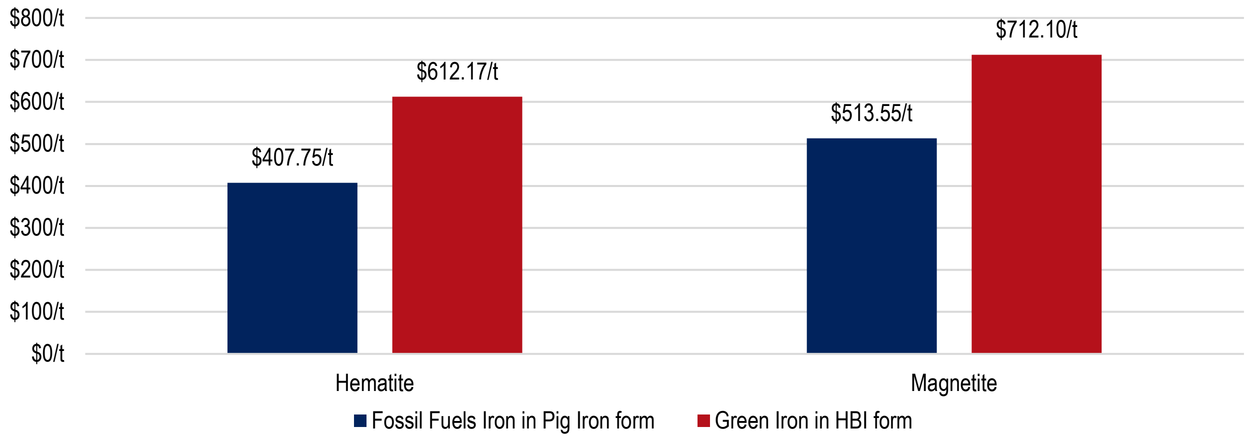
The analysis for this is summarised in Figure 7.26 which compares the levelised cost against a range of hydrogen costs for the fossil-fuel and green value chains. Price parity is reached for Green Iron in the form of HBI at a hydrogen price of $4 AUD/kg.

Table 7.6 Indicative capital and other resource requirements for HBI from Green Pellets using Renewable Hydrogen pathway

Indicative Requirements for:	1 Mtpa Shipped 100% Green Iron in the form of HBI		50 Mtpa Mined Ore Shipped as 100% Green Iron in the form of HBI		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$145	$198	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 x pellet plants
Shaft furnace	$1,400	$1,400	$14,230	$6,720	M AUD	Capex – H:1 M:1 / H:10 M:3 x shaft furnaces
Processing facility land use	140	140	1,400	500	Hectares	H:1 M:1 / H:5 M:3 x pellet plants H:1 M:1 / H:10 M:3 x shaft furnaces
Sustained power required	477	500	15,039	5,006	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$4,200	$4,300	132,738	44,186	M AUD	Capex
Renewable facility land use	2,600	2,700	82,633	27,507	Hectares	
Annual hydrogen required	69	69	2,183	690	Ktpa	
Hydrogen facility	$783	$779	24,676	7,798	M AUD	Capex
Ammonia facility	$0.8	$0.4	10	4	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$731	$244	M AUD	Capex
Water required	4,000	5,000	131,093	49,800	ML p.a.	
Mined ore required	1.59	4.88	50	50	Mtpa	
Shipped product	1	1	31.43	10.21	Mtpa	

Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (6c and 6), Magnetite (6d and 6b)); MRIWA

Figure 7.25 Levelised Cost of Production (AUD/tonne), HBI from Green Pellets using Renewable Hydrogen versus Fossil Fuels in Pig Iron form, 50 Mtpa mined ore



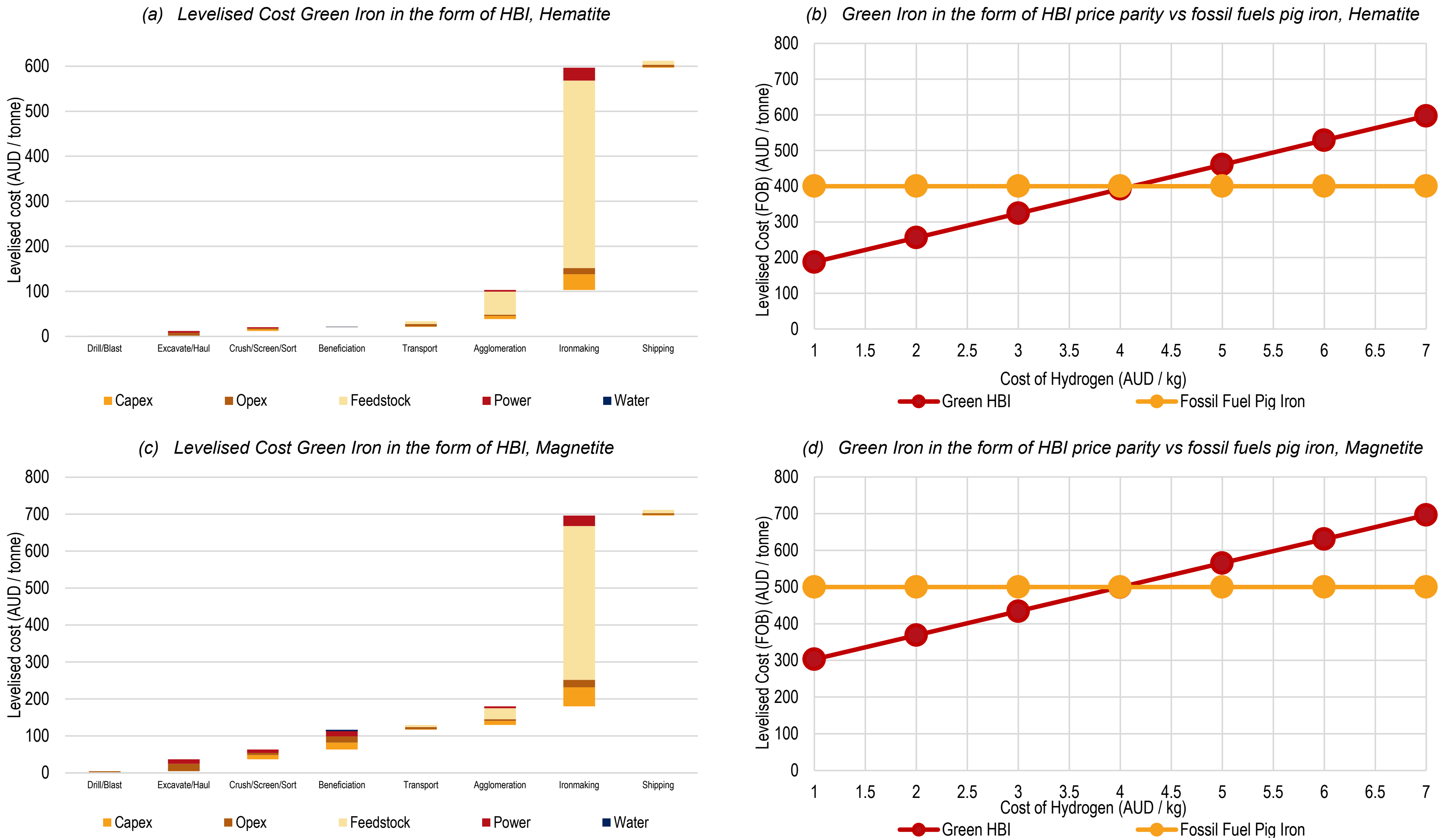
Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (5 and 6), Magnetite (5b and 6b))

Finding 13 Value chain modelling: HBI from Green Pellets using Renewable Hydrogen (Green Iron in the form of HBI)

Green Iron in the form of HBI produced from shaft furnaces can potentially replace coke and natural gas for ironmaking, eliminating emissions from this carbon intensive stage.

Green Iron in the form of HBI can be economically produced when compared to BF produced pig iron when the hydrogen price reaches $4 AUD/kg.

Figure 7.26 Green Iron in the form of HBI levelised costs and Hydrogen price parity points with fossil fuels pig iron, 50 Mtpa iron ore mined



Source: GHD Analysis (Model Value Chain Scenario 6 and 10a, switching from hematite to magnetite)
Note: Analysis based on HBI and steel production for a renewables value chain, with assumptions as listed in the Model Basis Document.

7.6 Pathway 5: Producing Green Steel in Western Australia

In moving to a fully Green Steel solution, shaft furnaces with a hydrogen heating and reducing agent replace BFs, and EAFs utilising renewable power which can turn green iron into Green Steel are necessary.

Fossil fuels used in powering operations and providing electrical power are replaced with renewable alternatives. This replaces the traditional BF steelmaking route as shown in Figure 7.27.

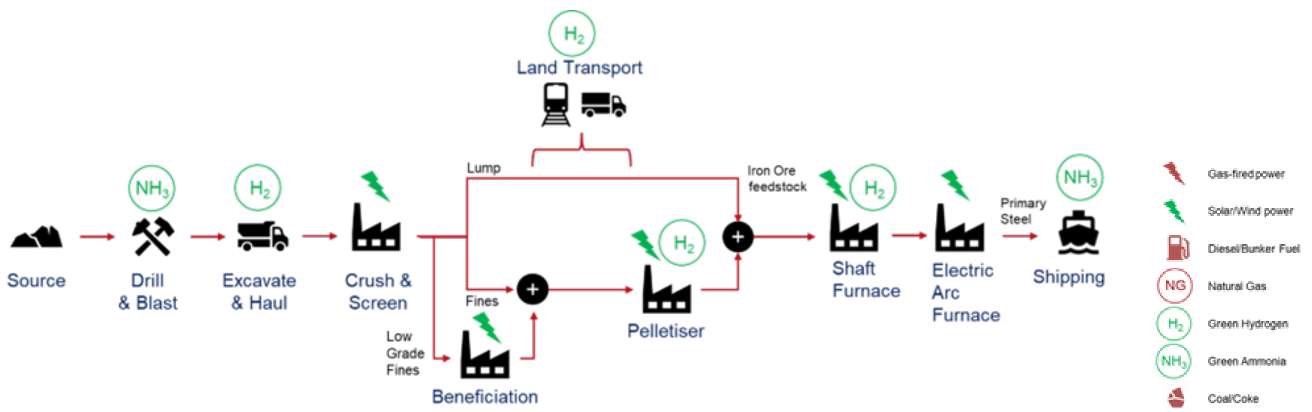
While this is not the only possible Green Steel value chain, it is considered the most feasible in the near to medium term due to:

1. It is a truly green value chain that does not rely on carbon capture.
2. The only alternative to this is iron reduction process which uses bio-fuels, however this is not as scalable as hydrogen-based iron reduction. Bio-fuel methods rely on slow plant growth rather than daily creation of hydrogen reductant directly from available power sources.

A fully Green Steel solution would produce almost no emissions along the value chain. All land and ocean transport use green hydrogen or green ammonia fuel sources. All onshore process plants from crush and screen through to electric arc furnacing use renewable electrical power and green hydrogen feedstock where required.

A summary of the infrastructure requirements to support a Green Steel value chain are shown in Table 7.7. Similarly to the Green Iron in the form of HBI case, the largest cost is supporting power infrastructure, which costs around $5-6 billion AUD for 1 Mtpa of shipped Green Steel. Most of this power is used in the manufacture of hydrogen, primarily for reduction of hydrogen.

Figure 7.27 Green Steel - Fully decarbonised iron ore to steelmaking pathway



The levelised cost and emissions for existing (fossil fuel) BF-BOF steelmaking are shown in Figure 7.28**.**

As with ironmaking, the dominating contribution to the cost profile is the ironmaking step, which involves substantial feedstock costs from pulverised coal injection (or PCI) coke and metallurgical coke.

This also results in the enormous increase in emissions from the previous stages of the value chain to several tonnes of CO_2 per tonne of product.

As hydrogen replaces coal and coke for ironmaking in the Green Steel scenario, its usage will be substantial and will be the key cost driver, as shown in the levelised cost for Green Steel Figure 7.29.

Table 7.7 Indicative capital and other resource requirements for Green Steel pathway

Indicative Requirements for:	1 Mtpa Shipped Green Steel		50 Mtpa Mined Ore Shipped as Green Steel		Units	Comments
	Hematite	*Magnetite*	*Hematite*	*Magnetite*		
Pelletisation facility	$162	$216	$2,800	$1,400	M AUD	Capex – H:1 M:1 / H:5 M:3 x pellet plants
Shaft furnace	$1,500	$1,500	$14,230	$6,720	M AUD	Capex - H:1 M:1 / H:10 M:3 x shaft furnaces
EAF facility	$240	$240	$2,200	$1,035	M AUD	H:1x M:1 / H:15 M:5x x EAF
Processing facility land use	230	230	1,550	680	Hectares	H:1 M:1 / H:5 M:3 x pellet plants H:1 M:1 / H:10 M:3 x shaft furnaces H:1 M1x / H:15 M:x3 EAF
Sustained power required	638	638	17,554	5,743	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$5,600	$5,600	$154,937	$50,693	M AUD	Capex
Renewable facility land use	3,500	3,500	96,452	31,557	Hectares	
Annual hydrogen required	79	76	2,179	688	Ktpa	
Hydrogen facility	$895	$864	$24,620	$7,780	M AUD	Capex
Ammonia facility	$0.8	$0.4	$9	$4	M AUD	Capex
H_2 rail trains	$14	$14	$421	$131	M AUD	Capex
Ammonia-powered vessels	$60	$60	$609	$244	M AUD	Capex
Water requirements	4,700	5,500	130,795	49,704	ML p.a.	Capex
Mined ore required	1.82	5.89	50	50	Mtpa	
Shipped product	1	1	27.47	8.92	Mtpa	

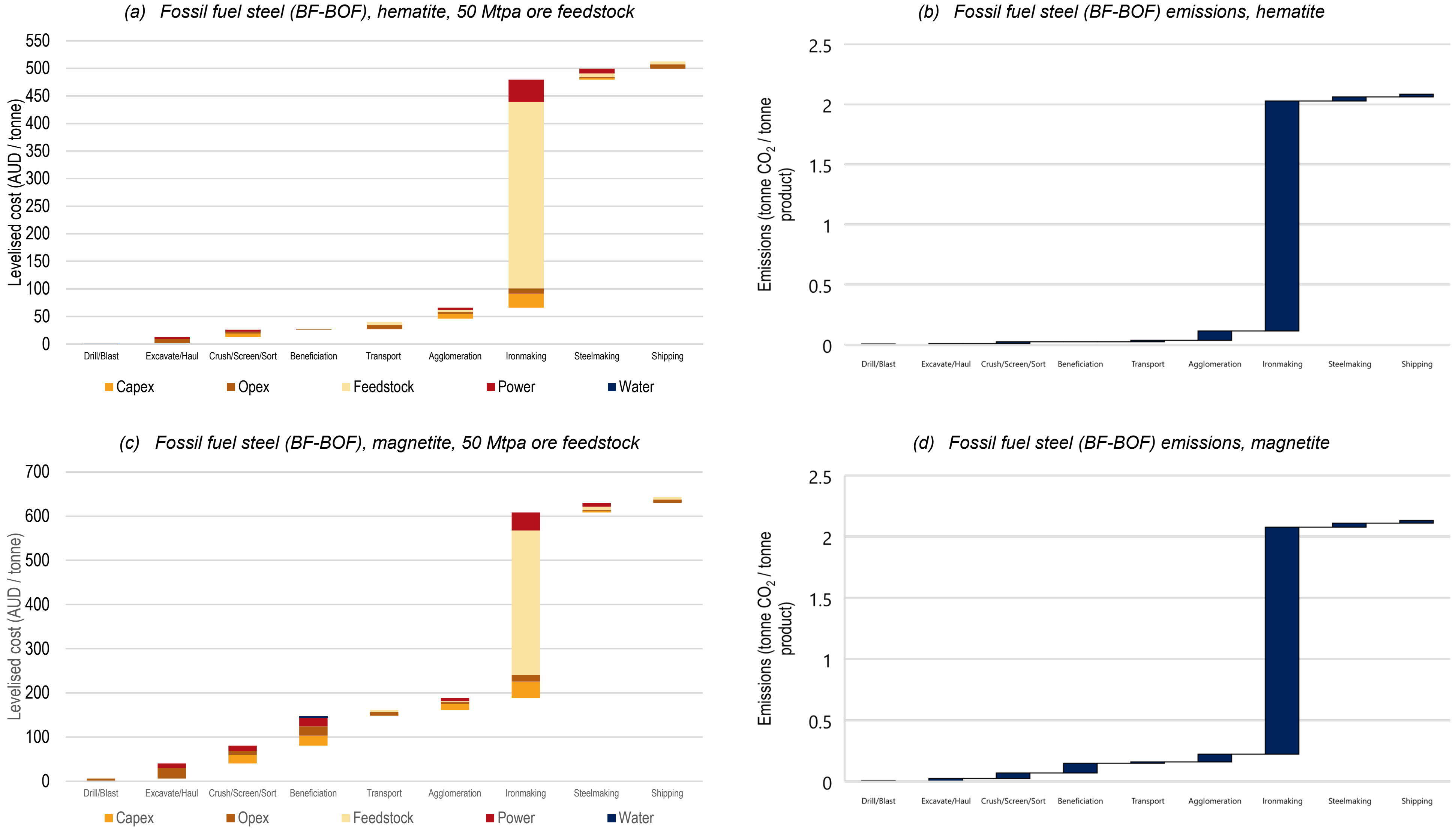
Source: GHD Analysis (Model Value Chain Scenarios: Hematite (10a1 and 10a), Magnetite (10b1 and 10b)); MRIWA

There are also substantial electrical energy requirements associated with steelmaking in the EAFs, accounting for around 10% of overall costs in the value chain. The amortised capital component is a relatively small contribution to overall costs, despite overall capital costs to establish Green Steel being significant.

Consequently, the make-or-break viability of Green Steel in competition with traditional steelmaking comes down to the cost of hydrogen. A like-for-like cost comparison of Green Steel against fossil fuels steel for assumed hydrogen prices of $7 AUD/kg is shown in Figure 7.30.

The levelised costs of Green Steel compared to fossil fuel steel is significantly higher. In a market with competitive margins, Western Australian Green Steel would need to see lowering of the hydrogen production costs and the renewable power price to be competitive. The breakeven price is met when hydrogen costs fall below $3.20 AUD/kg, shown in Figure 7.31.

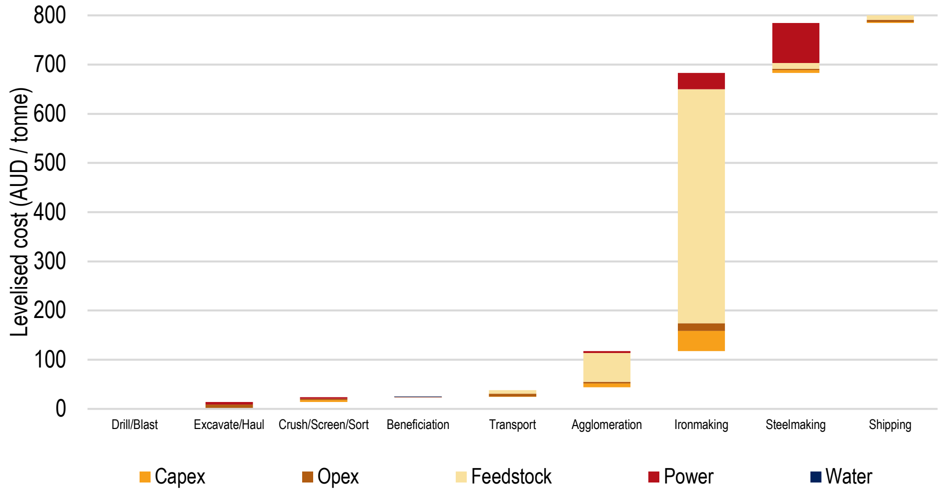
Figure 7.28 Existing (fossil fuel) BF-BOF steelmaking value chain levelised costs and emissions



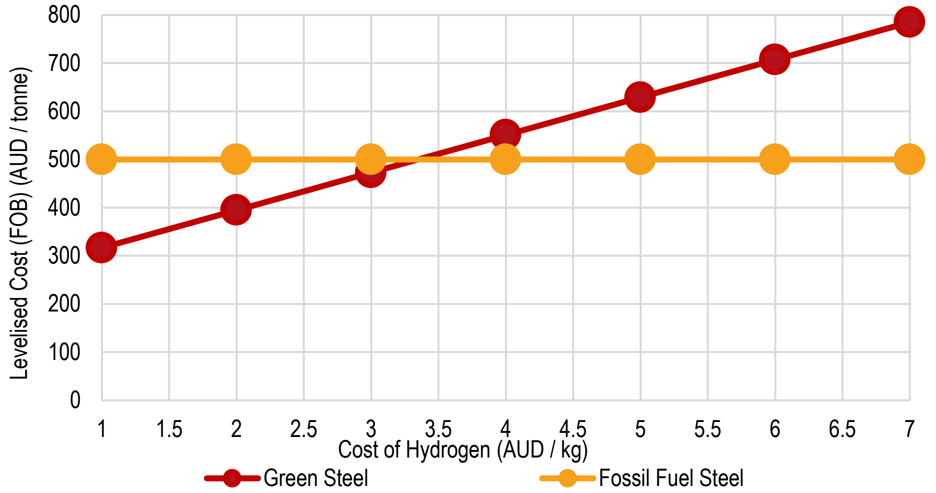
Source: GHD Analysis (Model Value Chain Scenario 9c and 9c1)
Note: Analysis based on HBI and steel production for a renewables value chain, with assumptions as listed in the Model Basis Document.

Figure 7.29 Green Steel value chain levelised costs and hydrogen price parity points with fossil fuels steel

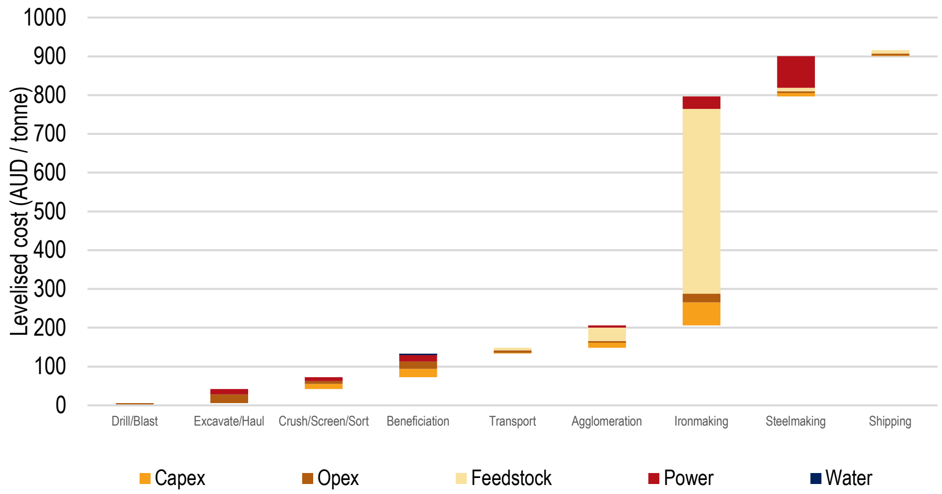
(a) Green Steel (shaft furnace-EAF), hematite, 50 Mtpa ore feedstock



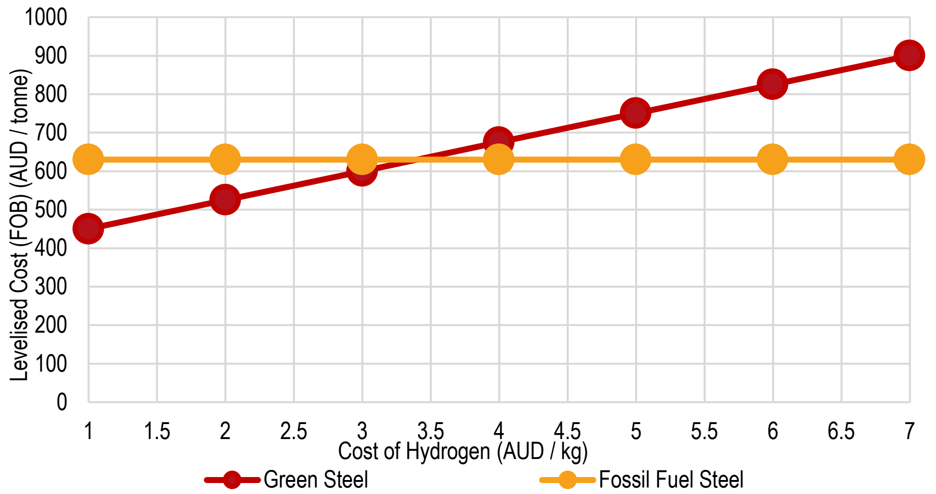
(b) Green Steel price parity vs fossil fuels steel, Hematite



(c) Green Steel (shaft furnace-EAF), magnetite, 50 Mtpa ore feedstock

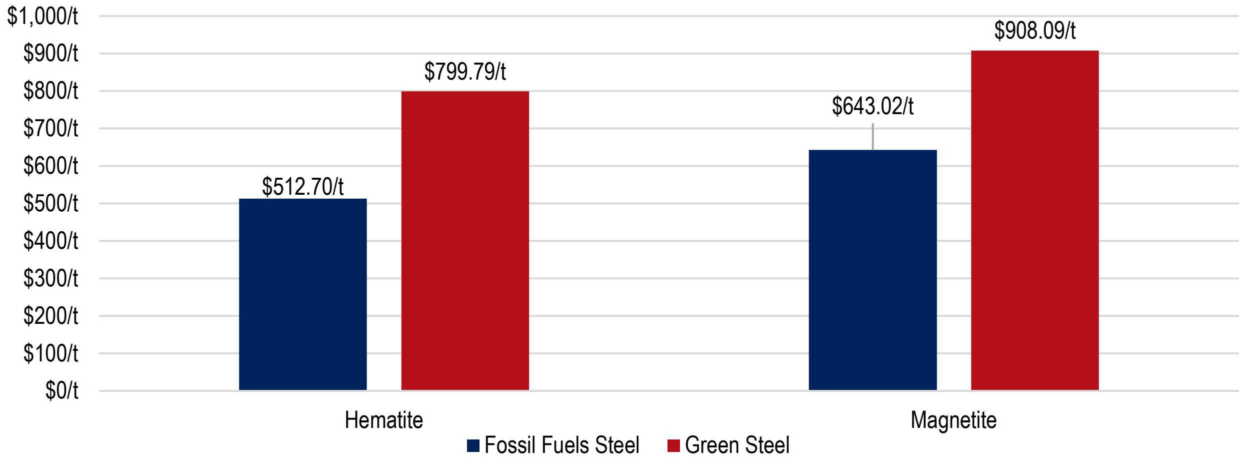


(d) Green Steel price parity vs fossil fuels steel, Magnetite



Source: GHD Analysis (Model Value Chain Scenario 10a and 10b)
Note: Analysis based on HBI and steel production for a renewables value chain, with assumptions as listed in the Model Basis Document.

Figure 7.30 Levelised Cost of Production (AUD/tonne), Green Steel versus Fossil Fuels Steel, 50 Mtpa mined ore



Source: GHD Analysis (Model Value Chain Scenarios: Hematite (9c and 10a), Magnetite (9c1 and 10b))
Notes: For H_2 cost of $7 AUD/kg

The price of power also strongly affects costs, particularly for electric arc furnacing, but it also dictates the price at which green hydrogen can be produced. The scales of production for green hydrogen are significant - around 0.08 MT of hydrogen is required to produce 1 MT of Green Steel. Power costs and how they affect hydrogen costs are discussed in Section 7.7.2 and total energy use for Green Steelmaking are shown in Figure 7.41.

Impacts of ore gangue on the cost of production of Green Steel

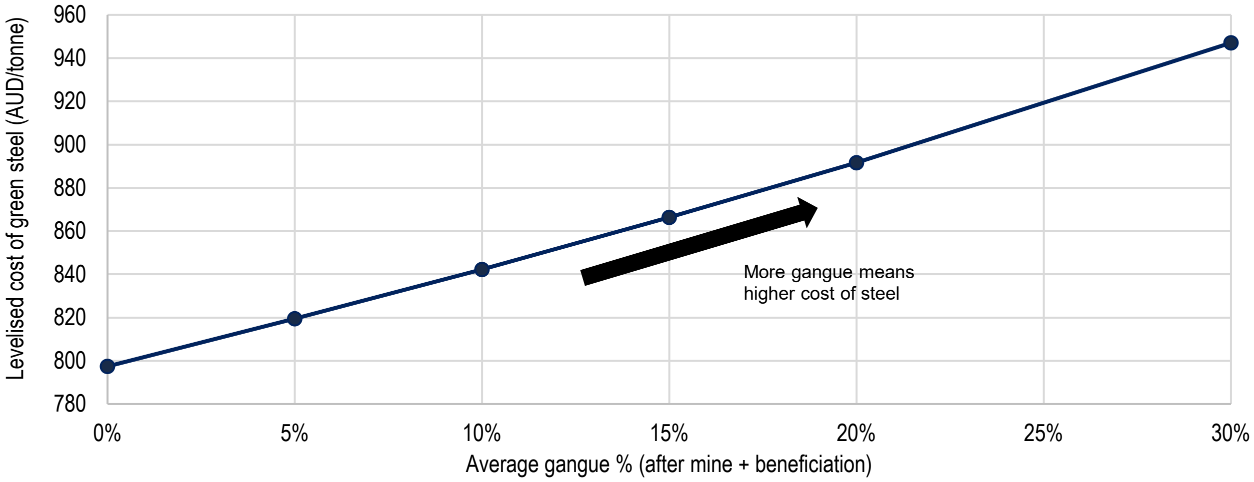
One further consideration is that higher quality, lower total gangue ore is preferred in the production of Green Steel. This is because gangue is present in DRI when it enters the EAF, and the energy costs associated with operating EAFs vary with the level of gangue. Whilst this does make lower gangue ores more desirable for furnace operators, and ore can be upgraded by miners, this creates additional costs for beneficiation.

As a result, ores are only worth upgrading from a total-value chain perspective if gangue levels in the ores are above a certain threshold, and these savings are only realised by the steelmaking stage. All the costs are borne in the ore processing stages. Furthermore, these ores are more costly to turn to steel overall than just having good quality ore in the first place.

Upgrading ore to reduce gangue content has benefits in the Green Steel value chain, due to the energy requirements in the EAF step – which varies with the level of gangue in the reduced iron. Typical mixed hematite/goethite direct shipping ores which can be sold straight to BFs as-is, is not as attractive to Green Steel producers. This section examines whether it is worth upgrading these ores for a Green Steel value chain, who benefits the most from doing this, and the consequences of inaction.

First, consideration on how the costs of Green Steel vary with fundamentally different grades of DSO mined ore used as-is (shown below in Figure 7.31). For every 10% gangue content, an additional $40 AUD/tonne is added to the cost of production. This is a high-value add which favours suppliers with access to good quality direct shipping ores.

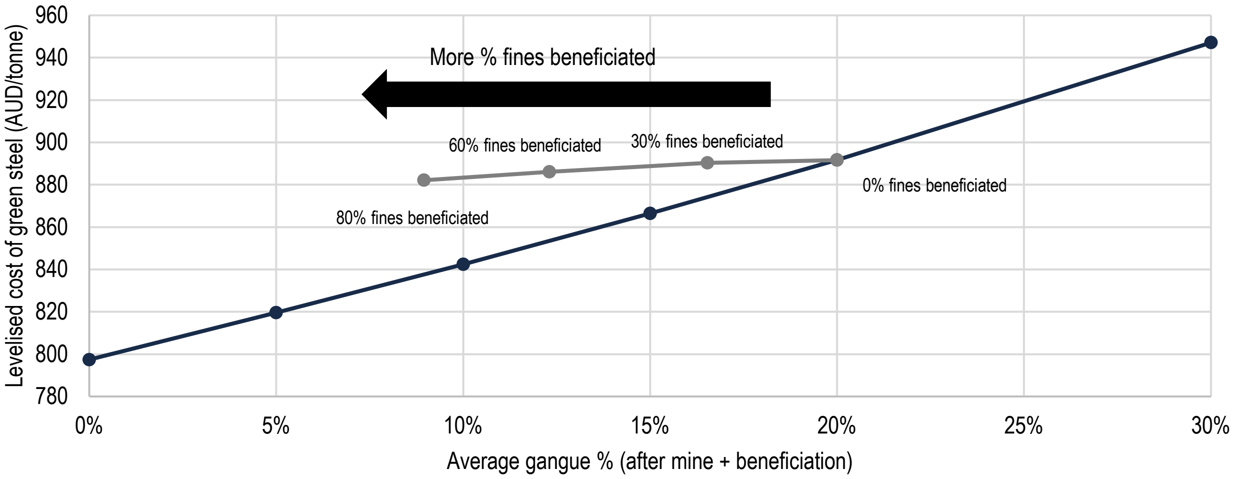
Figure 7.31 Relationship between gangue in ore mined and cost of Green Steel production



Source: GHD Analysis

If a higher mined total gangue ore is taken, it can be improved by beneficiating different proportions of the ore. This creates yield losses and adds to beneficiation process cost, however, creates value savings at the steelmaking step from reduced EAF power use. As a result, the overall cost of steel can improve with additional beneficiation.

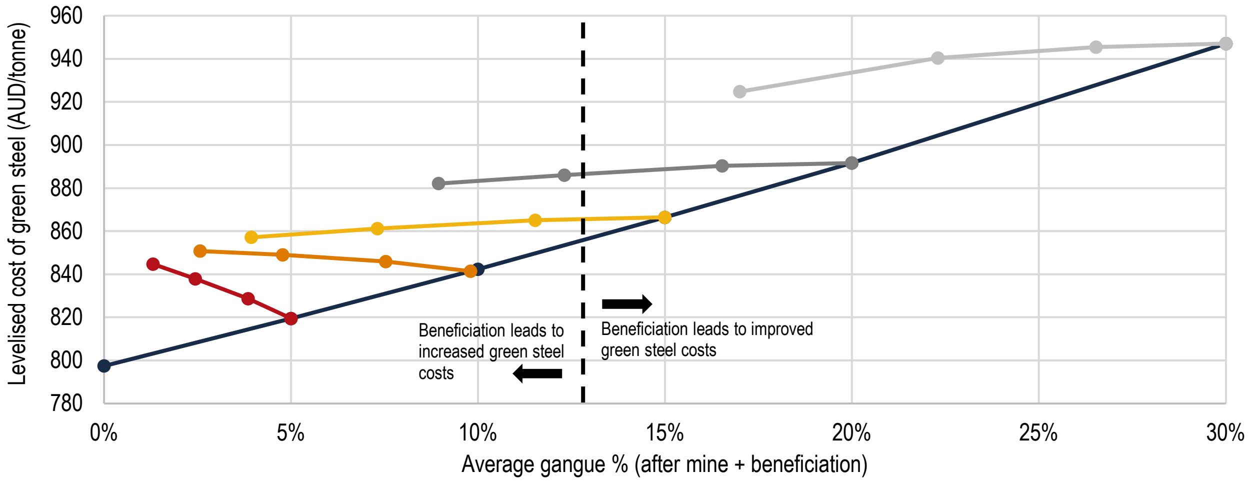
Figure 7.32 Gangue reduction benefit accrual



Source: GHD Analysis

Taking this analysis further shows there are net savings to the cost of Green Steel from ore upgrading only for ores above a certain mined gangue threshold. For ores that have gangue above this threshold (when mined), beneficiation improves the overall cost of Green Steel. Beneficiating ores with less than this threshold gangue is counterproductive and increases the net cost of steel as the extra costs and losses do not outweigh the gains from power savings in the EAF.

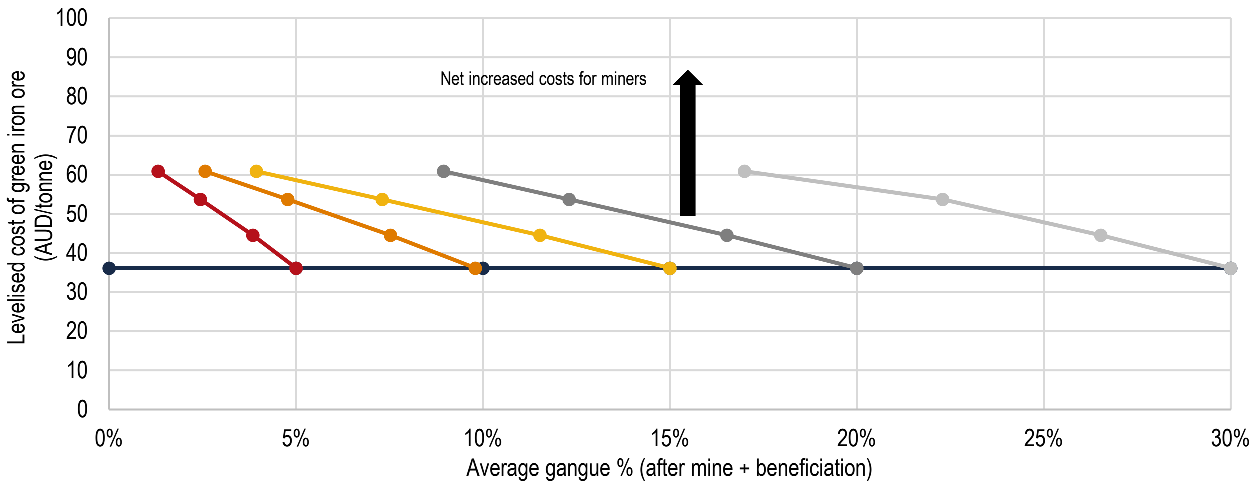
Figure 7.33 Gangue reduction benefit accrual to steelmakers, further analysis



Source: GHD Analysis

From the miner's perspective, ore upgrading introduces additional costs which are partially compensated by increased value to steelmakers but diminish margins for the miners. Also, a miner that can mine better as-is ores will have a sizeable market advantage against those who must beneficiate.

Figure 7.34 Gangue reduction benefit accrual to miners



Source: GHD Analysis

There are three important directions from this analysis.

- Beneficiation is worth doing when ores are mined with gangue above a certain level, from the point of view of integrated Green Steelmaking.
- The benefits are largely to steelmakers, and their savings (hence the premiums they will be willing to pay) may not equal the miners' increased costs.
- Upgrading ore producers will be hard pressed to compete against high quality DSO producers, when both are selling to the same steel producers.

Any decision to upgrade ores must take the full supply chain and ore process properties into account, and it is of clear benefit to own as much of the total Green Steel value chain as possible to benefit from ore upgrading.

What this means is that for Western Australia to benefit the most from Green Steel, fully Green Steel value chains are onshored. This would allow local industry to either benefit from the total supply chain savings in highly processed ores or accept the small overall cost increase in steel production from leaving them unprocessed.

If Australia is continuing to export ore to overseas steel producers at this stage, then the high margins from DSO will be eroded by the increased cost to upgrade the ores to stay competitive with higher quality ore suppliers – possibly leading to net decreases in royalties. This, coupled with no additional industries from lack of value chain expansion, leaves the sector stagnant and reactive.

Finding 14 Value chain modelling: Hydrogen cost and implications

The dominant costs in traditional steelmaking are those which arise from blast furnacing.

The price of hydrogen, which replaces coke as a reductant in the creation of Green Steel, is critical in ensuring price parity of Green Steel with blast furnacing.

Green Steel (SF-EAF) can be economically produced when compared to fossil fuels (BF-BOF) steel when the hydrogen price reaches $3.20 AUD/kg.

There are increased costs for processing high gangue HBI/DRI through electric arc furnacing, so higher quality or more refined ore is preferred. Though most cost benefit will accrue to whomever owns most of the value chain, including the steelmaking step.

7.7 Further Green Steel value chain considerations

A number of more generalised findings emerge from the review.

7.7.1 Transition strategy: Developing a 100% domestic green iron production industry

Based on the investigation of pathways to Green Steel considered above, a transition pathway exists for Western Australia to support the global steel industry achieve its ambitions to decarbonise by:

- Decarbonising existing onshore activities
- Developing and new iron ore products to supply into the market.

This strategy seeks to protect the existing iron ore export market while diversifying the opportunity for the state. Decarbonation efforts will need to be cost comparable with fossil-fuels based pathways as there will be no price premium in the short term.

Green iron pathways will become economical compared to fossil-fuel alternatives, as the price of hydrogen drops, before Green Pellets and Green Steel do.

Whilst a cost-competitive green iron industry is possible, hydrogen prices are not currently favourable and power infrastructure is not present to enable this to occur immediately. However, the low cost and currently abundant natural gas available in the North West allows a potential cost-effective transition to a fully green ironmaking industry.

One such transition pathway towards Green Iron in the form of HBI industry can be outlined in the following three stages.

Stage 1: Green Iron Ore Mining

Existing iron ore supply chains are converted to their emissions-free equivalents based on renewable power supplied by mixed solar/wind facilities. This is a sensible starting point, due to its cost-competitive nature at today's cost rates, largely due to low cost and effective renewable power that can be supplied to ore process operations.

The established power infrastructure will not only support existing industry but will also reduce ore production costs in the long run as the price of power decreases and allow energy intensive ore beneficiation to be done at lower cost. Including hydrogen and ammonia facilities for long distance transport also initiates the industrial base that will be required for the adoption of hydrogen shaft furnaces. As an example, around 0.003 tonnes of H_2 are needed to support fully green export of one tonne of ore, mostly in producing green shipping fuel.

These hydrogen requirements increase almost 100-fold to 0.08 tonnes of H_2 per tonne of Green Steel when shaft furnaces become involved. Clearly, a scale-up is required further down the line, and this early stage supports what will come later.

Stage 2: HBI from Green Pellets using fossil fuels (Transition HBI)

Onshore ironmaking facilities are established using shaft furnaces with natural gas as a reducing agent. Pelletisation facilities using hydrogen powered induration furnaces are also built to process onshore pre-ground fines and beneficiated ore into a form suitable to be shaft furnaced.

Due to the cost of natural gas, HBI can be produced for around $200/tonne cheaper than the equivalent pig iron product produced via the coal-fired BF route. This means green iron production is highly competitive against existing iron production practices, even with the additional expense of hydrogen use in pelletisation which is assumed to not come down in price from the base assumption cost. Green methods are used at all other points of the value chain, in line with the overall goal of minimising emissions at no detriment to the bottom-line price, and also to continue encouraging the growth of on-shore hydrogen production. The scale of hydrogen production required has jumped 3-fold from the last stage (Green Iron Ore Mining) to around 0.01 tonnes H_2 per tonne of semi-green HBI.

One of the consequences of this approach is that it will onshore the emissions from the shaft furnace step due to the conversion of natural gas to carbon dioxide. This amounts to around 0.5 tCO_2/t iron, however it is important to note this will reduce the overall emissions compared to existing ironmaking value chains. Currently, every tonne of iron produces 1.7 tCO_2 – all considered Scope 3 as they are produced by steelmaking countries overseas. Switching to the transition iron product can reduce overall emissions across the value chain by up to ~70%, the cost is these emissions are on-shored.

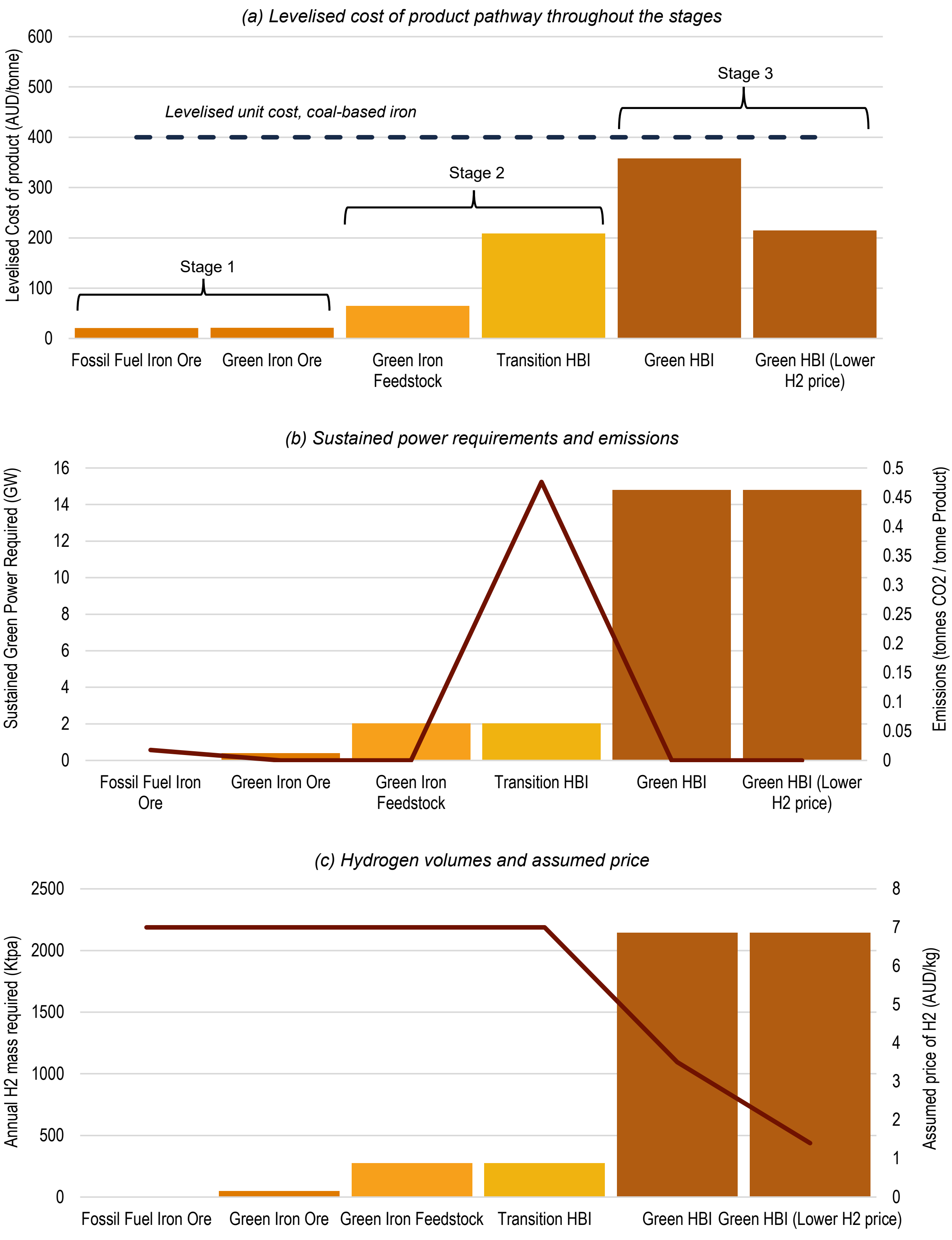
Stage 3: Green Iron in the form of HBI

As development of hydrogen production facilities continue, the costs of hydrogen should fall, which will incentivise the replacement of natural gas with hydrogen in shaft furnaces. Replacement of hydrogen in shaft furnaces is not all-or-nothing but can be a staged process where the gas blend can be varied over time. Once hydrogen prices reach $4 AUD/kg, fully Green Iron in the form of HBI with 100% hydrogen feed would become cost competitive against coal-fired pig iron.

The second transition comes when hydrogen reaches below $1.50 AUD/kg, when it becomes more cost effective to use in shaft furnaces rather than natural gas – incentivising Green Iron in the form of HBI as the most economical way to make iron. Several methods and policy controls could encourage the uptake of hydrogen earlier than this transition point. At this stage of development, robust renewable power infrastructure will exist to supply the 0.07 tonnes H_2 per tonne of HBI required across the value chain. Access to hydrogen at this scale opens opportunities for the state in the form of an exportable energy market.

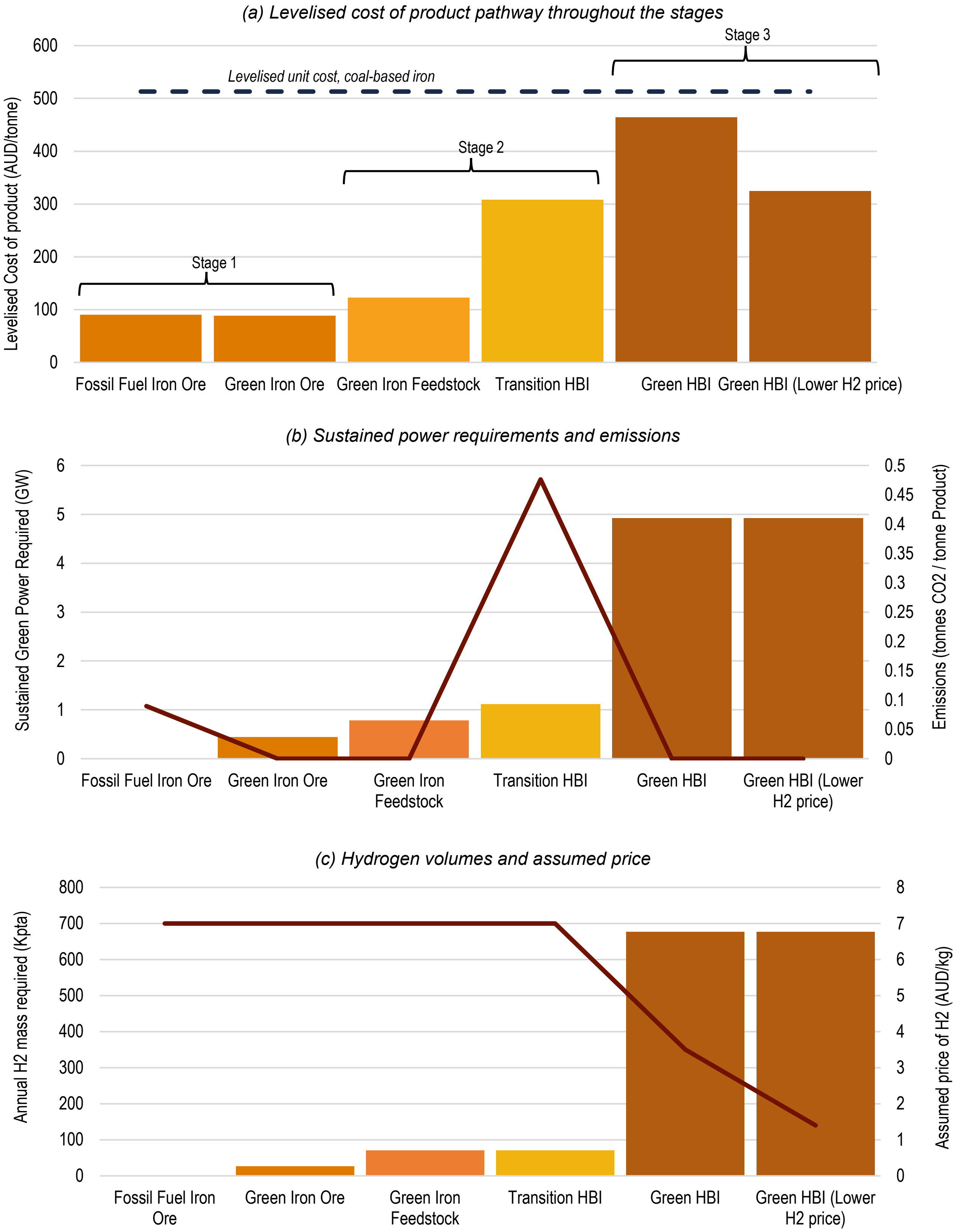
The levelised cost, sustained power and hydrogen requirements, and hydrogen volumes across the different stages of the value chain are shown in Figures 7.35 and 7.36. Of note is the substantial step-up requirements in hydrogen volume and decreases in cost in going to fully green iron. Enabling hydrogen costs and the scale of supporting infrastructure critical to the success of green iron are the focus of the next section. This transition pathway requires clear forward planning.

Figure 7.35 Green Iron in the form of HBI transition strategy pathway, using hematite ore



Source: GHD Analysis
Note: Excludes shipping, analysis for hematite type ores, 50 Mtpa mined and either 50 Mtpa ore/pellets or 31 Mtpa HBI delivered depending on final product type

Figure 7.36 Green Iron in the form of HBI transition strategy pathway, using magnetite ore

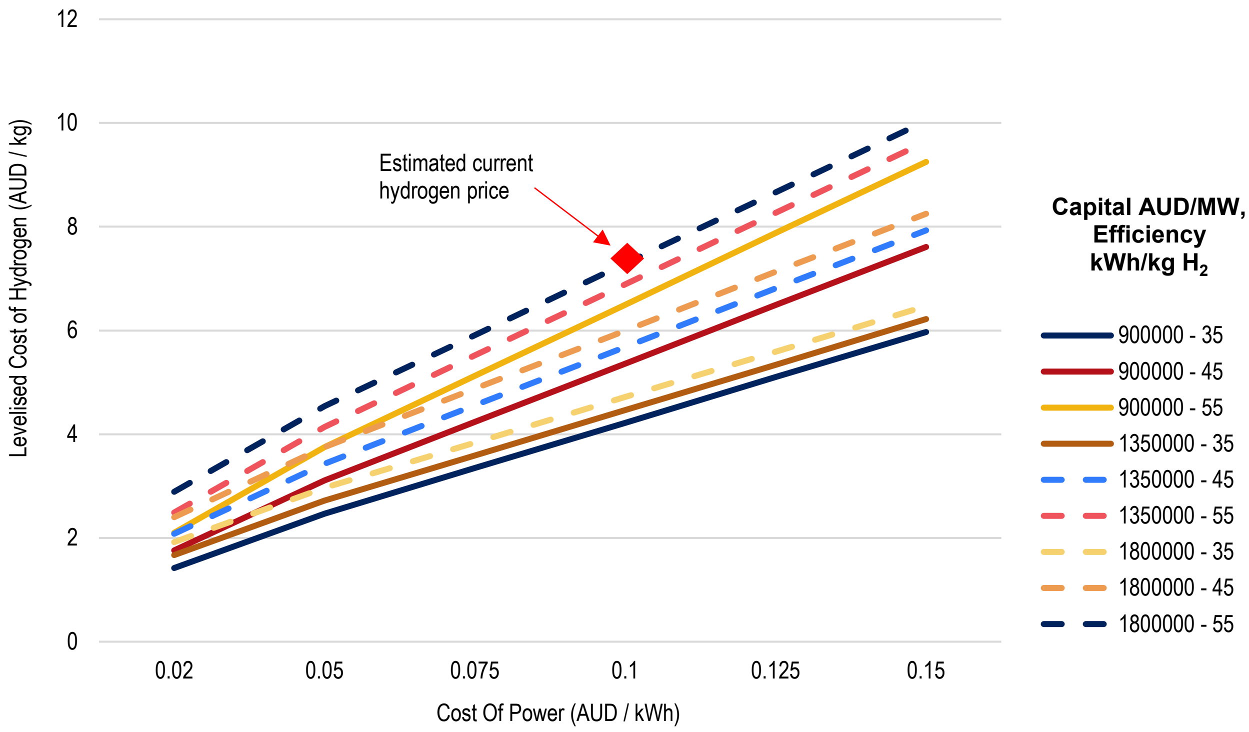


Source: GHD Analysis
Note: Excludes shipping, analysis for magnetite type ores, 50 Mtpa mined and either 15 Mtpa concentrate/pellets or 10.21 Mtpa HBI delivered depending on final product type

7.7.2 How to achieve the right price of hydrogen

The most critical factor in making green iron and steel a success is cost-effective access to hydrogen. This will be heavily impacted by the cost of power, by electrolyser capital costs and efficiencies. These technological capital and efficiencies are expected to improve over time, and the levelised cost of hydrogen is shown in Figure 7.38 as a function of these factors.

Figure 7.37 Levelised cost of hydrogen vs power price and capital



Source: GHD Analysis using linear capital cost scaling

An estimation of current day hydrogen supply costs places it around $7/kg. The opportunity for green iron and steel is when hydrogen can be supplied for less than $4/kg. One of the most important levers to bring this cost down is the price of power; once this falls below 0.04 – 0.05 AUD/kWh then cheap enough hydrogen production becomes feasible.

Reductions in electrolyser costs are expected over time[139] and indications are it can decrease by as much as 70-80% below present-day costs by 2040. This alone will not be sufficient to bring hydrogen costs into the feasible range and must be accompanied by falls in the price of power.

Analysis indicates renewable power prices of $100/MWh can be readily obtained with 50/50 solar/wind facilities, inclusive of storage and oversizing of facilities to ensure an uninterrupted supply along with key land resources as shown in Box 7.4.

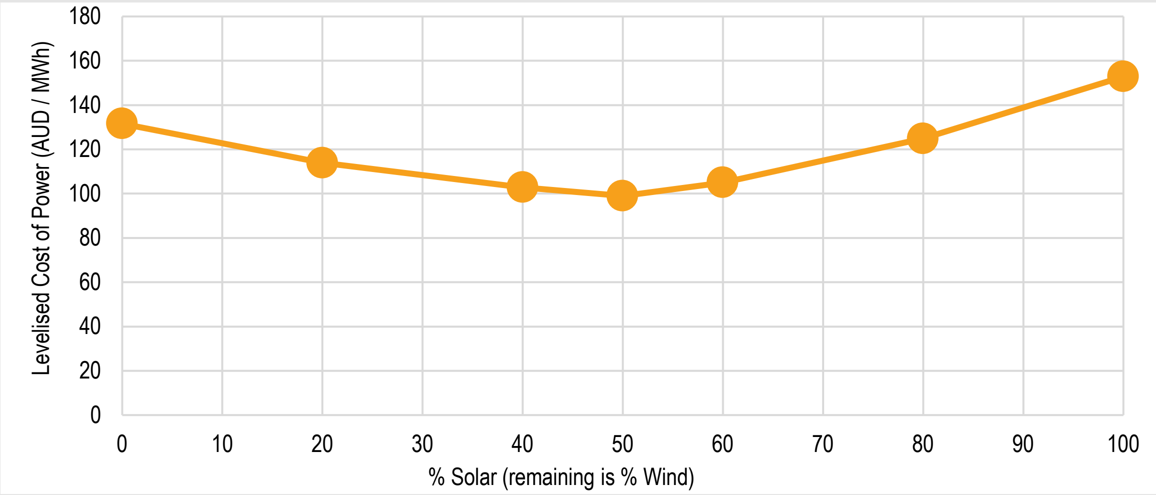
[139] Graham, P. 2020. *GenCost 2020-21: Consultation draft*. CSIRO.

Box 7.4 Analysis of renewable power prices and land requirements

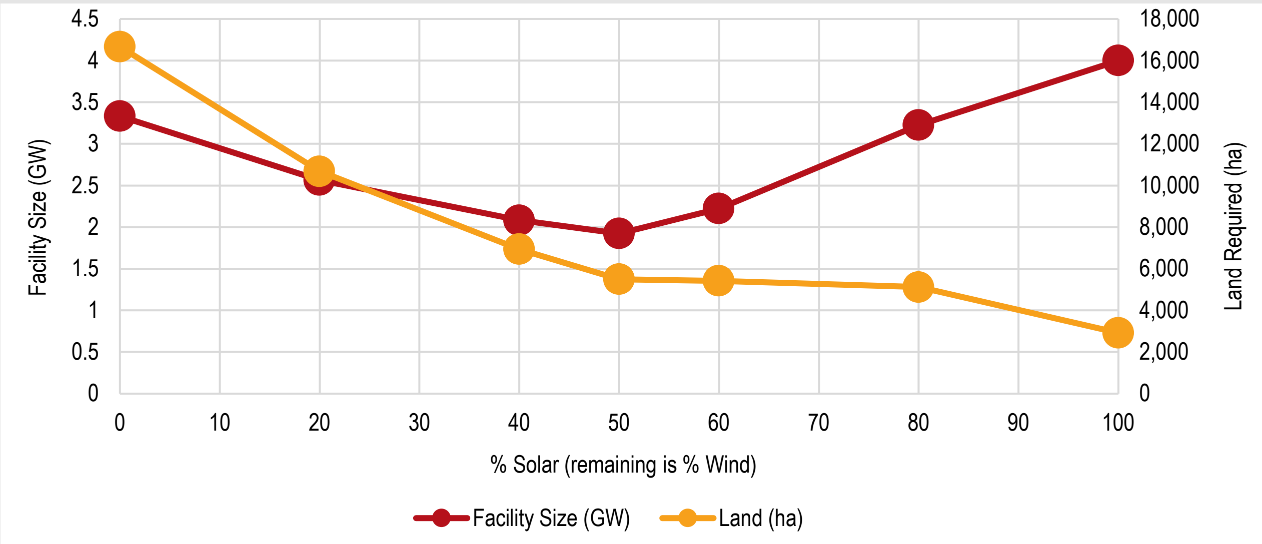
Shown below are the levelised cost of power for different wind/solar splits, and related land and oversizing facility required to supply a continuous load of 1GW. Solar power is more concentrated and requires smaller land footprint, however is not available 24 hours a day. Wind turbines require more land use then solar for a given peak energy collection capacity and have a different availability throughout the year then solar. Combining the two increases the net availability of power coverage across time.

The mixed solar/wind facility can supply a more reliable source of power overall and thus can be sized closer to the sustained load it is required to supply, saving capital costs. This creates a sweet spot in the levelised cost of power when around 50% of the facility is solar panels and 50% is wind turbines. One important caveat is it is assumed land is supplied at "no cost", although the land footprint itself can be substantial.

(a) Levelised cost of power



(b) Land and facility oversize requirements



Source: GHD Analysis
Note: This analysis is conducted for an example 1GW sustained load renewable energy facility. See Model Basis document for full assumptions, for each capacity factor the facility is oversized and 15 hours of battery storage is provided to deliver a sustained load of 1GW. Cost of capital at today's rates, not future. Assumed linear capital scaling and "no cost" to supply land, facility is co-located and levelised cost is power "at-gate".

However, this analysis uses a general capacity factor of 50% (sourced from the Geoscience Australia dataset[140]), and siting power facilities appropriately could improve on this factor considerably. Both the Pilbara and Mid West have high quality renewable energy resources, particularly the Mid West (as shown in Figure 7.39). Identifying and establishing these high energy yield sites should be a priority to support green hydrogen production.

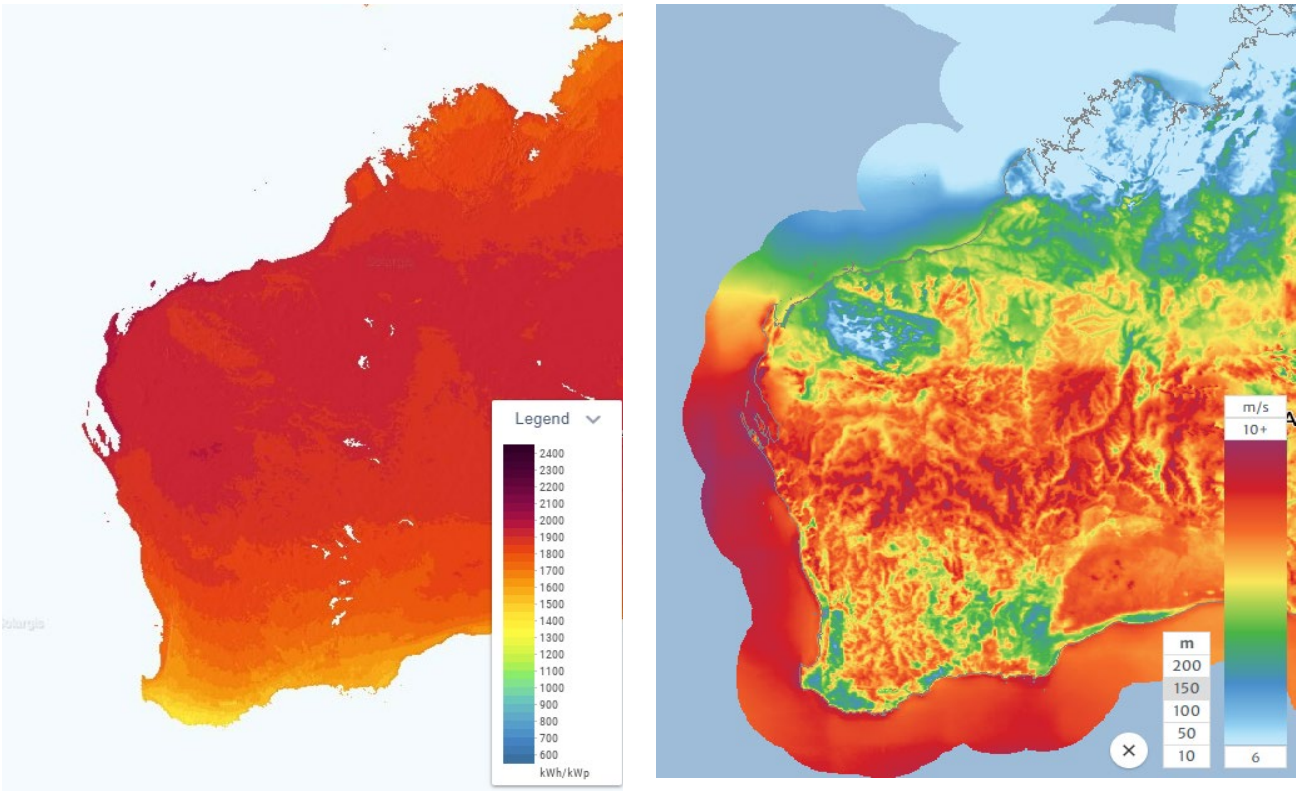
The other factor to support reduction in the price of power will be technological advancement which can lower capital costs. For example, currently solar panels have approximately 20% efficiency – meaning that they take advantage of up to 20% of the energy in sunlight. Experimental trials have demonstrated efficiencies of greater than 40%.[141] If these technological advancements scale well to bulk production, they can be effective in bringing costs down.

This is unlikely to be a quick fix but would require long term support of fundamental science and government initiatives. As Western Australia has little solar research or manufacture industry of its own, the establishment of this capability assist the technology to develop overall.

Given the potentially large amount of hydrogen required to support a local green iron industry, along with the additional power and other infrastructure, serious consideration should be given to both the cost and scale of the facilities required.

Figure 7.38 Solar and wind resource map in Western Australia

(a) Solar resource map of WA *(b) Wind resource map of WA*



Source: https://globalsolaratlas.info

Source: https://globalwindatlas.info

[140] Geoscience Australia, n.d., [*AusH2 - Australia's Hydrogen Opportunities Tool*]().
[141] King, R. R., Law, A., Edmondson, K. M., Fetzer, C. M., Kinsey, G. S., Yoon, H., ... & Karam, N. H., 2007, 40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells. *Applied physics letters*, 90(18), 183516.

Steel decarbonisation as a demand driver for renewable hydrogen

Both hydrogen production and Green Steel are being pursued globally. Many countries have made climate commitments and these products play a significant role in being able to meet them. When considering the State's potential Green Iron in the form of HBI transition strategy, these product volumes can be put into a global context.

Below are three what-if scenarios to explore how big a role hydrogen production could play in the future if Western Australia becomes a green iron producer to varying degrees.

Three possibilities are considered: firstly, do nothing, secondly be a significant producer or company exports Green Iron in the form of HBI (50 Mtpa mined hematite ore converted to 31 Mtpa HBI), lastly is the whole-of-state iron ore output is being converted to iron (~500 Mtpa ore to 315 Mtpa Green Iron in the form of HBI).

Table 7.8 Order of magnitude renewable hydrogen potential

	Low – Do nothing	Mid – One significant Green Iron in the form of HBI producer	High - All WA Ore to Green Iron in the form of HBI
Green Iron in the form of HBI (Mtpa)	0	31	315
Hydrogen needed (Ktpa)	0	2,183	21,830

Source: GHD Analysis

World annual crude steel production is approximately 1,800 Mtpa which corresponds to iron production around 2,000 Mtpa. Western Australia's iron production in the high case forms a substantial proportion of this iron (~15%).

The IEA reported only 90 Mtpa of hydrogen was produced in 2020, and mostly from fossil fuels. Looking into the future, this quantity may double or quadruple in 20 years depending on the level of climate commitment from different nations.[142]

Although taken in isolation the hydrogen requirements for total green iron production to occur in Western Australia seems big, on a global scale in the net zero target world this is not the case.

This anticipated green hydrogen requirement for Green Steel use must come from somewhere and presents the State with a first-mover advantage in this area due to a potential local market in the form of HBI producers. If these hydrogen production industries are established to support local ironmaking, there are additional potential export markets for green H_2 that will open.

Capital and power requirements to make it happen

Though there is a point at which it makes economic sense to produce green iron or steel, an important consideration is the upfront capital required to build processing facilities as well as the relatively large renewable energy and hydrogen electrolysis centres. In addition, there are land and project build timescales to be understood from a planning perspective.

An upfront capital cost breakdown is shown in Table 7.9, laying out the various indicative

[142] IEA Global Hydrogen Review, 2021, December 2021 crude steel production and 2021 global crude steel production totals.

investment levels required for production of 1 Mtpa of Green Steel.

The three largest items on this list are the renewable power facilities, followed by shaft furnaces and then hydrogen production, all critical to green iron or steel production. Furthermore, more than 70% of the power usage and facilities exist to supply hydrogen, as shown in the energy usage charts throughout the previous section with 80% of the hydrogen being produced used in the iron-reduction shaft furnace step.

Breaking down the overall capital requirements, roughly 0.07-0.08 MT of hydrogen is required overall to produce 1MT of Green Iron in the form of HBI or Green Steel. This needs to be supported by ~1GW over-sized power facility to produce this hydrogen per annum, with around 3,500 hectares of land to site the solar panels and wind turbines in a 50/50 mix along with battery storage.

The peak power generation is in excess to sustained requirements, along with additional storage, to compensate for the intermittent nature of renewable energy supply. This power generation is on par with the South West Interconnected System (SWIS) (current capacity around 6GW).

The total cost for this venture is approximately $1 billion AUD for an electrolysis facility and $5 billion for the power facilities.

Table 7.9 Indicative capital and other resource requirements for 1 Mtpa Green Steel production

Indicative Requirements for:	**1 Mtpa Shipped Green Steel**		**Units**	**Comments**
	Hematite	*Magnetite*		
Pelletisation facility	$162	$216	M AUD	Capex – H:1 M:1 x pellet plants
Shaft furnace	$1,500	$1,500	M AUD	Capex - H:1 M:1 / H:10 M:3 x shaft furnaces
EAF facility	$240	$240	M AUD	H:1x M:1 x EAF
Processing facility land use	230	230	Hectares	H:1 M: x pellet plants H:1 M:1 x shaft furnaces H:1 M1x EAF
Sustained power required	638	638	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$5,600	$5,600	M AUD	Capex
Renewable facility land use	3,500	3,500	Hectares	
Annual hydrogen required	79	76	Ktpa	
Hydrogen facility	$895	$864	M AUD	Capex
Ammonia facility	$0.8	$0.4	M AUD	Capex
H_2 rail trains	$14	$14	M AUD	Capex
Ammonia-powered vessels	$60	$60	M AUD	Capex
Water requirements	4,700	5,500	ML p.a.	Capex
Mined ore required	1.82	5.89	Mtpa	
Shipped product	1	1	Mtpa	

Source: GHD Analysis (Model Value Chain Scenarios: Hematite (10a1 and 10a), Magnetite (10b1 and 10b)); MRIWA

Finding 15 Green Steel industry capital costs are expected to be substantial

To decarbonise or lower emissions in Western Australia's current mining sector and potential future steelmaking value chain, infrastructure for renewable power generation and for hydrogen-based iron/steelmaking plants must be developed. The capital costs are substantial for renewable power production at scale.

An example to put this in perspective is Yandin Windfarm which, at 214MW, is currently the largest wind farm in Western Australia. However, the size and scales of renewable energy and hydrogen production required for Green Steel are consistent with other proposed export scale green hydrogen (and derivative products) projects currently planned in the State and across Australia and internationally. Development of gigawatt scale renewable energy developments is also broadly consistent with the large-scale energy transition requirements to displace fossils fuels to enable government, industry and societal net zero expectations.

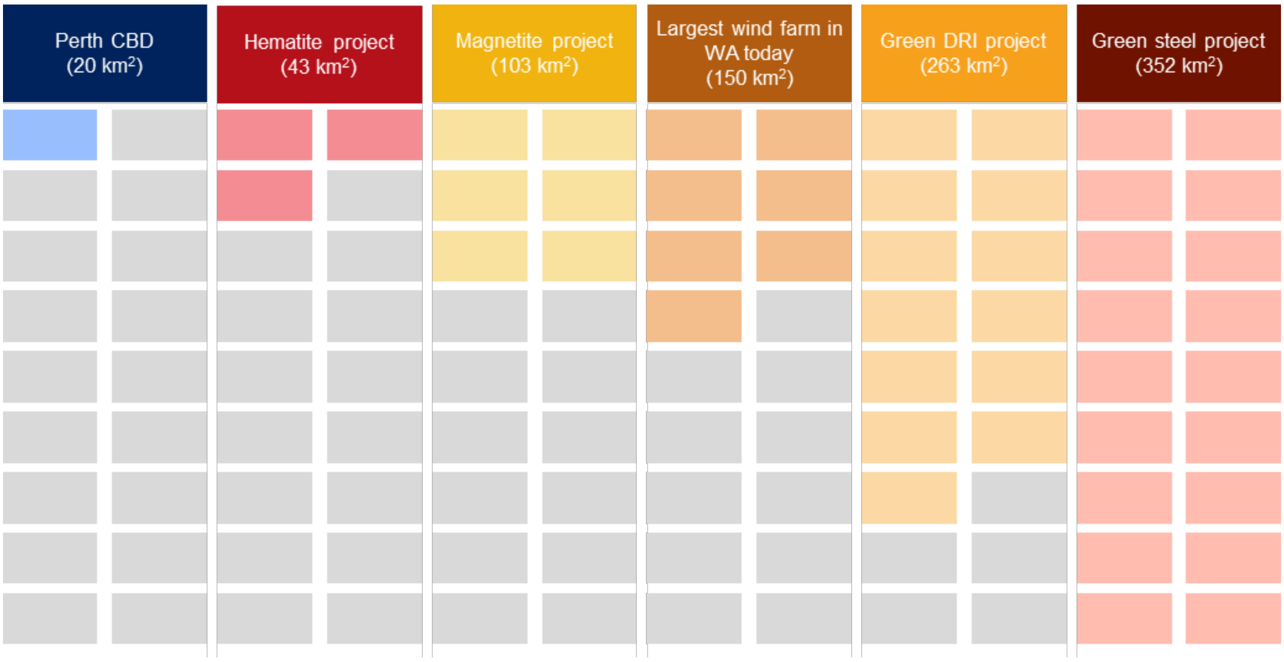
In addition, the land needs for both the processing infrastructure and renewable energy generation facilities is significant and well beyond the scale of the majority of renewable energy infrastructure projects currently operating or planned in Western Australia. This is illustrated in Figure 7.39 below, which compares the notional size of the land area required to facilitate the above projects compared contextualised.

Table 7.10 Land area required to facilitate processing facilities for Green Steel projects vs available strategic industrial areas, hectares of land area

Facility type / land parcel	Area available / required
Pelletising facility – 1 Mtpa shipped product	40 ha
Pelletising facility – 50 Mtpa mined ore	400 ha (hematite), 200 ha (magnetite)
Iron making – HBI form – 1 Mtpa shipped product	140 ha
Iron making – HBI form – 50 Mtpa mined ore	1,400 ha (hematite), 500 ha (magnetite)
Green Steel – 1 Mtpa shipped product	230 ha
Green Steel – 50 Mtpa mined ore	1,550 ha (hematite), 680 ha (magnetite)
Oakajee	1330 ha
Ashburton	8,000 ha
Anketell	1,250 ha
Boodarie	3,743 ha
Burrup SIA	1,000 ha

Source: MRIWA; Department of Jobs Tourism, Science and Innovation

Figure 7.39 Land area required to facilitate renewable energy facilities for Green Steel projects vs comparators, km² of land area



Source: ACIL Allen Analysis

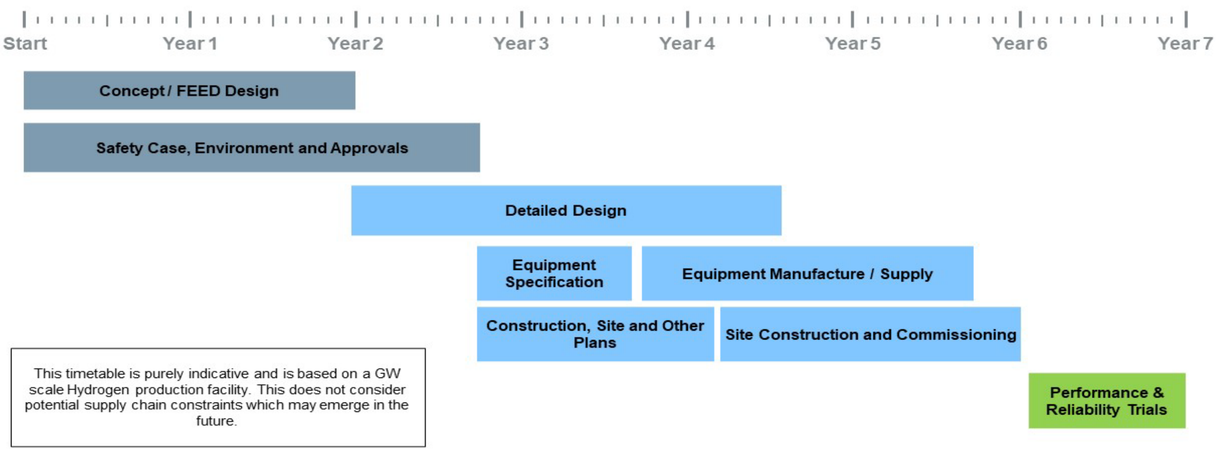
The development and delivery of this scale of the processing facilities and renewable energy infrastructure presents both a challenge and an opportunity for Western Australia.

The timing for development of a large-scale hydrogen industry to support a Green Steel development is likely to take significant time and planning over the course of a decade.

A generic project schedule for a large scale (1GW+) hydrogen plant is shown in Figure 7.40 which identifies a timeline of approximately seven years for the renewables and hydrogen plant only.

Key schedule risks which could significantly impact on the timeline include supply chain constraints (key renewable and hydrogen equipment and construction support) and access to large land areas for the renewables.

Figure 7.40 Indicative project timeline for green H_2 projects



Source: ACIL Allen Analysis

Given hydrogen prices may be at the breakeven point for Green Iron in the form of HBI production within a timeframe of 10 years[143] the decade-long timeframe to establish hydrogen operations means that projects initiated now will be in place ready to take advantage of cost competitive green iron production.

Delays in initiating these projects could mean by the time they come online, Western Australia will have missed the first-mover advantage at a time when they become financially feasible and established elsewhere.

In terms of the water requirements; 4.8GL of water is estimated to produce the 0.08 MT of hydrogen, partly desalinated but mostly as cooling water.

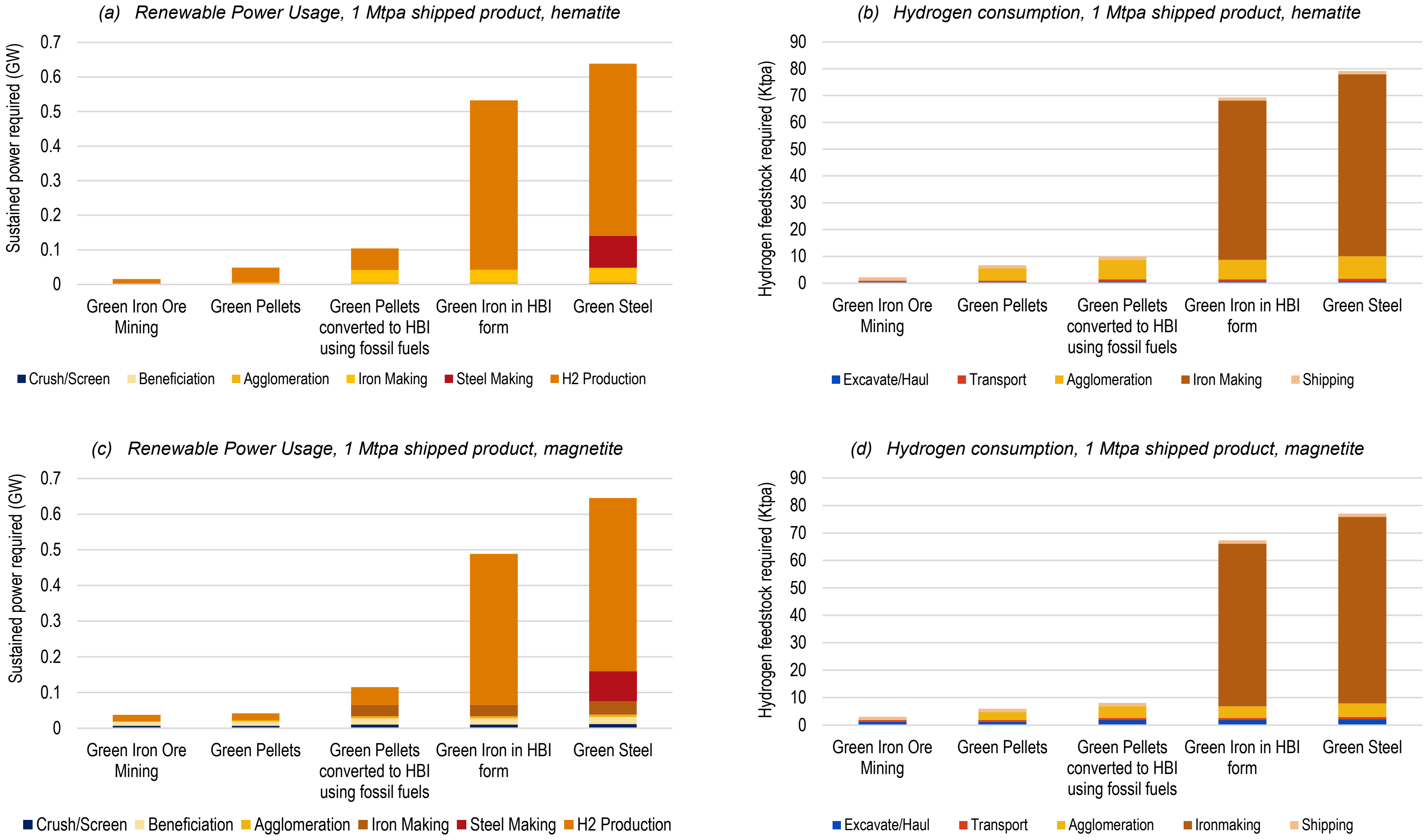
Whilst this is a large volume, it is on par with that needed to support beneficiation in a decent sized magnetite operation. In context, a dig and ship 15 Mtpa magnetite concentrate operation will require approximately 8GL p.a. of water for use in beneficiation. This leaves magnetite export operations as potentially being able to support hydrogen production by leveraging their existing water supply infrastructures.

In terms of renewable power and hydrogen, the requirements for 1 Mtpa of green products is shown in Figure 7.41. Comparisons between magnetite and hematite show similar requirements in energy.

In terms of ore mined, the 50 Mtpa cases are shown in Figure 7.42. The lower yield effects in magnetite are indicated by lower ironmaking outputs.

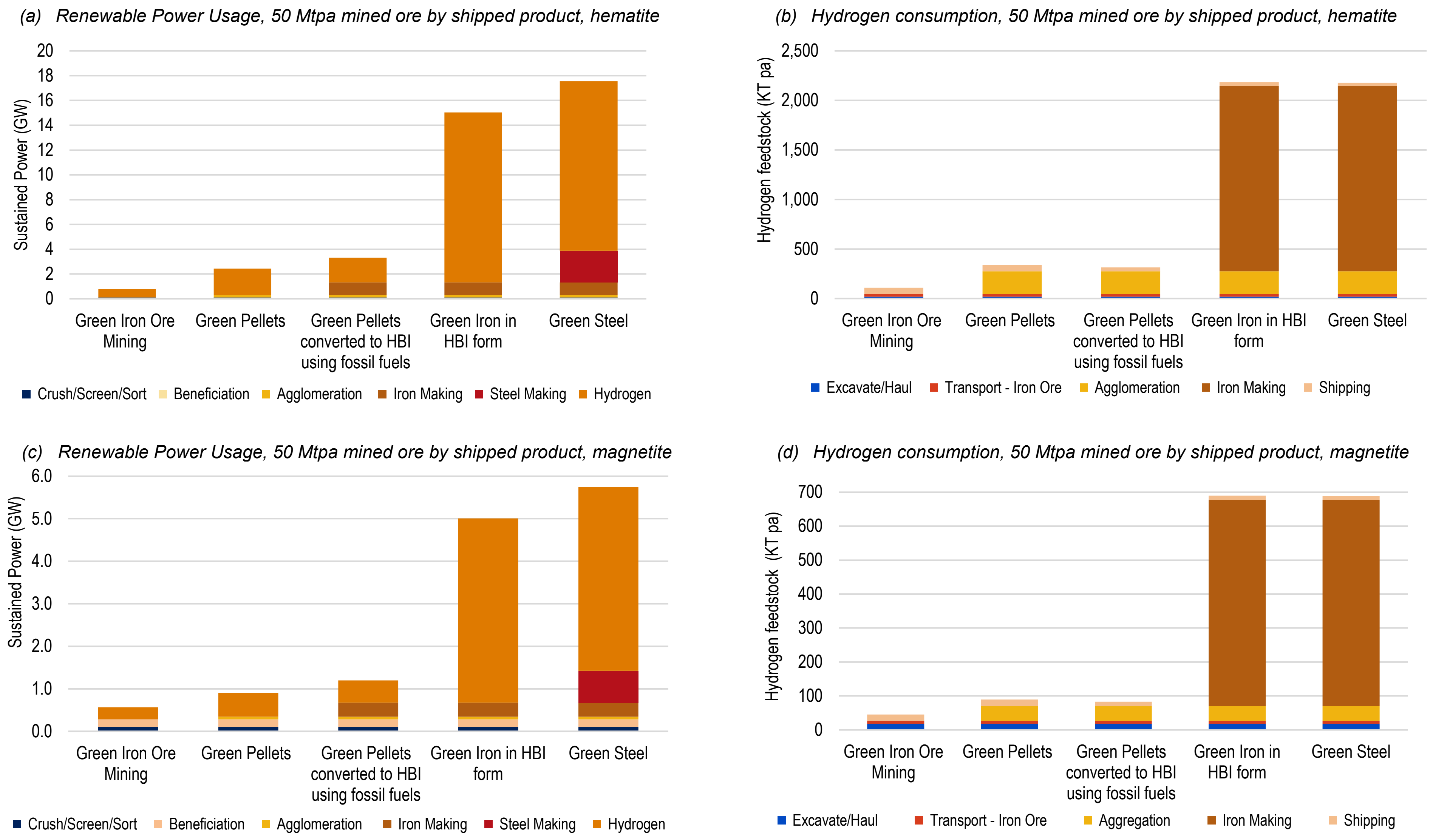
[143] Percy, S, 2022, Green hydrogen is coming - and these Australian regions are well placed to build our new export industry. *The Conversation*.

Figure 7.41 Installed energy consumption comparisons for 1 Mtpa of shipped product using hematite and magnetite ores



Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (2b,4b,6a1,6a2,10a1), Magnetite (2b1,4c,6a3,6d,10b1))

Figure 7.42 Installed energy consumption comparisons for 50 Mtpa of mined hematite ore and magnetite ore



Source: Source: GHD Analysis (Model Value Chain (Scenarios: Hematite (2a,4,6,10a), Magnetite (2a1,4a,6b,10b))

Sizing the Opportunity for Western Australia 8

The previous section, and first part of the report, explore a number of aspects of the future outlook for iron ore and steel in a net zero emissions world. This section of the report analyses the critical economic impacts of Western Australia's future place in the Green Steel value chain, through the lens of economy-wide modelling of new Green Steel-inspired development projects and an exploration of what's at stake if there is no response to the changing world.

8.1 Assessing the opportunities

8.1.1 Greening today's iron ore is economic now

Decarbonising the Western Australian iron ore industry sees existing and new iron ore mines become emissions-free by using renewable power supplied by solar and wind facilities.

Recent moves by most of Western Australia's iron ore industry to increase the use of renewable electricity generation on its projects, and for certain elements to push into the development of hydrogen-based production processes, is as much to do with economic imperatives as climate pressures.

The value chain modelling undertaken by GHD indicates transitioning the production of iron ores to green power delivers a broadly similar, or slightly improved, unit cost of production on today's costs.

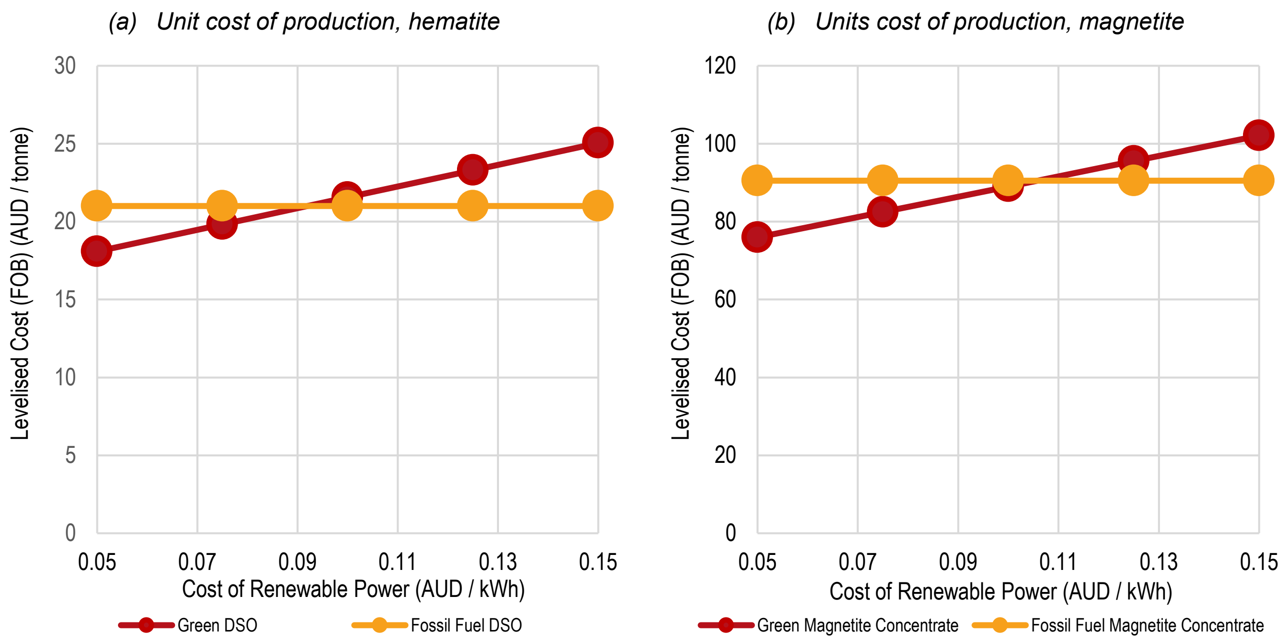
This pathway, for hematite and magnetite ores, is cost competitive compared to the prevailing practice at today's benchmark cost of $0.1 AUD/kWh for mixed solar/wind generated power.

The technical analysis is based on a diesel fuel price of $1.60 per litre. Recent global events have driven the price of diesel fuel up substantially, to above $2 per litre. This would create a further positive wedge between the emerging renewable energy advantage held by Western Australia and the traditional, diesel fuel-based mining operations which have existed in the State.

Establishing renewable power infrastructure will not only support the existing industry but also reduce iron ore production costs in the long run as the price of renewable power decreases.

Starting the Pilbara's and Mid West's electrification journey here could be a catalyst for further electricity infrastructure investments, fostering downstream and alternative industry developments like renewable hydrogen.

Figure 8.1 Unit cost economics, iron ore mining by energy scenario, $/tonne output product



Source: GHD Analysis (Model Value Chain Scenarios: Hematite 1c,2a, Magnetite 1f,2a1)
Note: Excludes shipping

8.1.2 Natural gas-based DRI in the form of HBI can be transformative, but domestic emissions would increase

Natural gas-based value adding has been shown by the technical analysis to be substantially cheaper than even today's BF-based iron reduction production processes. Using a conservative long term domestic gas price of approximately $4 per gigajoule (GJ) yields a highly competitive DRI product in the form of HBI in Western Australia.

Natural gas-based produced DRI in the form of HBI is around $200 per tonne cheaper than coal-fired pig iron produced in a traditional BF. Low natural gas prices will favour the production of DRI in the form of HBI in Western Australia, even accounting for the higher gangue contents which remains in the HBI. Refer Figures 8.2 and 8.3.

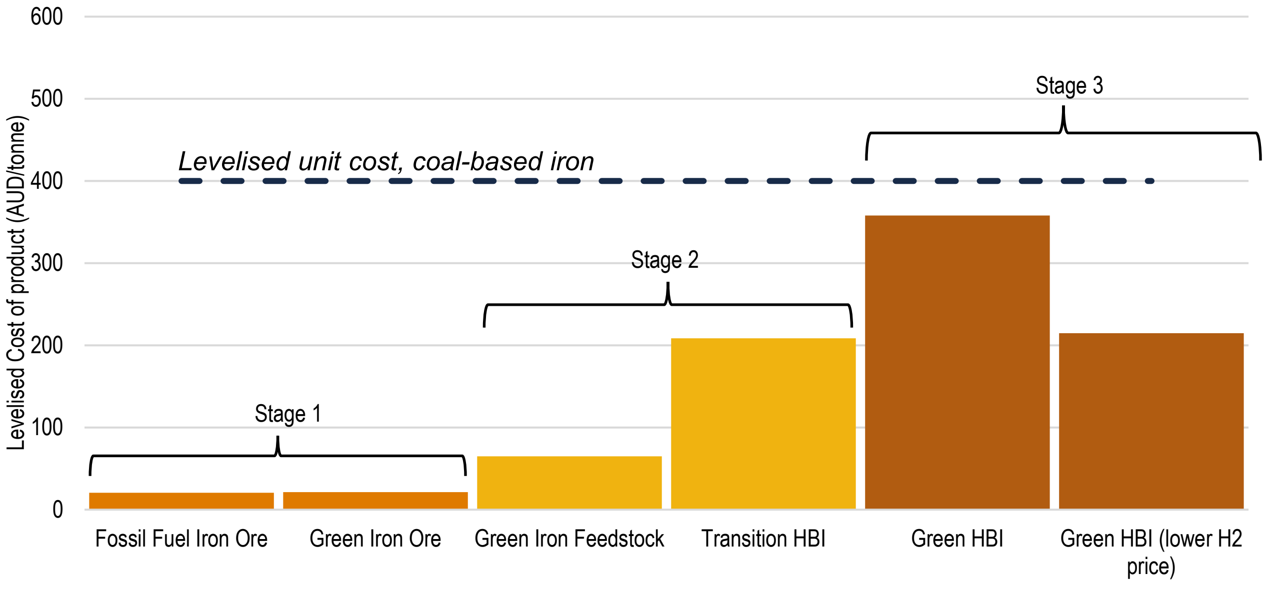
This includes provision for hydrogen-based pelletising, which could also be done using natural gas to lower the cost of supply even further.

By using natural gas, the whole-of-supply-chain carbon emissions of primary steel made through this production process are significantly lower, at around 0.85-0.89 tonnes CO_2 per tonne of steel (against 2.06-2.11 tonnes CO_2 per tonne of steel in the similarly modelled coal based pig iron supply chain).

The challenge with this version of the steelmaking value chain is the domestic emissions associated with Western Australia's participation increase sharply, from around 0.03-0.16 tonnes CO_2 per tonne of steel to 0.54 tonnes CO_2 per tonne of steel for a typical hematite and magnetite value chain. Refer Figures 8.4 and 8.5.

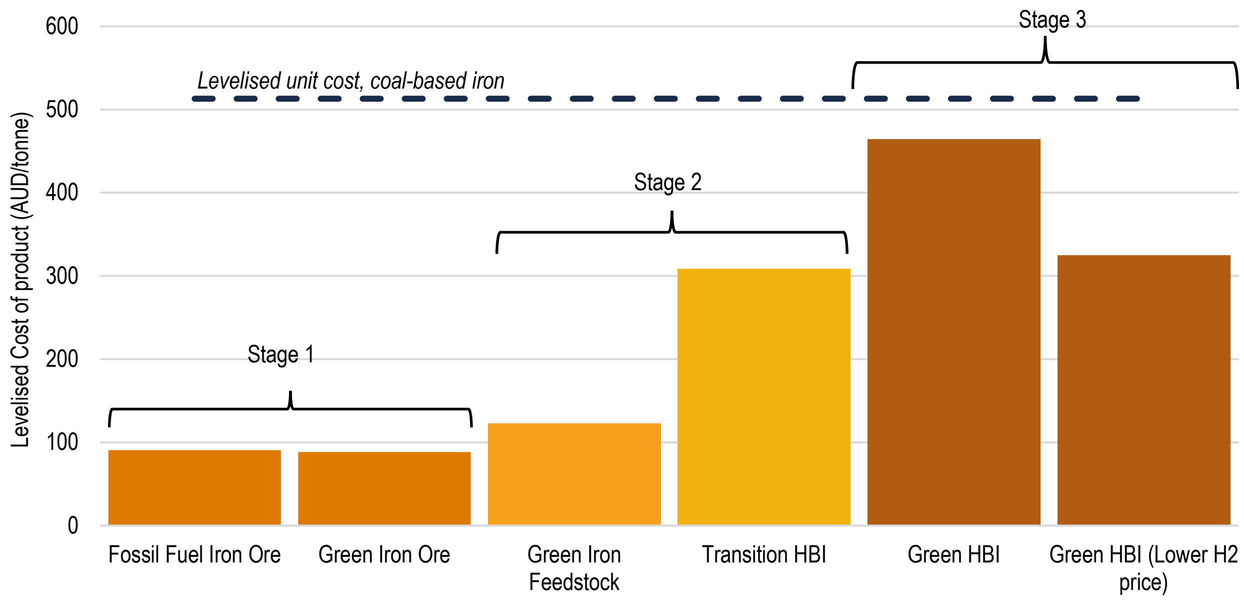
In effect, there is a five-fold increase in domestic emissions to realise an overall net reduction in steelmaking emissions of around 56-59%. This reduction in emissions for the steel industry is potentially increased if lower gangue Western Australian ores are used due to the lower impurities in the HBI requiring lower energy use in steelmaking.

Figure 8.2 Levelised cost of production for Green Iron in the form of HBI transition strategies using hematite ores



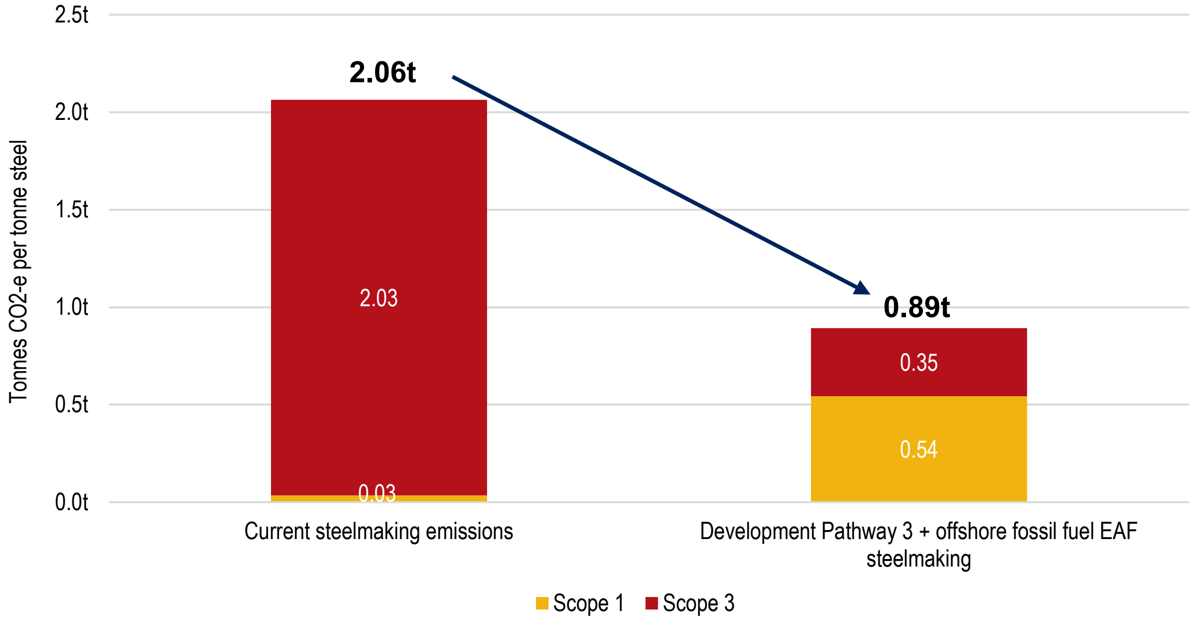
Source: GHD Analysis
Notes: Iron ore feedstock is Pilbara hematite DSO, produced at 50 Mtpa. Input hydrogen price of $7/kg, falling to $3.50 at to Stage 3a, and then to $1.40/kg in Stage 3b. Input product equivalent unit cost represents conversion of cost of production into unit cost per tonne of fossil fuel pig iron produced through coal-based BOF pathway.

Figure 8.3 Levelised cost of production for Green Iron in the form of HBI transition strategies using magnetite ores



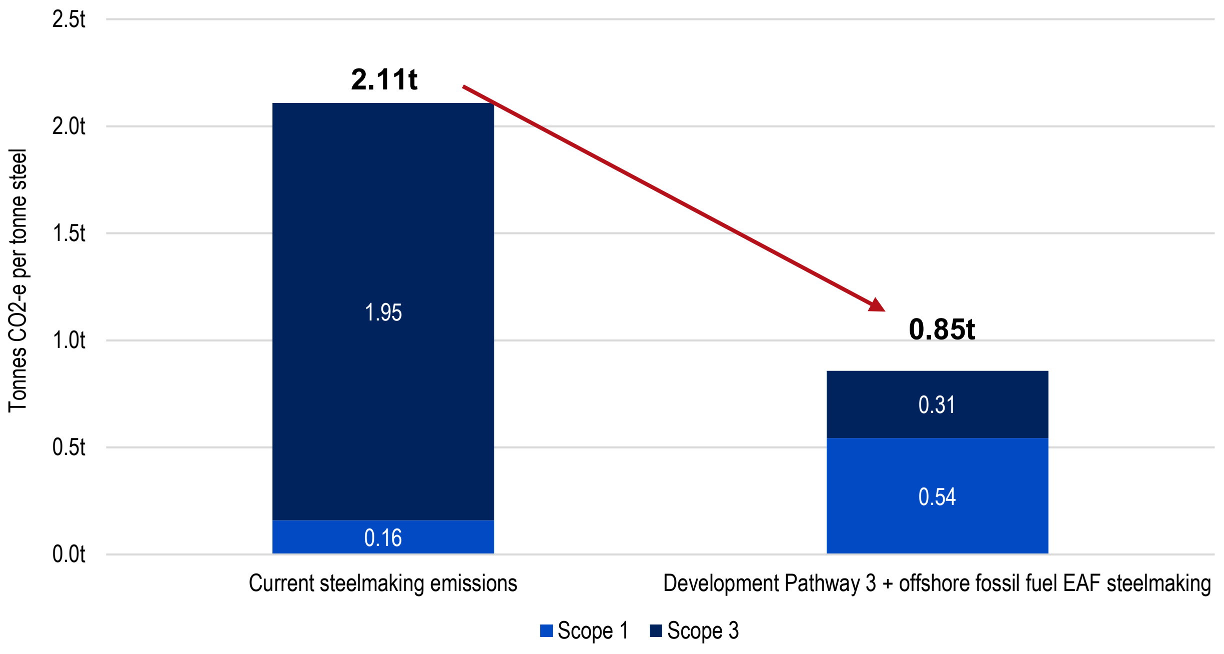
Source: GHD Analysis
Notes: Iron ore is magnetite mined on a 50 Mtpa basis. Input hydrogen price of $7/kg, falling to $3.50 at to Stage 3a, and then to $1.40/kg in Stage 3b. Input product equivalent unit cost represents conversion of cost of production into unit cost per tonne of fossil fuel pig iron produced through coal-based BOF pathway.

*Figure 8.4 Steelmaking emissions, Hematite: Fossil fuels steelmaking value chain vs HBI from Green Pellets usings Fossil Fuels with offshore fossil fuels based EAF, tonnes per tonne of steel, domestic (Scope 1) vs offshore (Scope 3)**



Source: GHD Analysis (Model Value Chain Scenarios: 9c, 9f)
Notes: Excludes shipping.
** Sensitive to iron ore gangue content both on scope 1 and scope 3 emissions saving*

*Figure 8.5 Steelmaking emissions, Magnetite: Fossil fuels steelmaking value chain vs HBI from Green Pellets usings Fossil Fuels with offshore fossil fuels based EAF, tonnes per tonne of steel, domestic (Scope 1) vs offshore (Scope 3)**



Source: GHD Analysis (Model Value Chain Scenarios: 9c1, 9g)
Notes:Excludes shipping
** Sensitive to iron ore gangue content both on scope 1 and scope 3 emissions saving*

8.1.3 Opportunities exist in domestically produced green iron products

The analysis in this study shows green hydrogen-based HBI as a feedstock in EAFs, is expected to reach cost parity with its fossil fuel counterpart sooner than fully Green Steel in the value chain.

This creates an opportunity for Western Australia, alongside the expected continuation of levelised cost reductions in the production of green hydrogen. In the medium term, fully Green Iron in the form of HBI production can be an aspirational target for Western Australia.

As it stands, green hydrogen is not available at an economic price point for widespread adoption of renewable energy in the ironmaking process in place of fossil fuels. But instead of waiting for the price to fall, the implementation of a transition strategy where HBI can be produced at a highly competitive cost of production using lower emissions natural gas as a fuel in the initial phase before transitioning to green hydrogen once costs become economic.

Substitution of hydrogen for the natural gas is also possible using current direct reduction technologies. This will have the effect of reducing emissions towards that of fully Green Iron in the form of HBI based on the cost competitiveness of hydrogen to natural gas. Substitution of hydrogen could be based on availability.

HBI can be a feedstock for existing EAFs but can also replace the supply of iron ore to existing fossil fuel steelmaking in a BF or BOF. In this transformation, HBI would not have to wait for Green Steelmaking technologies to evolve before having a good market.

For 100% hydrogen-based HBI production to be economic, analysis in this study shows infrastructure for renewable power fuelled hydrogen production plants must be developed to realise or support the price of hydrogen reaching $4 AUD/kg (in today's dollars).

The assessment for current delivered price of electrolytic green hydrogen in Western Australia is approximately $7 AUD/kg.

As development of hydrogen production facilities continue, the costs of hydrogen should fall, which will incentivise the replacement of natural gas with hydrogen in shaft furnaces.

Replacement of hydrogen in shaft furnaces is not all-or-nothing but can be a staged process where the gas blend can be varied over time. Once hydrogen prices reach $4 AUD/kg, fully Green Iron in the form of HBI with 100% hydrogen feed would become cost competitive against coal-fired pig iron.

The second transition comes when hydrogen reaches below $1.50 AUD/kg, when it becomes more cost effective to use in shaft furnaces rather than natural gas – incentivising Green Iron in the form of HBI as the most economical way to make iron.

At this stage of development, robust renewable power infrastructure will exist to supply the 0.07 tonnes of H_2 per tonne of HBI required across the value chain. Access to hydrogen at this scale also opens other opportunities for the state in the form of an exportable energy market.

The levelised cost, sustained power and hydrogen requirements, and hydrogen volumes across the different stages of the value chain are shown in Section 7.7.2. Of note is the substantial step-up requirements in hydrogen volume and decreases in cost in going to fully green iron. Enabling hydrogen costs and the scale of supporting infrastructure critical to the success of green iron are the focus of the next section.

This transition pathway requires clear forward planning and an intention to use green hydrogen long term, which will allow time to effect necessary infrastructure development.

8.1.4 In the long run, Green Steel may be possible subject to the price of hydrogen

While it may be feasible for Western Australia to produce Green Steel at a cost of supply not materially below current market prices, this requires the cost of hydrogen to reduce significantly.

As the cost of renewable electricity decreases, bringing the cost of green hydrogen down with it, the State has an opportunity to move up the value chain and manufacture green value-added steel products. However, for Green Steel to be economical in the State, the price of hydrogen must reach the so-called "stretch" target of approximately US$2/kg or $3 AUD/kg. Analysis of the breakeven price points for a variety of products is provided on the following two pages.

The replacement of over 60% of the worlds fossil fuel BFs is unlikely in the near term due to their age, so offshore foreign environmental factors must change before Green Steel in Western Australia can be cost competitive with the export steel markets.

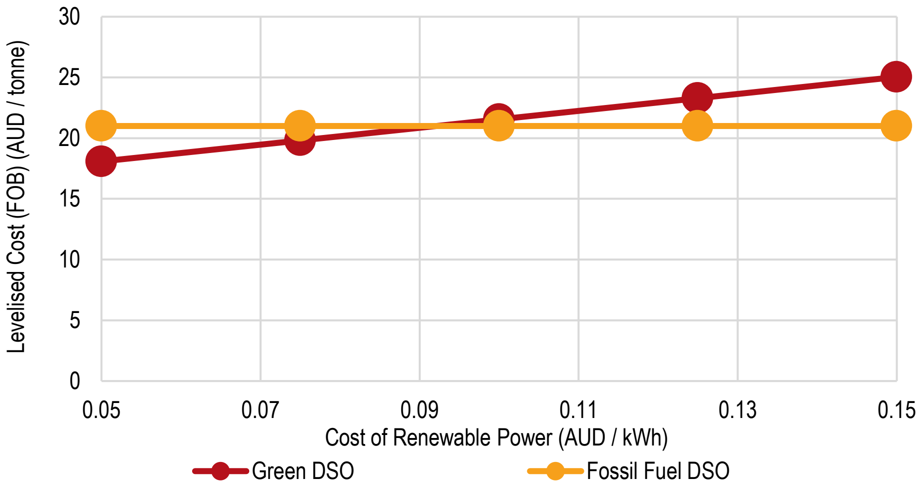
New Green Steel technologies involving other pathways to convert iron are also being explored by researchers and these technologies (such as the electrolysis of iron ore directly) in the future may perhaps require less prohibitive investment or involve more economic feedstock (such as low impurity pig iron). These alternative green pathways, not included as scenarios for full study, may improve the viability of Green Steel compared to green iron in Western Australia.

Currently much of the research is at pilot stage scale, and still involves green iron production rather than direct Green Steel production because of the large emissions step currently in ironmaking.

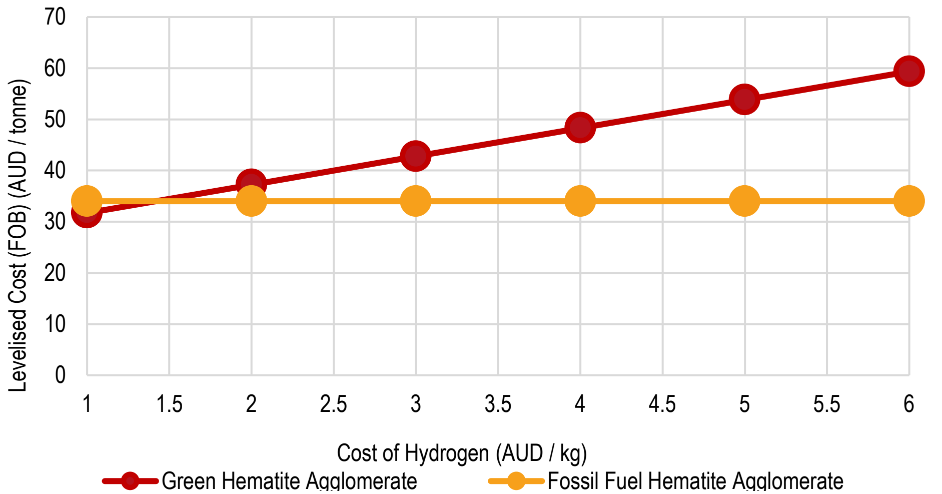
Analysis of the price hydrogen needs to be for each product to be competitive against its fossil-fuels alternative, suggests Green Iron in the form of HBI will become cost-competitive sooner than Green Steel. All other things being equal, this indicates a pathway focusing on development of Green Iron in the form of HBI in Western Australia should be pursued.

Figure 8.6 Breakeven hydrogen / electricity input costs, hematite ore based products, $/kg or $/MWh

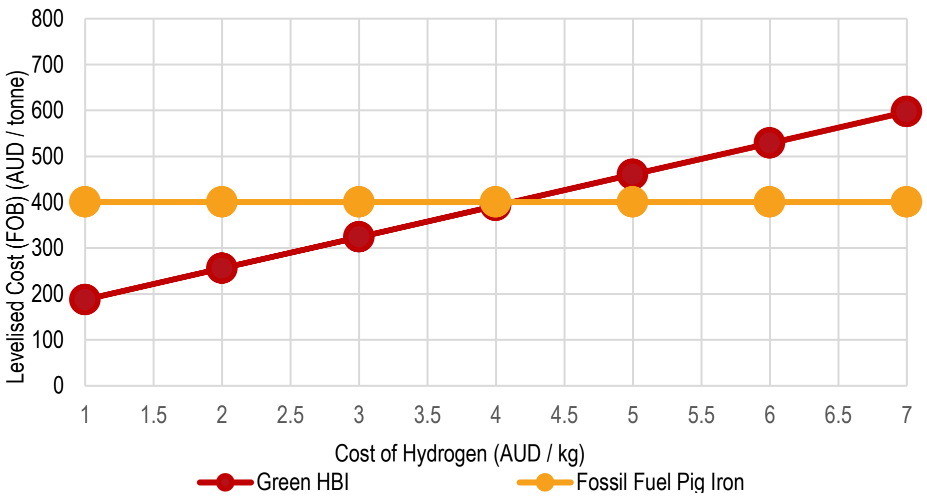
(a) Pathway 1: Green Iron Ore Mining



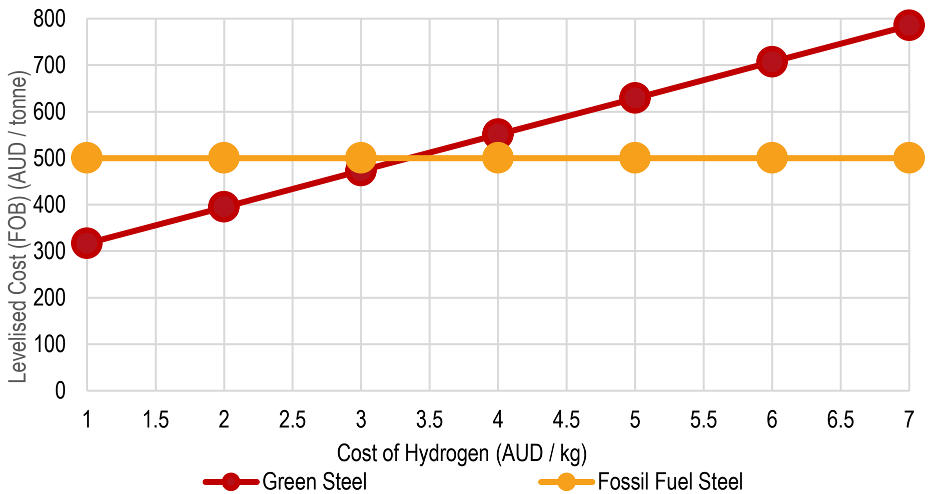
(b) Pathway 2: Green Pellets



(c) Pathway 4: HBI from Green Pellets using Renewable Hydrogen



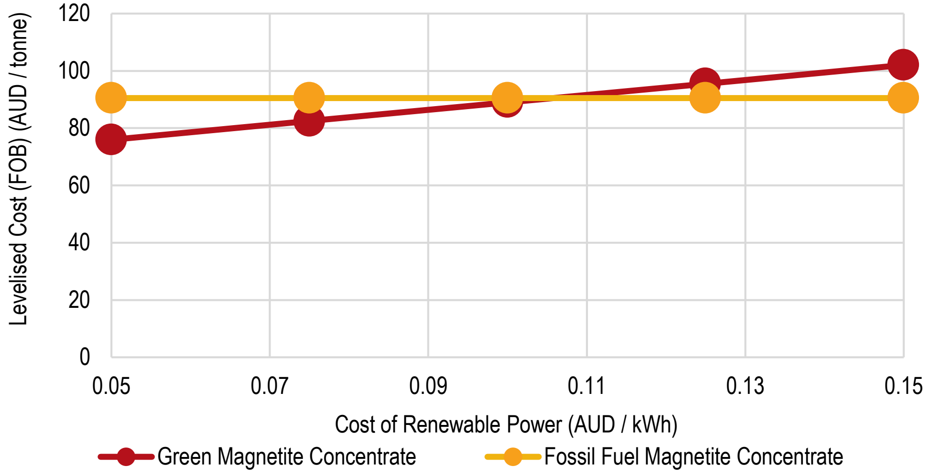
(d) Pathway 5: Producing Green Steel in Western Australia



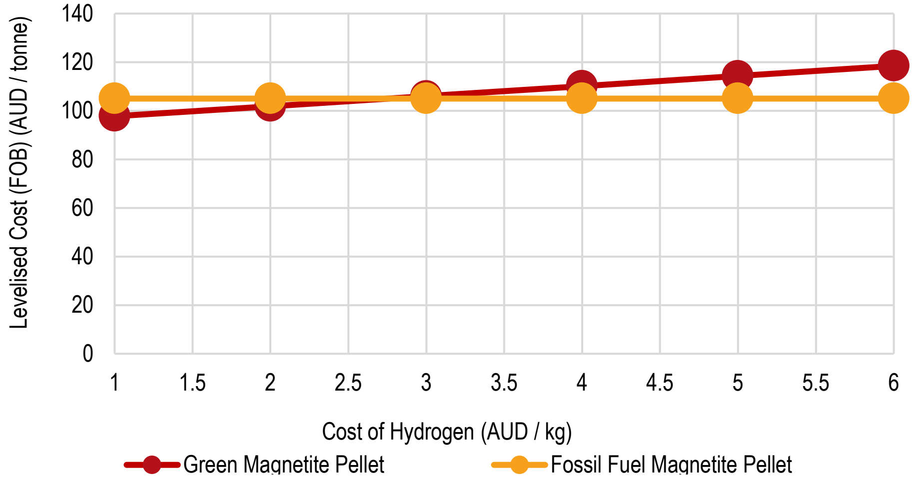
Source: GHD Analysis GHD Analysis (Model Value Chain Scenarios: Hematite (2b,4b,6a1,10a1)

Figure 8.7 Breakeven hydrogen / electricity input costs, magnetite ore based products, $/kg or $/MWh

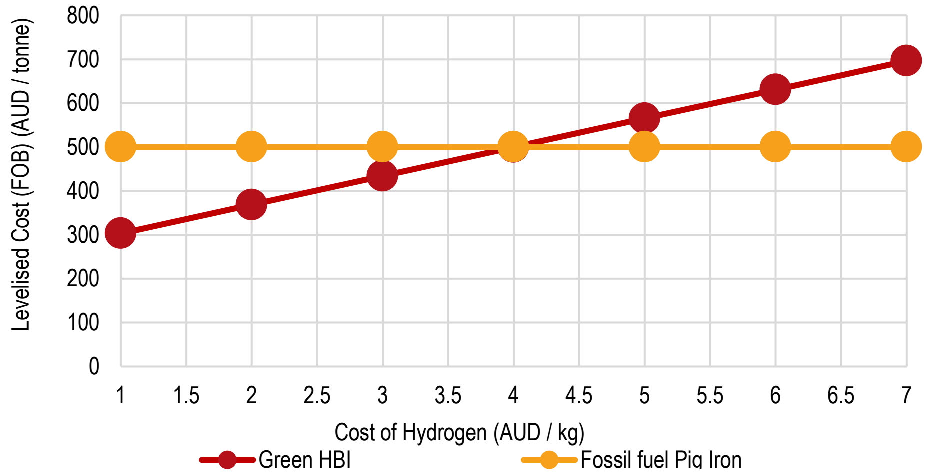
(a) Pathway 1: Green Iron Ore Mining



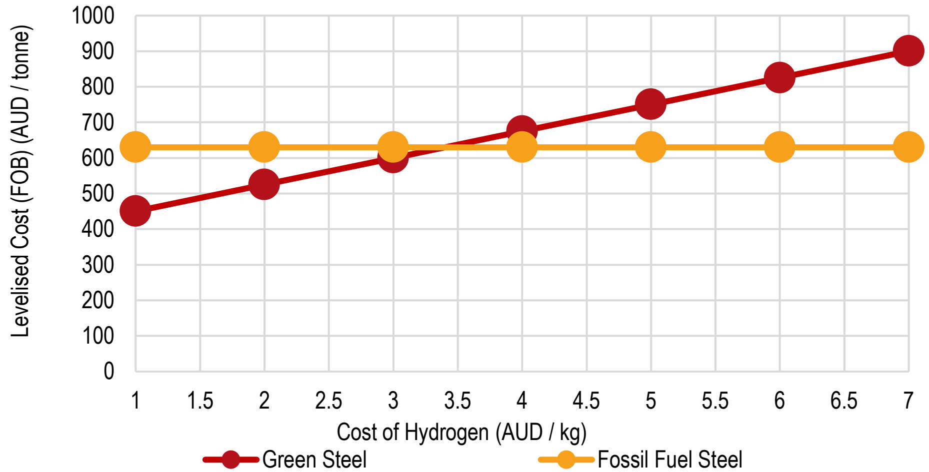
(b) Pathway 2: Green pellets



(c) Pathway 4: HBI from Green Pellets using Renewable Hydrogen



(d) Pathway 5: Producing Green Steel in Western Australia



Source: GHD Analysis GHD Analysis (Model Value Chain Scenarios: Magnetite (2b1,4c,6d,10b1))

Table 8.1 Rounded required H_2 price for each pathway to break-even in cost against fossil-fuels equivalent

Breakeven H_2 prices (AUD/kg)	Green Pellets	Green Iron in the form of HBI	Green Steel
Hematite	\$1.50	\$4.00	\$3.50
Magnetite	\$2.80	\$4.00	\$3.50

Source: GHD Analysis

Finding 16 Western Australia's Green Steel value chain opportunities and pathways

Overall, the assessment suggests of the options considered, pathways which involve the development of intermediate iron products, such as HBI, are the most prospective for Western Australia.

These products are a natural extension of the State's current place in the value chain and make best use of both current and emerging advantages in energy. HBI and other intermediate products allow the State to continue to capture significant value in the steelmaking value chain without the high capital costs and low margins associated with steel itself.

The export steel product market will be slower to adjust to environmental factors than drivers for the use of Western Australian HBI, particularly in a market for an increasing global demand for lower emission HBI.

8.2 Defining the Green Steel critical success factors

Western Australia hosts a globally significant iron ore resource. This has been developed into a sustainable competitive advantage in the production of ore products to feed into the steelmaking value chain across the world.

The critical success factors which have driven the growth and sustained the activity of this industry are well known and understood. They are an important source of economic activity and social development for the State of Western Australia. But they alone are not sufficient for Western Australia to take its place in the future Green Steel value chain.

Four factors are considered necessary to position the State to capture its share of the Green Steel opportunity. These are:

- **Resources**: Access to the physical iron ore resources required to produce the steelmaking feedstock which will be demanded by the Green Steel value chain. Western Australia has an abundance of iron ore, providing the platform for this opportunity.
- **Energy**: Access to renewable energy resources, and having the capacity to convert these into renewable hydrogen, is central to the development of Green Steel opportunities. Progressing through a natural-gas based DRI pathway requires access to natural gas.
- **Infrastructure**: Access to infrastructure to connect resources to processing plants, and to global markets, is a critical enabler of all industries. In Green Steel, the sheer scale of renewable energy infrastructure required makes this critical to success.
- **Technology and enterprise**: The technologies and processes required to produce greener iron and steel continue to evolve. Securing access to research, and the capacity to drive commercial outcomes, is expected to be central to Western Australia's Green Steel opportunity.

These critical success factors are considered throughout this report, through market dynamics analysis, and the value chain and project economic analysis.

The directions provided by this work are summarised on the following page. The table identifies how progress in these four areas builds to provide the platform for Western Australia to capture its share of the Green Steel opportunity.

Development pathway		Resources		Energy		Infrastructure		Technology and enterprise	
		What we have	What more is needed	What we have	What more is needed	What we have	What more is needed	What we have	What more is needed
Scale of industrial transformation required (top = less transformation)	Green hematite direct ship ore (including beneficiation)	Hematite ores in lump or fines form, with iron content of 58%fe or greater		Emerging green electrification of production processes using renewable electricity	Renewable hydrogen produced at moderate cost Investment in new hydrogen plant, machinery & equipment	Existing integrated DSO export supply chain (Pilbara) Distributed DSO export supply chain (Mid West) On-site power generation and distribution	Electricity network infrastructure to improve economics of green electricity (Pilbara, Mid West)	Established business relationships, processes and practices. Industrial base for producing and shipping DSO.	Adoption of new technologies to improve grade and remove gangue from DSO prior to export.
	Green magnetite ore for shipping	Magnetite ores with iron content of 67%fe or greater after processing		Emerging green electrification of production processes using renewable electricity			New port and rail capacity Water infrastructure for processing	Proven technologies and processes to produce magnetite shipping ore Existing magnetite projects in Western Australia	Customer demand and investment in new product mix Human capital to build and operate facilities
	Pelletised iron ore for sale into global steelmaking value chains	Existing ores and waste stockpiles which are suitable for processing					General cargo trading capacity in strategic locations (Pilbara, Mid West)	Customer momentum for grade maintenance and improvements	Commercial application of pelletisation technologies in Western Australia Appropriate metallurgy skills and expertise
	Direct Reduced Iron (natural gas reduction)	Ores with appropriate Fe content and low gangue for pelletisation.		Competitively priced natural gas, available on long terms in areas adjacent to mineral resources.		Strategic Industrial Areas and generalised industrial estates.	Natural gas transmission infrastructure to key locations.	Initial customer interest in exploration of HBI using WA ores	Commercial application of DRI technologies in Western Australia Appropriate metallurgy skills and expertise
	Direct Reduced Iron (green hydrogen)	Ores with appropriate Fe content and low gangue for pelletisation, with higher trade magnetite preferred.		Emerging green electricity production competitive advantage	Renewable hydrogen produced at a low cost. Increased green electricity generation capacity in key locations.		Appropriately zoned and cleared land for infrastructure Additional transmission infrastructure in strategic locations		Commercial scale hydrogen-based DRI success. Commercial application of DRI technologies in Western Australia Appropriate metallurgy skills and expertise
	Electric Arc Furnace steelmaking	Existing scrap steel production in public and private sectors	Green iron feedstock, predominately DRI-HBI produced domestically.	Confirmed green electricity production competitive advantage	Renewable hydrogen produced at a very low cost. Increased green electricity generation capacity in key locations.		Additional electricity infrastructure. Port infrastructure (regional general cargo export capacity)		Commercial-scale renewable electricity-based EAF steelmaking. Appropriate metallurgy skills and expertise

8.3 Understanding the Economic Impacts

To complete the economic impact assessment, ACIL Allen worked with GHD and MRIWA to consider a baseline, two development scenarios and a downside risk scenario. These are described below.

8.3.1 Scenario descriptions

Baseline

As part of the assessment, ACIL Allen developed a baseline for the total value of iron ore production in Western Australia between 2021 and 2050 as a projection to assess the impact of the development scenarios. The baseline provides a quantified view of a future where there is very limited change to the structure of the global steel value chain, beyond that which is contained within the long term outlook.

In the baseline, Western Australia continues to produce predominately hematite DSO for use in BFs, with a progressive greening of the domestic ore production value chain. The baseline assumes there are no additional magnetite mines beyond those which are currently in operation or under construction as of mid-2022.

Other critical inputs and assumptions are outlined below in Table 8.2. The baseline for total value of production is provided below in Figure 8.8.

Table 8.2 Baseline modelling inputs and assumptions

Input / assumption	Value	Source
Initial production – lump hematite	196.3 MT	DMIRS
Initial production – fines hematite	616.7 MT	DMIRS
Initial production – magnetite	26.1 MT	DMIRS
Growth scenario	Wood Mackenzie Base Case October 2021	Wood Mackenzie data [144]
Price scenario	Wood Mackenzie Long Run Flat Real Price October 2021	Wood Mackenzie data [144]
Price – lump hematite	US$76.30/tonne FOB	Wood Mackenzie data [144]
Price – fines hematite	U$61.30/tonne FOB	Wood Mackenzie data [144]
Price – magnetite	Lump premium + 40% (FOB basis)	ACIL Allen, from analysis of DMIRS Royalties by Iron Product data
Royalty rate – hematite	7.5%	*Mining Regulations 1981*
Royalty rate – magnetite	5.0%	*Mining Regulations 1981*
Exchange rate	1AUD = 0.72USD	ACIL Allen

Source: ACIL Allen

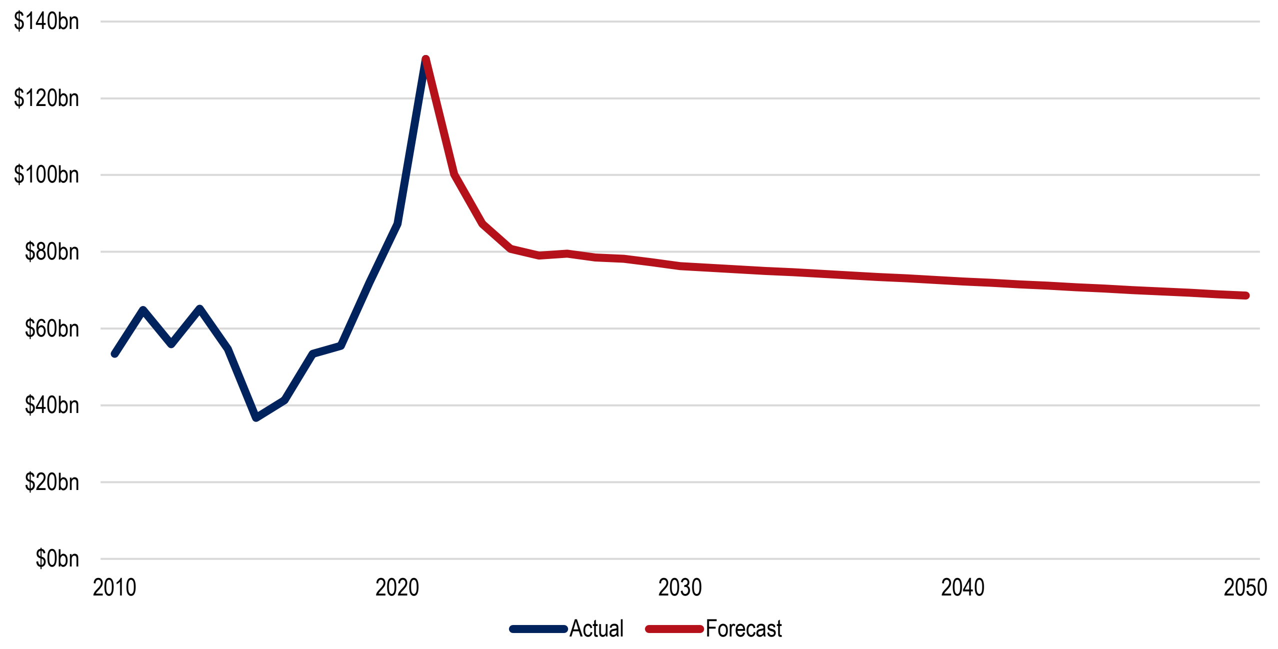
[144] Refer Wood Mackenzie disclaimer at the beginning of this report.

The baseline projection suggests the value of Western Australia's iron ore industry will remain higher than the level set at the end of the previous iron ore price boom, on account of a larger production base and higher flat real price in the long run.

This is underpinned by the volume projections for type of ore produced and exported, as indicated below in Figure 8.9.

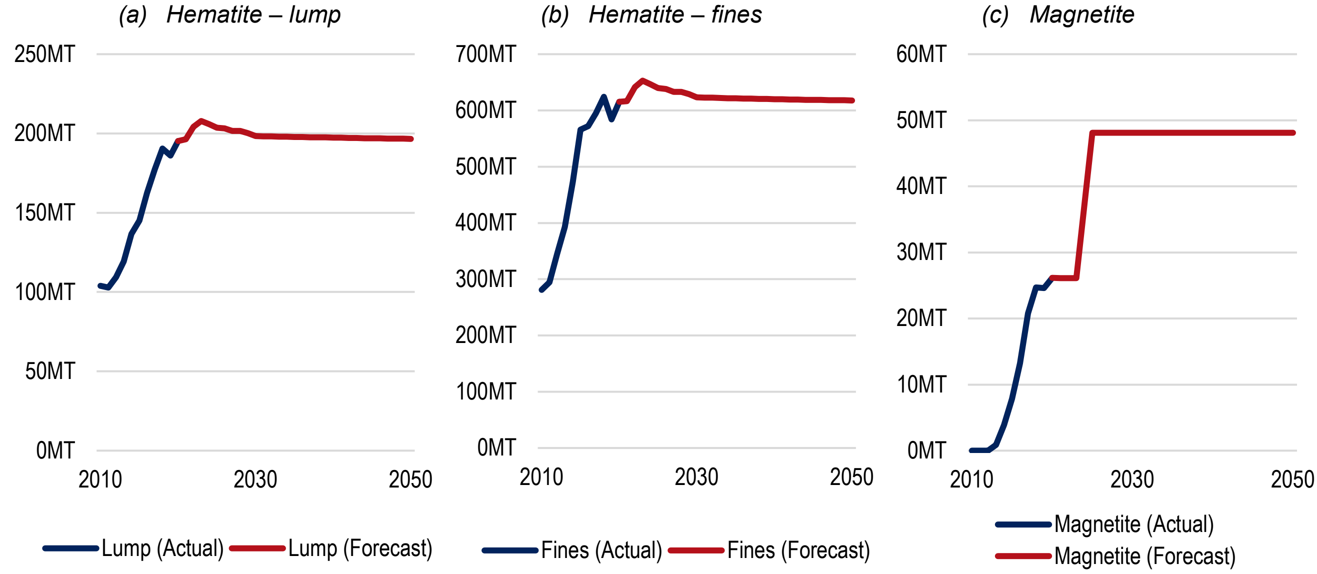
The value of the sector does decline significantly from the 2020-2021 highs, on account of a technical modelling assumption the iron ore price will converge to a long run average over a five-year period.

Figure 8.8 Economic impact assessment: Baseline, value of iron ore production, $bn per annum real 2022 dollars (AUD terms)



Source: ACIL Allen Analysis

Figure 8.9 Baseline scenario, volume of production / export, by ore type, MT per annum



Source: ACIL Allen Analysis

The projections show in this baseline there is limited growth for ore production in Western Australia in the short term before a plateau and slight decline following the middle of this decade as steel production capacity matures in the State's key markets.

It is assumed there is no impact on the trajectory for magnetite production given the higher grades associated with this output and the prospect of this remaining a higher priority feedstock for steelmakers in all scenarios.

ACIL Allen's baseline projections have been fed into their CGE model, which determines the level of expenditure, employment, profit and taxation based on historic trends versus the input volumes and prices.

These values have been calibrated using DMIRS' historic employment information, and own in-house experience modelling the economic value of the iron ore industry and iron ore projects in Western Australia.

The results of the analysis are considered in Section 8.3.2.

Development scenarios

The scenarios used to demonstrate the upside opportunities associated with a Green Steel future for Western Australia are outlined below.

These scenarios are additive to the baseline level of iron ore production forecast for Western Australia, meaning they do not displace the forecast level of production from other projects.

- **Development Scenario 1: Green Iron in the form of HBI.** As part of the evolution of Western Australia's role as a supplier of iron-based feedstock to the global steel value chain, a fully vertically integrated HBI plant is developed in the Pilbara region of Western Australia. The HBI plant uses green hydrogen-based DRI production technologies, with beneficiated magnetite iron ore feedstock. This product is wholly exported to international customers in South East Asia.
- **Development Scenario 2: Green Steel**. As an extension on the green iron development, an opportunity to produce fully green primary steel for export is identified and actioned. This would take the form of a fully integrated magnetite-based DRI-HBI pathway, with an EAF used to produce the primary steel for export.

Each of the development scenarios has been calibrated using the value chain model, which provide details on the unit costs associated with production of each of the intermediate products in the value chain. The exception to this are costs associated with the production of electricity and renewable hydrogen, which have been exogenously imposed on the model. This is discussed in more detail in Box 8.1.

The development scenarios have been selected to demonstrate the potential of value-adding projects to Western Australia, and to the regional economies where the projects may take place.

The selection of a HBI project reflects the findings and directions of the value chain modelling with respect to the potential role of HBI as both a transitional and eventually largely green product. The project itself is modelled on pathway 4 of the Green Steel transition strategy discussed in Section 7. The selection of a green DRI-EAF project reflects the "ultimate" development of a fully Green Steelmaking value chain.

There are a range of additional inputs and assumptions required to facilitate the economic impact assessment. These are introduced in Table 8.4 below and discussed thereafter.

Box 8.1 Imposing economic hydrogen and electricity prices

As discussed in Section 7, the current modelled renewable hydrogen price for a fully integrated iron or steelmaking facility in Western Australia inclusive of the capital and operating cost of renewable electricity generation plant and equipment is approximately $7. This occurs despite considering the economies of scale associated with the size of plant required to facilitate the energy needs of this value chain. This results in a delivered product (FOB) price which is outside of the tolerance of the current market for iron and steel products.

To address this in the economic impact assessment, ACIL Allen has exogenously imposed production costs for electricity and hydrogen in the model. This allows the model to solve for a fully economic value chain that can generate a return on capital at market prices. Without this, the modelling would project a negative economic impact, as it would imply the development results in the destruction of capital and labour resources on an uneconomic project.

The implication of this is the economic impact assessment should be viewed as a **projection of success**, rather than a forecast of what will come.

Source: ACIL Allen

The approach to modelling the development projects is based on the value chain model, which itself is based on a representative year of production approach. This means the various inputs and assumptions regarding production rates, feedstock requirements, and operating costs are the same in each year of the study.

This provides a flat profile (i.e., the values are the same in each year of the modelling period) of outputs in real terms. This is considered reasonable for these particular value chains, given the economic benefit for the project of direct feeding intermediate products from one production process to the next.

A range of additional modelling parameter assumptions are made, as detailed below in Table 8.3. These parameters are consistent across both modelling scenarios.

Table 8.3 Modelling parameterisation

Input / assumption	Value	Source
Project life (operations)	30 years	ACIL Allen
Construction period	6 years	ACIL Allen
Modelling basis	Real 2022 dollars	ACIL Allen
Discount rate	~8.3%	In line with derived WACC for project
Exchange rate	1AUD = 0.72USD	ACIL Allen
Ownership of capital	25% Australia 75% international	ACIL Allen. Values following stakeholder feedback regarding need for joint venture arrangements and international partnerships to progress opportunities.

Source: ACIL Allen

Table 8.4 Baseline modelling inputs and assumptions

Input / assumption	Development Scenario 1 (Green Iron in the form of HBI)	Development Scenario 2 (Green Steel)	Source
Final product plant production capacity	4.8 Mtpa	2.8 Mtpa	ACIL Allen
Implied ore feedstock volume	23.5 Mtpa	15.7 Mtpa	GHD Value Chain Model
Capital structure (debt / equity ratio)	Debt: 30% Equity: 70%		ACIL Allen, from Stern University Global Cost of Capital Study
Term interest rate	7% p.a.		ACIL Allen, from RBA
Debt term	10 years		ACIL Allen, illustrative purposes only
Construction interest rate	4% p.a.		ACIL Allen, illustrative purposes only
Required return on equity	12% post-tax		ACIL Allen, from Stern University Global Cost of Capital Study. Actual equity return = ~10%, with 2% premium applied to reflect additional equity risk associated with greenfield downstream development in Western Australia
Weighted average cost of capital / discount rate	~8.3%		ACIL Allen, derived
Hydrogen price (exogenous)	$4.50/kg		ACIL Allen
Electricity price (exogenous)	$0.05/kWh		ACIL Allen
Royalty rate applied	2.5% (metals rate)		*Mining Regulations 1981*
Company income tax rate	30%		Australian Taxation Office
Market price	$791/tonne FOB	$898/tonne FOB *Market price = $855/tonne FOB, based on UN Comtrade*	For iron, ACIL Allen analysis of UN Comtrade (as project economics meet threshold price). For steel, price is set using outputs of ACIL Allen's project economic model, as the project economics do not meet a market price threshold.

Source: ACIL Allen

The economic impact assessment also requires an assessment of the direct employment associated with the development scenarios.

ACIL Allen undertook a review of a number of existing and planned ore mining, and iron and steelmaking developments to build a profile of the number of FTE jobs that would be required to fulfil a target level of production. These projects are summarised below in Table 8.5.

The development scenarios are discussed further below and the results of the modelling are discussed in Section 8.3.2.

Table 8.5 Employment in iron ore, ironmaking and steelmaking projects

Asset name	Production capacity	FTE employment	FTE / tonne capacity
Iron ore – hematite			**54.1**
Roy Hill Mine	60 Mtpa	3,173	52.9
Eliwana	30 Mtpa	1,633	54.4
Brockman 4	22 Mtpa	1,248	56.7
Iron ore – magnetite			**142.5**
Sino Iron	24 Mtpa (concentrate)	3,293	137.2
Karara	8 Mtpa (concentrate)	1,268	158.5
HBI plant			**132.0**
Zheleznogorsk (Ukraine)	2.08 Mtpa	400	192.3
Voestalpine (USA)	2 Mtpa	190	95
Toledo (USA)	1.6 Mtpa	160	100
Steel plant (EAF)			**172.1**
Alabama (USA)	3 Mtpa	600	200
Fairfield (USA)	1.6 Mtpa	150	93.8
Fort Wayne (USA)	1.5 Mtpa	300	200

Source: ACIL Allen, from DMIRS (iron ore), various media sources (HBI, steel)

Development Scenario 1: Green Iron in the form of HBI

To develop a 4.8 Mtpa, vertically integrated mine-to-export value chain, the value chain modelling suggests the following capital expenditure is required:

- Development of a 23.5 Mtpa magnetite mine, with processing and concentration infrastructure to yield 7.1 Mpta of high grade magnetite-based feedstock for ironmaking. **Total capital cost: $2.9 billion.**
- Development of a 4.8 Mtpa DRI-HBI plant, to process magnetite-based feedstock into iron briquettes with near-100% iron content. The plant uses green hydrogen as the reductant to produce the iron. **Total capital cost: $4.1 billion.**

Other capital costs and resource requirements are outlined in Table 8.6.

Table 8.6 Indicative capital and other resource requirements for 4.8 Mtpa of Green Iron in the form of HBI from Magnetite, Pilbara

Indicative requirements for:	4.8 Mtpa Shipped as Green Iron in the form of HBI	Units	Comments
	Magnetite		
Mining facility (crush, screen, beneficiation)	$2,100	M AUD	Capex
Pelletisation facility	$733	M AUD	Capex
Shaft furnace	$4,070	M AUD	Capex
Processing facility land use	672	Hectares	
Sustained power required	2,356	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$20,793	M AUD	Capex
Renewable facility land use	12,944	Hectares	
Annual hydrogen required	325	Ktpa	
Hydrogen facility	$3,670	M AUD	Capex
Ammonia facility	$3	M AUD	Capex
H_2 rail trains	$72	M AUD	Capex - 1 train
Ammonia-powered vessels	$122	M AUD	Capex - 1 ship
Water required	23,436	ML p.a.	
Mined ore required	23.5	Mtpa	
Shipped product	4.8	Mtpa	

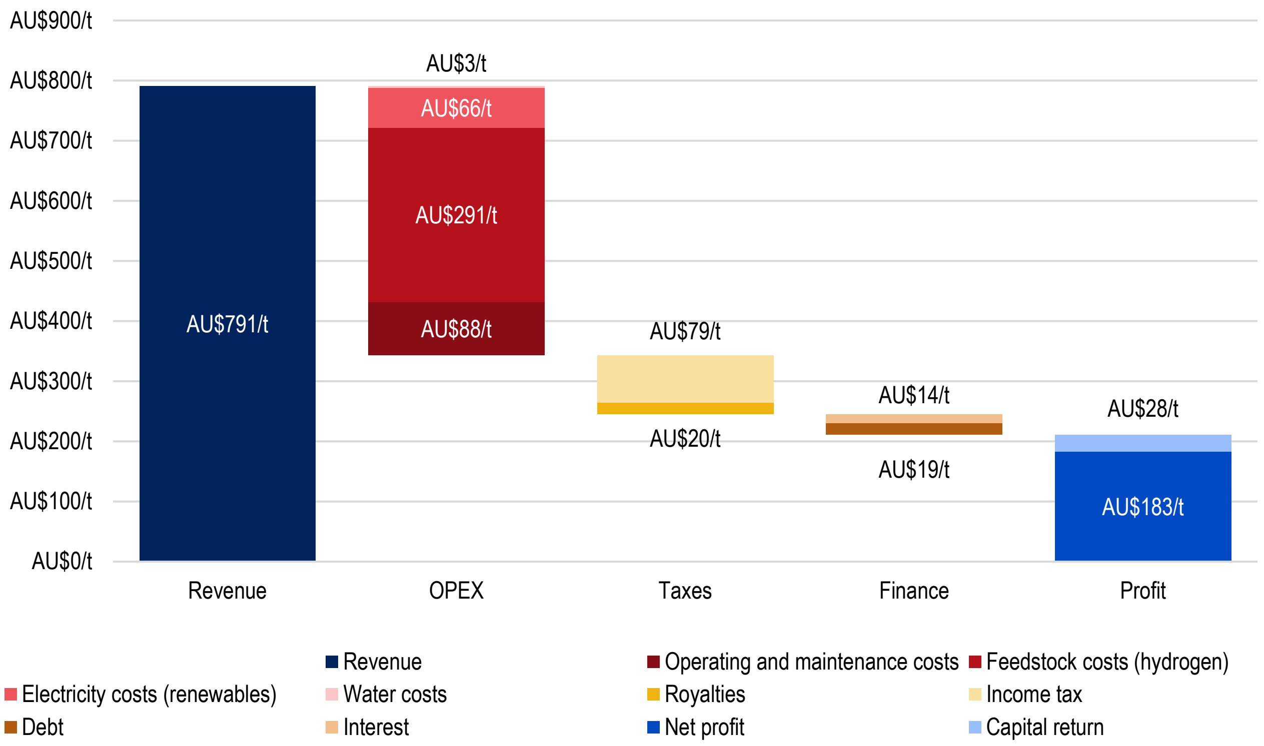
Source: GHD Analysis (Model Value Chain Scenario 6b1); MRIWA

In this economic impact assessment, the development of electricity and hydrogen production is kept out of scope. This is to ensure an economically viable prices are made available to the project (see Box 8.1), but also to focus the economic impact assessment on the development of iron ore and iron production infrastructure.

Under the inputs and assumptions developed in the value chain model, an additional capital expenditure of $24.6 billion would be required to produce the volume of electricity and hydrogen required for the value chain, and to procure vessels capable of shipping the final product to market using green fuels.

The overall output of the Green Iron in the form of HBI development project model is provided below in Figure 8.10. The model demonstrates a project with the parameters introduced in the previous section can deliver a positive return over a 30 year project life assuming an iron price of approximately $800 per tonne on an FOB basis.

Figure 8.10 Development Scenario 1 (Green Iron in the form of HBI) project economics, modelling outputs per tonne of product, 4.8 Mtpa capacity, Present Value terms (8.3% discount rate)



Source: ACIL Allen Analysis

Development Scenario 2

To develop a 2.8 Mtpa, vertically integrated mine-to-export value chain, the value chain modelling suggests the following capital expenditure is required:

- Development of a 15.7 Mtpa magnetite mine, with processing and concentration infrastructure to yield 4.8 Mtpa of high grade magnetite-based feedstock for ironmaking. **Total capital cost: $2.1 billion.**
- Development of a 3.2 Mtpa DRI-HBI plant, to process magnetite-based feedstock into iron briquettes with near-100% iron content. The plant uses green hydrogen as the reductant to produce the iron. **Total capital cost: $3.1 billion.**
- Development of a 2.8 Mtpa EAF steelmaking facility, which outputs primary carbon steel utilising renewable electricity for energy.

  Total capital cost: $0.5 billion.

Other capital costs and resource requirements are outlined in Table 8.7.

As above, in this economic impact assessment, the development of electricity and hydrogen production is kept out of scope. This is to ensure an economically viable prices are made available to the project (see Box 8.1), but also to focus the economic impact assessment on the development of iron ore and iron production infrastructure.

Under the inputs and assumptions developed in the value chain model, an additional capital expenditure of $18.4 billion would be required to produce the volume of electricity and hydrogen required for the value chain, and to procure vessels capable of shipping the final product to market using green fuels.

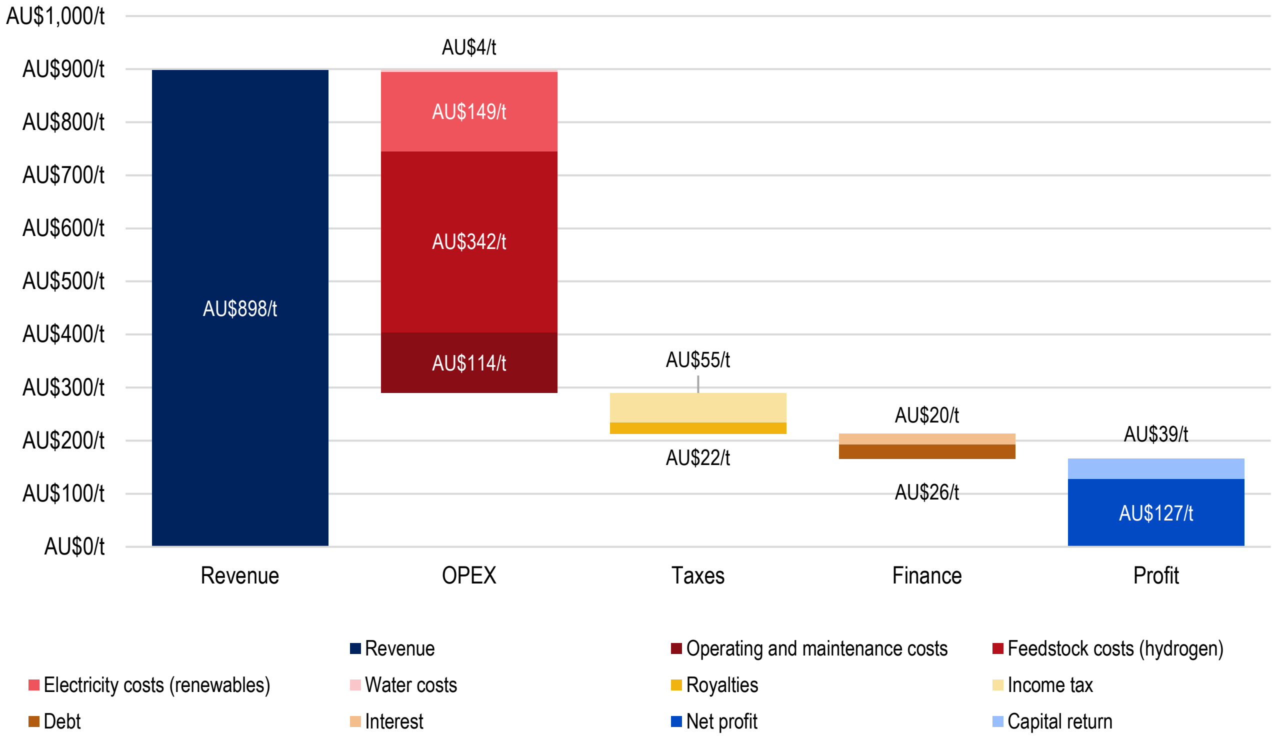
The overall output of the Green Steel development project model is provided below. The model demonstrates a project with the parameters introduced in the previous section can deliver a positive return over a 30 year project life assuming an iron price of approximately $900 per tonne on an FOB basis. This is in line with primary steel product prices in the first half of 2022.

Table 8.7 Indicative capital and other resource requirements for 2.8 Mtpa of Green Steel from Magnetite.

Indicative requirements for:	2.8 Mtpa Shipped as Green Steel	Units	Comments
	Magnetite		
Mining facility (crush, screen, beneficiation)	$1,513	M AUD	Capex
Pelletisation facility	$517	M AUD	Capex
Shaft furnace	$3,107	M AUD	Capex
EAF facility	$479	M AUD	Capex
Processing facility land use	672	Hectares	
Sustained power required	1,802	MW	Ongoing 24hr load
50/50 mixed solar/wind + batteries	$15,904	M AUD	Capex
Renewable facility land use	9,900	Hectares	
Annual hydrogen required	216	Ktpa	
Hydrogen facility	$2,441	M AUD	Capex
Ammonia facility	$2	M AUD	Capex
H_2 rail trains	$43	M AUD	Capex
Ammonia-powered vessels	$61	M AUD	Capex
Water requirements	15,594	ML p.a.	Capex
Mined ore required	15.7	Mtpa	
Shipped product	2.8	Mtpa	

Source: GHD Analysis (Model Value Chain Scenario 10b2); MRIWA

Figure 8.11 Development Scenario 2 (Green Steel) project economics, modelling outputs per tonne of production, 4.8 Mtpa capacity, Present Value terms (8.3% discount rate)



Source: ACIL Allen Analysis

Downside risk scenario

The final scenario for analysis is to consider a future where Western Australia iron ore loses significant market share as a steelmaking feedstock, and there is little or no response by producers. While an extreme scenario, this represents a view of the future where the State's most important industry contracts over time, as other global suppliers of iron ore and iron feedstock better position to succeed in a Green Steel world.

To model this scenario, ACIL Allen has relied upon a projection contained within a report by Wood Mackenzie,[145] provided by MRIWA which presents a scenario where iron ore falls substantially out of favour on global markets.

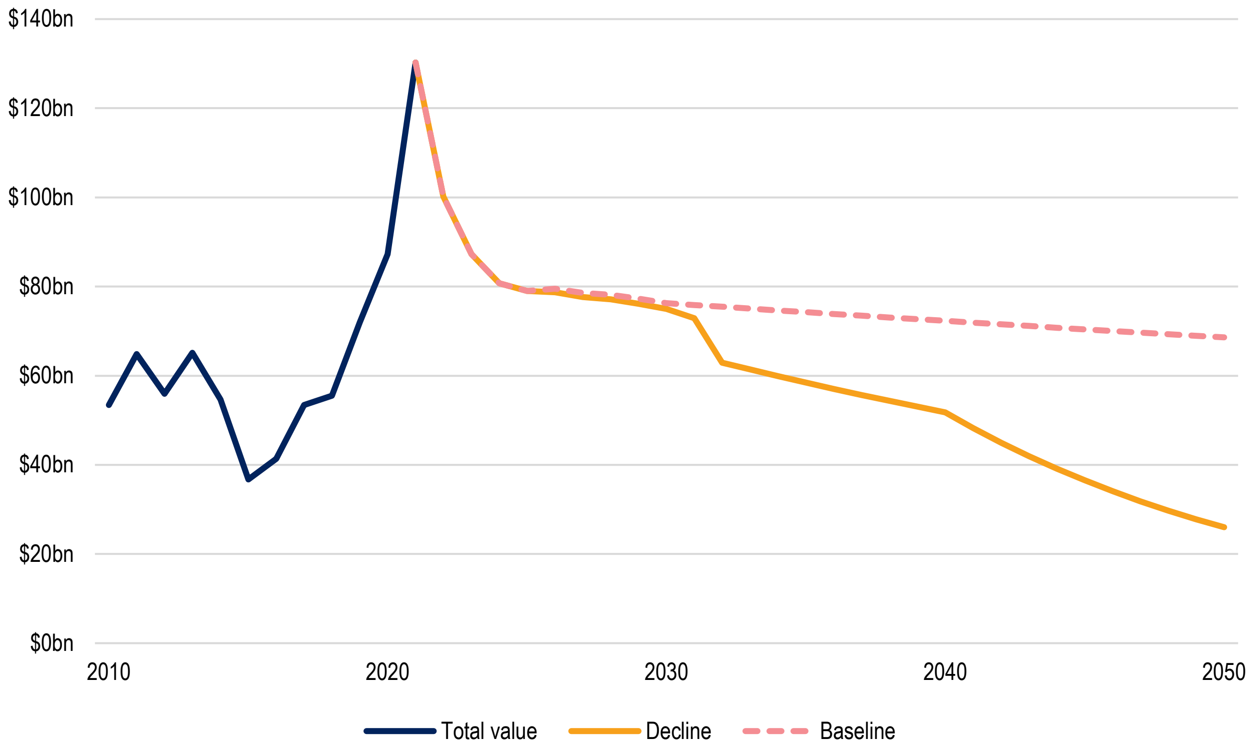
The decline occurs in both iron ore lump and iron ore fines markets, with the decline in demand for iron ore fines being larger than the fall in demand for lump. Magnetite ores are unaffected in this scenario due to the higher grade of the output, and consequent downstream impact on carbon emissions.

The reduction in iron ore industry activity occurs through both price and volume reductions against the baseline prepared by ACIL Allen. Due to confidentiality requirements, the raw numbers contained within this report are not able to be published.

ACIL Allen's contextualisation of the downside risk scenario projected by Wood Mackenzie is provided below in Figure 8.12.[146]

[145] Wood Mackenzie. 2021. *Iron ore outlook under steel's accelerated energy transition two-degree scenario* provided by MRIWA. Refer Wood Mackenzie disclaimer at the beginning of this report.
[146] Ibid 146

Figure 8.12 Economic impact assessment: Decline scenario, value of iron ore production, $bn per annum real 2022 dollars (AUD terms)



Source: ACIL Allen Analysis

The downside scenario suggests the size of Western Australia's iron ore industry would be expected to shrink to approximately $26 billion in real 2022 dollar terms from approximately $130 billion today, or a terminal value in 2050 of approximately $70 billion in the baseline.

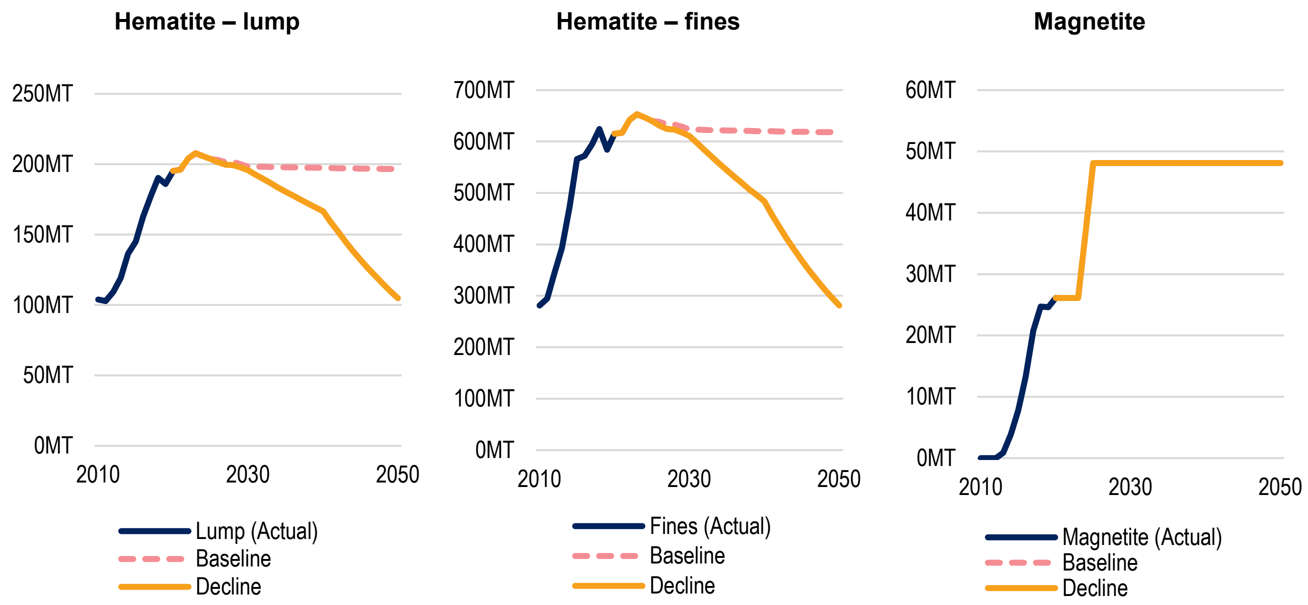
A decline of this magnitude would be equivalent to reducing the iron ore industry to the value of production in 2008-09. The decline would be gradual, with a step change projected to occur in the early years of the 2030s as technological change in steelmaking begins to take hold in Western Australia's key markets of China and South Korea. The decline accelerates thereafter, with the value of the industry shrinking by roughly half between 2040 and 2050 in this scenario.

Price projections are unable to be published. In the decline scenario, the real price of fines ore declines versus the baseline each decade, ending up around 29% below the baseline level in 2050. This flows through to the realised prices for lump and magnetite ores, given these are priced using a premium versus the fines price. The coincident decline in both volume and price illustrates how a decline in the demand for iron ore as a steelmaking feedstock is driven by market factors.

These projections are underpinned by the volume forecasts contained in Figure 8.13. The decline in fines ore production / export accelerates earlier than lump, with lump ore demand sitting around 24% below the baseline by 2040 compared to 32% for fines.

However, by 2050, demand for lump ore is projected to decline by 59% and fines by 68%. Demand for magnetite is expected to remain unchanged due to the higher grade of this feedstock with the realised price being lower.

Figure 8.13 Decline scenario, volume of production / export, by ore type, MT per annum



Source: ACIL Allen Analysis

8.3.2 Economic impact assessment: Results

The scenarios introduced in the previous section have been analysed using ACIL Allen's in-house CGE modelling framework, *Tasman Global*.

Development Scenario 1: Green Iron in the form of HBI

Under Development Scenario 1, a fully vertically integrated HBI plant is developed in the Pilbara region of Western Australia, using green hydrogen-based DRI production technologies, with beneficiated magnetite iron ore feedstock.

Impact on output

Overall, ACIL Allen's economic impact assessment on 4.8 million tonne per annum HBI project suggests a project of this size would generate an additional $85 billion in Gross Domestic Product during construction and over a 24 year operational life through to 2050, or $3 billion per annum. The vast majority of this would be realised in the regional economy hosting the project (modelled as the Pilbara region in this study), with $83.5 billion in Gross Regional Product ($2.98 billion per annum), with the remainder generated across Western Australia ($1.9 billion, $69.4 million per annum).

The output impact of the project at a State level is broadly equivalent to a 33% increase in the size of Western Australia's manufacturing industry – a compelling outcome given the State's focus on this sector in recent years as part of its economic diversification agenda.

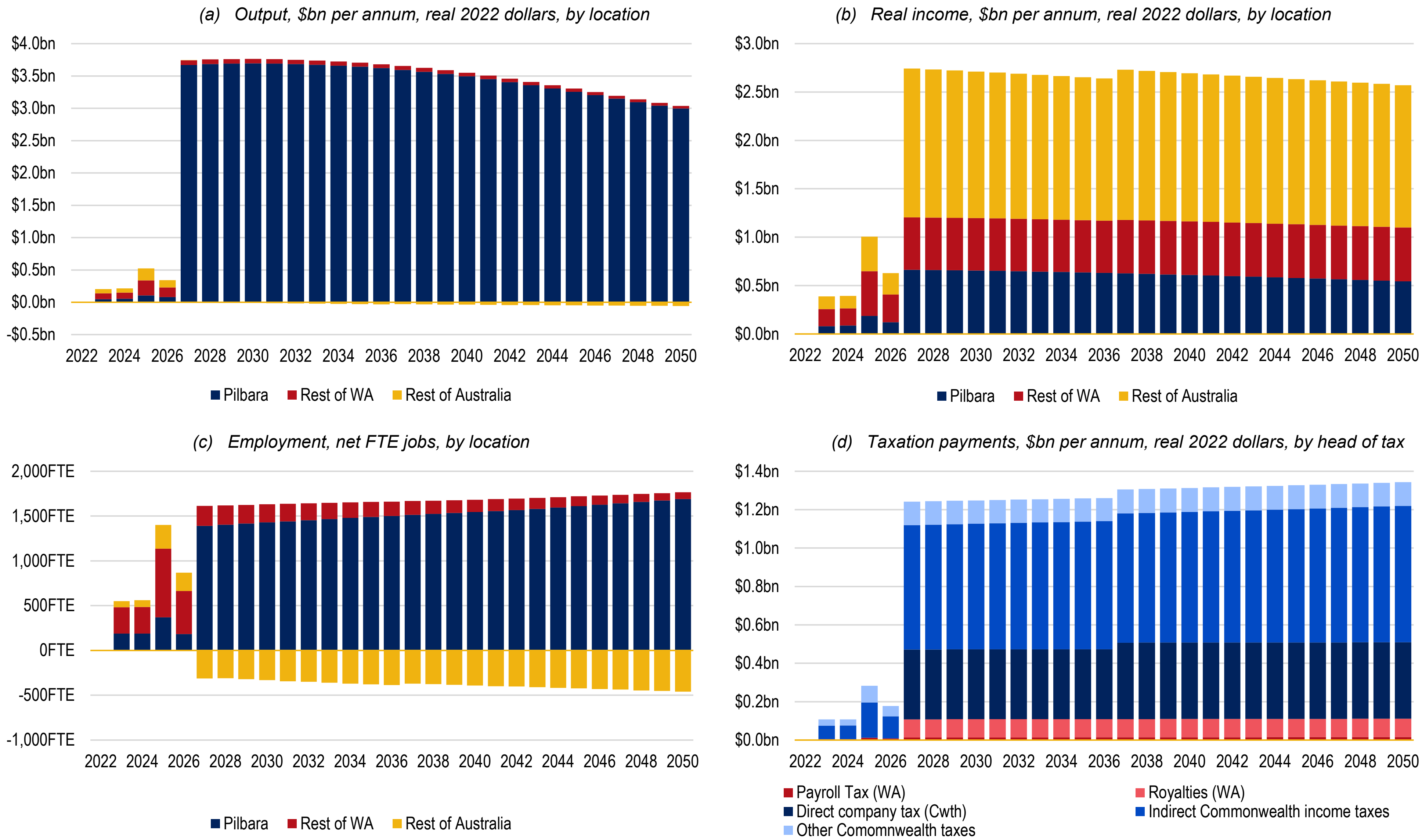
The project has a small negative impact on the rest of Australia on account of the dynamic resource allocation effects in the model.

Impact on real incomes

Overall, ACIL Allen's economic impact assessment on 4.8 Mtpa HBI project suggests a project of this size would generate an additional $66.5 billion in real income across the local, State and national economies during construction and over a 24 year operational life through to 2050, or $2.4 billion per annum. This is a significant result, reflecting the realisation of the value of a non-renewable resource and the compelling financial return price for HBI which can be realised in today's market.

The majority of the income gain accrues to the Rest of Australia, on account of the Commonwealth taxation revenue generated by

Figure 8.14 Economic Impact Assessment Results Summary: Green Iron in the form of HBI Development, Pilbara



Source: ACIL Allen Analysis

the project. The income gain retained within Western Australia remains significant, at $29.5 billion over the life of the project ($1.1 billion per annum), of which half occurs in the region where the project occurs. This reflects the increase in State taxes and royalties, employment, and the retained earnings by the integrated project.

Impact on employment (FTE jobs)

Impacts on employment reflect the net overall change in employment levels across the economy as a result of the project. In dynamic economic models, crowding out effects – where scarce resources are redirected to their most productive use – result in net impacts on total employment which lower than direct impacts may allow.

This is the case with this assessment, with an average operational employment impact across the Western Australian economy of 1,540 FTE jobs, of which 1,347 FTE jobs are created in the region where the project takes place. The impact during the construction period is relatively modest, on account of the current tight labour market conditions and the associated crowding out effects on other sectors of the economy. During operations, the peak in employment across Western Australia rises to 1,765 FTE jobs, of which ultimately 1,690 FTE jobs are based in regional Western Australia.

The employment outcomes associated with this project are a demonstration of the significant benefits a value-adding project can have to a regional economy.

Impact on taxation payments

Overall ACIL Allen estimates the HBI project would generate a total of $31.7 billion in Commonwealth and State taxation benefits during the construction and operations through to 2050, or $1.1 billion per annum. The taxation payment includes the royalties payable to the State Government associated with the extraction of iron ore resources, as well as other applicable income and inputs taxation.

The vast majority of the taxation benefits accrue to the Commonwealth, raising $29.1 billion across company income tax, excises and international trade taxation, and consumption taxes.

Western Australian Government revenue streams include payroll tax ($381.8 million, $13.6 million per annum) and royalties ($2.3 billion, $81.4 million per annum).

This analysis demonstrates the benefits resources projects generate for the national economy through the Commonwealth income tax system, particularly at times of elevated commodity prices.

A summary of the impacts of a Green Iron in the form of HBI development on the Pilbara and Western Australian economies is presented in Figure 8.14.

Development Scenario 2: Green Steel

Development Scenario 2 represents an extension on the Green Iron in the form of HBI development, with the opportunity to produce fully green primary steel for export in the form of a fully integrated magnetite-based DRI-HBI pathway, with an EAF used to produce the primary steel for export.

Impact on output

Overall, ACIL Allen's economic impact assessment on 2.8 million tonne per annum Green Steel project suggests a project of this size would generate an additional $56.2 billion in Gross Domestic Product during construction and over a 24-year operational life through to 2050, or $2 billion per annum. The vast majority of this would be realised in the regional economy hosting the project (modelled as the Pilbara region in this study), with $56 billion in Gross Regional Product ($2 billion per annum), with the remainder generated across Western Australia ($0.9 billion, $33.8 million per annum).

The output impact of the Green Steel project is smaller than the HBI project, in part because the feedstock capacity is smaller but also because the production of Green Steel is less profitable. This results in a reduction in indirect impacts through reinvestment of profits, and through lower Commonwealth taxation payments. This demonstrates the importance of project selection, and ensuring that a future Green Steel industry is able to best meet the needs of the market.

The output impact of the project at a State level is broadly equivalent to a 25% increase in the size of Western Australia's manufacturing industry – still a compelling outcome for Western Australia. It would be the largest single manufacturing project operating in Western Australia if delivered.

The project has a small negative impact on the rest of Australia on account of the dynamic resource allocation effects in the model.

Impact on real incomes

Overall, ACIL Allen's economic impact assessment on 2.8 million tonne per annum Green Steel project suggests a project of this size would generate an additional $45.6 billion in real income across the local, State and national economies during construction and over a 24-year operational life through to 2050, or $1.6 billion per annum. In line with the lower output impact, the lower real income impact of the Green Steel project versus the HBI project is a product of lower volumes and lower margins.

This effect is demonstrated by the ratio of State to Commonwealth real income realisation. In the Green Steel project, Western Australia realises $22.6 billion of real income gains (about 50% of the total), while the Rest of Australia realises $23 billion. This is primarily a function of a smaller Commonwealth income tax payment stream flowing from the project.

Impact on employment (FTE jobs)

Impacts on employment reflect the net overall change in employment levels across the economy as a result of the project. In dynamic economic models, crowding out effects – where scarce resources are redirected to their most productive use – result in net impacts on total employment which lower than direct impacts may allow.

This is the case with this assessment, with an average operational employment impact across the Western Australian economy of 1,434.2 FTE jobs, of which 1,285 FTE jobs are created in the region where the project takes place. The modelling shows the employment impact of the project on a per-unit of production basis is substantially higher in the Green Steel project (512.2 FTE per MT) compared to the Green Iron in the form of HBI project (320 FTE per MT), on account of the additional processing step and associated need for more jobs.

The employment outcomes associated with this project are a demonstration of the significant benefits a value-adding project can have to a regional economy.

Impact on taxation payments

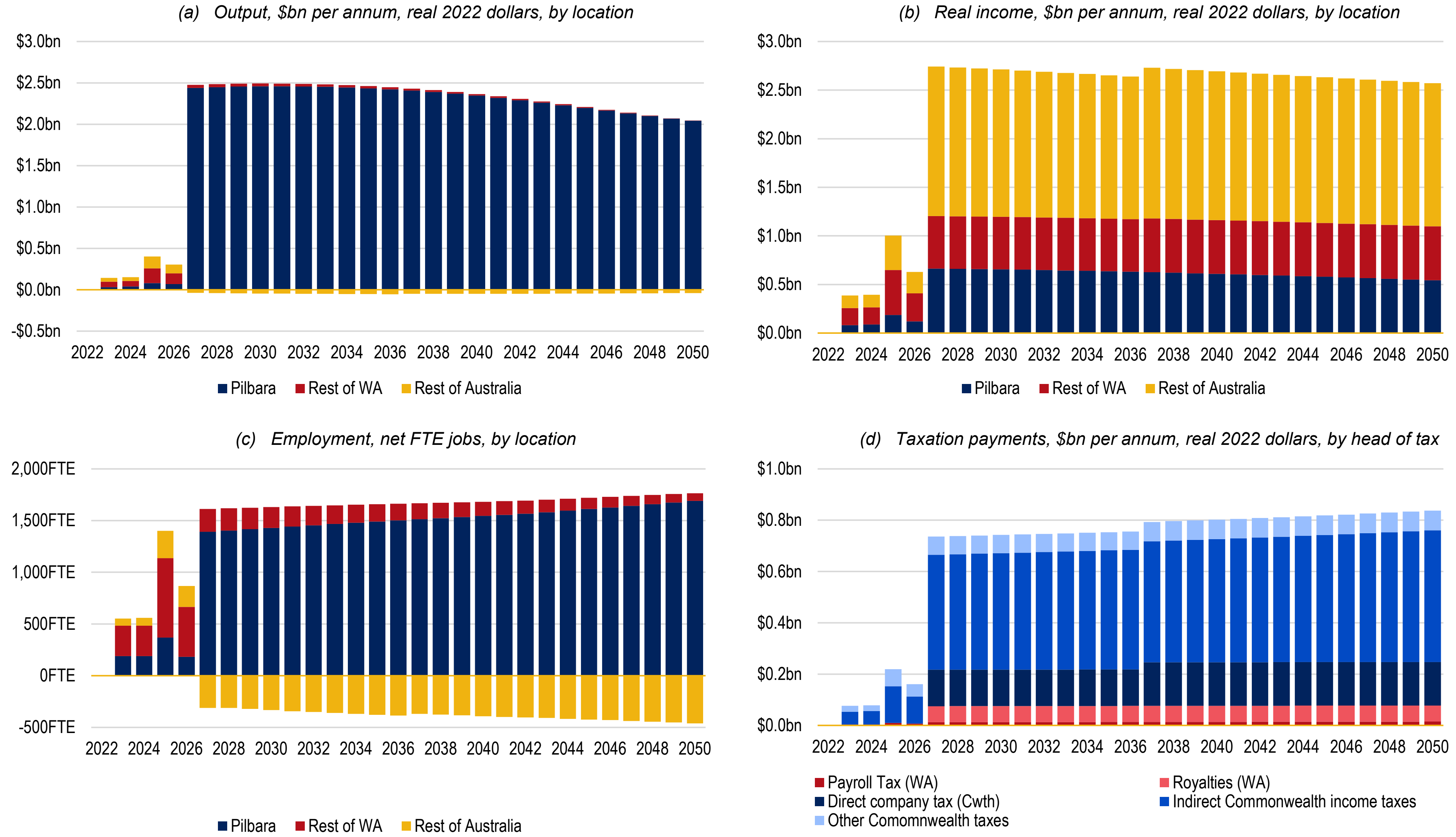
Overall ACIL Allen estimates the Green Steel project would generate a total of $19.4 billion in Commonwealth and State taxation benefits during the construction and operations through to 2050, or $692.5 million per annum. The taxation payment include the royalties payable to the State Government associated with the extraction of iron ore resources, as well as other applicable income and inputs taxation.

While a smaller taxation stream than the HBI project, the majority of the taxation benefits still accrue to the Commonwealth, with $17.5 billion across company income tax, excises and international trade taxation, and consumption taxes. Western Australian Government revenue streams include payroll tax ($348.2 million, $12.4 million per annum) and royalties ($1.5 billion, $53.9 million per annum).

This analysis demonstrates the benefits resources projects generate for the national economy through the Commonwealth income tax system, particularly at times of elevated commodity prices.

A summary of the impacts of a Green Steel development on the Pilbara and Western Australian economies is presented in Figure 8.15.

Figure 8.15 Economic Impact Assessment Results Summary: Green Steel Development, Pilbara



Source: ACIL Allen Analysis

Decline scenario: What's at risk?

Under the Decline Scenario, a future is presented where iron ore falls significantly out of favour as a steelmaking feedstock as other global suppliers of iron ore and iron feedstock better position to succeed in a Green Steel world. In this scenario there is a significant decline in both the value of Western Australia's iron ore exports, and a reduction in the volume of ores produced and sold to the world.

The modelling shows the scenario would greatly impact on the Pilbara region's economy, with an associated decline in Commonwealth and State Government income tax receipts and royalty payments. The results are discussed below in Figure 8.16.

In the decline scenario, the cumulative reduction in Australia's GDP is estimated to be $313.3 billion over 25 years between 2026 (when the changes are modelled to commence) and 2050. The annual average decline of $11.2 billion effectively nets out the annual average GDP growth of the Australian economy over the same period. The impact is initially slow to build, but increases to an annual average of just under $20 billion per annum in the decade ending 2050.

This impact occurs almost wholly in the Pilbara region, as this is where the projects which would be expected to feel the effects of the decline in volumes and prices are based. The negative impact on the Pilbara region's output is $319.7 billion, or $11.4 billion per annum. By 2050, the annual average impact on the Pilbara region's economy is equivalent to one third of the size of the economy today.

This would have significant consequences for the region. The economic impact assessment suggests the Pilbara region would see 34,570 FTE reduction in total employment through to 2050, equivalent to more than one out of every two jobs today.

This would be expected to have a compound impact on the region's population given the substantial role employment plays in regional population growth and stability.

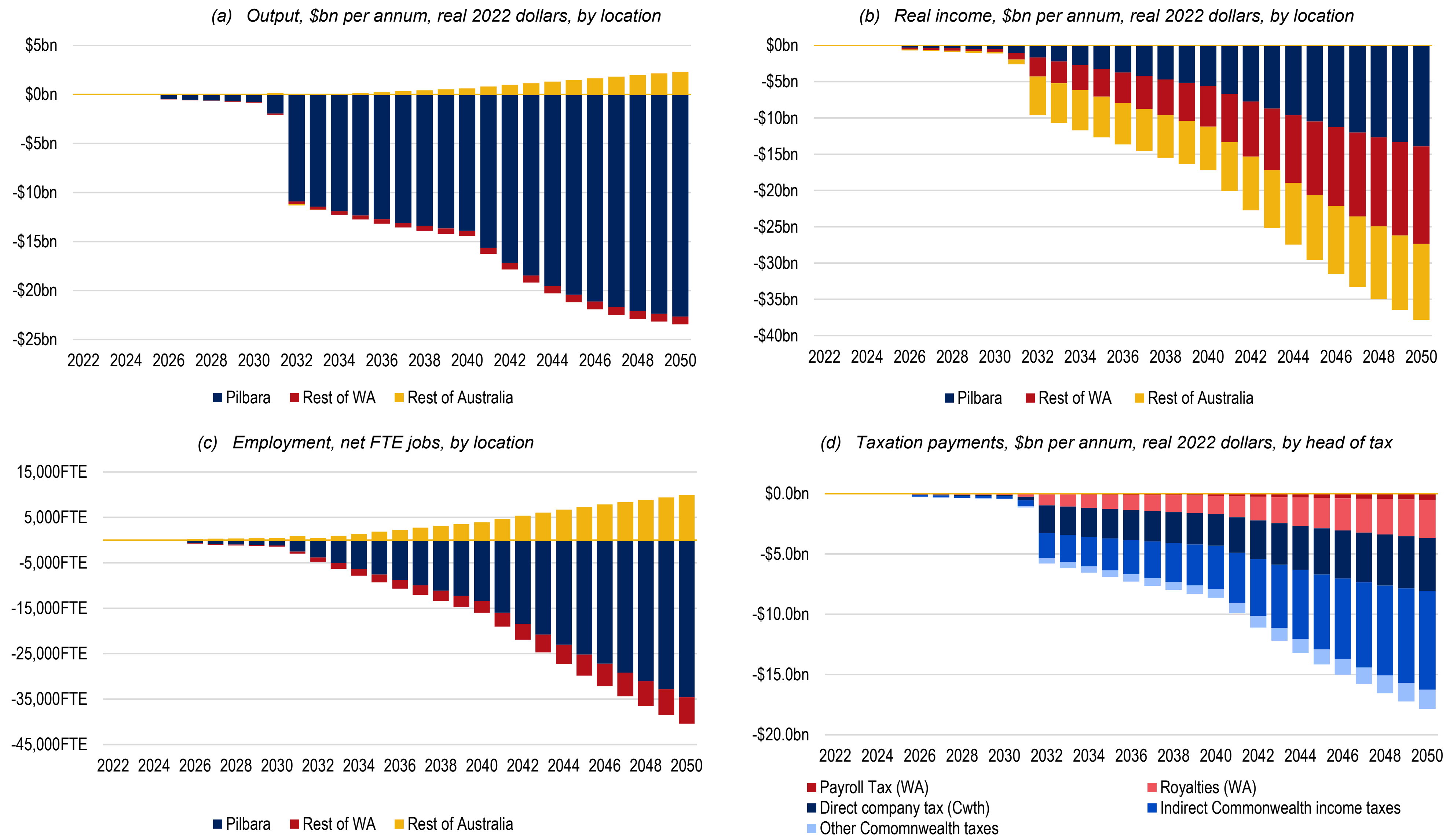
For Western Australia at large, the impact is largely felt through the royalties system. Across the modelling period, Western Australia's royalty income would decline by $37.2 billion (in real terms), or $1.3 billion per annum. As with the other metrics, the scale increases over time, to the point where by 2050 the State's royalty income stream would be $3.2 billion lower on an annual basis – equivalent to one third of the iron ore royalty income which is forecast to have been raised in the 2021-22 financial year.

Commonwealth taxation payments are impacted even more significantly, with a $169.5 billion reduction in total Commonwealth taxes over the modelling period. At $6 billion per annum, this is equivalent to the Commonwealth Government's commitment to the disaster relief efforts associated with floods in New South Wales and Queensland in 2021-22.

These scenarios take into account the dynamic impacts associated with the freeing up of resources which are currently employed in the mining industry, to service the iron ore industry's demand. This means industries outside of the minerals industry are able to grow at a faster rate than they are able to in the base case scenario. Even taking this offsetting growth into account the impacts are sizeable and would transform the Australian economy.

This scenario is not expected to be realised; however the modelling provides insights into the potential risks to both the State and Commonwealth in-light of a declining iron ore sector in Western Australia.

Figure 8.16 Economic Impact Assessment Results Summary: Decline scenario, Pilbara



Source: ACIL Allen Analysis

Regionalising the Green Steel Challenge

9

This section provides a detailed assessment of the capacity for three key regions in Western Australia to potentially host Green Steel opportunities now and into the future. This assessment has been based on ACIL Allen’s 2021 multicriteria assessment which informed Infrastructure WA’s State Infrastructure Strategy as well as the critical success factors defined in a previous section of this report which were identified as necessary to enable Green Steel opportunities to be realised.

9.1 Approach to assessment

ACIL Allen’s assessment of the Pilbara, Mid West, and the South West Western Australia regions aims to identify the capability of each region to realise Green Steel opportunities in the future. The assessment of these three regions has been based on ACIL Allen’s 2021 analysis[147] for Infrastructure WA and their State Infrastructure Strategy: *Foundations for a Stronger Tomorrow State Infrastructure Strategy* (2021).

In order to progress the development of the State Infrastructure Strategy, Infrastructure WA identified a need to contextualise and ground its Vision to the current and future economic and social context of Western Australia through the State’s existing regional development framework.

In this regard, ACIL Allen was engaged to help “regionalise” Infrastructure WA’s vision through the development of an economic and social baseline assessment of each of Western Australia’s 10 regions (the nine Regional Development Commission regions, plus the Perth Metropolitan Area), and identify the geographic spread of strengths and opportunities across the regions.

Western Australia’s regions all have unique competitive and comparative advantages, centred on their natural assets, access to human capital, and existing built infrastructure. These unique strengths mean not all regions are alike when it comes to their suitability for particular industries and economic development opportunities.

ACIL Allen’s approach to objectively assessing regional strengths in the context of the State Infrastructure Strategy Vision (and in particular the six economic development opportunities) was centred on a Multicriteria Assessment (MCA) tool. This tool allows ACIL Allen to assess each region against a number of economic and non-economic indicators which together provide an objective and holistic view of its economic and social potential in relation to the opportunities identified in the State Infrastructure Strategy Vision.

ACIL Allen’s MCA was designed to assess the relative strengths of each of Western Australia’s regions, and how these relative strengths determine which regions are best suited to hosting each of the six economic development opportunities identified in the State

[147] ACIL Allen. 2021. *Regionalising the State Infrastructure Strategy*. Accessed online at https://infrastructure.wa.gov.au/sites/default/files/2021-07/Regionalising%20the%20State%20Infrastructure%20Strategy%20Vision_Final%20Report_June%202021.pdf

Infrastructure Strategy Vision. Of these six opportunities, two are particularly relevant in the context of realising Green Steel opportunities in the State. These include:

1. Transitioning to net zero emissions technologies (referred to as Opportunity 4); and
2. Value-adding for strategic commodities (referred to as Opportunity 6).

In total, the MCA framework and assessment was based on 71 individual indicators, which are grouped into seven categories including economy, industry, human capital, liveability, infrastructure, climate and natural environment.

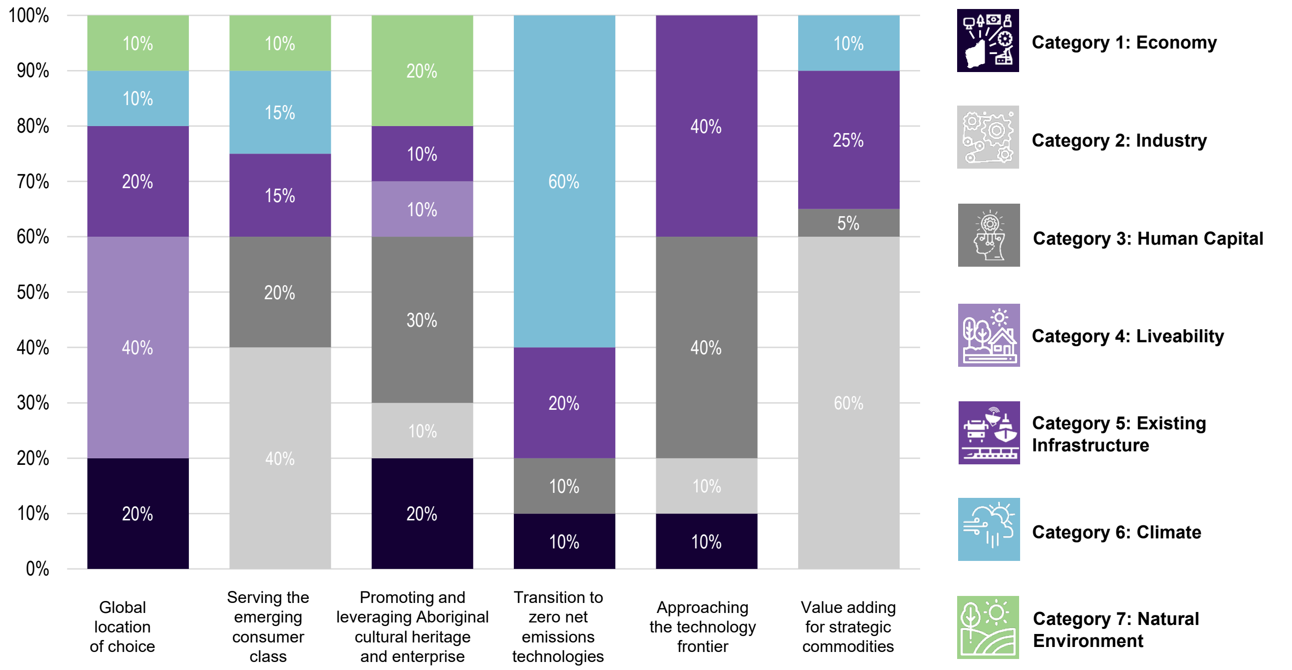
To assess each region's capacity to realise a particular opportunity, ACIL Allen's MCA framework weighted the importance of each of the seven categories (e.g. Category 1: Economy) to realise each opportunity.

Each of the category-to-opportunity weightings is different, reflecting the fact the combination of strengths required differs across the opportunities.

When each of the individual indicator weightings is multiplied by the category weightings, a set of detailed MCA indicator weightings was calculated for each opportunity.

A summary of the Opportunity weightings (how each Category drives the assessment of a region's capacity to host an Opportunity) is presented below in Figure 9.1.

Figure 9.1 Opportunity weightings: Summary of Opportunity to Category weightings



Source: ACIL Allen. 2021. Regionalising the State Infrastructure Strategy. Accessed online at http://www.infrastructure.wa.gov.au/

The most important category indicators for *Opportunity 4: Transition to zero net emissions technologies* was determined to be a region's 'climate' (allocated a 60% weighting) as climate indicators capture a region's potential to adopt renewable energy technologies and generate renewable energy through solar and wind sources.

'Existing infrastructure' (20% allocation) was also considered to be important in supporting the transition to renewable energy in the form of ports, airports and road, rail freight infrastructure, and also telecommunications.

'Human capital' (10% weight) and 'economy' (10% weight) categories were also seen to be relevant to this opportunity which measure a region's economic structure and sophistication, and population, labour and skills capacity.

The most applicable category for *Opportunity 6: Value adding for strategic commodities* was viewed as 'industry' which was allocated a weighting of 60%. The weightings reflect the intent of this opportunity as a measure of the economic development associated with downstream processing of primary products.

ACIL Allen also allocated a 25% of the opportunity's allocation to 'existing infrastructure' (which indicates a region's access to ports, airports and freight infrastructure), as the majority of value added commodities are likely to enter export markets. 'Climate' was also allocated 10% weighting to identify regions with the most suitable cheap, reliable, renewable energy sources.

The weightings are summarised in Figure 9.2 and Figure 9.3.

9.1.1 Assessment results

Opportunity 4: Transition to zero net emissions technologies

ACIL Allen's analysis ranked the Pilbara region second in terms of its potential to enable the transition to net zero carbon emissions and advancing renewables due to its comparative advantages in solar and existing infrastructure assets.

The Mid West region also scored relatively highly due to its favourable climate in terms of renewable energy generation potential. However, it is weighed down by weaker scores in terms of its infrastructure provision.

The South West Western Australia region also scores strongly in the South West and Great Southern sub regions due to high average wind speeds that may support renewable energy generation, and its infrastructure provision including existing port, airport, road and rail infrastructure.

Opportunity 6: Value adding for strategic commodities

Based on ACIL Allen's opportunity assessment, the Pilbara region ranked the highest due to its significant measured and proven mineral resources, the number of operating mines in the region, and its strong performance in renewable energy generation potential.

Some of the sub regions within the South West Western Australia ranked highly (i.e., Goldfields-Esperance second place) predominantly due to their mineral deposits and share of existing mine sites, while the Mid West region scored strongly due to its renewable energy generation potential (from both solar and wind) and its share of operating mine sites.

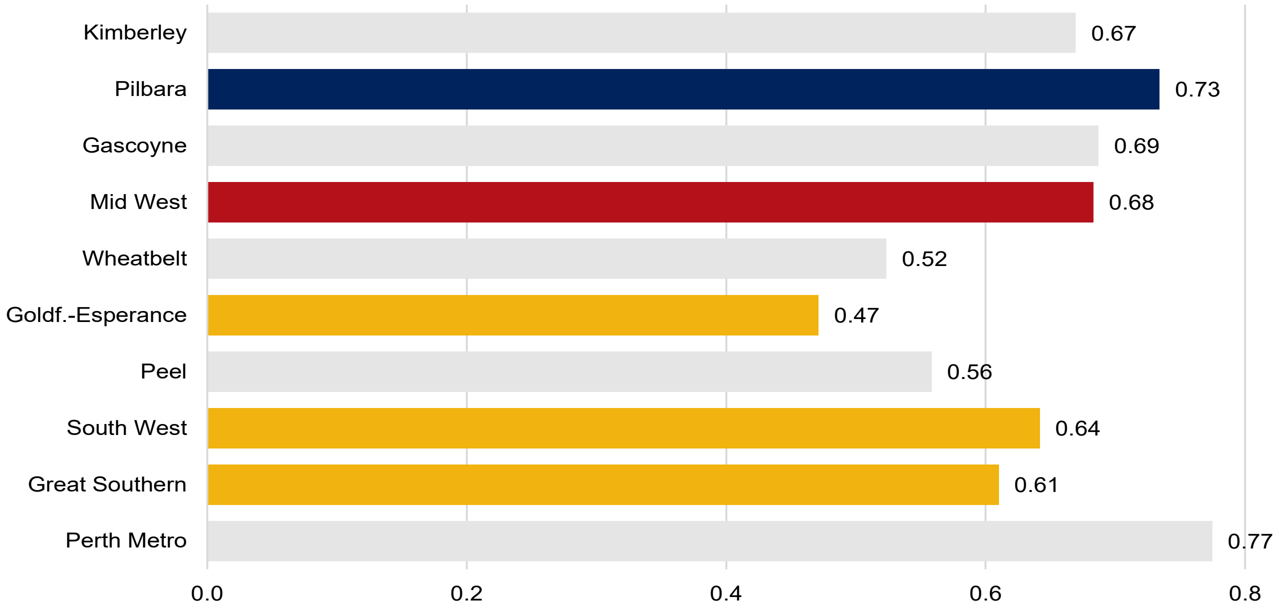
Pilbara Region

According to ACIL Allen's assessment, the Pilbara region is the strongest performing region in relation to its solar radiance capacity (although the solar radiance capacity of other regions in the north of the State such as the Gascoyne and Kimberley are similarly strong).

The Pilbara region is ranked equal second in the 'Industry' category due to its large mining and resources sector and its large share of the State's proven and measured resource reserves and operating mine sites.

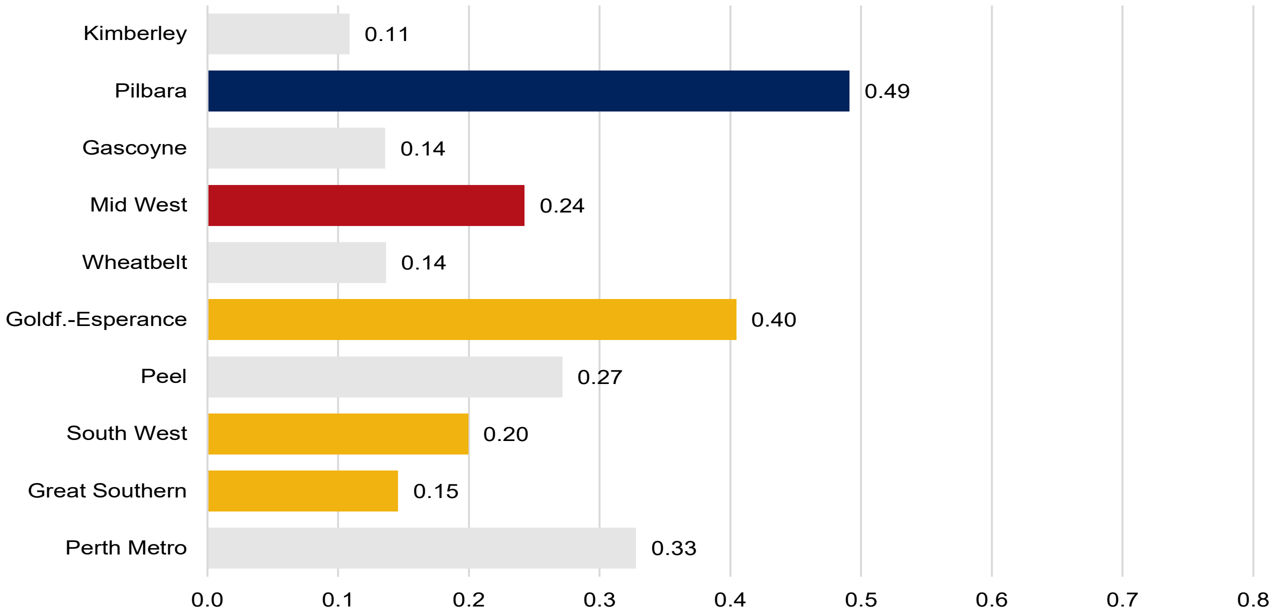
The Pilbara region's access to port infrastructure means it scores relatively higher than other northern Western Australian regions.

Figure 9.2 Regional analysis – Opportunity 4: Transition to zero net emissions technologies



Source: Adapted from ACIL Allen. 2021. Regionalising the State Infrastructure Strategy. Accessed online at https://infrastructure.wa.gov.au/sites/default/files/2021-07/Regionalising%20the%20State%20Infrastructure%20Strategy%20VisionFinal%20Report_June%202021.pdf
Note: South West Western Australia is represented by Goldfields-Esperance, South West and the Great Southern regions.

Figure 9.3 Regional analysis – Opportunity 6: Value adding strategic commodities



Source: Adapted from ACIL Allen. 2021. Regionalising the State Infrastructure Strategy. Accessed online at https://infrastructure.wa.gov.au/sites/default/files/2021-07/Regionalising%20the%20State%20Infrastructure%20Strategy%20VisionFinal%20Report_June%202021.pdf
Note: South West Western Australia is represented by Goldfields-Esperance, South West and the Great Southern regions.

However, the general lack of population density in the region means access to airports, freight routes and telecommunications is more limited.

The Pilbara's score across these categories reflects its vast geographic space and relatively limited coverage of key public infrastructure. The Pilbara region hosts significant private sector infrastructure across ports, airports, roads, rail and electricity networks in particular, however a significant portion of this is for the use of the private sector owners or users only.

Mid West Region

According to ACIL Allen's regional strengths assessment, climate is a source of strength for the Mid West region and is the highest ranking region in the State for this strengths category. This reflects its balanced scoring across the climate indicators included in the assessment, in that it performs well in both solar and wind renewable energy generation potential.

The Mid West region scores relatively lower in terms of 'Industry' due to its lack of tertiary education, residential and commercial activity, and availability of commercial land, however, the region has some industry strengths in relation to agriculture, availability of land, and its prospects for future mine sites.

The Mid West's lack of population density means access to ports, airports, freight routes and telecommunications is more limited compared to the southern regions in the State, but does have strengths in having access to established port infrastructure at the Port of Geraldton.

South West Western Australia Region

This assessment combines the sub regions of the South West, Great Southern and Goldfields-Esperance to form South West Western Australia which combines to form a significant area of the State.

ACIL Allen's regional strengths assessment suggests the South West Western Australia region is above average across the suite of climate indicators. Notably, the South West and Great Southern regions score above average in terms of average wind speeds making them suitable for wind energy generation, however, all three regions in South West Western Australia have below average level of solar exposure.

In terms of industry, the South West and Great Southern regions ranks relatively high due to the availability of industrial and commercially zoned land, building activity, water resources, and tertiary education offerings.

Broadly, the South West Western Australia region is assessed as having a relatively high rating in terms of existing infrastructure (less so in the Goldfields-Esperance region), mainly due to the access to port infrastructure but also to freight road and rail, airports and telecommunications infrastructure.

9.1.2 Regional iron resource availability assessment

Where the regions differ is in resource availability and prospective infrastructure developments. The regional dimensions to these matters is discussed below.

The most critical determinant of a region's suitability to meet the Green Steel challenge is the availability of feedstock iron. To provide a quantitative perspective on this, ACIL Allen sought information from the Department of Mines, Industry Regulation and Safety's Geological Survey. This unit within the Department is critical to the functioning of Western Australia's minerals industry, through the provision of information on the State's geology through a variety of platforms.

DMIRS' data set is a comprehensive, project-by-project assessment of the most recent (and historical) reserve and resource position of Western Australia's mineral tenements. The data is built using the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves, better known as the 'JORC' Code.

The JORC Code provides a mandatory system for the classification of minerals Exploration Results, Mineral Resources and Ore Reserves according to the levels of confidence in geological knowledge and technical and economic considerations in Public Reports. The position of a particular project is classified into the following tiers:

- Reserves, which are either Proven or Probable based on a 90% and 50% certainty of commercial production respectively
- Resources, which are either Measured, Indicated or Inferred. A Measured Resource holds a high degree of confidence but is considered commercially unviable for a variety of reasons (including market supply tolerance). Indicated and Inferred Resources are estimates of the gross potential of the tenement absent consideration of commerciality or market tolerance.

ACIL Allen's summary of the database is provided below in Table 9.1.

The data contained in the table is subject to a number of caveats and limitations. Principal among these is the fact under various State Agreement Acts there is no requirement for individual tenement holders to regularly report the reserve position of held tenements to the DMIRS. As a result, DMIRS undertakes extensive data analysis to estimate the reserve and resource position of individual tenements based on publicly available information and other sources.

Notwithstanding this challenge, it is clear from the data Western Australia's regional areas host an abundance of iron ore in a variety of mineralisation types. Across the full scope of the information DMIRS has available, it is estimated Western Australia hosts 167,632 MT of iron ore across hematite / goethite, magnetite, and vanadium-titanium-magnetite deposits. All other things being equal, depletion of this would take 209 years at the State's current production capacity of approximately 800 Mtpa.

The largest orebodies are in situ in the Pilbara region, across both hematite / goethite and magnetite mineralisation. Across the region DMIRS estimates the current ore contains some 64,695 MT of contained Fe. The majority of this ore is hematite / goethite ore, however there is also more proven and probable magnetite ore in situ in the Pilbara than in any other region within the scope of the study.

Magnetite mineralisation in the Mid West and South West regions is the next largest ore type, although the vast majority of this remains in the Indicated and Inferred category in the JORC framework. According to DMIRS there is some 2.4 billion tonnes of magnetite ore in the Mid West region which fits within the Probable and Measured categories in the JORC framework, suggesting a strong likelihood of commercialisation.

9.1.3 Enabling infrastructure

Enabling infrastructure would assist in the creation of a future green iron or Green Steel industry.

Consideration of longer term infrastructure priorities which would be expected to have a positive impact on the opportunity in the future are summarised in Table 9.2.

Finding 17 A significant common user infrastructure build is required

This report has highlighted the critical role of infrastructure in development and delivery of future iron ore, value-added iron and steel project opportunities in Western Australia. This, combined with the similar challenges associated with large-scale renewable energy development projects, suggests a significant common user infrastructure build program in the years and decades ahead is required.

Table 9.1 Western Australia's iron resources, by region and primary mineralisation, MT ore in situ

	Proven (MT Fe)	Probable (MT Fe)	Measured (MT Fe)	Indicated & Inferred (MT Fe)
Hematite / Goethite				
Pilbara	5,178.0	6,054.8	8,682.6	77,250.3
Mid West	6.3	74.3	248.1	5,495.3
South West	37.9	35.5	30.5	166.1
Rest of Western Australia	0.0	1.1	4.7	62.3
Total	**5,222.2**	**6,165.7**	**8,965.9**	**82,974.0**
Magnetite				
Pilbara	0.0	4,212.6	915.0	23,254.6
Mid West	3.0	1,122.3	1,258.2	9,785.2
South West	384.6	3.1	530.8	9,874.1
Rest of Western Australia	0.0	149.1	0.0	593.1
Total	**387.6**	**5,487.1**	**2,704.0**	**43,507.0**
VTM				
Pilbara	0.0	0.0	0.0	0.0
Mid West	0.0	0.0	0.0	316.2
South West	0.0	0.0	0.0	0.0
Rest of Western Australia	0.0	0.0	1,104.0	10,798.0
Total	**0.0**	**0.0**	**1,104.0**	**11,114.2**

Source: ACIL Allen, from DMIRS

Table 9.2 Green Steel Challenge Regional Infrastructure Priorities

Region	Infrastructure type	Project name / identifier	Description	Estimated cost (if avail.)	Time horizon for delivery
Pilbara	Electricity transmission	East Pilbara Link Transmission Infrastructure	Development of a High Voltage electricity transmission network connecting the remaining parts of the fragmented North West Interconnected System (NWIS) to allow for the creation of a fully integrated electricity transmission system. This would involve the construction of a HVDC line spanning Port Hedland to Newman, with various spur lines to interconnect mine sites along the route. The project has recently been added to the Infrastructure Australia Priority List.	Not publicly available	Short term (<5 years)
Pilbara	Electricity transmission	Burrup Common User Transmission Line	Development of a HVDC line to further connect the Burrup Strategic Industrial Area (SIA) to the NWIS in the Pilbara region. This would assist in building baseload demand for renewable electricity in the region surrounding Karratha and the Burrup SIA. The project has been identified by Infrastructure WA as a priority.	Not publicly available	Short term (<5 years)
Pilbara	Large scale renewable electricity generation	The Asian Renewable Energy Hub	As the first mover for gigawatt-scale renewable electricity generation infrastructure in the Pilbara region, Infrastructure WA has identified delivery of the Asian Renewable Energy Hub as a priority for Western Australia. This would assist in building baseload renewable electricity generation capacity at a scale required to facilitate green iron and Green Steelmaking.	$52 billion	Medium term (5-10 years)
Pilbara	General cargo port capacity	Lumsden Point General Cargo Facility	The Lumsden Point General Cargo Facility is a long-planned additional general cargo facility to be developed at the Port of Port Hedland. The development is intended to provide additional general cargo import and export capacity to relieve the constraints at existing general berths. This is required to facilitate the significant project cargo requirements of new developments.t	$200-$300 million	Short term (<5 years)
Pilbara	Water	Fresh water availability for industrial-scale hydrogen production	The assessment has identified a need for significant volumes of purified H_2O as a feedstock for the production of green hydrogen. Less purified water is also required for the production and processing of magnetite ores, and beneficiation of all ores into higher grade products. There is currently no publicly available planned or proposed water infrastructure project in the Pilbara region.	Unknown	Medium term (5-10 years)
Pilbara	Hydrogen	Hydrogen / ammonia pipeline to support Pilbara Hydrogen Hub	The Western Australian Government has committed to the development of a common user hydrogen or ammonia pipeline to link the Maitland and Burrup SIAs. This would assist in providing backbone infrastructure for hydrogen as a reductant in green ironmaking or as a fuel for green electricity generation in Green Steelmaking.	At least $117.5 million	Medium term (5-10 years)

Region	Infrastructure type	Project name / identifier	Description	Estimated cost (if avail.)	Time horizon for delivery
Pilbara	General cargo port capacity	Dampier Cargo Wharf upgrade	The Western Australian Government has committed to the expansion of the Port of Dampier through the development of a new Cargo Wharf. The project includes the Perdaman Urea Project as a foundation customer for bulk export, but also includes additional capacity for general cargo trade which will be critical to realisation of renewable energy projects in the region.	$255 million	Short term (<5 years)
Pilbara	General cargo port capacity	Port of Port Hedland Development Plan (excluding Lumsden Point)	Pilbara Ports Authority has recently had endorsed a revised Port Development Plan which includes a range of capacity upgrades and new infrastructure to support both the existing iron ore industry and the growth and development of renewable energy and value-added iron products in the region.	Unknown	Medium term (5-10 years)
Pilbara	Carbon capture use and storage	Common use carbon sequestration pipeline infrastructure	This report has identified natural gas-based DRI as a potential transitional product on the pathway to the development of green ironmaking and Green Steel. The Western Australian Government's Pilbara Hydrogen Hub includes a proposed carbon sequestration pipeline to transfer captured carbon to offshore reservoirs for storage. This would assist in building capacity for natural gas-based DRI to progressively decarbonise as CCS becomes more economic.	Unknown	Long term (10+ years)
Mid West	Strategic Industrial Area development	A major renewable hydrogen hub in the Oakajee Strategic Industrial Area (SIA);	The Western Australian Government has committed to establishing the Oakajee SIA as a hydrogen hub. The State's initial commitment to this project is a series of targeted investments in roads, electricity transmission and water infrastructure to position the SIA as a hydrogen hub.	At least $117.5 million	Medium term (5-10 years)
Mid West	General cargo port capacity	Oakajee Port	The Oakajee Port is connected to the Oakajee SIA, conceived as a deep-water port connected to a range of in-bound and outbound transport infrastructure. The project has been long discussed, having been considered as part of a vertically integrated port-and-rail project to service the Mid West iron ore industry in the late 2000s / early 2010s.	$5 billion +	Medium term (5-10 years)
Mid West	General cargo port capacity	Geraldton Port Capacity Upgrades	The Western Australian Government has committed to the Mid West Port Maximisation Project, a 10-year program of works to lift the annual trade capacity of the Port of Geraldton from 15 Mtpa to 25 Mtpa.	$332 million	Medium term (5-10 years)

Region	Infrastructure type	Project name / identifier	Description	Estimated cost (if avail.)	Time horizon for delivery
Mid West	Water	Fresh water availability for industrial-scale hydrogen production and iron processing	The assessment has identified a need for significant volumes of purified H_2O as a feedstock for the production of green hydrogen. Less purified water is also required for the production and processing of magnetite ores, and beneficiation of all ores into higher grade products. A privately-funded seawater desalination plant, built on the back of a long term offtake agreement with the State Government was proposed in early 2021 by Australian Gas Infrastructure Group.	Unknown	Medium term (5-10 years)
Mid West	Rail	Common user rail infrastructure from Yilgarn region to Geraldton / Oakajee	An opportunity to adequately plan and deliver a common user rail infrastructure solution for iron ore tenement holders in the eastern Mid West region was raised multiple times in the study. This would aid in "opening up" the province for production and export of magnetite-based iron ore and value-added iron products.	Unknown	Medium term (5-10 years)
Mid West	Electricity transmission	Extension of HVDC network at edge of SWIS to Geraldton / Oakajee	The South West Interconnected System is Western Australia's largest high voltage electricity grid. It currently extends north to Three Springs, before becoming relatively low voltage for the 150km journey to Geraldton (and a further 20km to the Oakajee SIA). Extension of the high voltage infrastructure of the SWIS to these locations, with sub-stations in between, has been considered on a number of occasions but deemed economically unviable due to the increased transmission cost on existing customers for no material benefit. However, the prospective investment in renewable electricity generation infrastructure to support hydrogen production in the Mid West may warrant a reassessment of the project. This would also assist in improving the economics of generators in the Mid West and providing more reliable baseload power to prospective users in the region through interconnection with the broader SWIS.	$500 million	Short term (<5 years)
South West	Electricity generation	Decarbonisation of the South West Interconnected System	The Western Australian Government has committed its State-owned power generation / retail (Synergy) and transmission (Western Power) companies to reduce emissions to 20% of 2020 levels by 2035. This will be an important means for the broader SWIS, which would be required to support any green iron ore, green value-added iron or Green Steel projects in the South West part of the State.	Unknown State has committed $3.8 billion to meeting 2035 target.	Long term (10+ years)

Region	Infrastructure type	Project name / identifier	Description	Estimated cost (if avail.)	Time horizon for delivery
South West	Electricity transmission	Goldfields-Esperance electricity transmission capacity	Horizon Power, Western Australia's regional power company, is investigating the development of a South East Region Hydrogen Hub & Spoke Model Feasibility Study, centred on identification of opportunities to increase the penetration of renewable electricity, and eventually green hydrogen, into the economies and industries of the Goldfields-Esperance region. This would be expected to centre on addressing bottlenecks in the existing transmission infrastructure of the Goldfields-Esperance region.	Unknown	Medium term (5-10 years)
South West	Water	Esperance Seawater Desalination Plant	The assessment has identified a need for significant volumes of purified H_2O as a feedstock for the production of green hydrogen. Less purified water is also required for the production and processing of magnetite ores, and beneficiation of all ores into higher grade products. A desalination project has been considered for the region previously, through a State-funded desalination plant at Esperance. With the emerging needs of industry this concept could be revived to assist in providing the water needed for projects.	Unknown	Long term (10+ years)
South West	General cargo port capacity	General Port Capacity in South West region	The assessment has identified general cargo port capacity as a critical project enabler, principally during construction and commissioning of large-scale renewable electricity generation infrastructure but also during operations and export. The South West part of Western Australia has access to a number of ports across the southern and western parts of the State, with no outward signs of capacity constraints. However if there were to be one or multiple major value-added iron or steelmaking projects in the region this would be expected to trigger a need to review capacity.	Unknown	Long term (10+ years)

Source: ACIL Allen

Moving Towards Green Steel 10

This section presents a summary of the findings presented throughout this report, which together provide the foundation to understand the challenges and opportunities to moving towards downstream processing of iron ore in Western Australia.

10.1 Key Findings

Green Steel – the question is not 'is it possible', but rather 'how to make it possible'.

Western Australia has played a central role in the growth of the global steel industry for over 60 years. Global demand for finished steel products is expected to remain robust, albeit without the same levels of compound growth experienced over the past 20 years.

Technologies are emerging which can, and will, begin to reduce the energy and emissions intensity of BF based steelmaking. There are multiple pathways to progress beyond energy and emissions intense reduction and the development of net zero emissions steelmaking.

Throughout this report, and over the course of the engagement, MRIWA, GHD and ACIL Allen have identified Green Steel production globally is not only possible, but inevitable. Changing market dynamics, and the race to reduce carbon emissions across industry and government, will take time to fully revolutionise the global steel industry. As technologies change, and renewable energy costs fall, a shift towards a Green Steel future will begin.

This will not be a sudden, dramatic change as has been experienced in a range of other industries in recent years. The complexity, interconnectedness, and capital investment in today's steelmaking value chains means the process will take time.

There is a future for Western Australia in the production of iron ore and supply of alternative iron products to the market.

Existing iron ore exports remain relevant for the largest steelmaking value chains, albeit customer preferences are shifting towards higher grade feedstock.

This presents the State with an emerging advantage due to the vast reserves of magnetite, and capacity to beneficiate the ores produced and shipped today. The value chain modelling shows this can be done using increasingly green energy.

The real Green Steel prize for Western Australia lies in further value-adding, to build new projects centred on production of intermediate iron products like HBI and pig iron. The State's existing natural gas energy advantages suggest this can be done on an economic basis, so long as a market for it emerges.

Progressing down the value chain to produce intermediate iron brings with it the potential for a significant domestic demand base for renewable hydrogen as technologies improve and the cost of production falls.

Co-industry development of this nature could compound the benefits for Western Australia, while bringing forward the renewable hydrogen future the State is committed to realising.

The final step towards steelmaking looks the most difficult part of the Green Steel challenge for Western Australia, on account of the truly global marketplace for this product and the dominance of major steelmakers within it. But the journey towards domestic steel begins with iron, where the opportunity is clear.

Industry announcements show a commitment to investment in a greener future, with Western Australia’s major iron ore players all having a strong focus on opportunities to decarbonise both their own operations and assist in meeting their customers’ ambitions.

Business is exploring value-adding to Western Australia’s iron ore, because of the economic and climate outcomes which can be achieved.

Hosting the iron ore resources and a renewable energy advantage are necessary but not sufficient to meet the Green Steel challenge.

Alongside these two critical success factors sit infrastructure, and technology and enterprise. Building the connection of resources to infrastructure, services and paths to market is critical.

It is the same for technology and enterprise, where Western Australia has an opportunity to tap into its enormous mineral wealth as a funding source to become a global leader in research, development and commercialisation.

Western Australia should be the home of a world class centre for research and development into the Green Steel value chain.

This report is the first step towards Western Australia’s Green Steel future with the key findings summarised below.

Finding 1 Significance of the iron ore industry

Western Australia is the largest iron ore supplier in the world, accounting for 38% of global supply, which is more than double the next largest iron ore supplier, Brazil which supplies 17% of global supply. The iron ore industry is the State’s largest and most important industry, providing direct and indirect economic and social contributions which are greater than any other industry to the State. Through the royalties it pays, it is also the largest contributor to State Government finances, generating $11.35 billion which represented 28% of general government revenues in 2020-21.

Finding 2 The long-term outlook for steel

The long-term outlook for global steel demand is expected to remain robust through to the middle of the century. However, there are a range of scenarios which could eventuate regarding the type of feedstock most in demand, and the production processes used to produce steel, which have several implications for Western Australia’s existing iron ore industry.

Moreover, given the size of the investments and the time taken to make investment decisions, there is a need to begin positioning in the short term.

Overall, it is considered likely Western Australian iron ore will remain a valued commodity in the global steel industry through to the middle of the century. However, there are clearly opportunities for development of new kinds of iron products to meet the emissions and energy reduction task facing customer countries.

Finding 3 Increasing focus on the quality of ore used by steelmakers is driving change

There is increasing focus on the quality of iron ore feedstock being used by steelmakers. This is increasingly observed through the price penalties received on lower grade ores, which has implications for Western Australia.

This provides a strong incentive for iron ore producers to pursue opportunities to improve the average grade of their product, through beneficiation or investment in new kinds of steelmaking feedstock products, but also a renewed interest in magnetite iron ore projects throughout Western Australia.

Finding 4 Lack of liquid markets and benchmark prices for intermediate iron products

There is currently limited or no benchmark products and associated prices available for intermediate iron products such as pig iron, HBI and even for iron ore pellet indexes they are often referenced to local sources of pellets which is not a true benchmark. This creates complexity for project development and project economic assessment as there is no commonly understood definition of products, of benchmark attributes or product quality, or market worth. The lack of benchmark products and associated prices contrasts strongly with iron ore where there is an abundance of these.

Finding 5 Economics of steelmaking is significantly more challenging than iron ore mining

The market for steel is fundamentally different to iron ore. While both industries are highly capital intensive, they have vastly different rates of profit. It is estimated the gross margin for steelmakers over the past 20 years has been 13.6%, which is in stark contrast to iron ore miners which regularly report gross margins of many multiples of the levels achieved by steelmakers. Western Australia's three largest iron ore miners have delivered an average gross margin on sales of 61.1% over the past six years where data on Western Australian specific operations is available.

Given the capital intensity of iron ore is substantially lower than in the steel industry, an iron ore mine can deliver a substantially higher rate of gross profit for a much smaller initial capital outlay.

Finding 6 Overcapacity in steelmaking

The current glut of capacity in global steelmaking results in a situation where it is challenging for new entrants to compete on price and deliver a return on capital to justify a new investment. This is because existing entrants have sunk capital and significant incentives to increase plant utilisation.

Finding 7 Age of BFs will influence rate of change

Given the long useful life of BFs, countries will progressively face a decision to either retire BFs early to transition to greener production methods or operate existing carbon-intensive steelmaking infrastructure for a regular life, and focus on other strategies to reduce emissions such as carbon capture use and storage.

Finding 8 Increasing potential for scrap steel will drive change in the industry

Future investment in EAF steelmaking is expected due to the sheer increase in availability of scrap steel as a feedstock from the growth in steel production; a lower hurdle of entry to construct a production facility such as a 'close-to-source' modular EAF; and consumption over the past two decades.

Finding 9 The decarbonisation of the global steel industry is a significant challenge

The global steel industry is one of the largest carbon emitters in the world, but also one of the hardest to abate. Recognising the challenges to decarbonising existing production, hydrogen-based steelmaking has emerged as a potential pathway to producing Green Steel. However, the production of green hydrogen needed for Green Steel is not yet available at a commercial scale.

Finding 10 Value chain modelling: Green Iron Ore Mining

Conversion of existing iron ore mines, and development of new iron ore mines to be emissions-free based on renewable power supplied by mixed solar/wind facilities is cost-competitive at today's cost rates, largely due to low cost and effective renewable power.

Green Iron Ore Mining, including ore upgrading through beneficiation, provides opportunity to marginally reduce emissions in the steelmaking value chain.

Potential cost savings is a natural incentive for industry to switch to renewable power and fuels in existing mining operations.

There are substantial power requirements to adopt Green Iron Ore Mining at scale.

The established power infrastructure will not only support existing industry but will also reduce ore production costs in the long run as the price of power decreases leading to substantial savings and allow energy intensive ore beneficiation to be done at lower cost.

Including hydrogen and ammonia facilities for long distance transport initiates the industrial base required for further downstream processing of iron ore.

Finding 11 Value chain modelling: Green Pellets

Green Pellets are a necessary product to have fully Green Steel, however hydrogen costs are too expensive at this point to produce them competitively against the equivalent fossil fuel process.

Magnetite concentrates are more economic to turn into Green Pellets, as they do not require as much heat to form pellets as hematite fines.

Finding 12 Value chain modelling: HBI from Green Pellets using Fossil Fuels

Green Pellets converted to HBI using fossil fuels are a cost competitive product when compared to pig iron produced with BFs, the dominant process for ironmaking today.

This approach will onshore Scope 3 emissions. However, it also has the potential to reduce overall emissions from ironmaking when compared to the pig iron BF route.

Shaft furnaces running on natural gas may be transitioned to hydrogen feedstock over time to produce fully Green Steel.

Finding 13 Value chain modelling: HBI from Green Pellets using Renewable Hydrogen (Green Iron in the form of HBI)

Green Iron in the form of HBI produced from shaft furnaces can potentially replace coke and natural gas for ironmaking, eliminating emissions from this carbon intensive stage.

Green Iron in the form of HBI can be economically produced when compared to BF produced pig iron when the hydrogen price reaches $4 AUD/kg.

Finding 14 Value chain modelling: Hydrogen cost and implications

The dominant costs in traditional steelmaking are those which arise from blast furnacing.

The price of hydrogen, which replaces coke as a reductant in the creation of Green Steel, is critical in ensuring price parity of Green Steel with blast furnacing.

Green Steel (SF-EAF) can be economically produced when compared to fossil fuels (BF-BOF) steel when the hydrogen price reaches $3.20 AUD/kg.

There are increased costs for processing high gangue HBI/DRI through electric arc furnacing, so higher quality or more refined ore is preferred. Though most cost benefit will accrue to whomever owns most of the value chain, including the steelmaking step.

Finding 15 Green Steel industry capital costs are expected to be substantial

To decarbonise or lower emissions in Western Australia's current mining sector and potential future steelmaking value chain, infrastructure for renewable power generation and for hydrogen-based iron/steelmaking plants must be developed. The capital costs are substantial for renewable power production at scale.

Finding 16 Western Australia's Green Steel value chain opportunities and pathways

Overall, the assessment suggests of the options considered, pathways which involve the development of intermediate iron products, such as HBI, are the most prospective for Western Australia.

These products are a natural extension of the State's current place in the value chain and make best use of both current and emerging advantages in energy. HBI and other intermediate products allow the State to continue to capture significant value in the steelmaking value chain without the high capital costs and low margins associated with steel itself.

The export steel product market will be slower to adjust to environmental factors than drivers for the use of Western Australian HBI, particularly in a market for an increasing global demand for lower emission HBI.

Finding 17 A significant common user infrastructure build is required

This report has highlighted the critical role of infrastructure in development and delivery of future iron ore, value-added iron and steel project opportunities in Western Australia. This, combined with the similar challenges associated with large-scale renewable energy development projects, suggests a significant common user infrastructure build program in the years and decades ahead is required.

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