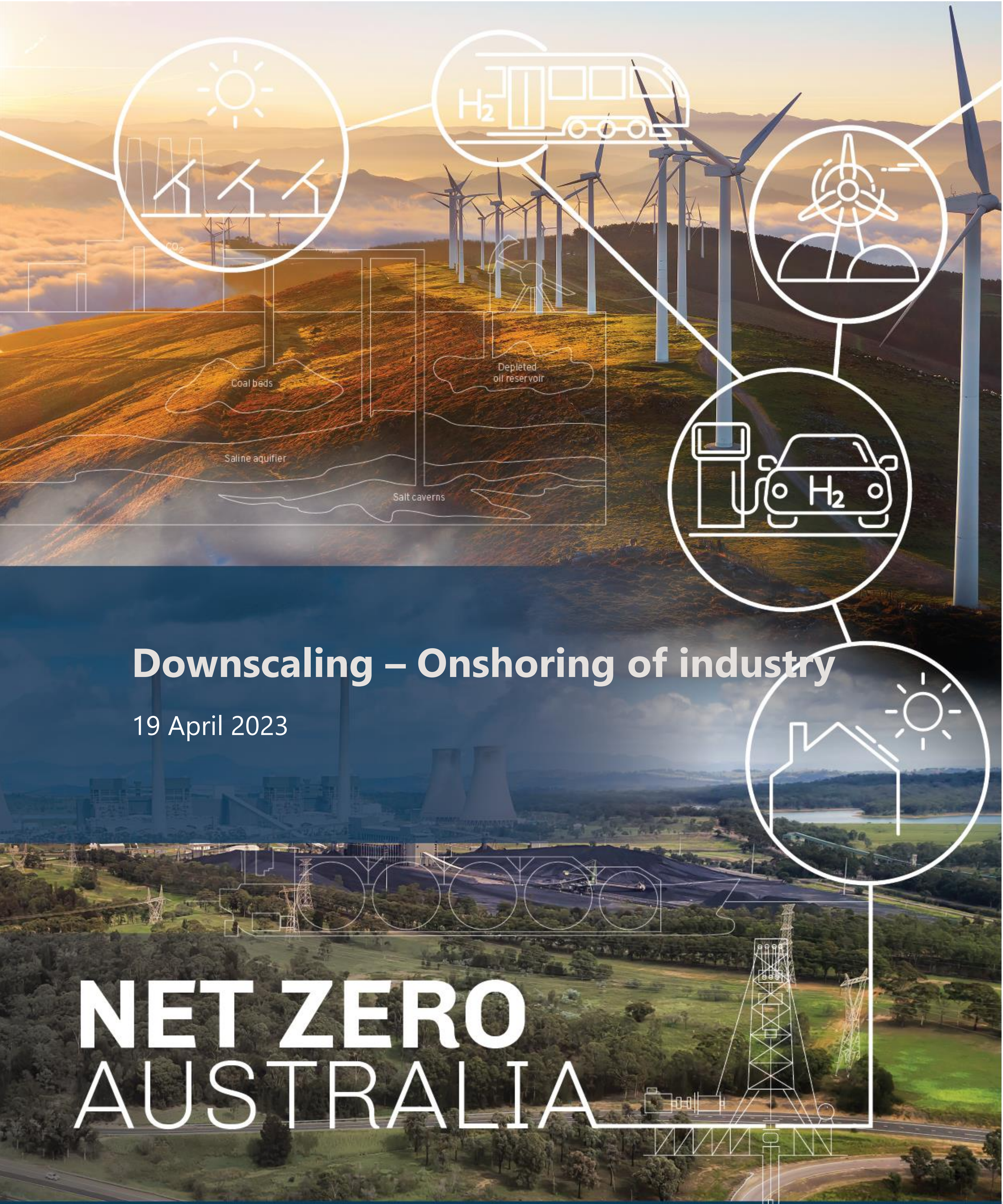

Downscaling – Onshoring of industry

19 April 2023

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The Net Zero Australia (NZAu) project is a collaborative partnership between the University of Melbourne, The University of Queensland, Princeton University and management consultancy Nous Group. The study identifies plausible pathways and detailed infrastructure requirements by which Australia can transition to net zero emissions, and be a major exporter of low emission energy and products, by 2050.

Net Zero Australia

Downscaling – Onshoring of industry

19 April 2023

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Contents

1 Onshoring industry

Australia exported 876 Mt of iron ore, 780 kt of steel and 171 Mt of metallurgical coal in 2020-21, worth $152 billion and $24 billion respectively [1]. By contrast, Australia only produced 5.7 Mt, of which 780 kt were exported at an estimated value of $773 million, highlighting that despite being one of the world's largest iron ore exporters, Australia's contribution to finished steel products is limited to roughly 0.3% of world output [2]. Most of the iron ore deposits and operational iron mines are in WA (See Figure 1).

Similarly, Australia produced 103 Mt of bauxite, 20.8 Mt of alumina and 1.58 Mt of aluminium metal in 2020. The majority of bauxite is refined to alumina onshore with only 0.35 Mt exported. Of the 20.8 Mt of alumina produced in Australia, 18.6 Mt are exported, worth an estimated $6.9 billion. Of the 1.58 Mt of aluminium produced, 1.40 Mt are exported at an estimated value of $3.7 billion.

The Net Zero Australia (NZAu) study therefore seeks to examine how some of our energy exports might be used to displace our iron ore, bauxite and alumina exports with domestically processed pig iron and aluminium for export. In the Onshoring Scenario, we treat the energy required for onshore alumina refining, aluminium smelting and iron ore reduction as taking away from the modelled energy exports, and not adding to it. Further details defining the scenario and the technical assumptions behind the modelling of NZAu's decarbonization and onshoring approach for the iron and steel and aluminium industries are given in the MASS document [3].

Figure 1 | Australia major iron deposits and mines. Source Geoscience Australia [4].

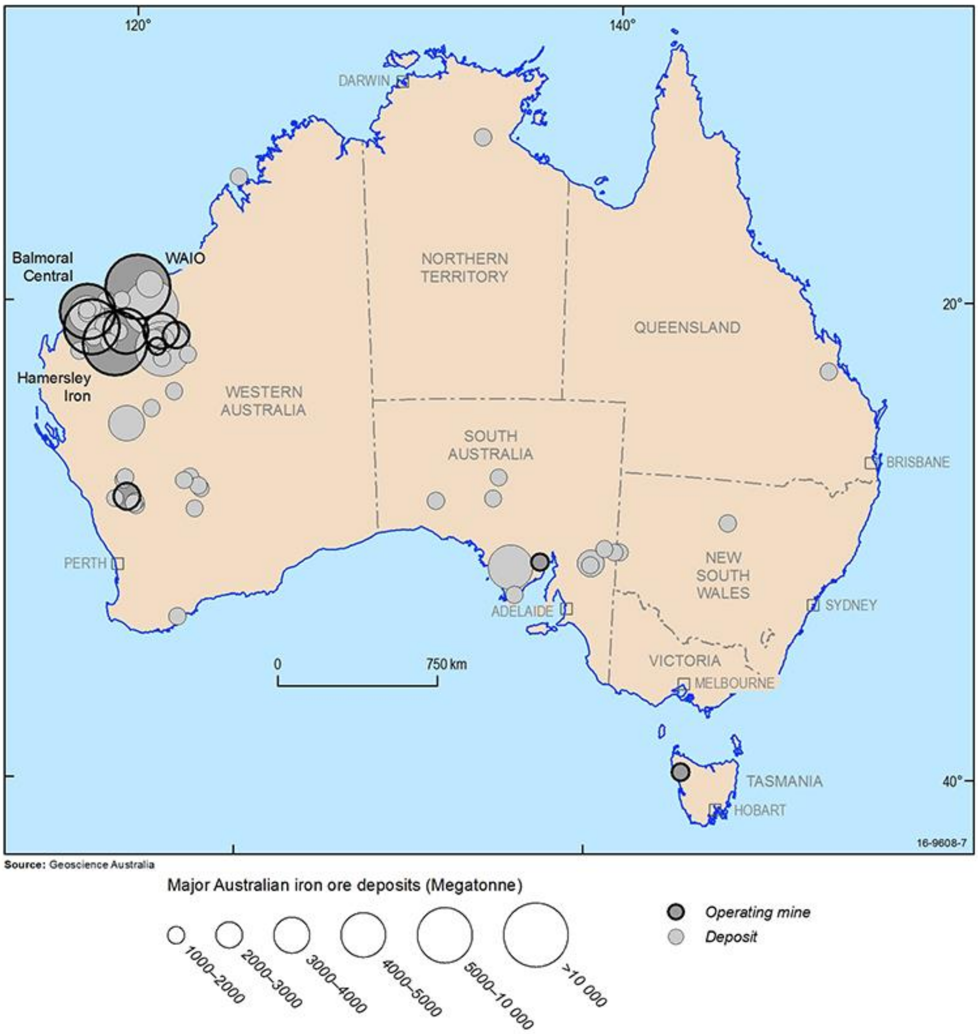


Table 1 and Figure 2 indicates that by 2060 in the ONS scenario, Australia avoids exporting 10.1 EJ of energy (or 67% percent of total energy exports in 2060 in other scenarios) by onshoring iron production. Similarly, Table 1 and Figure 2 that in the ONS scenario in 2060, Australia avoids exporting 1.2 EJ of energy (or 8% percent of total energy exports in 2060 in other scenarios) by onshoring aluminium production. The companion report *Downscaling – Energy export systems* provides a detailed focus on the energy export industry. While mining of iron ore and alumina are not included explicitly in NZAu modelling, they are discussed in the context of onshoring portions of those industries in the NZAu MASS [5] and this document.

Table 1 Energy exports in 2060 for NZAu scenarios (EJ), along with export energy avoided by onshoring iron and aluminium production in the ONS scenario

Scenario	Ammonia	FT Liquid	LNG	Clean LNG	Coal	Electric cable	Onshore DRI (avoided)	Onshore aluminium (avoided)	Total
REF	0	0	4.1	0	10.9	0.1	0.0	0.0	~15
E+	13.7	0.2	0	0.5	0	0.8	0.0	0.0	~15
E+RE+	14	0	0	0.2	0	0.8	0.0	0.0	~15
E+RE–	13.5	0.3	0	0.6	0	0.8	0.0	0.0	~15
E–	13.8	0.3	0	0.2	0	0.8	0.0	0.0	~15
E+ONS	2.4	0.2	0	0.5	0	0.8	10.1	1.2	~15

Figure 2 | Proportion of energy export by energy sources in E+ONS in 2060

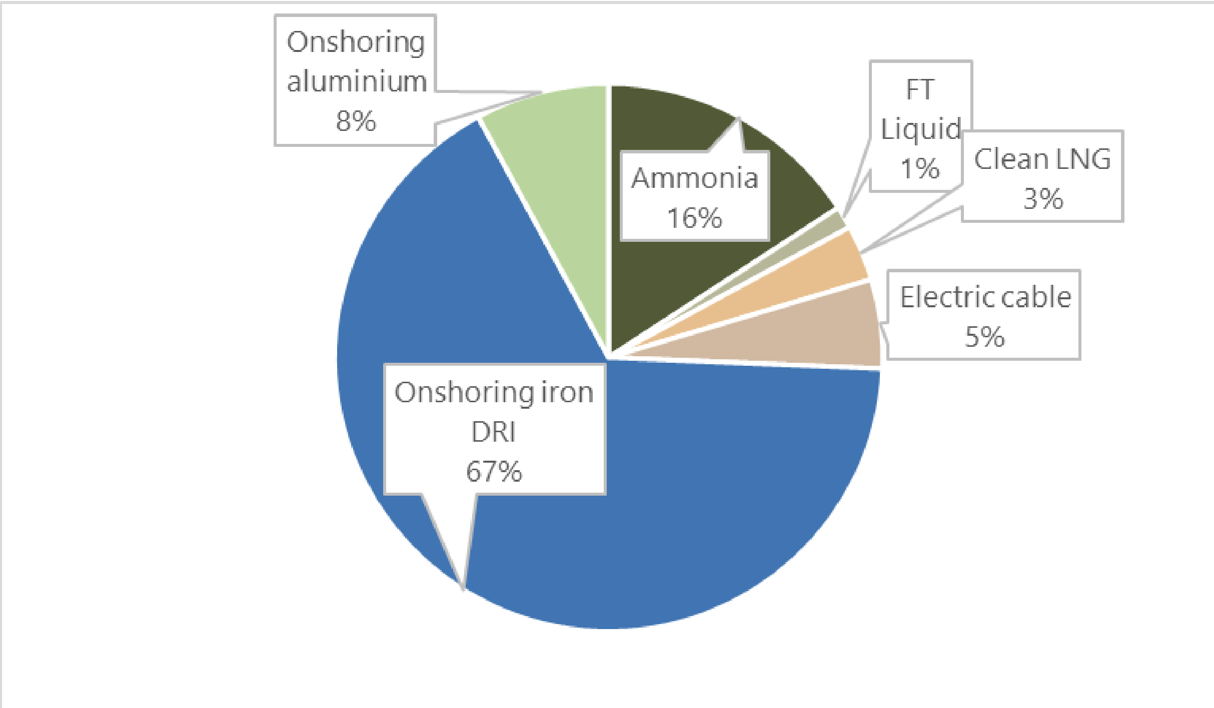


Figure 3 from MASS document[3] indicates that after 2030, energy consumption for DRI and aluminium smelting increases linearly in NZAu modelling, while the export of metallurgical coal and other energy exports decreases linearly in response.

Figure 3 | Energy export in E+ONS (source: figure 4 of Batterham, Beiraghi [3])

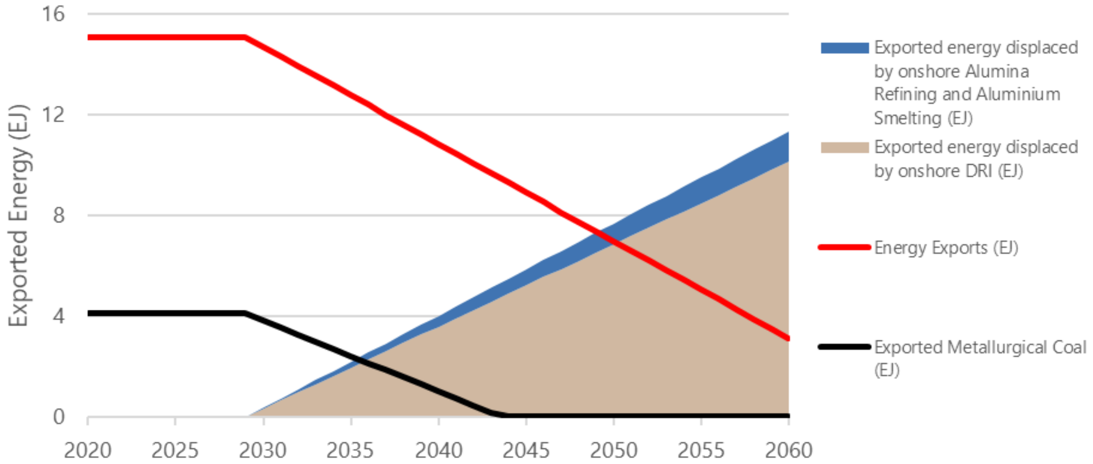
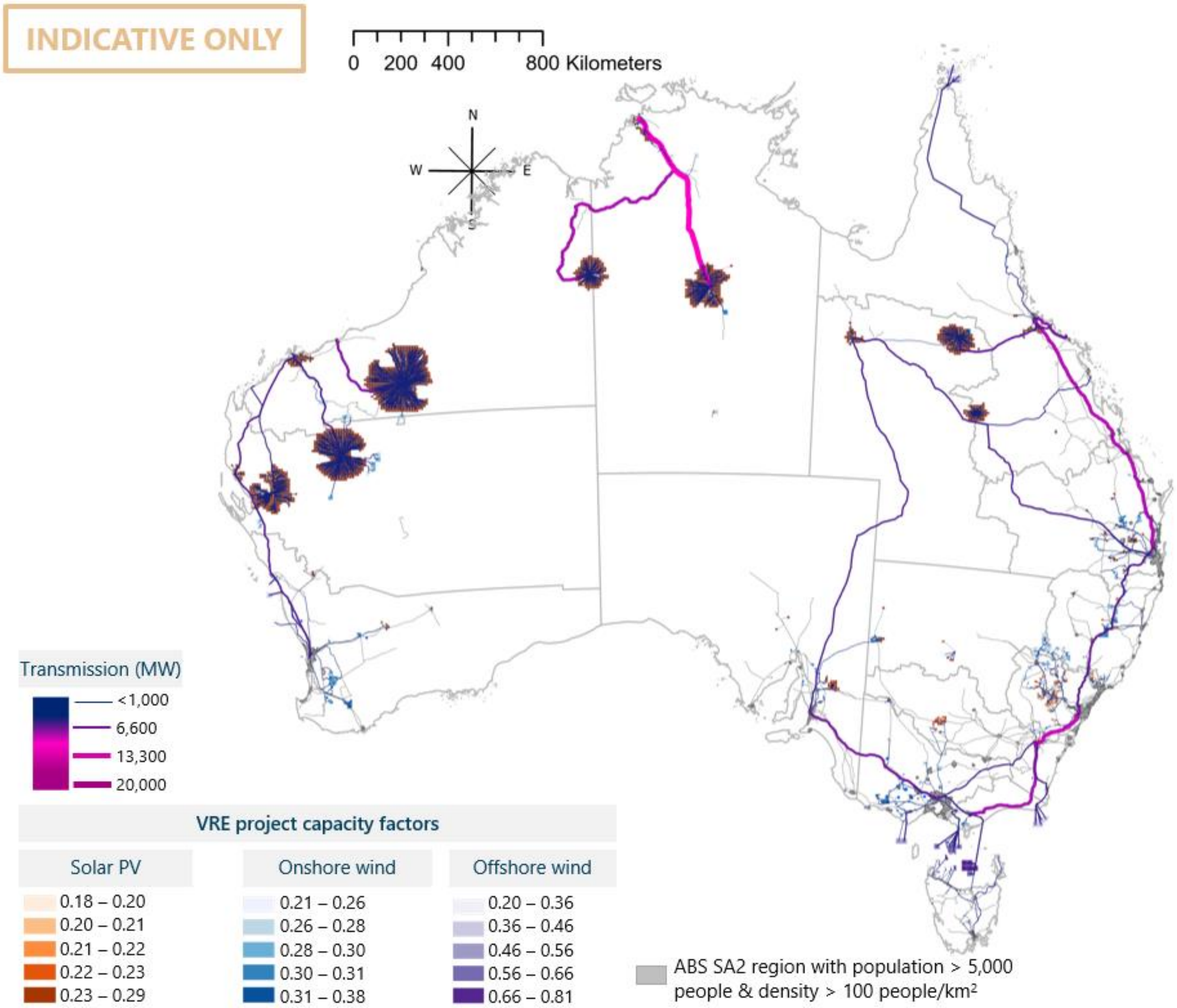


Figure 4 shows the downscaling of solar PV, wind and transmission infrastructure for the E+ONS scenario highlighting that the Northern Territory and Queensland see a significant decrease in the size of their energy export hubs. They experience the majority of the reduction in solar PV infrastructure, ~1.5 TW compared to ~3 TW in the E+ scenario. Northern WA experiences a marginal increase in solar PV in export zones which is predominantly the result of the location of the existing iron ore industry and the proposed location for the new DRI industry.

Figure 4 | Downscaled electricity transmission and variable renewable electricity (VRE) generation infrastructure for the E+ONS Scenario in 2060.



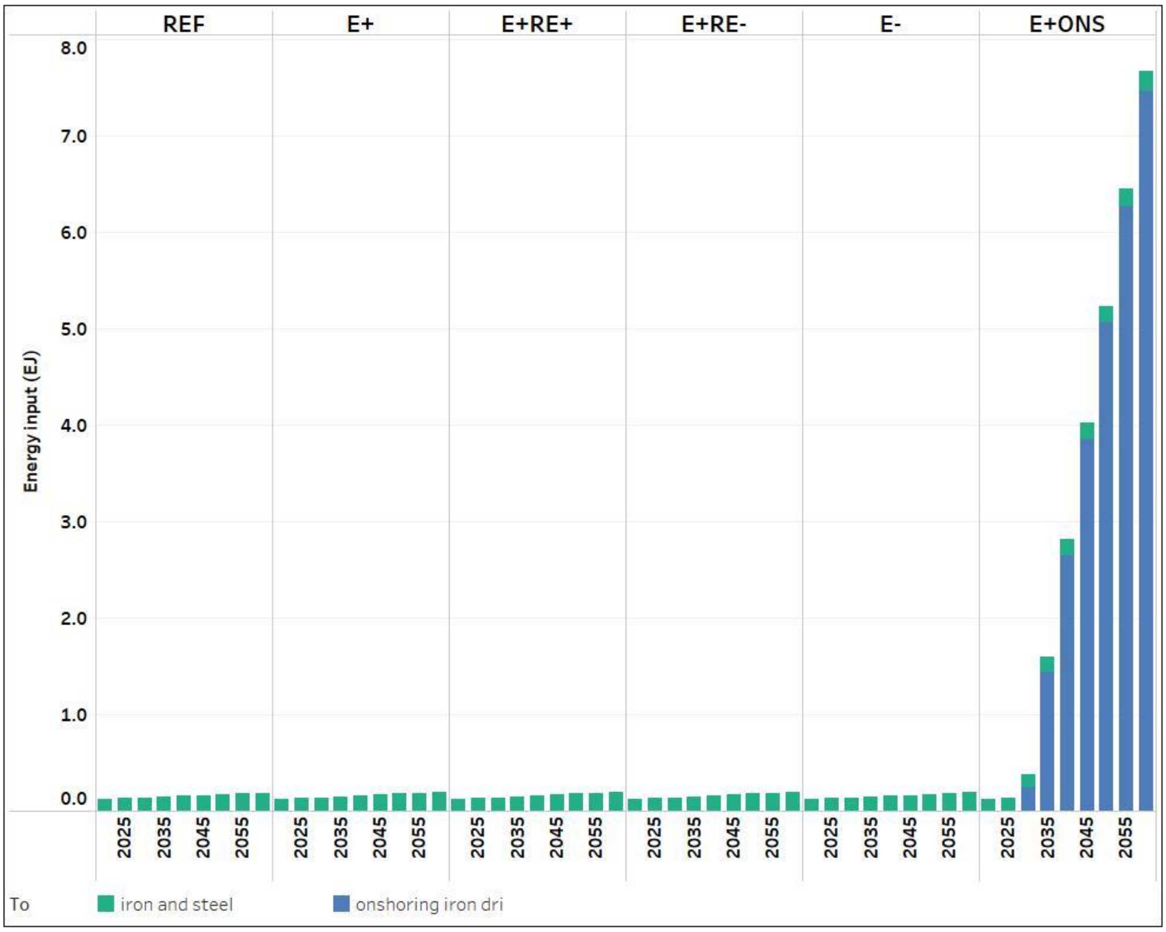
2 Iron and steel industry

2.1 Decarbonisation approach

Iron and steel are energy intensive industry that contribute to ~8% of Australia's total emissions. With rapid development of infrastructure and urbanisation, global demand for iron is increasing [6]; however, there is a lack of mature technology available for decarbonizing the iron and steel industry which poses a significant challenge to global decarbonisation pathways [7]. For the domestic integrated iron and steel industry, NZAu chose to hold domestic iron and steel production constant from 2020 levels out to 2060 in all scenarios. Decarbonization efforts are pursued in Australia's integrated iron and steel industry – shown in green in Figure 5 – using hydrogen to produce decarbonized direct reduced iron (DRI) products. Figure 5 shows demand for energy to supply Australia's integrated iron and steel industry increasing linearly by a percentage point every year.

In the onshoring (ONS) scenario, NZAu takes the additional step of building a world-scale, decarbonised DRI industry – shown in blue in Figure 5. NZAu does so by onshoring iron ore exports, and then decarbonising the energy streams feeding the DRI process. Figure 5 shows demand for energy to supply a world-scale and decarbonized DRI industry at roughly 40x the energy demand from the domestic integrated iron and steel industry in 2060.

Figure 5 | Energy demand for iron and steel for domestic use and DRI iron export

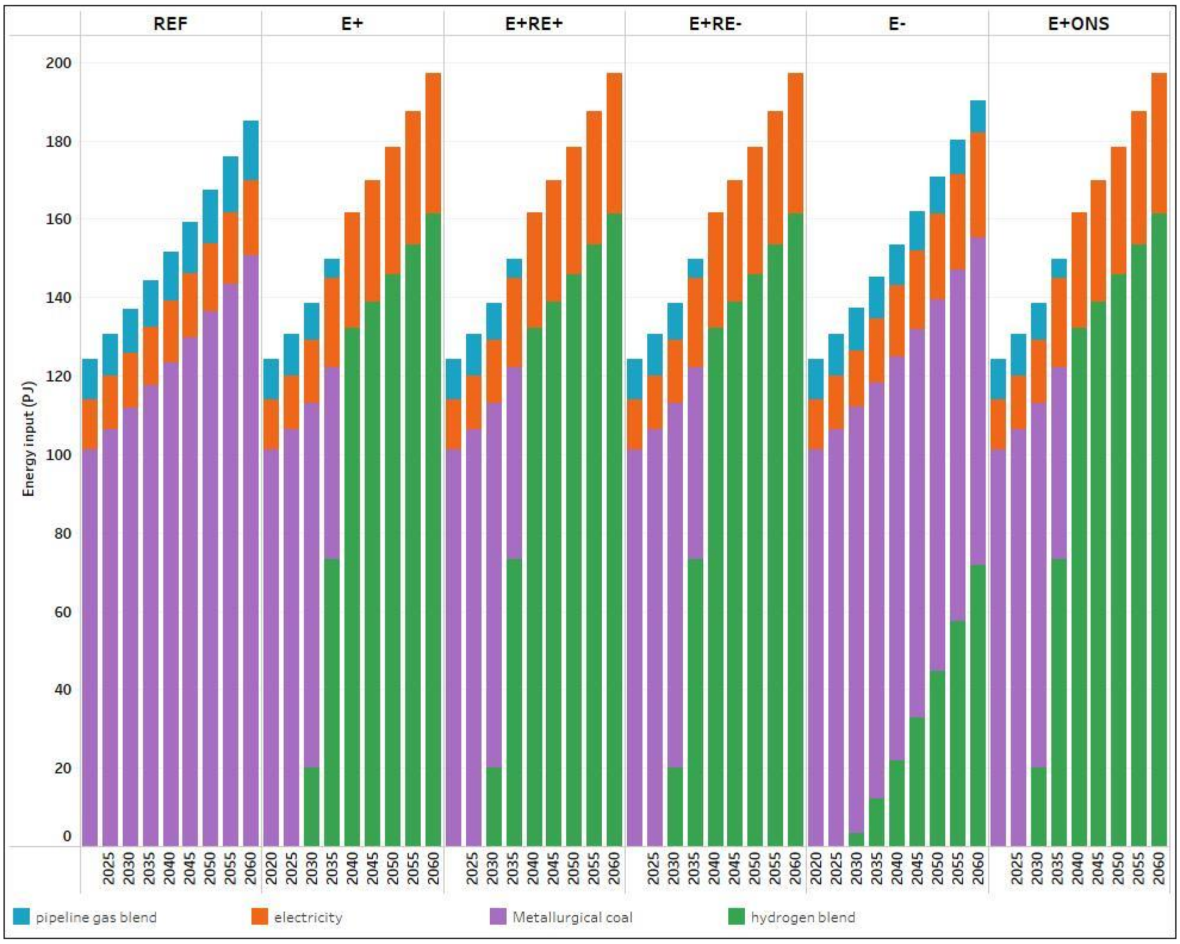


A small amount of decarbonised DRI produced using the decarbonized energy in Figure 5 is used in the domestic integrated iron and steel industry. The majority of the decarbonized DRI is not used domestically and is sent overseas. NZAu chose this approach as domestic iron and steel production are insignificant when compared to the amount of iron ore Australia exports annually, along with the quantity of energy exported to process that iron ore. The 10.1 EJ of exported energy avoided by onshoring pig-iron production in the ONS scenario in Table 1, dwarfs the integrated iron and steel industry energy demand illustrated in Figure 5.

2.2 Australia's integrated iron and steel industry

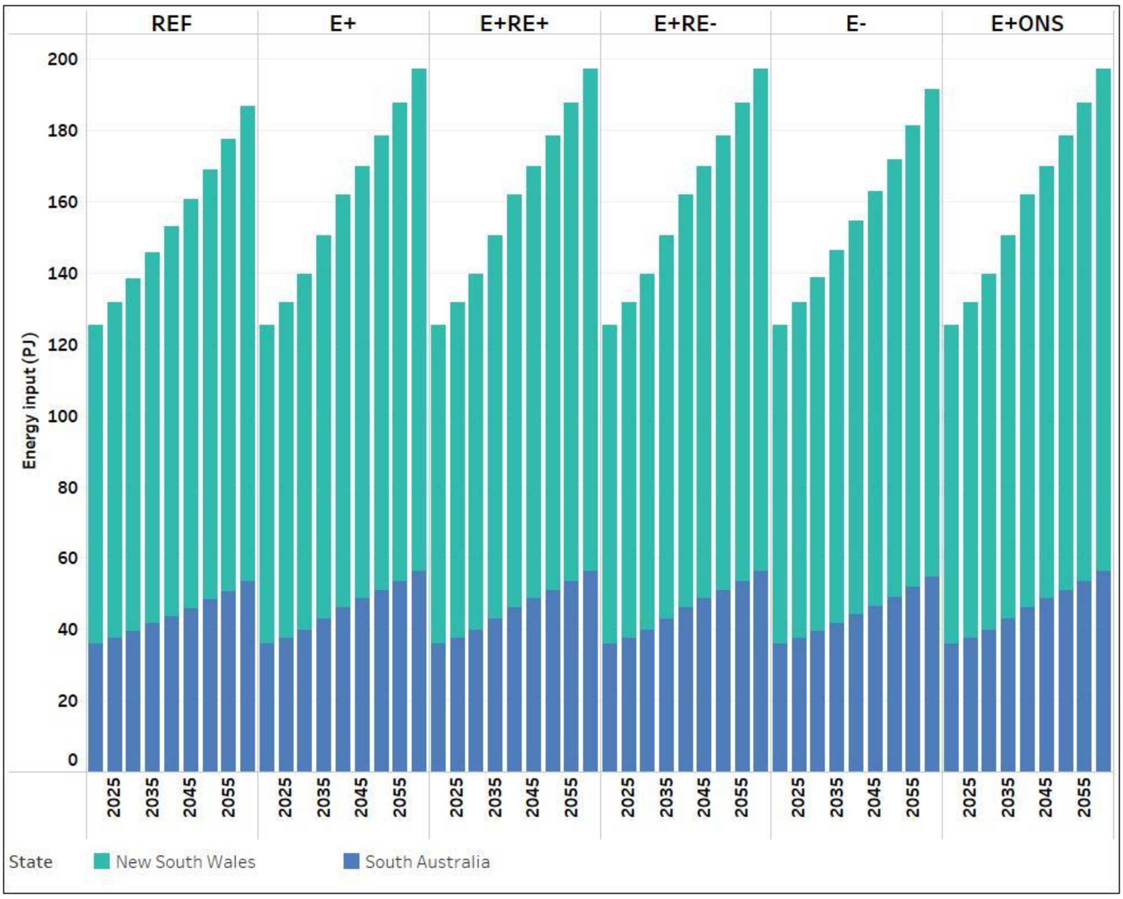
The decarbonisation of Australia's integrated iron and steel industry doesn't happen smoothly, as is shown in Figure 6. Use of black metallurgical coal drops sharply after 2030 as does the use of pipeline gas in all but the RE– scenario. Decreased reliance on coal and gas leads to a subsequent increase in the use of hydrogen from 2030 in all scenarios, and an expanded role for electricity in all but the E– scenario. In E– only a part of steel energy transitions to hydrogen energy and more diverse range of fuels supports decarbonization of the industry. Biofuels replace some black coal use (i.e. non-reducing energy provision), especially for the E– scenario. Biomass based synthetic fuels are substituted for some of the coal and gas in the E- scenario and emissions for any fossil fuels that remain in use in that scenario are offset by DAC + sequestration. See the companion reports *Downscaling – Fossil fuel industries*, *Downscaling – Bioenergy systems* for detail.

Figure 6 | Energy use by iron and steel by energy sources



Australia's existing integrated iron and steel facilities remain in their 2020 locations in South Australia (SA) and New South Wales (NSW) as shown in Figure 7, with a greater portion of the energy demand occurring in NSW.

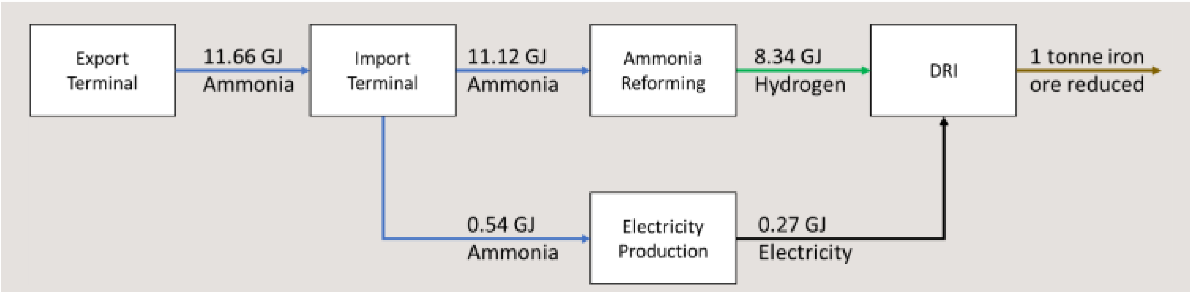
Figure 7 | Iron and steel industry in SA and NSW.



3 A decarbonised direct reduced iron (DRI) industry using hydrogen

Producing DRI using hydrogen (referred as DRI here after) offers a clean and efficient alternative to traditional pig iron production methods. As shown in Figure 8 instead of using carbon-based reducing agents such as coal or natural gas to reduce iron ore, DRI uses hydrogen as the primary reducing agent. Electricity is also used in the process. DRI typically produces high quality iron that can be used as a feedstock for steelmaking without the need for further refining. It is well understood that the grade and oxidation state of the iron ore influences both the efficiency and product quality of DRI; however in NZAu we assume all Australian iron ore is of similar DRI quality.

Figure 8 | Energy export transformation for DRI (Source Figure 5 of MASS pack[3]



In the NZAu DRI process, as outlined in the MASS pack [3], 1.61 tonne of iron ore produce 1 tonne of DRI [3]. In the E+ONS scenario, Australia starts building its DRI industry in 2030, and then DRI production increases linearly every year from 2030 to 2060 (see Figure 10). By 2060, all iron ore projected for export from Australia in that year is processed by Australia's DRI industry to produce the 538 Mt of pig iron. This equates to a 2060 demand of 6.6EJ of hydrogen and 0.21EJ of electricity, while avoiding the export of 10.1 EJ of ammonia (see TABLE 1). The reduction in Australia's ore exports is reported in Figure 9. Figure 10 shows the reduction in ore exported and increase in DRI production.

Figure 9 | Quantity of historical ore export [1], ore export reduction and iron export in NZAu scenario.

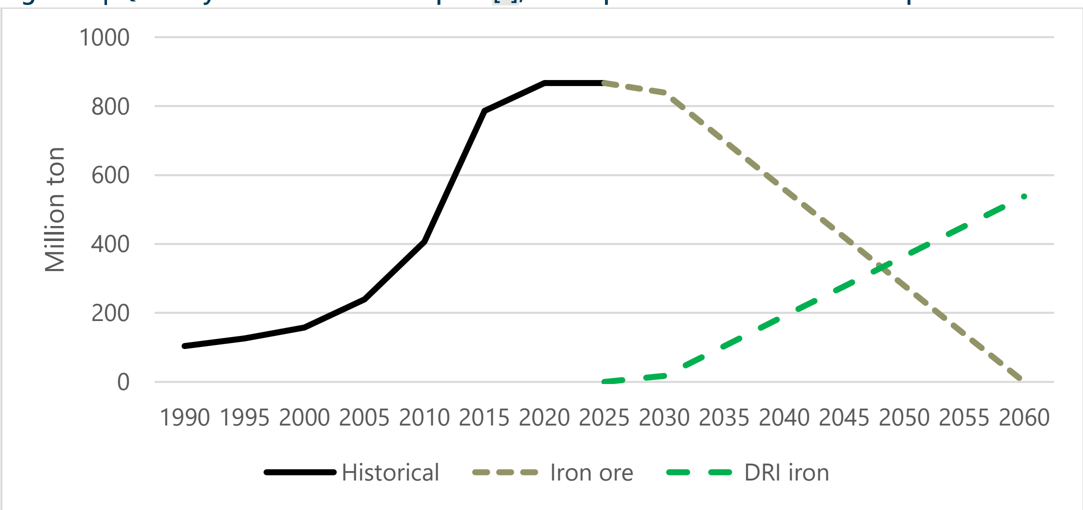
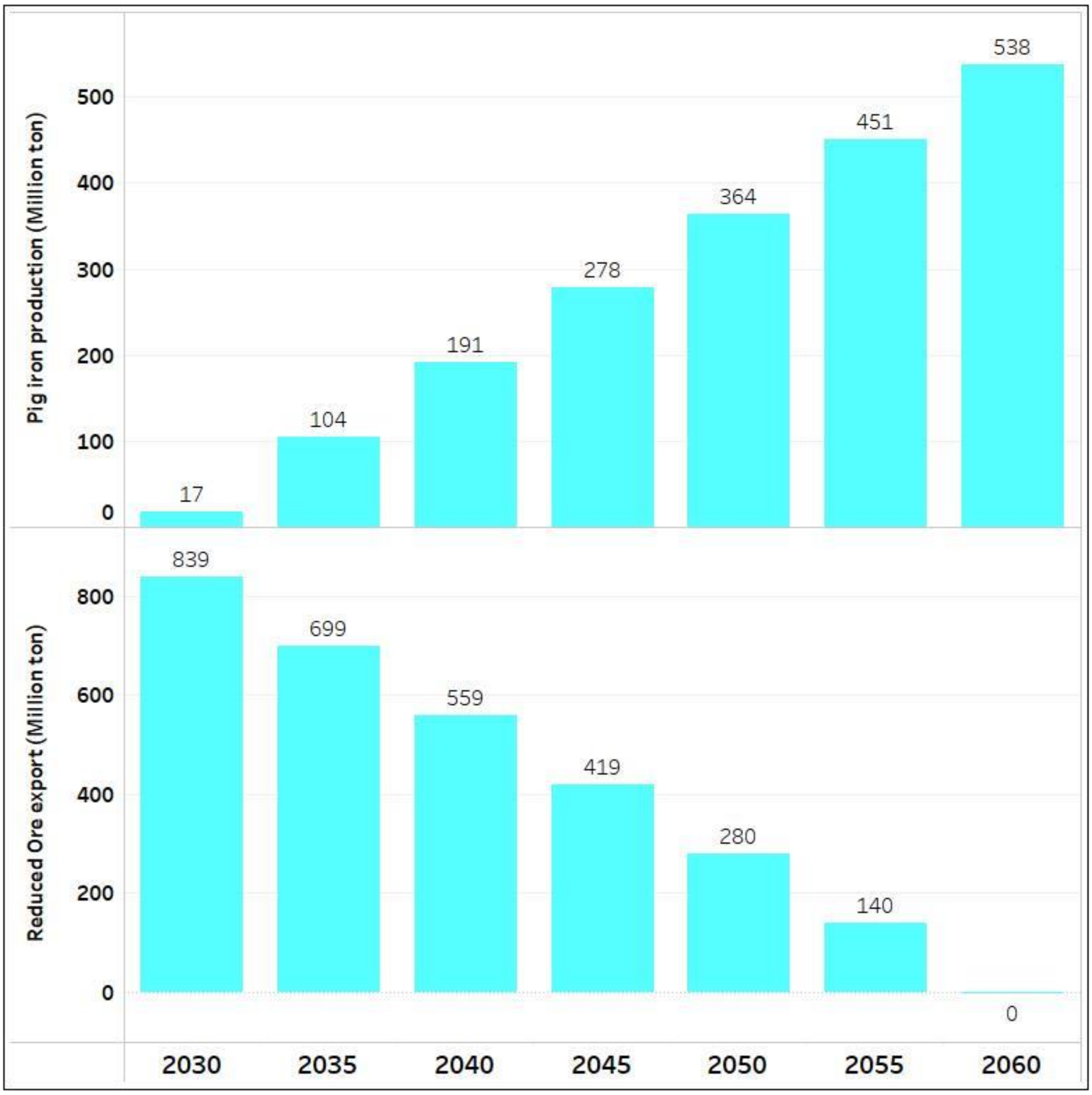


Figure 10 | Reduction in ore export from Australia and increase in pig iron production.



3.1 The DRI transition

In the MASS document [3] it was reported that the reduction of one tonne of iron ore required 8.61 GJ of process energy [3, 8, 9]. The back conversion of that 8.61 GJ of process energy to its primary energy requirement of 20.73 GJ is shown in Table 2 and assumes that the form of clean energy export sourced from Australia is Ammonia. The conversion factors listed in Table 2 are taken from the MASS document [3].

Table 2 | Energy required to reduce one ton of ore.

Description	Input in GJ	
	Electricity	Hydrogen
Energy required		
Energy input in DRI	0.27	8.34
Ammonia converted for power (conversion factor of 50%)[10]	0.54	
Ammonia converted to hydrogen (conversion factor of 75%)[11]		11.12
Ammonia exported from Australia and import for DRI (negligible losses)	11.66	
Energy produced in Australia for DRI		
Hydrogen to produce Ammonia (conversion factor of 75%)	15.55	
Power to produce hydrogen (conversion factor of 75%)	20.73	

Table 2 illustrates that if Australia's clean energy resource is used onshore for the reduction of iron in the DRI process, rather than converting to and from Ammonia during the export process, a 55.4% energy savings is achieved.

However, the actual energy avoided is less than converting to and from ammonia, as Australia has to export ammonia anyway if it doesn't use it for onshoring DRI. Therefore, the actual efficiency of energy avoided is 73.8%.

3.2 DRI infrastructure

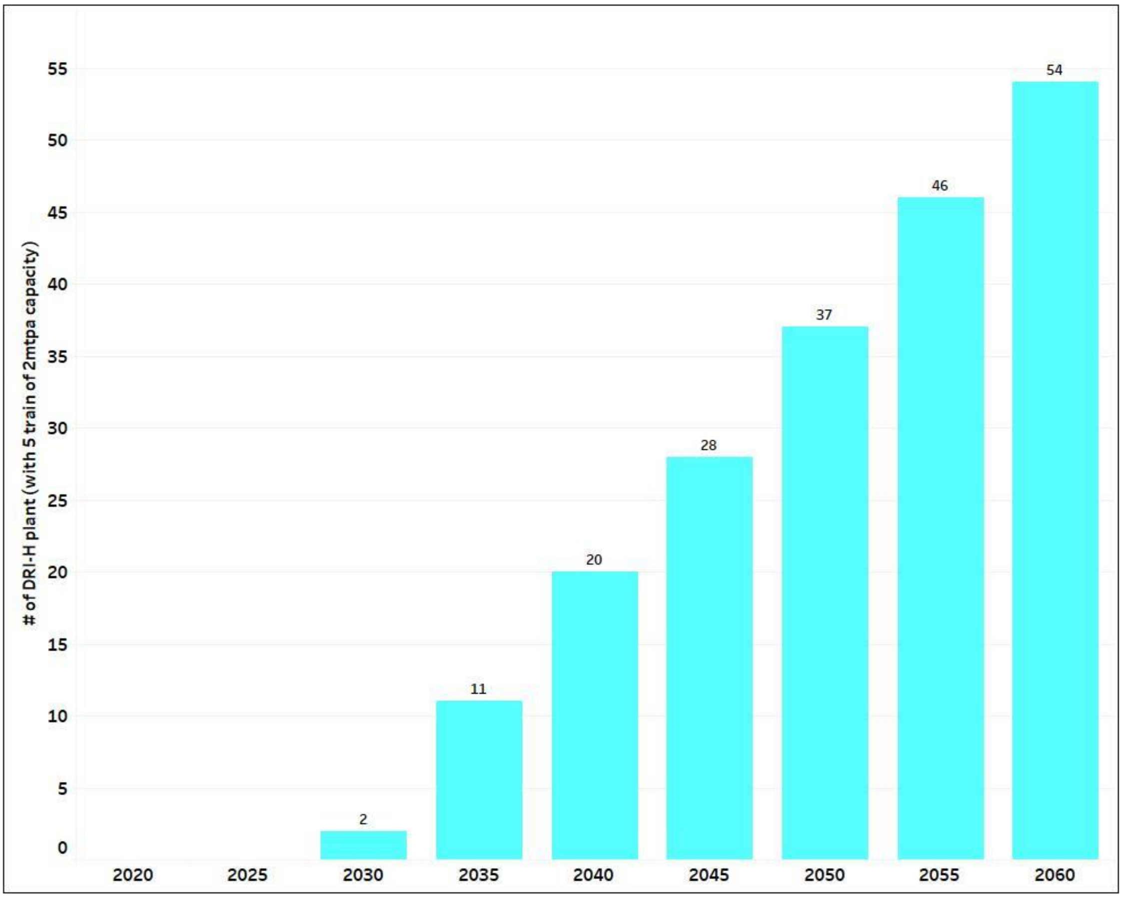
3.2.1 DRI train

The current market leader for direct reduced iron (DRI) production is the Midrex process. Midrex currently produce modules to facilitate DRI production using natural gas or coal. These modules are sized between 0.5 – 2 Mtpa of DRI produced [12]. Most plants worldwide are made up of 1 – 2 modules run as parallel trains. The Mobarakeh Steel plant in Iran is made up of 5 parallel modules totalling a production of 4 Mtpa of DRI capacity [13].

Midrex are developing modules to take hydrogen as a the only reducing feedstock. These modules do not require any gas reforming, acid removal or water gas shift units and thus will occupy a lower footprint. Given the largest Midrex module has a capacity of 2 Mtpa, and a plant exists with 5 parallel trains, it is reasonable to assume that the capacity of a future green DRI plant to be at least 10 Mtpa (5 x 2 Mtpa trains in parallel). Using the input quantities in the MASS document [1] demand from a 10 Mtpa DRI plant would be 0.94 Mtpa H_2 and 3.7PJ of electricity.

As shown in Figure 11 by 2060 in the ONS scenario, 54 DRI plants (each with 5 trains of 2Mtpa capacity) are required to process all 876 Mt of Australia's iron ore. By comparison, in 2035, 11 DRI plants are needed, or roughly 4 plants in each port of WA. In 2060, each port of WA contains 18 DRI plants.

Figure 11 | Number of DRI plants required. One DRI plant has 5 x 2 Mtpa capacity trains



3.2.2 Plant footprint

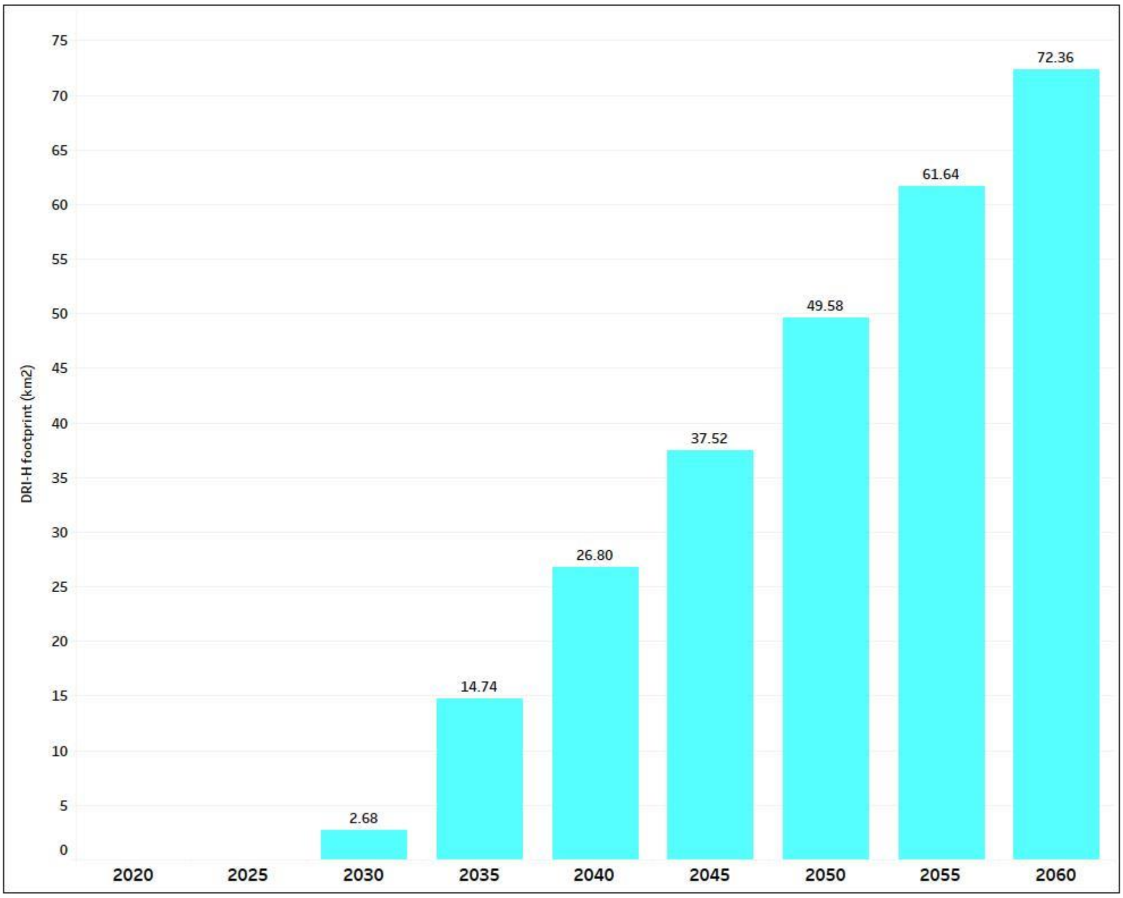
A similar strategy to what was done for ammonia plant sizing in the companion Export Downscaling document, has been employed for DRI plant sizing. A variety of DRI plants around the world were mapped for their apparent footprint. The footprint was scaled according to each plant's nameplate capacity to approximate the footprint of a 10 Mtpa DRI plant. The results are given in Table 3.

Table 3 | Footprints of existing DRI plants [13]

Plant	Footprint (km^2)	Production (Mtpa)	10 Mtpa footprint (km^2)	Year of construction
Nu-iron Trinidad	0.2001	1.6	1.25	2006
ArcelorMittal South Africa Saldanha Bay	0.7666	0.8	9.58	2009
Cleveland-Cliffs HBI Plant, Ohio	0.291	1.6	1.82	2020
ArcelorMittal Hamburg	0.2749	0.4	6.87	1971
voestalpine Texas	0.1923	2	0.96	2016

Footprints vary substantially between the existing plants in Table 3. This is likely due to a combination of factors, including the selected equipment layout (due to process and neighbouring hazards) and the constraint on available land at time of construction. For NZAu green DRI plants, it would be reasonable to take an average of similarly sized dense plants – given the scale at which DRI plants are to be deployed. Thus, the footprint of a 10 Mtpa green DRI plant in NZAu is 1.34 $km^{2.}$ Figure 12 presents the land required for DRI plants, based on 1.34km^2 of footprint for an DRI plant processing 16 Mt of ore and producing 10 Mt of pig iron. Due to the proximity of the iron ore mining industry, all DRI happens in the three WA ports selected for export (see MASS and companion Export downscaling document) resulting in a minimum land requirement of approximately 24 km^2 for DRI facilities in each WA port.

Figure 12 | Area needed to establish DRI plants



3.3 The impact on shipping of onshoring DRI

3.3.1 Ammonia transport

We use a shipping capacity of 105,000 m^3 used in MASS document number [3] to calculate the ship call required for ammonia. Based on 680 kg liquid ammonia per 1m^3 liquid ammonia, we calculate an ammonia ship exports 70400 tons per ship.

Calculations for ammonia fuel demand were done for two cases – the shipping of ammonia and the shipping of iron-based products. The first case was adapted from a 2021 study by Seo and Han [14] where a techno-economic analysis was conducted on an ammonia powered fuel tanker. Ammonia is stored as a cryogenic liquid. Boiloff gas is used as fuel, with excess boiloff gas condensed through an onboard refrigeration system. The calculation parameters from Seo and Han [14] are included in Table 4. Note that these parameters correlate to a round trip basis of 20,000 km.

Table 4 | Ammonia carrying calculation parameters based on Seo and Han [14]

Parameter	Value	Unit
Ammonia shipping density	0.682	t/m3
Ship ammonia carrying capacity (20,000 km round trip basis)	84,000	m3
Ship ammonia fuel consumption (20,000 km round trip basis)	4,170	m3

These values required adjustment for the round-trip distance. Energy demand is primarily associated with engine power and ammonia boiloff condensation, both of which are a function of distance and time. Thus, it is reasonable to linearly extrapolate ammonia fuel consumption. Thus, for a 14,000 km roundtrip, 2,919 m^3 of ammonia will be consumed. Converting units yields a fuel consumption of 36 kg per tonne of delivered ammonia, which is 3.6% of total ammonia delivered.

3.3.2 Iron transport

Estimations of ship calls avoided uses the largest ships currently used to ship iron ore from Port Headland in Western Australia. These vessels have a capacity of 270 kilotonnes of iron ore each[i].
We assume all ships will use ammonia as fuel in future. Given iron-based products (iron ore and direct reduced iron (DRI)) are transported in bulk cargo carriers rather than gas tankers, a different methodology was used to determine ammonia consumption. The calculation was based off a study by Kim, Roh [15] which involved a technoeconomic analysis of transitioning container ships to ammonia fuel. The key parameters taken from Kim et al (2020) are included in Table 5.

Table 5 | Calculation basis based on Kim, Roh [15]

Parameter	Value	Unit
Annual ship ammonia consumption (280 days at sea basis)	22 - 34	kt-NH_3/year
Ship travel speed	19	knots
Time spent at sea	280	days/year
Ship carrying capacity	2500	TEU

The round-trip travel time was calculated using a round trip distance of 14,000 km and average ship travel speed of 19 knots, coming out to be 17 days. Assuming the 280 days at sea is consistent with the maximum capacity for a ship – inclusive of loading and unloading time, a ship would be able to complete roughly 16 trips per year. Assuming a twenty-foot container equivalent unit (TEU) to weight conversion rate of 24 t/TEU, a similar ship would be able to carry roughly 58.75 kt of product per trip. Thus, taking the annual ship ammonia consumption (Table 5) along with the aforementioned values, a rough fuel consumption can be estimated at 29 kg NH_3 per ton of iron-based product.

3.3.3 Change in ship calls

Changes in the quantity of iron and energy exported in the ONS scenario have impacts (energy and otherwise) on Australia's shipping sector and its ports. In 2030 in the ONS scenario, Australia ships 839 Mt of ore and 17 Mt of pig iron. In 2050 in the ONS, 280 Mt of iron ore and 364Mt of pig iron are exported. This change in the quantities of iron products shipped reduces the ship calls (from 2020 levels in the [REF] scenario) as shown in Figure 13 (A). Australia's choice in the ONS scenario to avoid shipping significant quantities of ammonia overseas reduces ship calls to Australia ports for ammonia as shown in Figure 13 B.

Figure 13 | Ship call avoided due to onshoring DRI

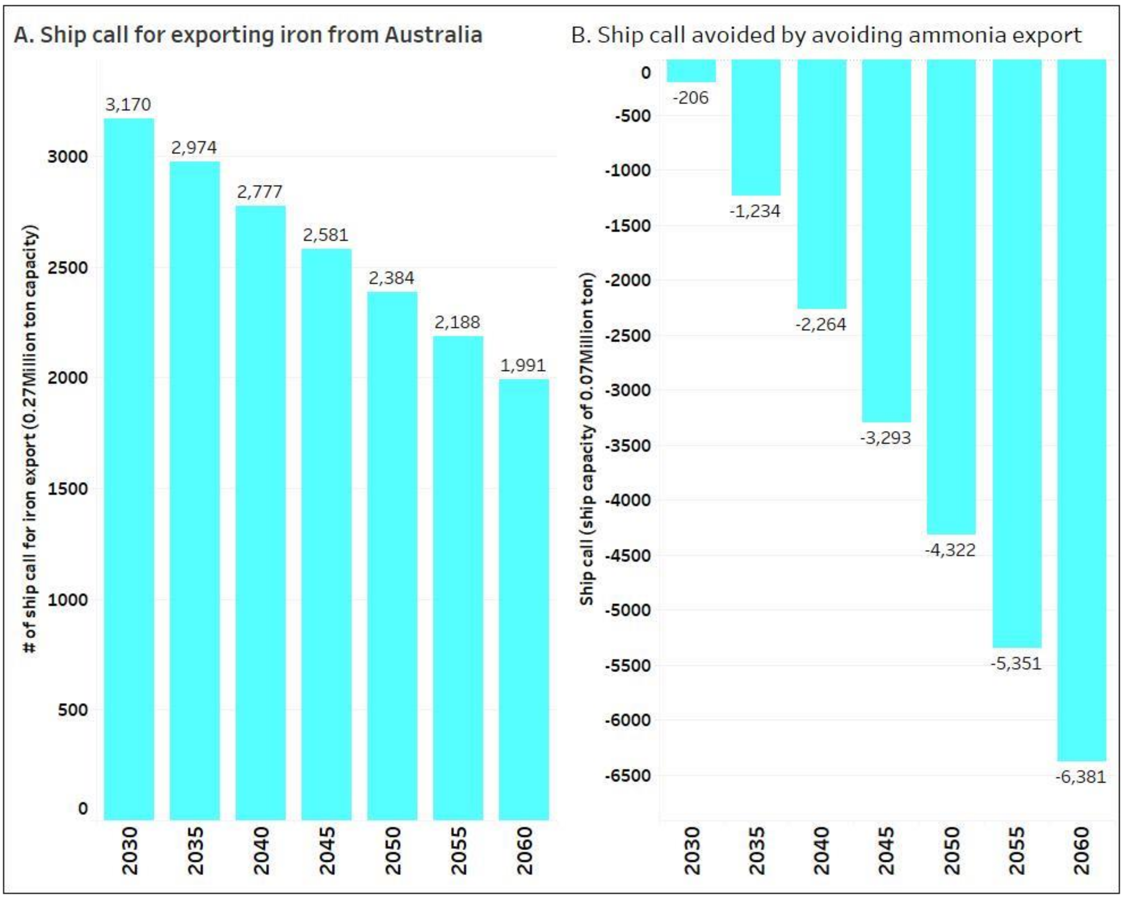
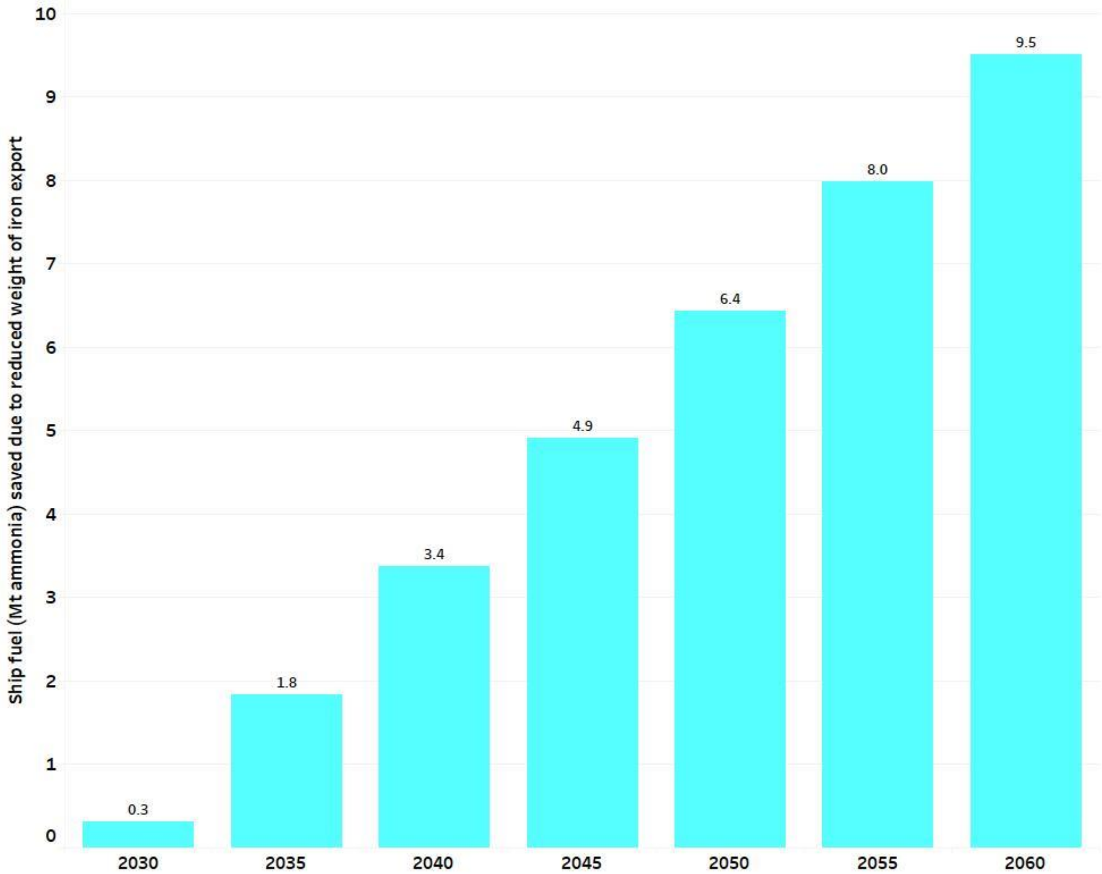


Figure 13 indicates that in 2060, ship calls for Australia's iron ore have reduced from 3170 in 2020 to 1991. Additionally, in 2060 in the ONS, Australia also avoids the 6,381 ships calls connected to the export of 449.2 Mt of Ammonia (70,000 t of ammonia per ship [3]) in that year in all other scenarios.

Using average value of 0.029 t-NH3 / t-iron, the onshoring of DRI would save 4.6 Mt of ammonia in 2060. Figure 14 presents a bar graph of ammonia (in Mt) saved per year by onshoring DRI. The quantities presented in Figure 14 only consider the reduction in the weight of iron products from onshoring DRI. For example, in 2060 in the ONS scenario, Australia exports 538 Mt of pig iron instead of exporting 876 Mt of iron ore to reduce 338Mt of iron ore being shipped.

Figure 14 | Ship fuel saved by onshoring DRI due to reduced weight of iron product exported.



4 Onshoring aluminium production

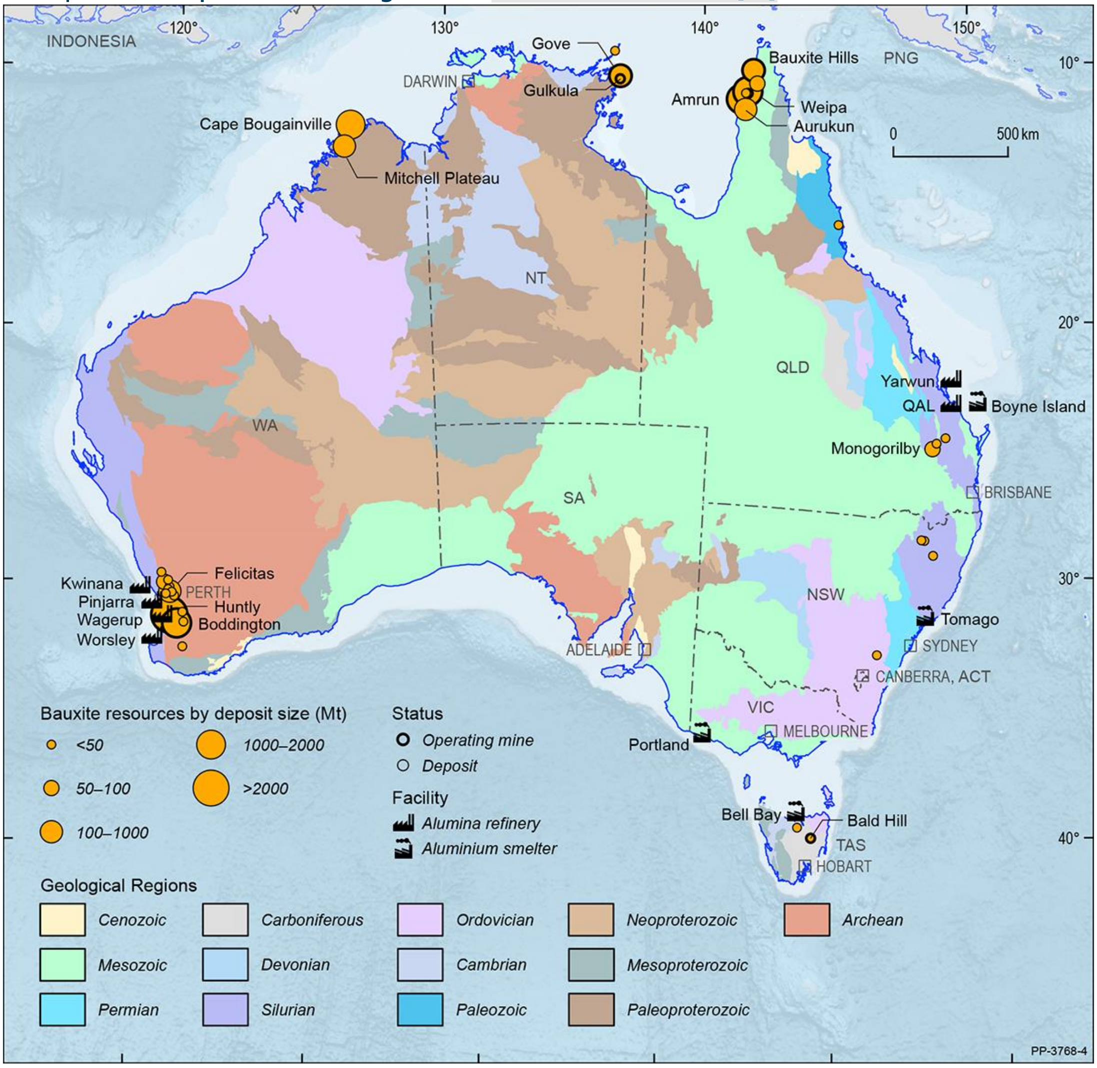
4.1 Context

Figure 15 shows the bauxite deposit in Australia. According to Geoscience Australia [16], Australia's Economic Demonstrated Resources (*EDR*) for bauxite is 5,292 Mt in 2019. In 2020-21, Australia produced 103Mt of Bauxite, 20.45Mt of alumina and 1.57Mt of aluminium and exported 35.7Mt of Bauxite, 18.6Mt of Alumina and 1.36Mt of aluminium in 2021-22[17]. Despite being largest producer of Bauxite accounting 28% of global bauxite production, Australia's contribution to alumina is 15% and aluminium is 2% of global production[16].

The production and export of bauxite indicate, 35% of bauxite was exported in 2020-21 and majority of the bauxite is processed onshore to produce ~21Mt of alumina. In 2020-21, 89% of the alumina is exported. The remaining 2.2Mt alumina is further processed to produce 1.58Mt of aluminium. Out of the total aluminium, 87% is exported.

This indicates Australia has the opportunity to onshore its bauxite to produce alumina and smelt aluminium using clean energy and hydrogen to decarbonize the aluminium industry.

Figure 15 | Bauxite deposit. Source: Figure 8 of Geoscience Australia [16]



4.2 Aluminium production process

Aluminium production happens in two steps. First, bauxite is processed to produce alumina. For this analysis, 4 ton of bauxite produces 1 ton of alumina. In the second step, alumina is smelted to produce aluminium. Currently roughly 13% of aluminium is produced onshore. Therefore, NZAu only accounts the remaining (87% of energy export avoided by onshoring the aluminium production.

Smelting one ton of aluminium uses 2.1GJ of hydrogen and 52.5GJ of electricity. In the MASS document [3] it was reported that the smelting of one ton of aluminium required 54.6 GJ of process energy [3, 8, 9]. The back conversion of that 54.6GJ of process energy to its primary energy requirement of 191.59GJ is shown in Table 6 and assumes that the form of clean energy export sourced from Australia is Ammonia. The conversion factors listed in Table 6 are taken from MASS[3].

Table 6 | Energy required to reduce one ton of ore

Description	Input in GJ	
	Electricity	Hydrogen
Energy required		
Energy input in DRI	52.5	2.1
Ammonia converted for power (conversion factor of 50%)[10]	105	
Ammonia converted to hydrogen (conversion factor of 75%)[11]		2.8
Ammonia exported from Australia and import for DRI (negligible losses)	107.8	
Energy produced in Australia for DRI		
Hydrogen to produce Ammonia (conversion factor of 75%)	143.69	
Power to produce hydrogen (conversion factor of 75%)	191.59	

Table 6 illustrates that if Australia's clean energy resource is used onshore for aluminium smelting, rather than converting to and from Ammonia during the export process, a 50.6% energy savings is achieved. The energy saving when compared as primary energy for smelting alumina in Australia and energy export is 28.5%.

However, the actual energy avoided is less than converting to and from ammonia, as Australia has to export ammonia anyway if it doesn't use it for onshoring aluminium smelting. Therefore, the actual efficiency of energy avoided is 53.2% as show in Figure 16 which presents the hydrogen required (blue) and energy saved abroad (red). if the energy savings achieved in
are applied to the smelting of 21.6Mt Mt of alumina in Australia.

Figure 16 | Energy activities and avoided energy abroad by Onshoring aluminium in 2060 in GWh

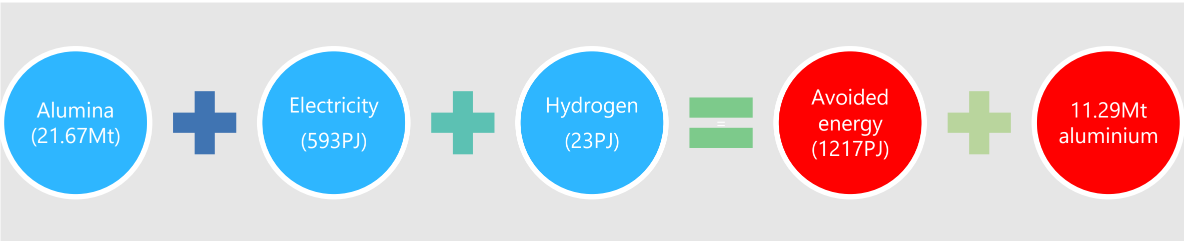
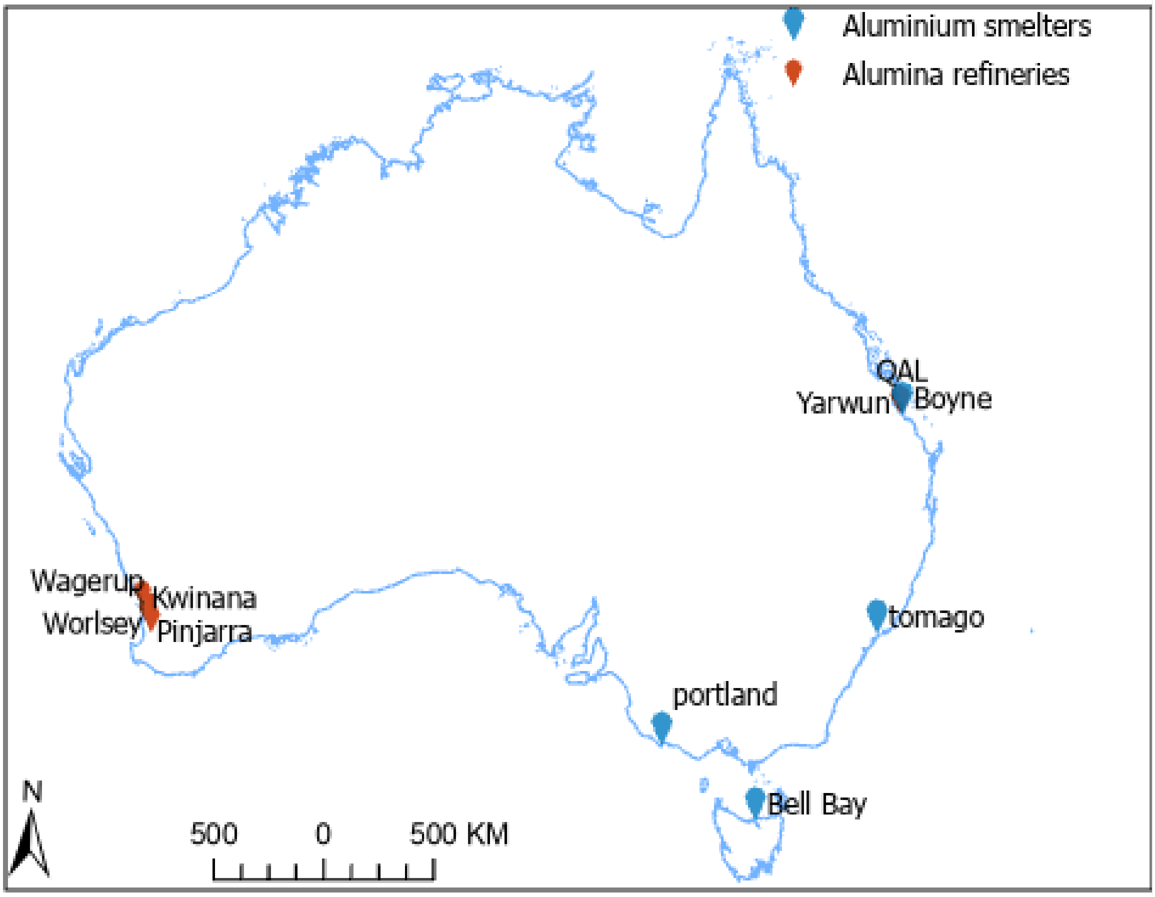


Figure 17 maps the existing bauxite processing and aluminium smelting sites in Australia. NZAu assumes these sites will be expanded by 2060 to enable all exported bauxite is processed domestically to produce alumina and then smelted to make Aluminium and then exported.

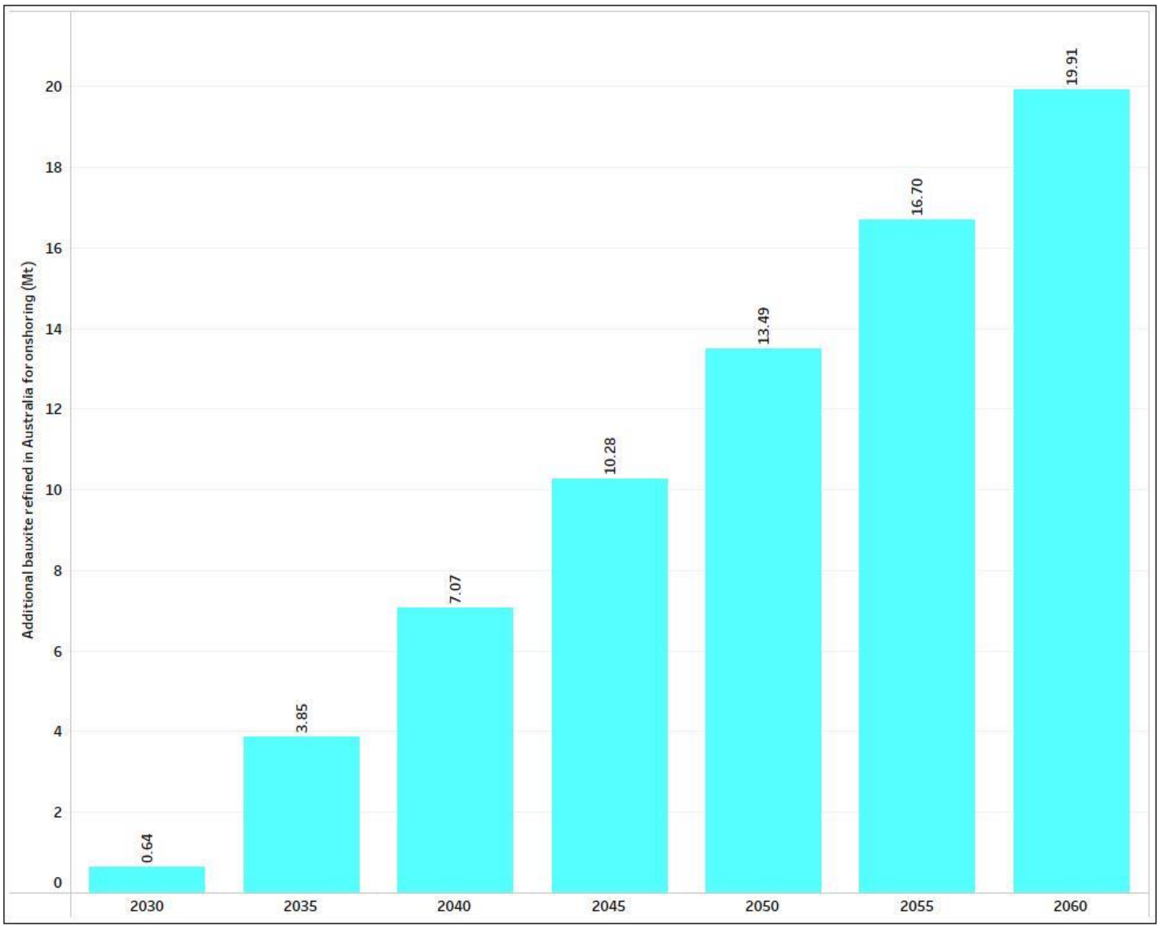
Figure 17 | Existing bauxite processing and aluminium smelting sites



4.2.1 Alumina production

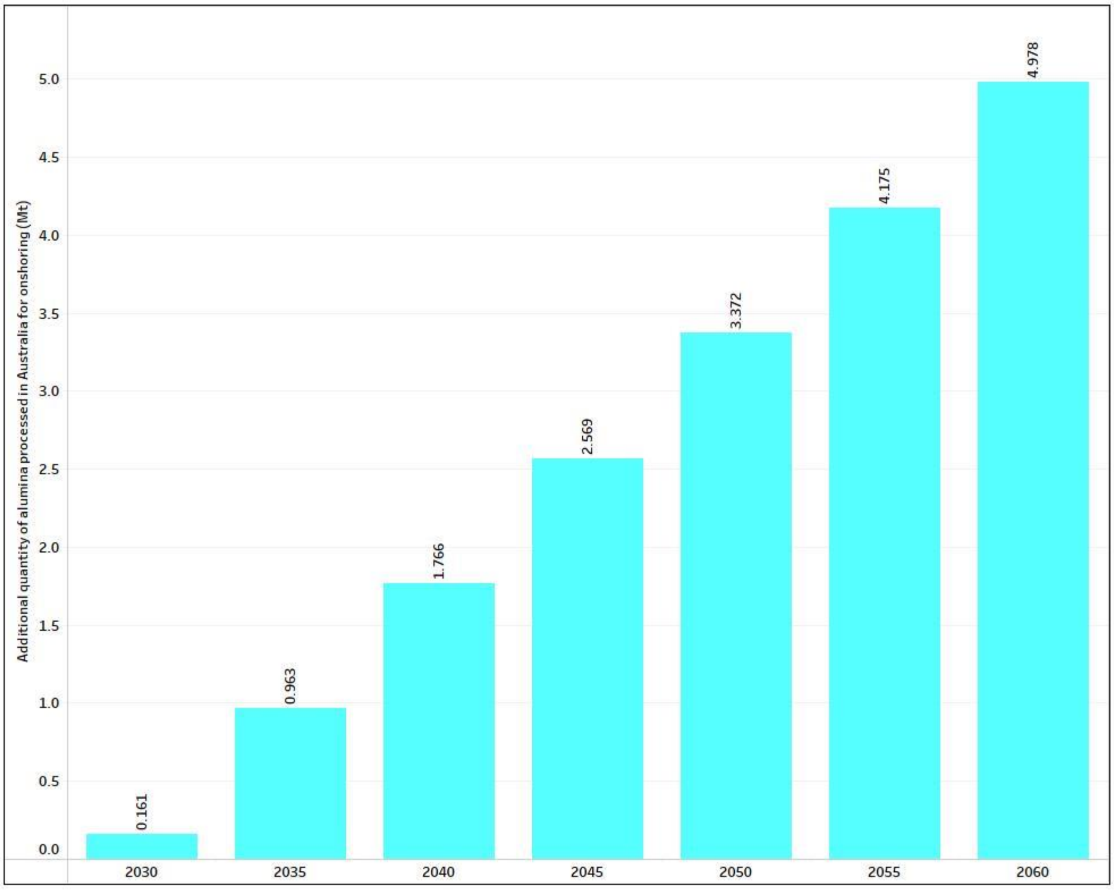
Figure 18 reports the total quantity of bauxite that has to be processed to onshore alumina production. Australia produced 20.8Mt of alumina in 2020 which is 83.2Mt of bauxite. Out of this, 74.4Mt bauxite produces 18.6Mt of alumina for export is already happening. Therefore, Australia has to refine additional 19.9Mt of bauxite to onshore alumina.

Figure 18 | Total bauxite processed to onshore aluminium (Million ton)



Alumina refineries employ the Bayer process to convert bauxite into alumina. Alumina is the precursor product to aluminium. Caustic soda and large amounts of heat (traditionally provided by combusting natural gas) are used to remove oxygen and hydrogen from aluminium bearing minerals. Processes often employ high levels of heat integration, however, still have significant energy demands. The quantity of aluminium produce to onshore aluminium is provided in Figure 19. As explained earlier, Australia requires processing of additional 4.9Mt of alumina production to completely onshore the processing of 103Mt of its bauxite production.

Figure 19 | Production of alumina required to onshore aluminium (million ton)



Six alumina refineries already exist in Australia, with a combined capacity of 21 Mtpa alumina production. As outlined in the MASS document, alumina production increases to 25.7 Mtpa by 2060 in the onshoring scenario. Footprints of existing alumina refineries in Australia, along with estimated required footprints by 2060 are given in Table 7. Note that plant footprint analysis included the area utilised for red mud ponds, which in some cases accounted for up to 90% of plant footprint.

Table 7 | Alumina refineries

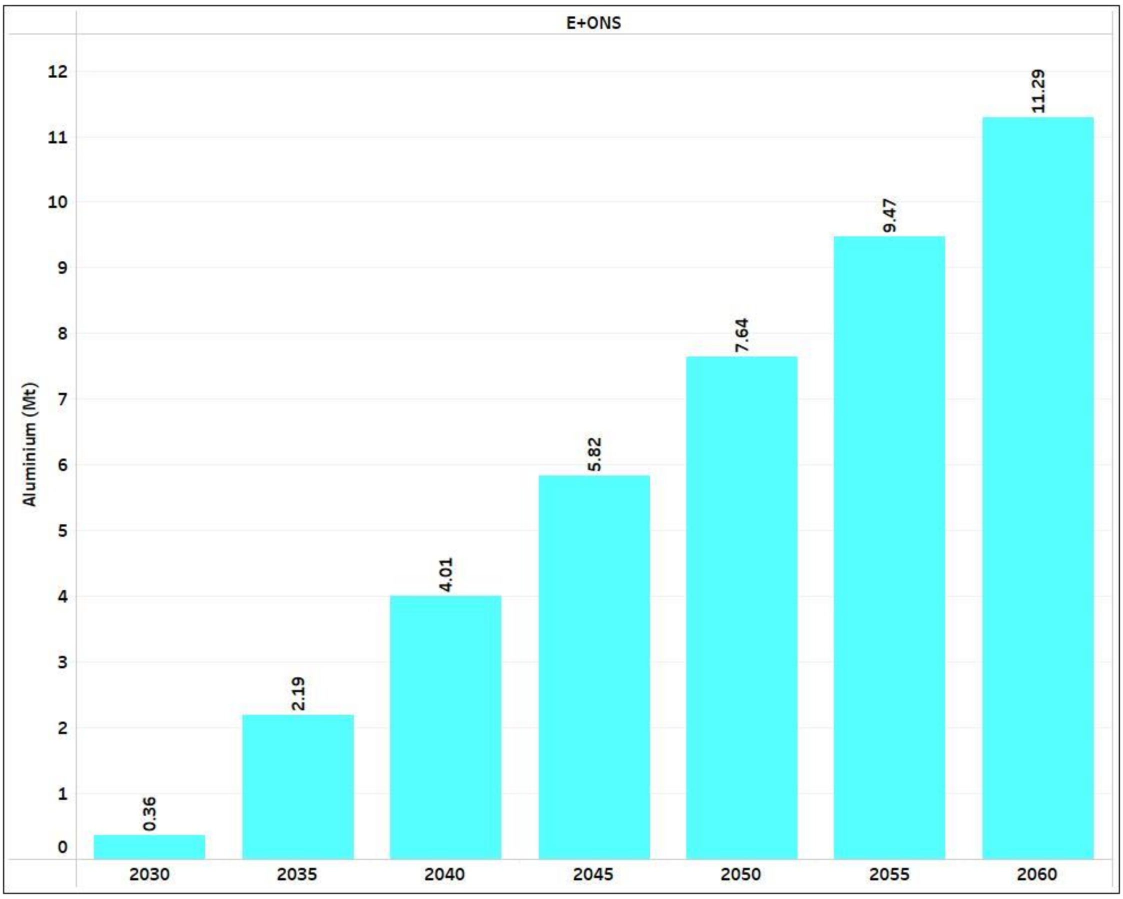
Facility	Location	Capacity (kta)			Existing footprint		Upgraded footprint
		Nameplate	Adjusted	Upgraded 2060	km^2	km^2/’000 ktpa	km^2
Overall	–	**21,020**	**20,772**	**25,750**	**57.0**	**2.55**	**68.8**
Kwinana	WA-south	1,870	18,47.9	2291	4.7034	2.37	6.12
Pinjarra	WA-south	4,700	46,44.6	5758	10.9959	2.77	15.38
Wagerup	WA-south	2,800	2,767	3430	7.6626	3.61	9.16
Worlsey	WA-south	4,600	4,545.7	5635	16.4161	1.53	15.05
Yarwun	QLD-south	3,100	3,063.4	3798	4.69	3.20	10.14
QAL	QLD-south	3,950	3,903.4	4838	12.4836	2.55	12.92

Red mud ponds don’t necessarily need to be located onsite with the alumina refineries. While some alumina refineries have onsite red mud ponds, others have them located up to 7 km away with the red mud transported via slurry pump.

4.2.2 Aluminium production

Figure 20 shows additional aluminium smelting that must be done in Australia to onshore the production of aluminium using 103Mt of bauxite. Note, Australia produces 1.57Mt of aluminium in 2020 and this Figure 22 doesn't include it.

Figure 20 | Production of aluminium (million ton)



Australia currently has four operational aluminium smelters. These facilities take alumina produced in the alumina refineries and convert it into metallic aluminium. This aluminium is mixed with alloys and cast into products fit for downstream manufacturing.

Aluminium smelters are comprised of three main operational areas; anode production; smelting; and casting. Anodes are carbon based and are consumed during the smelting process (releasing CO_2). As outlined in the MASS document[3], low carbon aluminium smelting involves the use of inert anodes. Thus, green smelters do not require onsite anode production facilities. The footprints of existing aluminium smelters were estimated *not* including the anode production facilities. An average of the normalised existing plant footprint was extrapolated to estimate the plant footprint required to achieve the production increases in the onshoring scenario. The current and future plant production capacities and footprints are detailed in Table 8.

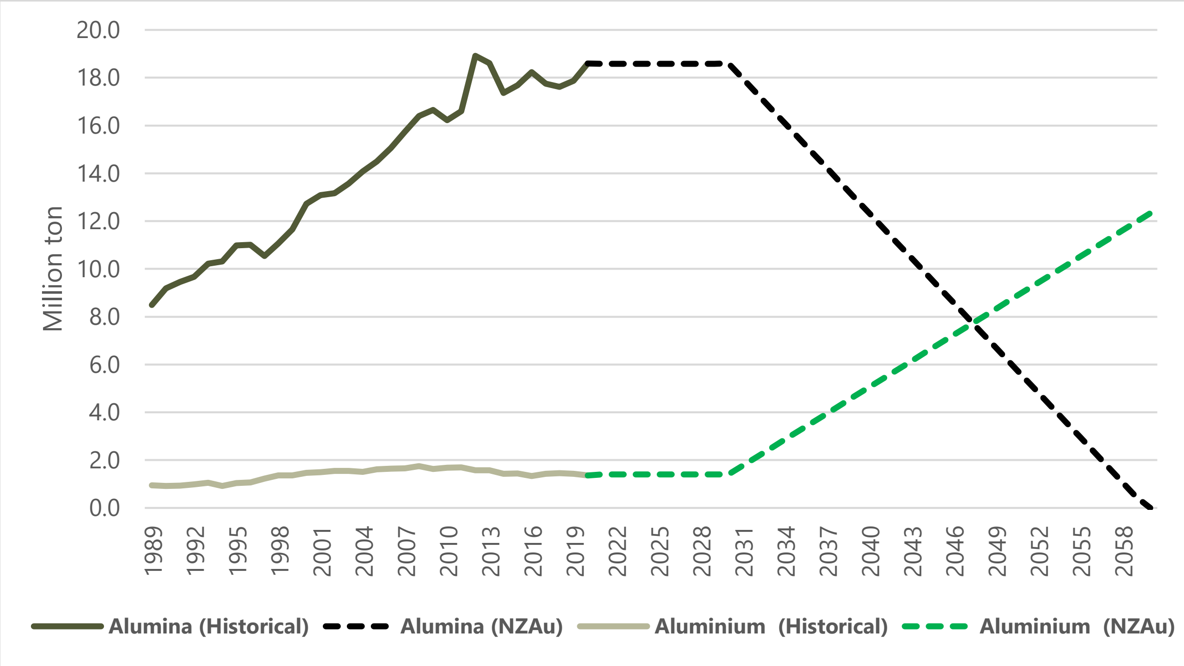
Table 8 | Aluminium smelters

Facility	Location	Capacity (kta)			Existing footprint		Upgraded footprint
		Nameplate	Adjusted	Upgraded 2060	km^2	km^2/'000 ktpa	km^2
Overall	–	1,640	1,579	1,2875	2.4689	1.41	20.76
Boyne	QLD-south	502	483.3	3,941	0.6824	1.48	6.35
Tomago	NSW-central	590	568.1	4,631	0.8432	1.81	7.47
portland	VIC-west	358	344.7	2,810	0.6249	1.74	4.53
Bell Bay	TAS	190	182.9	1,492	0.3184	1.61	2.41

The expansion of existing aluminium smelters is relatively simple as the plants are already designed as multiple parallel trains (referred to as potlines) which operate highly independently. The largest potline in the world is the Al Taweelah Potline 3 in Abu Dhabi, with a capacity just over 500 ktpa aluminium[18]. Multiple potlines of this scale can be added to existing smelters in NZAu to achieve desired production capacity.

Figure 21 uses historical data from Department of Industry [1] and combines it with NZAu onshoring scenario data to plot the change in production of aluminium and reduction in export of alumina. As we see, the production of aluminium starts to increase from 2030 and the export of alumina reduces linearly.

Figure 21 | Transition to onshoring aluminium



4.3 Energy avoided from onshoring aluminium

Onshoring aluminium by processing 103Mt of bauxite to produce 25.8Mt of alumina and smelting it to 12.8Mt of aluminium requires electricity and hydrogen as input. Noting, more than two third of bauxite is process into alumina in Australia in 2020, the Figure 27 reports the additional energy and hydrogen required to onshore the alumina exported in 2020. In 2060, 23.4PJ of hydrogen and 592.7PJ of electricity is used on onshoring aluminium. So doing, we avoid 1217PJ of energy abroad. The avoided energy is ammonia equivalent and accounts the loss in producing ammonia for export from Australia and then converting back to electricity and hydrogen to be used in smelter abroad.

Figure 22 | Energy required to onshore aluminium, and energy avoided abroad.

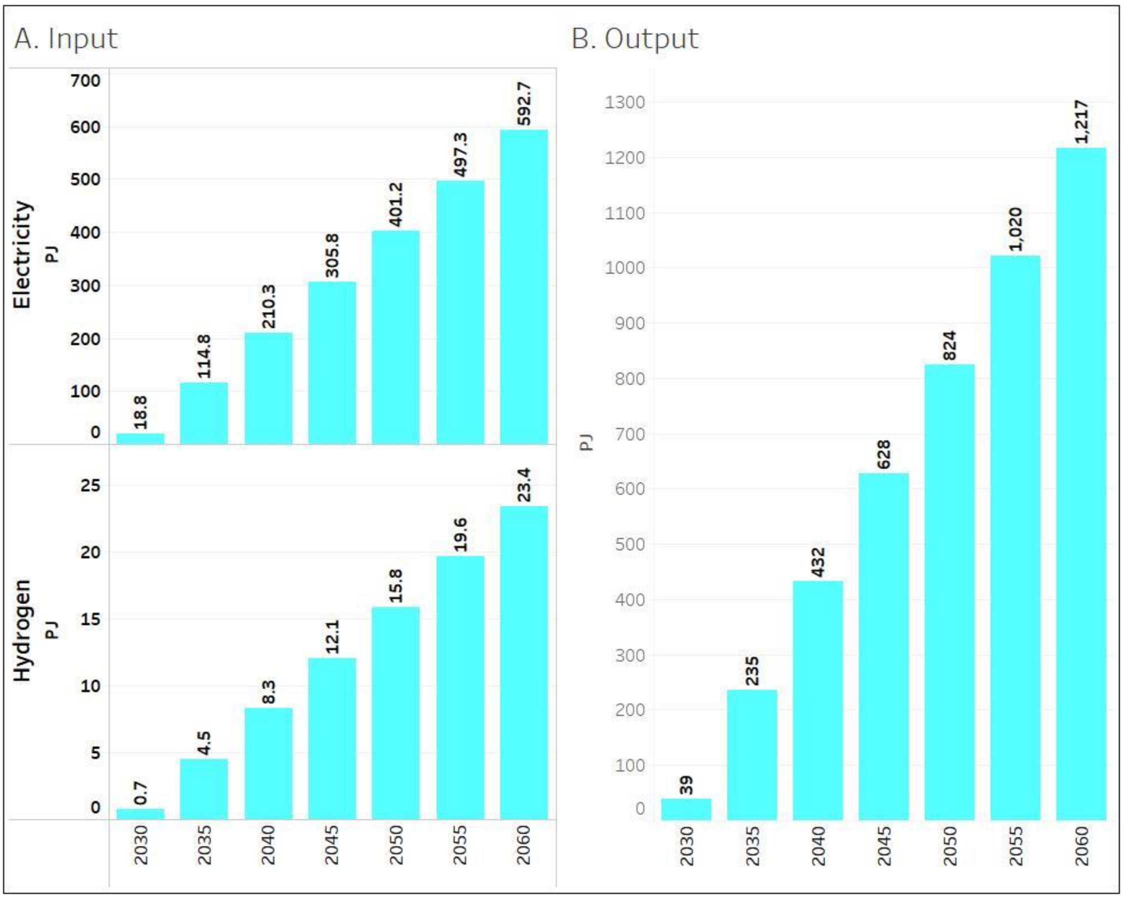


Figure 23 presents the quantity of hydrogen production required to smelt alumina in Australia and export for smelting in foreign countries. When alumina is smelted outside Australia. In 2060, 11.42 million ton of hydrogen has to be produced and exported as ammonia to smelt the 21.68Mt of alumina whereas smelting in Australia requires producing 0.165Mt of hydrogen. This indicate hydrogen production is 70X as compared to smelting in Australia. The reason for vast difference in hydrogen production is because most of the energy input in smelting is electricity, which can directly feed from VRE without needing to make hydrogen. However, for export it must be converted to and from ammonia. Australia must export 54.09Mt of ammonia to smelt the alumina.

Figure 23 | Hydrogen production required to smelt alumina in Australia

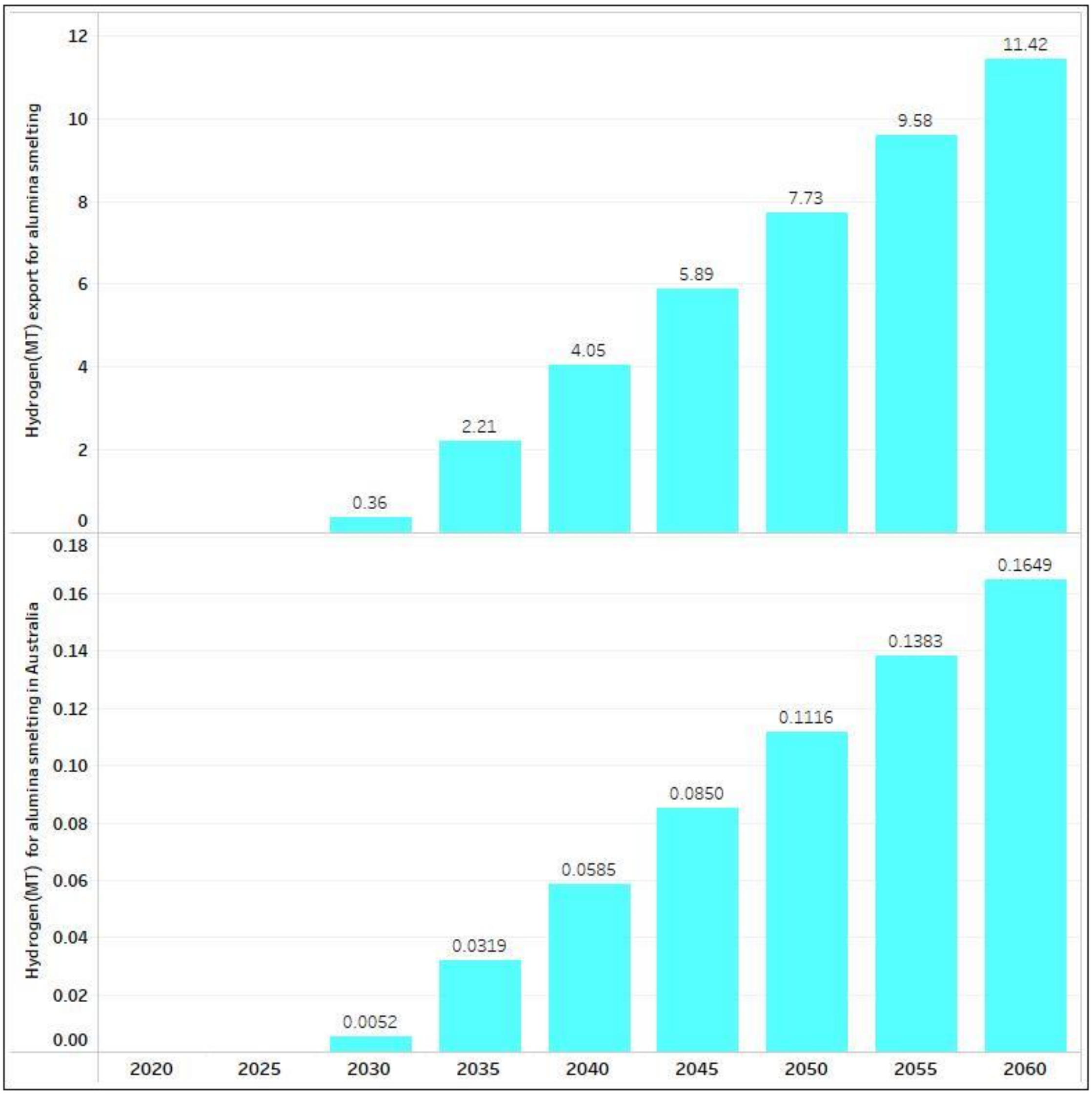
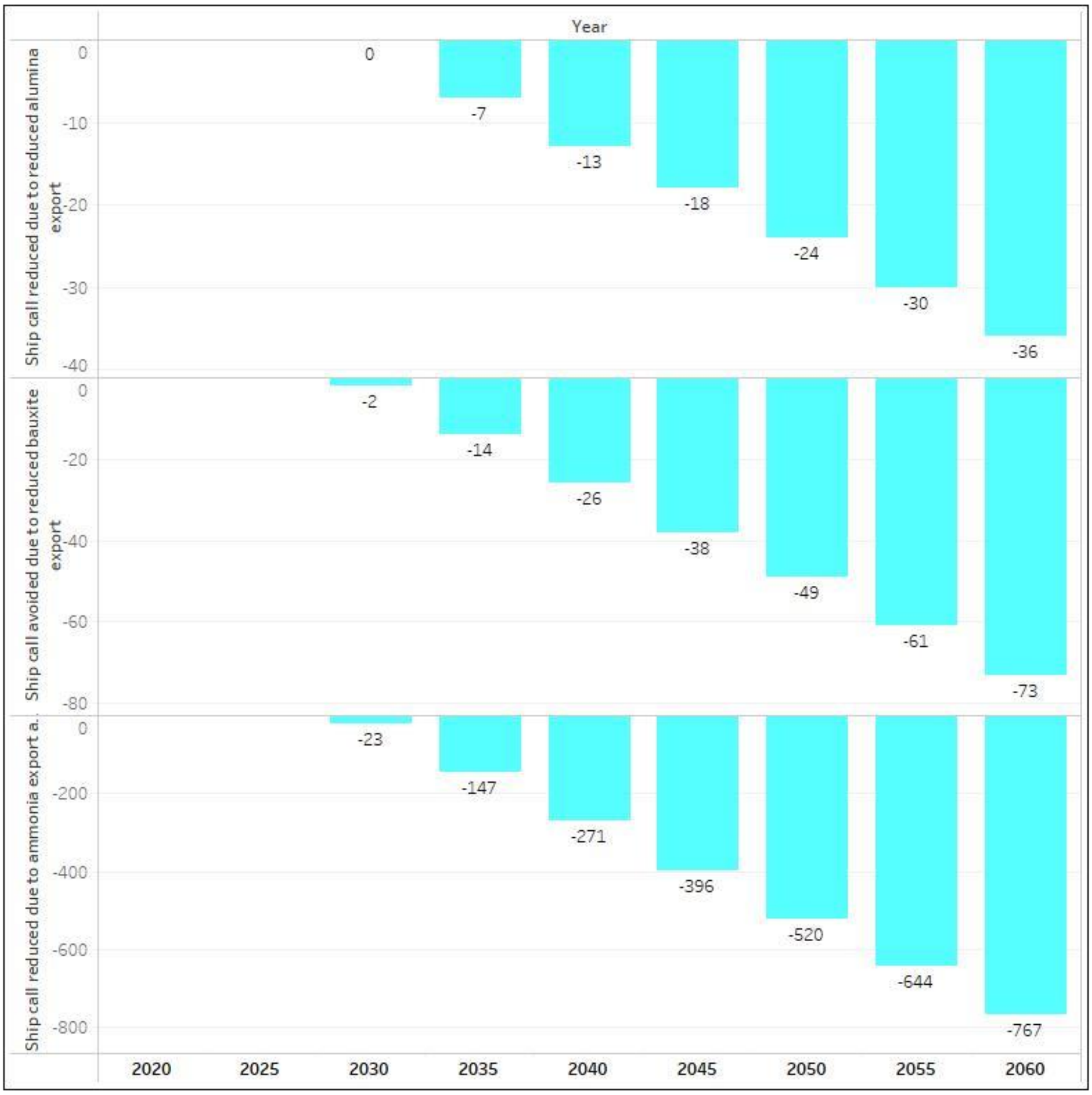


Figure 24 presents the total ship call avoided by onshoring aluminium in Australia. Onshoring aluminium reduces ship call by avoiding export of ~20Mt of bauxite, ~20Mt of alumina (but increases ~11Mt of aluminium) and avoiding ammonia export to smelt alumina. Total ship call saved due to reduced weight by onshoring aluminium in 2060 is 109. Note, the ship tonnage is same used for iron ore (27000ton).

Figure 24 | Ship call reduced and avoided due to reduced weight of alumina product and avoiding ammonia export for smelting abroad

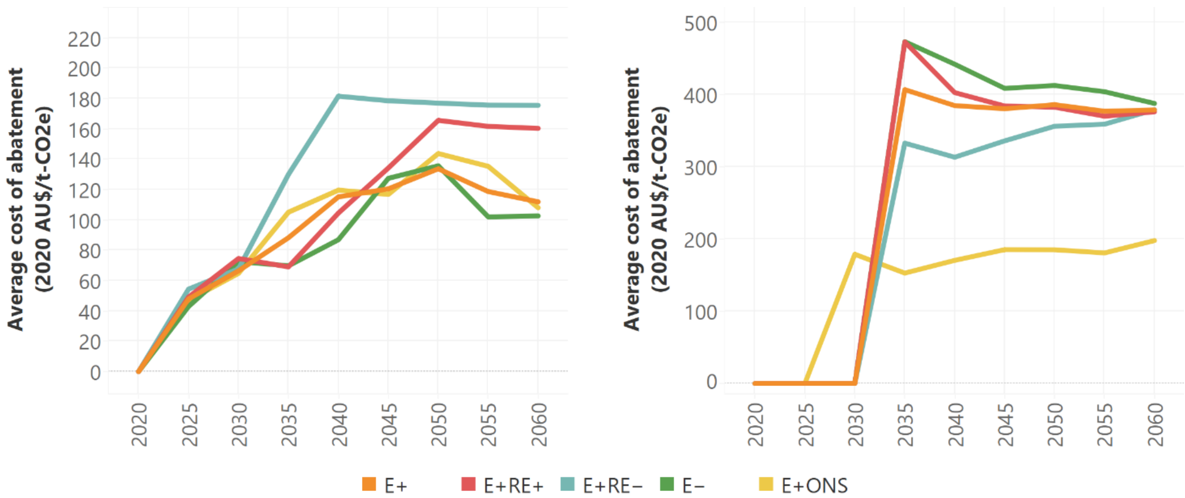


5 Costs of abatement

The average cost of GHG emissions abatement for the domestic and export energy systems is shown in Figure 25. This is this the net levelised cost in a year (relative to REF) per annual emissions saved in that year (relative to REF). The costs of domestic emissions abatement rise to ~\$150/t-CO_2e in 2050, which is a similar value to that found for other countries' net-zero decarbonisation studies (e.g. Net Zero America).

For the export system, average costs of abatement rise to >\$300/t-CO_2e from 2030, which reflects both the relatively high cost of the modelled clean energy export system, and the low cost of the current fossil fuel export system. Of particular note, the cost of abatement for the E+ONS onshoring Scenario is much lower than the other exports and comparable to domestic costs of abatement. This suggests that importing countries could save significant expense by importing Australian refined commodities, while achieving costs of emissions abatement that are comparable to Australia and the US, even if they are major energy importers. This also suggests that Australia may be in a strong position to pivot to clean non-energy commodity exports if other countries end up producing more of their energy domestically.

Figure 25 | Average costs of GHG emissions abatement for the (left) domestic, and (right) export energy systems.



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