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ENERGY CHANGE INSTITUTE

## ZERO-CARBON STEEL MAKING:

The opportunities and role of Australia  
in nurturing a 'green steel' industry

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## 1. Introduction

Steel is arguably the most important structural material used in society, especially in those countries undergoing rapid development. There is a strong correlation between a country’s economic development and its cumulative metal consumption. Zheng et al. [1], for example, find that a country’s ‘metal footprint’ (in tonnes per capita) tends to increase by 1.9% for every 1% increase in gross domestic product (GDP) per capita. The global production of crude steel has increased steadily on an average by 1.8% in the last five years. In 2018, it reached an astounding 1,808 million tonnes [2], with most of the growth in demand occurring in developing countries such as India and China [1, 3].

There is a very high environmental cost associated with traditional steelmaking at the present scale. The greenhouse gas (GHG) emissions from steelmaking account for ~9% of the total global fossil and industrial emissions (assuming 1.8 tonnes of CO<sub>2</sub> per tonne of crude steel, tCO<sub>2</sub>/tCS [2]). Although there have been significant ongoing efforts to reduce the GHG emissions from steelmaking over the last several decades, major technological breakthroughs are certainly still required if the sector is to keep up with the across-the-board emissions reductions needed under the Paris Agreement [4]<sup>1</sup>, which aims to limit the global temperature rise at the turn of this century to well below 2°C above pre-industrial levels, and states that efforts should be directed towards a more ambitious target of only 1.5°C of temperature rise.

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<sup>1</sup>It should be noted that the 2°C target may not be sufficient for subverting catastrophic and irreversible effects of climate change. The impacts of climate change at 1.5 vs 2°C are enormous (<https://is.gd/MRuxMn>) and it is increasingly being accepted that the global climate action should be aimed at achieving the more challenging target.

In line with the Paris Agreement, the global net cumulative emissions<sup>2</sup> from the years 2015–2100 should not exceed a total ‘budget’ of 510 GtC (1,978 GtCO<sub>2</sub>-e) [5]. At the current emissions level, this would imply that the total carbon budget until 2100 would be exhausted by the year 2054 and all technologies would need to be completely decarbonised beyond that. Of course, in reality this transition would be gradual and may even be achieved for some sectors, such as electricity and most land transport, probably earlier than 2054. However, the transition for industrial emissions will be more challenging and costly, and the process is likely to take longer either due to technical feasibility/reliability, or due to long-run infrastructure lock-ins [6, 7].

Current estimates of future steel demand vary widely with projected annual growth rate between 1.4% [8] and 3.3% [9, 10], resulting in a projected demand as high as 2.4 billion tonnes by 2025. Partial decarbonisation of this growing steel industry could be achieved through efficiency improvements and the integration of renewable electricity in conventional steelmaking routes, whereas, complete decarbonisation would require new zero-carbon and/or negative emissions technologies. However, attempts to decarbonise the steel production processes have not seen any large-scale industrial adoption, despite substantial on-going research efforts [11]. The feasibility and applicability of carbon capture and storage in the context of steel-making remain highly questionable [12, 13]. Therefore, advancing renewably powered, low- or zero-carbon steel technologies and investment deserves special emphasis and investigation.

In the context of reducing emissions in the steel industry, what then could be the role of a country like Australia which is well endowed with both mineral and renewable resources? Currently, Australia is the largest exporter of iron-ore and metallurgical coal [2], and its exported iron ore accounts for around one-third of the global steel production. In the past, Australia has not been able to capture any significant share of the value of the steel made from its iron ore. However, the envisaged future for green steel presents an opportunity to nurture a new industry and lead this renewable transformation. Australia’s international competitiveness in this potential new industry will rely on its low-cost clean (zero-carbon) energy, high quality ore and skilled labour. Australia is well positioned to attract, absorb or create technological innovation due to its knowledge stock and competitive markets. If Australia is to realise its natural comparative advantage, long-sighted and high-quality environmental and industrial policies will be crucial. In this report, two important aspects of reducing carbon emissions in the steel industry are presented: firstly, answering the question of whether breakthrough zero-carbon technologies are required to align ourselves with the IEA B2DS emission targets for the steel industry, and secondly, what role can Australia potentially play in leading this industrial transformation.

## 2. Current iron and steel making technologies

The earliest steel production can be dated back to ancient Iran, China, India, Greece and Rome, where the steel was made in a primitive furnace called bloomery. Until the 18th Century, steel was

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<sup>2</sup>including emission due to Agriculture, Forestry and Other Land Use (AFOLU)

mostly produced in small quantities. The industrial revolution marked the advent of large-scale steel production, and the development of Bessemer process and open-hearth furnaces have revolutionised the steelmaking industry [14].

The modern processes for producing virgin crude steel consists of several stages — reduction of iron ore to iron, removal of carbon and other impurities, secondary refining and alloying, and continuous casting. There are several fossil-based variants through which these steps can be achieved in present day commercial processes, most notably,

- the blast-furnace (BF) route followed by a basic oxygen furnace, in which the ore is reduced to molten metallic iron using a form of processes coal called coke and then the impurities are removed in a controlled oxidising atmosphere in a basic oxygen furnace (BOF)<sup>3</sup>.
- the direct reduced iron (DRI) route, wherein solid-state reduction of the iron ore is performed in a shaft furnace (eg. MIDREX, HYL, Energiron etc.), rotary kiln (eg. Krupp-Codir), rotary hearth furnace (eg. FASTMET) or a fluidised bed (eg. FINMET), followed by reduction in an electric arc furnace (EAF). DRI can be produced using coal or natural gas, the latter of which implies lower emissions compared to coal-based DRI.
- the smelting reduction route (eg. COREX) which has relatively lower carbon consumption compared to the blast furnaces. The smelting reductions routes are advantageous because they use non-coking coal and eliminate the need for a coking plant. However, the use of pure oxygen increases the total energy requirement. The molten metallic iron is further processed using a BOF.

In addition to the aforementioned ‘virgin’ steel manufacturing routes, steel can also be produced through the recycling of scrap. Scrap recycling, either in a standalone EAF process, or as an addition to BOF or EAF stages of other processes is possible and accounts for 27% of global steel production [2]. Although some have argued that the global projected growth in steel demand could be completely catered for by recycling [15], it is highly questionable whether or not the steel quality requirements can be met solely from recycled steel in the long run [16]. This is primarily due to the presence of contaminated ‘tramp elements’ such as copper and tin in the recycled steel which cause ‘hot-shortness’ or surface cracking during the hot-rolling process. Consequently, the large-scale use of recycled steel is confined to certain applications such as reinforcing bars for the building industry, where the steel requirements are less critical.

A secondary constraint on steel recycling is the availability of scrap, especially in regions where there has been sustained economic growth [16]. In these regions, scrap availability will limit the recycling to below ~60% of the total steel demand through until 2030 [17]. In fact, several studies have found

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<sup>3</sup>Basic Oxygen Furnace (BOF) route is also called the Basic Oxygen Process (BOP) or Basic Oxygen Steelmaking (BOS) and all of these are commercial variants of the Linz-Donawitz-steelmaking process (LD-process) named after the Austrian towns of Linz and Donawitz where the process was commercialised by VOEST and ÖAMG in 1952–1953.

<sup>3</sup>Copper contaminant in the steel scrap can come from several sources such as wiring in vehicles, appliances and equipment, copper-alloyed steel engine blocks, wiring entangles with fragmented steel scrap and winding in steel-encased motors.

this claim to be too optimistic, arguing that disparity in the location of scrap generation and steel production, together with copper contamination may constrain recycled steel production to only  $\sim 30\%$  of the global demand [9, 18, 19]. Even with careful management of copper-rich scrap on a global scale, recycled steel-quality requirements can only be met up to 2050. The expected demand for copper-tolerant applications (e.g. reinforcement steel) is likely to grow more slowly compared to that of higher-quality steels (e.g. cars and white-panel goods), suggesting eventual accumulation of unusable steel scrap [16].

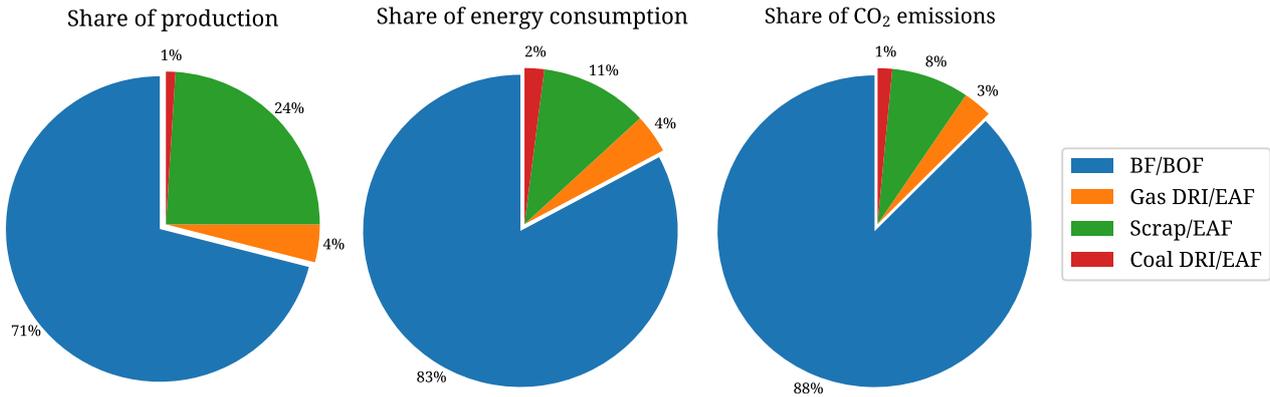


Figure 1: Share of (a) production, (b) energy consumption and (c) CO<sub>2</sub> emissions from different steel making routes [20].

Figure 1 shows (a) the current share of steel production through different technologies, (b) the energy consumption in different routes and (c) the CO<sub>2</sub>-emissions associated with each route. As evident from the figure, BF-BOF has the largest share in production and a disproportionately large CO<sub>2</sub>-emissions profile. With the projected increase in worldwide steel demand, these emissions are also expected to proportionally increase, unless major technological changes take place in the steel sector [9, 21]. These changes could be in the form of new alloy development with higher strength-to-weight ratio, improving material usage during fabrication (e.g. near-net shaped casting), or moving to new low- or zero-carbon steel making routes.

In the conventional BF–BOF route, carbon (in the form of coke and coal) is used to drive the endothermic reduction reaction as well as for providing the high temperatures required. A typical BF/BOF process produces 1.6–2.2 tCO<sub>2</sub>/tCS (tonnes of CO<sub>2</sub> per tonne of crude steel) [22]. Significant regional differences in steel-related emission exists, with India and China having much higher CO<sub>2</sub>-emissions footprint compared to the OECD countries. There are also significant differences between different steelmaking routes such as BF-BOF, DRI-EAF and scrap-EAF [23]. Through technological improvements, steel plants have steadily reduced their fuel consumption rate over the last five decades [11] to the point that the BF-BOF route can now be considered to be largely optimised; the most efficient blast furnaces in the world can operate within  $\sim 5\%$  above the theoretical minimum in terms of their CO<sub>2</sub>-emissions [24–26].

### 3. Technologies for reducing the carbon footprint of the steel industry

The second half of the 20<sup>th</sup> century saw a surge in technological innovations to reduce the carbon footprint of the BF-BOF steelmaking route. These included the use of non-coking coal smelting (COREX,  $\sim 20\%$  reduction in CO<sub>2</sub>-emissions versus BF-BOF), direct reduction of iron-ore using either non-coking coal or natural gas (MIDREX, MIDREX-NG, MX-COAL, HYL/Energiron, ITmk3 etc., up to  $\sim 40\%$  emissions reduction in the iron making stage), and other efficiency improvement measures. Direct reduced iron (DRI), in particular, now makes up 5.5% [2] of global steel production. In 2004, under the Ultra-Low CO<sub>2</sub> Steelmaking (ULCOS) initiative, a consortium of 48 European companies and organisations from 15 countries was formed with the aim of reducing the embodied emissions in steel by at least 50% compared to the best available technology. The ULCOS initiative identified several pathways including renewably-powered electric arc furnaces (EAF), incremental efficiency improvements using top-gas recovery turbines (TRT), new thermochemical processes such as “ultra low CO<sub>2</sub> direct reduction” (ULCORED), cyclone converter reactor (HIsarna, up to 80% emission reduction if coupled with CCS), H<sub>2</sub>-based DRI, and electrowinning [11]. It should be noted that, except for the H<sub>2</sub>-DRI and electrowinning routes, these other processes provide low-carbon pathways for steel making, however they do not completely eliminate the associated emissions [9].

Any technology with the potential to completely decarbonise the steel manufacturing process would need to either utilise alternative reducing agent to coal, for instance, charcoal (biomass-derived carbon)<sup>4</sup>, hydrogen and electricity, or else use a closed-loop carbon cycle<sup>5</sup>. Charcoal was used in steelmaking up until the 19th century, and still continues as a partial substitute for coal in some countries, notably Brazil [9]. The Australian Steel Industry CO<sub>2</sub> Breakthrough Program (2006) [27] found that there is enough biomass available to allow biomass-fuelled steelmaking in Australia, where annual steel production is 5.3 Mt/y [2]. However, Australia is exceptional in its ratio of arable land to population, so given the high global volumes of steel production, this route may not be globally scalable and will likely remain unsustainable as a long-term primary alternative [28]. To put this in perspective, the land required to cater to the current world BF-steel production would be of 1.7 million square kilometers (based on numbers from [29]). The magnitude of land-use change emissions due to this, would far outweigh the avoided fossil fuel emissions [9, 29, 30]. In addition, the economics of biomass-based steelmaking are currently highly unfavourable and would require high CO<sub>2</sub>-emission allowance prices to be competitive [31]. For this reason, we will exclude charcoal as a potential replacement for coal in our discussion.

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<sup>4</sup>Charcoal-based steelmaking emits CO<sub>2</sub>, but this carbon is biogenic, having been extracted from the atmosphere by plants. It can be considered carbon-neutral, if the associated land-use change impacts are negligible.

<sup>5</sup>Closed-loop carbon-based steelmaking can potentially be C-neutral. An example would be HIsarna+CCS coupled with CO<sub>2</sub>-splitting and then recycling the carbon for reducing iron-ore. Several technological challenges in this route are still to be resolved.

### 3.1. Hydrogen-based steelmaking

Hydrogen-based reduction of iron-ore has been seen as the holy grail for carbon-free steel technologies for several decades. In hydrogen-based reduction, the iron ore is reduced via a gas-solid reaction, similar to the DRI routes. The only differentiating factor is that the reducing agent is pure hydrogen instead of CO, syngas or coke. Although commercial-scale reactors for this technology do not currently exist, there was a large-scale prototype plant built in Trinidad in 1999 using Circored technology with fluidised bed reactors fuelled with hydrogen from steam methane reforming, which failed for combination of technical challenges and commercial factors. More recent efforts have been dedicated to development of hydrogen-fuelled shaft reactors similar to those in the MIDREX or HYL-III processes. HYBRIT, short for HYdrogen BReakthrough Ironmaking Technology, a joint venture between three Swedish companies — SSAB, LKAB and Vattenfall — aims to completely eliminate carbon from steelmaking, using H<sub>2</sub>-reduction. The construction of a pilot scale demonstration started in 2018 with expected completion in 2021 [32].

The world's largest steel company, Arcelor-Mittal, aims to reach carbon-neutrality by 2050 and has recently announced its plans for demonstrating a 100,000 t/y pilot plant in Hamburg [33]. The process will separate out the H<sub>2</sub> from the top-gas of their existing DRI plant using pressure-swing adsorption (to remove CO<sub>2</sub> from the top-gas) and then subsequently use it in a new pilot-scale shaft furnace using H<sub>2</sub> reduction. Other European steelmakers including Thyssenkrupp and Voestalpine have also announced plans to develop processes for renewable H<sub>2</sub>-based steelmaking routes [34–36]

As with conventional DRI steelmaking, the iron produced using H<sub>2</sub>-based DRI route can be further processed into steel using commercially available electric arc furnace (EAF) technology. The H<sub>2</sub>-production and EAF steelmaking steps can be made carbon-free if the electricity and hydrogen are produced using renewable sources such as PV/wind/hydro-powered electrolysis, photochemical H<sub>2</sub> production or solar-thermal water splitting. This integrated pathway is also being studied by SALCOS (Salzgitter Steelworks and Fraunhofer Institute), building upon GrInHy (a technology to produce Green Industrial Hydrogen through electrolysis) [37]. The CO<sub>2</sub>-emission mitigation under 55% and 100% H<sub>2</sub>-supply could be as high as 82% and 95%, respectively, compared to a reference blast furnace (BF-BOF) process. However, the cost of steel production using H<sub>2</sub>-reduction is estimated to be 20–30% higher than that of a reference greenfield BF-BOF plant [32]. The H<sub>2</sub>-DRI steelmaking, although the most promising green steelmaking route, is still very much in the development stage, with large-scale commercial deployment anticipated around 2030 [32]. Identifying the kinetics of iron reduction using H<sub>2</sub> as reducing agent and designing the H-DR reactor at a large scale are the major technical challenges. Moreover, the future development of this technology heavily depends on the availability of cheap and renewable-H<sub>2</sub>.

### 3.2. Electrolytic production of iron

Electrowinning is one of the oldest electrolytic techniques used for extraction of metals from their ores using electricity. The most common electrowon metals include lead, copper and rare-earth elements. There are some commercially-available ore-specific electrowinning technologies for iron:

the Boucher process, electrorefining in  $\text{FeSO}_4\text{-FeCl}_2$  solution; the Eustis process, electrowinning in  $\text{FeCl}_2$  solution using iron sulfide ore; and the Pyror process, electrowinning in  $\text{FeSO}_4$  solution using iron sulfide ore. However, the more generally applicable electrowinning of Fe from iron-ore has only been demonstrated at a laboratory scale [38]. Depending on the carbon footprint of the electricity mix used for electrolysis, this route can be potentially carbon free. In a futuristic scenario, in which the world’s primary energy supply is dominated by renewable sources, this technology offers significant carbon reduction potential. The current European SIDERWIN initiative [39]—a project under the Horizon 2020 framework with a target of  $\text{CO}_2$  emissions and energy consumption reduction of 87% and 31% (cf. BF-BOF), respectively—aims to validate this technology at the pilot scale, and demonstrate a technology readiness level (TRL) of 6 by 2022.

Another electrolytic route which has recently received interest for steelmaking is the molten oxide electrolysis of iron ore (also known as pyro-electrolysis). The process is similar to the standard method for the reduction of aluminium from alumina ( $\text{Al}_2\text{O}_3$ ) through the Hall–Héroult process, in which  $\text{Al}_2\text{O}_3$  is dissolved in a  $800^\circ\text{C}$  bath of molten cryolite (aluminium sodium fluoride) and then electrolysed between anodes of graphite (above) and a cathode of molten aluminium (below). The operation of a similar process for iron ore reduction at very high temperatures is expected to yield a potential decrease in energy consumption compared to the low-temperature electrolysis routes. Proofs-of-concept have been demonstrated, but the technical feasibility with acceptable efficiencies is still elusive. Challenges include the corrosivity of molten electrolytes, lack of suitable anode materials, and limited mechanistic understanding of very high temperature electrolytic processes [40]. Although steel production by molten oxide electrolysis offers potential economic and environmental advantages over classic extractive metallurgy, its feasibility is far from being convincingly demonstrated as an immediate zero-carbon alternative.

Fischedick et al. [41] compared the energy requirement and  $\text{CO}_2$ -emissions from four different steel production routes, namely, BF-BOF reference case, BF-BOF with carbon capture (BF-CCS),  $\text{H}_2$ -DRI and electrowinning (EW). The electrowinning pathway had an energy requirement 50% lower than the reference BF-BOF case, followed by  $\text{H}_2$ -DRI and BF-CCS at 28% and 13% lower energy requirements respectively. Importantly, the analysis also concludes that >50% reduction in  $\text{CO}_2$ -emissions is not possible through the BF-CCS route, whereas, both  $\text{H}_2$ -reduction and EW routes can eventually lead to complete decarbonisation of the steel sector. Although, the market entries for  $\text{H}_2$ -DRI and EW are not expected until 2035 [32] and 2040 [41, 42] respectively.

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<sup>5</sup>It should be noted that the lower energy requirement for the BF-CCS case is due to the implementation of top-gas recycling (TGR) which outweighs the additional energy required for CCS

<sup>5</sup>Even with the  $\text{H}_2$  reduction process, there could a small amount of  $\text{CO}_2$  emitted. Currently, lime is used as a fluxing agent for removing oxide-based impurities from the hot-metal. Lime ( $\text{CaO}$ ) is produced by calcining calcium carbonate ( $\text{CaCO}_3$ ) which leads to  $\text{CO}_2$ -emissions.

## 4. Is zero-carbon steelmaking really necessary?

The urgency required to decarbonise the iron and steel industry is quite clear [43, 44]. The IEA has suggested a long-term CO<sub>2</sub>-emissions target for different sectors and industries, accounting for the global carbon budget associated with at least a 50% chance of limiting the global warming by <2°C (2DS scenario) and 1.75°C (B2DS scenario) by 2100, compared to the pre-industrial levels [43, 43]. It is important to understand what technologies can have the (theoretical) potential to align with the CO<sub>2</sub>-emissions target set by the IEA for iron and steel industry.

To answer the question of whether new breakthrough technological intervention is required in the context of steelmaking to align ourselves with the IEA B2DS scenario, we analysed the carbon emissions from the steel industry on a global scale and evaluated five scenarios with different mix of the aforementioned technologies. Our analysis takes into account the anticipated demand growth until 2060, carbon footprints of existing and new research-stage technologies, the anticipated commercial deployment of new technologies, scrap availability and recycling limits, optimistic deployment of best-available-technologies, gradual phasing-out of C-intensive routes, and integration of carbon capture and storage (CCS) in existing plants. The scenarios evaluate the yearly and cumulative C-emissions from business-as-usual (BAU), best available technology (BAT), BAT with integrated CCS and increased recycling (CCS+Recyc), limited deployment of low-carbon (HIsarna) and zero-carbon (H<sub>2</sub>-DRI and EW) technologies (Low-C) with maximum recycling, and complete decarbonisation wherein all carbon-based steelmaking routes are completely phased-out culminating in only zero-carbon technologies being used for steel production (Zero-C). Each scenario builds on the previous one with further reductions in the CO<sub>2</sub>-emissions possibilities. Figure 2 shows the assumed installed capacities of different technologies in each year from 2017–2060 for different scenarios. The common assumptions for all the scenarios include that (a) there are no legal barriers to large-scale deployment or capacity reduction for any of the existing and new technologies, (b) substantial progress in R&D and its application is achieved worldwide, and is coupled with favourable incentives that are sufficient to ensure cost-effectiveness of new technologies, (c) the availability of scrap is not limited by the disparity between the site of scrap generation and steel production.

The steel demand growth projections from various sources do not show a clear consensus; some estimates predict an increase in demand to ~2.5 billion tonne by 2050 [45], whereas others predict a much higher growth rate leading to a demand of ~4.5 billion tonnes in 2050 [46]. In our analysis, we have assumed a steel demand profile, for each year during our analysis period, to accommodate these two extremes. This is also consistent with the two demand stagnation scenarios (2050 and 2100) evaluated by Morfeldt et al. [47]. The CO<sub>2</sub>-emissions trajectory was calculated for each of the five aforementioned scenarios, as shown in Figure 3(a). The BAU scenario emissions, as expected, followed the same trend as the steel demand and shows a 40% increase in steel sector GHG-emissions by 2060. The BAT scenario, wherein all the best available emissions reduction measures/possibilities are exhausted by 2050, shows a slight initial increase in CO<sub>2</sub>-emissions until 2030, followed by a decrease until 2050 and finally a slight increase until 2060. This can be attributed to two reasons, (a) in the initial years the steel demand increase offsets any decrease in CO<sub>2</sub>-intensity per tCS, but as

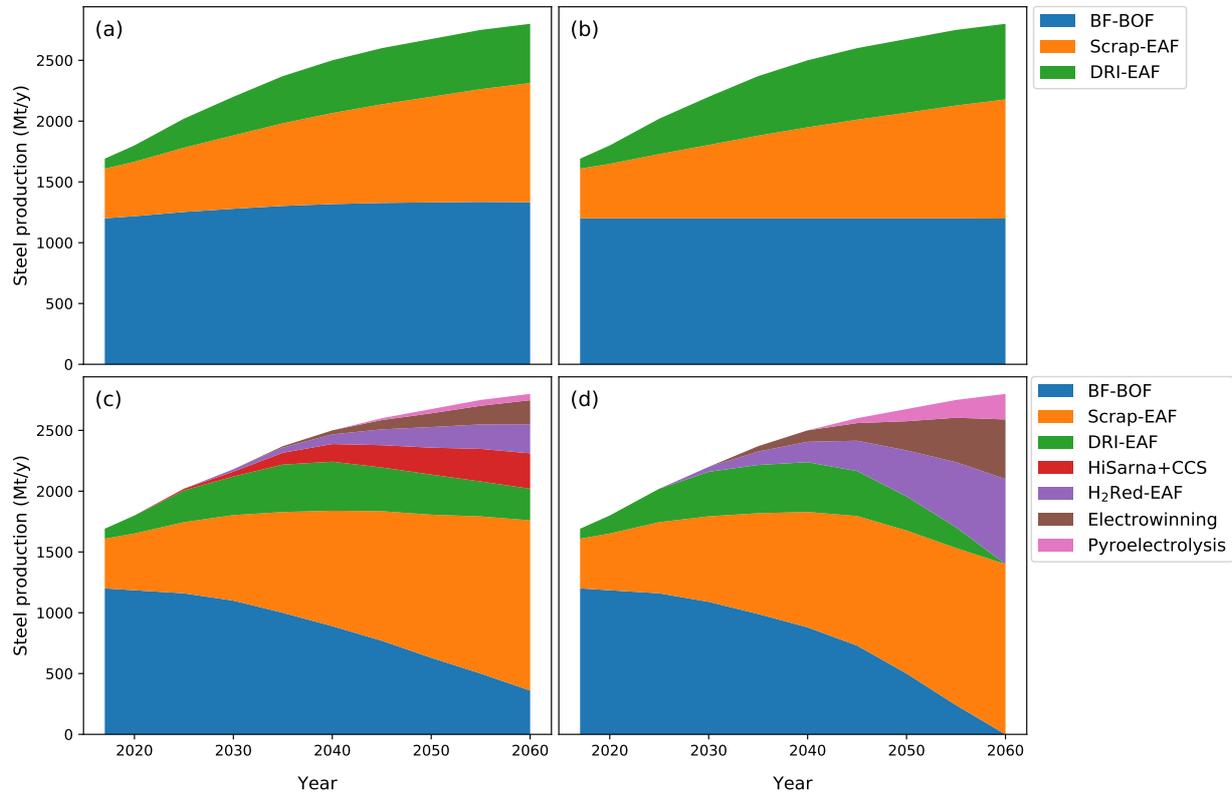


Figure 2: Assumed installed capacities of different technologies in each year from 2017–2060. (a) Business-as-usual (BAU), (b) Best-available-technology (BAT) and BAT+CCS, (c) Limited deployment of low- and zero-carbon technologies and maximum recycling, (d) Zero-carbon scenario.

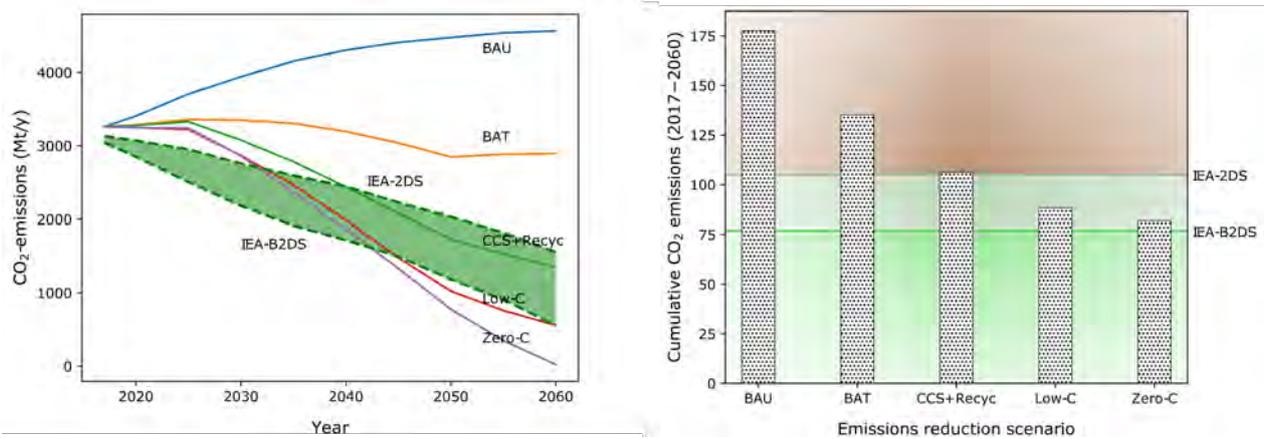


Figure 3: Yearly and cumulative carbon emissions between 2017–2060 under different scenarios compared with the IEA-2DS and IEA-B2DS targets.

steel demand growth slows down in later years, leading to a decrease in the average CO<sub>2</sub>-intensity of the entire industry, and (b) the new capacity built is assumed to be built through DRI-EAF which again brings down the average CO<sub>2</sub>-intensity across the industry. The BAU and BAT scenarios are well over the emissions trajectory for the IEA-2DS goals. In the CCS+Recyc scenario, the emissions increase slightly until 2025, driven by steel demand, and thereafter show a rapid decline until 2050 due to the simultaneous implementation of industry-wide CCS, increased steel recycling and the assumed decarbonisation of the electricity market. The emissions reduction rate slows down in the final 10 years, as the CO<sub>2</sub>-intensity reduction driven by CCS is exhausted. The emissions at the end of the analysis period, under this scenario, are below the 2DS-target for 2060 but well above the B2DS targets.

In the low-C and zero-C scenarios, increased penetration of renewables, decarbonised electricity market, industry-wide CCS-implementation in remaining fossil-based plants etc. rapidly decrease the emissions between 2030 and 2060. Both scenarios end up below the B2DS targets around 2045, however, the low-C scenario overshoots the B2DS target in 2060 (and later years, based on the trajectories).

Figure 3(b) shows the cumulative carbon-emissions for 2017–2060, for the global steel sector in each of the scenarios. As has been discussed earlier, the cumulative emissions should also be considered while evaluating the CO<sub>2</sub>-mitigation strategies. The total GHG-budget for the period from 2017–2060, under the 2DS and B2DS scenarios, can be obtained from the integration of their respective target C-trajectories. It is evident that even with the most optimistic scenario wherein the zero-C technology deployment is fast-tracked, the B2DS carbon budget targets cannot be met. Although, the analysis has been limited to 2060 only, the zero-net emissions from the industry in the years beyond 2060, will be sufficient to remain under the total GHG-budget until 2100. ***It should be emphasised that, amongst the analysed scenario, the zero-carbon pathway is the only one which has a realistic chance of achieving the B2DS targets.***

## 5. Australia's role in the zero-carbon steelmaking transition

Australian export of iron ore accounts for roughly half of the global iron ore trade and is the raw-material input to around one-third of the global annual steel production (worth more than 1.5 trillion AUD). However, Australia does not currently capture any significant share of the value of steel made from its iron ore. Figure 4(a) shows the historical production, direct import and direct export of crude steel in Australia. Despite being (by far) the biggest exporter of iron ore and metallurgical coal — essential raw materials for steel making — Australia's steel industry has been in steady decline. In fact, in the recent years, the direct imports have accounted for up to one-third of the total domestic crude steel consumption in Australia, and the steel exports only limited to certain niche products and applications. Figure 4(b) shows that close to 72% of the Australian crude steel is made using the highly C-intensive BF-BOF route whereas scrap-recycling using EAFs accounting for the rest.

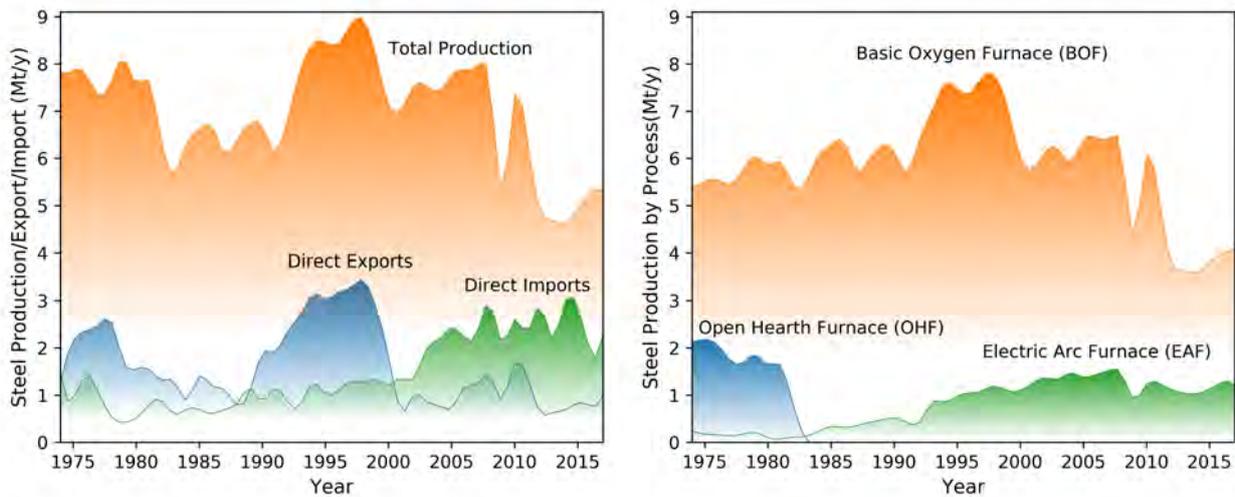


Figure 4: (a) Historical data on Australia’s production, export and import of steel products. (b) Proportion of different steel production routes used in the Australian steel manufacturing [48].

Despite being tiny compared to the global market, or indeed its own iron ore exports, the current Australian the iron and steel industry has substantial economic and environmental impacts for the country. The resultant emissions from primary steel making were 7% of the total GHG-e emissions in Australia in 2017–2018 (including Land Use, Land Use Change and Forestry (LULUCF)) [49]. Including all the small, medium and large scale production, manufacturing and fabrication entities, the industry employs over 100,000 workers, with an annual turnover of AUD 44.4 billion.<sup>6</sup> Crude steel production alone has a turnover of ~13.6 billion AUD and employment of ~22,300 personnel [51]. Using the Australian Steel Institute’s estimates [52], the value-add by virtue of steel production is quite high; for every AUD 1 million worth of steel produced, 1.87 million AUD is added to the economy, 165,000 AUD is delivered in welfare savings and 590,300 is returned in tax revenue.

It is important to understand that GHG-emissions reduction strategies tailored to the European or Chinese steel industries may not be the best fit for Australia’s needs, partly because of the location, type of ore, availability of renewable resources, government policy regulations, size and industry best practices in different countries. The following section is aimed at highlighting the current initiatives in Australian steel industry for reducing their carbon footprint and the shortcomings in these approaches, pathways for claiming the first-mover’s advantage in green steel manufacturing, Australia’s resource advantage and identifying the economic, policy and other key drivers for achieving this transition.

### 5.1. Australian initiatives for reducing emissions in the steel industry

Australia has been at the cutting edge of the CO<sub>2</sub>-Breakthrough Program [53], an initiative to exchange information on regional activities all over the world. Some of the key research and technology

<sup>6</sup>Integrated steel plants (ISPs) are operational in Port Kembla, NSW (BlueScope Steel) and Whyalla, SA (Liberty Primary Steel Whyalla Steelworks), whereas scrap recycling through EAF is primarily located in Rooty Hill and Waratah, NSW and Laverton, VIC [50].

integration initiatives in Australia are summarised below:

- *Dry Slag Granulation (DSG)* – The blast furnace process produces  $\sim 300$  kg of molten slag per ton of pig iron at  $1500^{\circ}\text{C}$ , which is conventionally cooled and granulated using water. This granulated slag can then be used as a replacement of Portland cement with significant added value and eliminating  $\text{CO}_2$ -emissions that would otherwise be produced from calcination of limestone (indirect  $\text{CO}_2$ -emissions savings by using Ground Granulated Blast furnace Slag can be estimated to be around  $150 \text{ kg-CO}_2$  per ton of crude steel produced). Dry slag granulation technique, developed at CSIRO, offers a fundamental change in slag treatment. In DSG, the molten slag is atomised using centrifugal forces on a spinning disc, and the droplets generated are quenched using air, with simultaneous heat recovery. This significantly reduces the water usage for slag granulation and also produces electricity using the recovered heat ( $0.54 \text{ GJ/t}$  of hot metal,  $\sim 3\%$  of the total energy requirement of BF-BOF route), which would otherwise be wasted. The technology is close to commercialisation with anticipated large-scale demonstration in the next few years.
- *Charcoal-based reduction* – A new self-sustaining (auto-thermal) slow pyrolysis technique developed at CSIRO for producing charcoal or ‘designer biochar’ has the potential to be a like-for-like replacement for coke in the blast-furnace. Additionally, the bio-oil and bio-gas by-products from the process can partly substitute the liquid and gaseous fossil fuel requirement in steel making. However, apart from being the reducing agent and heat source, coke also serves the purpose of supporting the ‘burden’ (iron ore, flux and coke) and ensures smooth burden descent due to its high structural strength. Hence, the replacement of 100% coke in current blast furnace designs is not possible. Another concern, as mentioned previously, would be the land area required and the indirect emissions resulting from land-use change, if the Australian green steel industry was to expand beyond its current steel making capacity.
- *SMaRT recycling and Polymer Injection Technology (PIT)* – A new technology developed at the Centre for Sustainable Materials Research and Technology, UNSW and commercialised in Australia has the potential to “revolutionise waste recycling”. The technology uses carbonaceous waste, such as rubber from used tyres, for injection into molten steel in place of coking coal. In the right proportion, the waste can serve two purposes — removal of impurities from steel and also putting more iron (from tyre cords) back into steel. The commercial viability of this Polymer Injection Technology has been shown at Arrium’s (now Infrabuild) Laverton and Rooty Hill sites. In addition to the reduced strain on landfills from passenger car tires, the technology can reduce the coke rate in steel making by up to 16%.
- *Renewable electricity integration* – The electricity supply in Australia has become increasingly unaffordable and potentially unreliable for large, energy-intensive plants, such as the steel industry [54]. For such large electricity consumers, energy affordability, reliability and security are fundamental to the keeping the business cost-competitive. Recent commitments from both Australian steel manufacturers pertaining to large-scale low-cost renewable electricity integration (Bluescope through Finley solar farm [55] and Liberty Primary Steel through

SIMEC Energy Australia’s USD 1 billion Renewable Energy Program in Whyalla [56]) are a great step in the right direction. The opportunity to decarbonise steelmaking through integration of renewable electricity is quite limited, however, since  $>70\%$  of current Australian steel production is through the BF-BOF route, in which the share of electricity in the total energy consumption is only  $\sim 17\%$  [15]. On the other hand, renewable electricity integration is imperative for EAF-based route where the electricity share of primary energy usage could be up to  $80\%$  [15].

- *HIs melt/HIsarna coupled with CCS* – The HIsarna technology is a combination of the Cyclone Converter Technology and the HIs melt process for steel making. Through the Ultra-Low Carbon Dioxide Steelmaking (ULCOS) consortium and cooperation between former Corus and the Rio Tinto Group, a pilot scale plant was trialled at Tata Steel Europe’s IJmuiden site between 2014–2018. The process has the potential to be cheaper and have  $20\%$  lower  $\text{CO}_2$ -emissions compared to the conventional BF-BOF route, in addition to providing much more feedstock flexibility. In conjunction with carbon-capture and storage, the  $\text{CO}_2$ -emissions reduction potential of up to  $80\%$  [57] is envisaged. Although this is the most promising carbon-based alternative, large-scale deployment of two relatively unproven technologies — CCS and HIsarna — is required to realise this potential.

In the last few decades, Australia has successfully demonstrated the technical expertise in developing several home-grown technologies for reducing the carbon emissions in the domestic and global steel sector. Some of these aforementioned technologies can be retrofitted to existing plants for partial decarbonisation of our steel industry. However, as discussed previously, *complete decarbonisation of the steel sector* within a relatively short time-frame is required for achieving our GHG-emission targets. This can only be achieved through rapid development of green steel making infrastructure. The attractiveness and the key enablers for an Australian green steel industry is discussed in the next section.

## 5.2. Potential for a green steel industry in Australia

Currently,  $\sim 98\%$  of iron ore mining in Australia is concentrated in Western Australia (WA). WA meanwhile has some locations that are on par with some of the highest average solar irradiation in the world (Figure 6); these other locations include parts of the Atacama desert in S. America, small regions in Nevada, USA and isolated regions in western China [58]. The on-shore wind resource in WA is adequate and complementary to solar, thus enabling high capacity factors and smaller storage requirements for dispatchable electricity. The co-location of mineral and solar/wind resources offer the possibility of low cost green steelmaking which could potentially be cheaper compared to alternative green steel production locations around the world. For instance, Figure 5 shows the relative decrease in the levelised cost of electricity (LCOE) for PV and solar-thermal

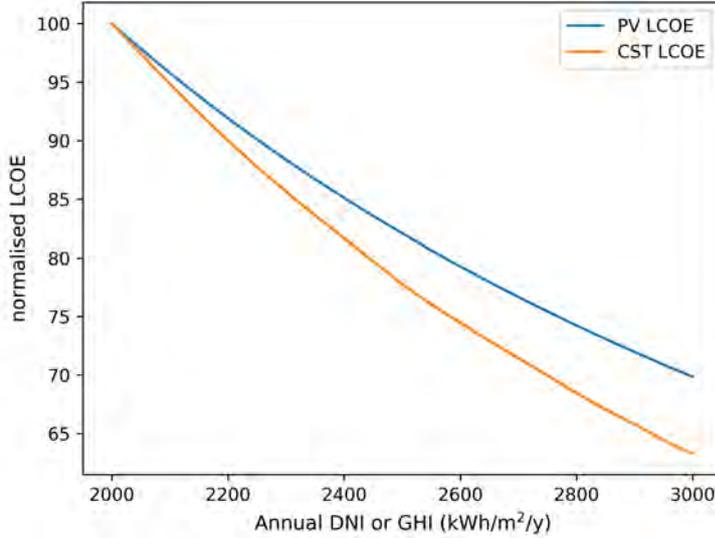


Figure 5: Levelised cost of electricity production using PV and CST as a function of global horizontal irradiation (GHI) and direct normal irradiation (DNI) respectively. The Pilbara, with an annual DNI near 3000 kWh/m<sup>2</sup>/y, offers significantly lower-cost solar electricity than most other locations in the world.

power plants as a function of the annual solar irradiation<sup>7</sup>. Compared to eastern China (Hebei, Shandong, Jiangsu and Liaoning provinces), which accounts for the majority of its steel production, the cost of renewable electricity in Australia could potentially be ~30% lower.

The most prospective zero-carbon steel making technologies include H<sub>2</sub>-based DRI and electrowinning. A significantly large share of the total energy input into both of these processes would be in the form of electricity. Hence, it can be argued that our renewable resource abundance and high quality iron-ore can lead to a much lower cost of green steel production in Australia compared to most other countries. To capitalise on this opportunity and expand our total steel production, a pathway for zero carbon steel making should consider the following aspects: (a) electricity infrastructure development (b) supply chain and transport infrastructure (c) skilled labour requirement (d) social license and native title land use (e) the risk of political interference in procuring critical materials (such as rare-earth metals) for a zero-carbon economy.

Figure 7 shows the requirements for establishing a 540 Mt/y green steel making industry in Australia. This would be equivalent to converting all of our currently exported iron-ore ( 835 Mt/y [59]) into steel. For the H<sub>2</sub>-DRI route, 33 Mt/y of clean hydrogen would be needed, which itself would require ~2100 TWh/y of clean electricity (Note: the total electricity generation in Australia in 2018 was ~260 TWh [60]). Assuming that solar PV and wind, in equal shares, are used for supplying the required electricity, ~506 GW of solar-PV, ~435 GW of wind and >5.6 TWh of storage

<sup>7</sup>The LCOE have been determined using NREL’s System Advisory Model by choosing locations with different DNI/GHIs around the world. Differences in the location-specific financial parameters such as land cost, cost of capital etc. have not been accounted for and have been assume to be the same. Note: The LCOE have been normalised with respect to a location with GHI/DNI = 2000, separately for the PV and CSP plants. Hence, the curves should not be compared with each-other on a relative basis.

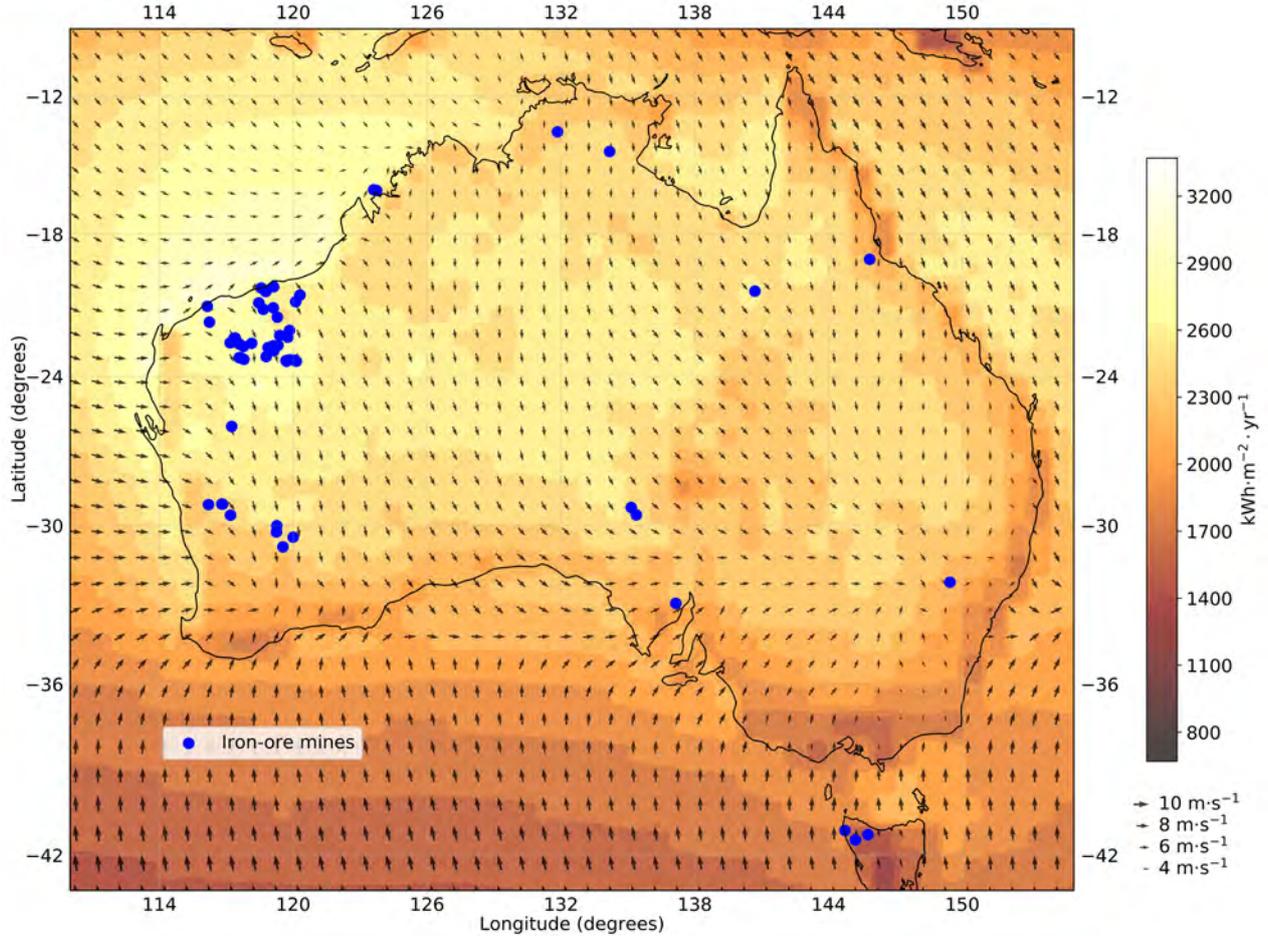


Figure 6: Solar (DNI) and wind resource in Australia with geographic locations of major iron-ore mines. Data Sources: The wind and DNI data are from NASA Prediction of Worldwide Energy Resources (POWER) database [61] whereas the iron-ore mine locations are taken from the Australia Mines Atlas [62].

capacity needs to be developed. Apart from the direct infrastructure which contributes to clean electricity production, several other materials would be needed in large quantities for enabling these technologies. For instance, if the unlikely scenario of battery storage is considered, large amount ( $\sim 0.9$  million tonnes) of lithium metal would be needed. Other essentials would include 200 Mt concrete, 73 Mt steel, 35 Mt glass, 10 Mt aluminium, 5 Mt copper, 3 Mt plastic, 3.6 Mt silicon, 3 Mt fibreglass and 9 Mt cast iron. A critical metal for deployment of wind turbines is neodymium, which is used in their high-performance magnets. For the scenario illustrated here, around 0.1 Mt of Nd would be required, which is more than 16 times the annual global production of metallic Nd.

With many governments and major international corporations moving increasingly strongly towards decarbonisation, there will be a growing market for green steel in the decades to come, and with appropriate policies, Australia could be a global leader in this industry. There is a risk of dwindling revenues from Australia's coal exports in future given the global climate action, which acts as an additional incentive to establish a new revenue source through green steel. There is good reason to expect that the green steel production in Australia could be internationally competitive as it will rely more on clean energy, ore and skilled labour costs and less on low-skilled labour. In addition to the

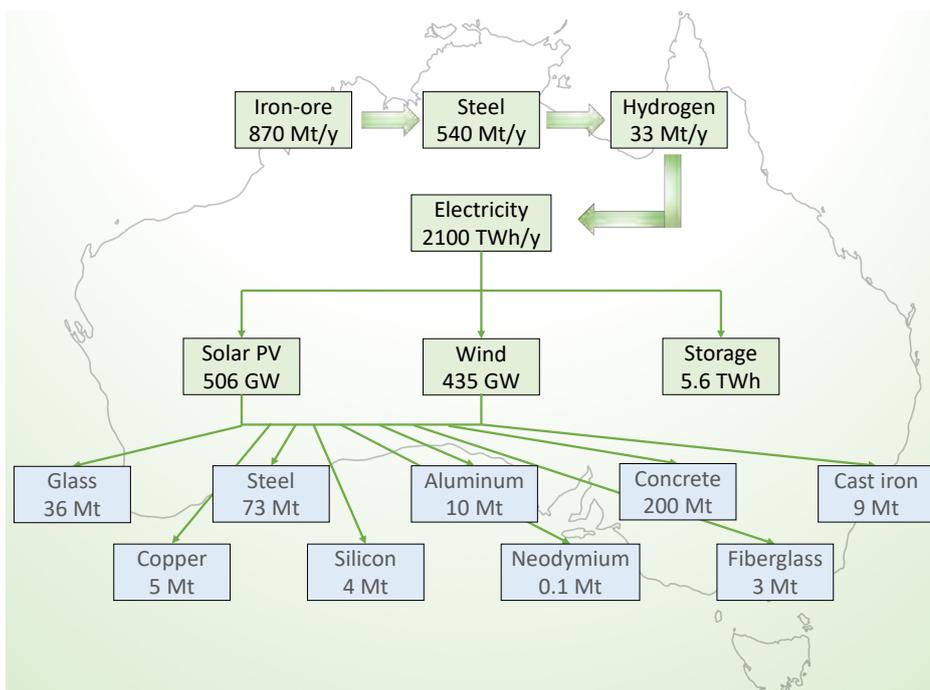


Figure 7: Key materials requirement for establishing a green steel industry in Australia. Case study for converting all of our current iron-ore export to steel onshore using renewables.

value addition to the economy and the associated expansion in high-skilled employment, Australia could facilitate a faster decarbonisation of the global steel industry resulting in significant reduction in the consequential emissions from its exports. If Australia is to realise its natural comparative advantage and become a sustainable green steel exporter in the near future, long-sighted and high-quality environmental and industrial policies will be crucial. It has been argued in the past that legal loopholes in contracts and gaps in regulatory regimes have made it possible for imported fabricated steel to avoid complying with the same standards as the steel made in Australia [63]. This means that the locally produced steel is more expensive than imported products that do not necessarily have to meet the same level of quality [63]. Apart from favourable policies and incentives for the green steel industry, some of the important considerations will include long-term prospects, infrastructure for training a skilled labour-force, expanding our manufacturing in clean electricity technologies, politico-economic relations with Australia’s trade partners and opportunities for foreign direct investment. A critical assessment of such key enabling technologies from the perspective of hedging our huge investment risks is necessary to ensure success and security.

## 6. Outlook

The iron and steel industry is one of the most energy-consuming sectors in the world, and has major technological and investment lock-in. In order to comply with the IEA 2°C scenario (2DS) [43], while maintaining universal energy access and lowered air pollution, the CO<sub>2</sub>-intensity of crude steel production has to fall by 1.9% annually between 2017 and 2030. For the IEA 1.75°C B2DS

scenario or for the 1.5°C scenario of the Paris Agreement, the rates of CO<sub>2</sub>-emissions reduction need to be even higher. In the last decade, this rate has been around 1.4–1.5% per year. However, the decarbonisation of the steel industry will become progressively more difficult in future given the projected growth in steel demand and the fact that the existing routes only offer limited carbon reduction potential. Thus, the needed long-term improvements can only be realised by replacing current technologies with significantly lower emissions intensive pathways.

The objective of this report has been to demonstrate that the impending decarbonisation of steel production infrastructure can only be achieved through a multi-pronged approach as envisaged below:

- Actively increasing the recycling of scrap up to the limit of limit of recycling (as dictated by the scrap availability and steel quality requirements), and ensuring that the required electricity for that is made available from renewable sources. Recycling will be particularly important in emerging economies as greater amounts of steel-containing products begin to reach the end of their lifetimes.
- Long term strategic investment into the adoption of new decarbonised steelmaking technologies (via routes such as direct electrolysis or hydrogen direct reduction), as well as the evaluation of pathways which may allow this to happen faster, for example through processes that initially operate from natural gas, and are migrated to green H<sub>2</sub> as soon as the supply chain is in place.
- Enhancement of material efficiency strategies to optimise the use of steel, including reduction of fabrication scrap and usage of alternate inherently low-carbon materials in certain application.
- Developing/promoting early-adopter markets for green steel products.
- Implementation of government policies that facilitate the transition to green steel industry with efforts required in developing standards/certification for green metals, creating an environment conducive to nurture a green steel industry and adopting mandatory CO<sub>2</sub>-emissions reduction policies.
- Undertaking research and development to address innovation gaps/opportunities through a global effort to accelerate the deployment of green steel technologies.

The potential for Australia to flourish in a carbon-constrained world are enormous. For Australia to realise economic benefits from this opportunity, it needs to develop a new and stable system of incentives for low-emissions manufacturing and production industries, to ensure security and reliability of this new industry, and undertake regulatory reforms and transformation to the ways in which Australia trades with the world. In addition to the institutional reforms, research and development cooperation between industry and academia with a focus on zero-carbon technologies—and their deployment—is required. Consumer markets for zero-carbon steel must be explored both in Australia and abroad, keeping in mind the potential value added to the Australian economy and the prospects of added jobs. Pioneering the technology for green steel would increase Australia’s probability of (a) making substantial contributions to Paris Agreement undertakings, (b) competitively

providing a worldwide export commodity (not only the steel but potentially also the steelmaking technology itself), and thus (c) contributing to faster global decarbonisation, especially in countries which rely on our currently carbon-intensive exports. Australia can lead the low carbon economy of the future, however, the time to act is now.

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