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Green steel: Synergies between the Australian iron ore industry and the production of green hydrogen

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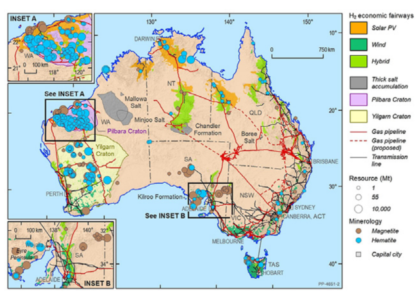
HIGHLIGHTS

- Australia could produce low-cost green steel for value-added export
- Strong correlation between hydrogen hubs and iron ore operations
- Existing infrastructure supports the roll-out of the industry
- Optimized generation mix reduces storage, curtailment and production costs
- Iron ore prices substantially influence green steel prices in the long term

GRAPHICAL ABSTRACT



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ABSTRACT

Green steel, produced using renewable energy and hydrogen, presents a promising avenue to decarbonize steel manufacturing and expand the hydrogen industry. Australia, endowed with abundant renewable resources and iron ore deposits, is ideally placed to support this global effort. This paper's two-step analytical approach offers the first comprehensive assessment of Australia's potential to develop green steel as a value-added export commodity. The Economic Fairways modelling reveals a strong alignment between prospective hydrogen hubs and current and future iron ore operations, enabling shared infrastructure development and first-mover advantages. By employing a site-based system optimization that integrates both wind and solar power sources, the cost of producing green steel could decrease significantly to around AU$900 per tonne by 2030 and AU$750 per tonne by 2050. Moreover, replacing 1% of global steel production would require 35 GW of well-optimized wind and solar photovoltaics, 11 GW of hydrogen electrolysers, and 1000 square kilometres of land. Sensitivity analysis further indicates that iron ore prices would exert a long-term influence on green steel prices. Overall, this study highlights the opportunities and challenges facing the Australian iron ore industry in contributing to the

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decarbonization of the global steel sector, underscoring the crucial role of government support in driving the growth and development of the green steel industry.

Abbreviations

AEMO	Australian Energy Market Operator
BESS	Battery energy storage system
BF	Blast furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon capture and storage
DR	Direct reduction
DSO	Direct shipping ore
FeO	Wustite
Fe_2O_3	Hematite
Fe_3O_4	Magnetite
EAF	Electric arc furnace
FET	Full-time equivalent
IEA	International Energy Agency
HBI	Hot briquetted iron
HDR	Hydrogen direct reduction
HEFT	Hydrogen Economic Fairways Tool
LCOS	levelized cost of steel
LHV	Lower heating value
MIP	Mixed integer programming
MUREIL	Melbourne/Monash University Renewable Energy Integration Lab
OPEX	Operational expenditure
PEM	Polymer electrolyte membrane
PV	Photovoltaics
SA	South Australia
SEC	Specific energy consumption
WA	Western Australia

Introduction

Steel is a vital commodity for all modern economies. The steel industry, however, is energy- and emission-intensive. As of 2019, steel production accounted for approximately 8% of the global energy demand and produced 7% of all energy-related emissions [1]. Meeting the international goal of a net zero future will require a fundamental shift to low-emission iron and steel manufacturing processes; particularly as per the IEA's Net Zero by 2050 scenario [1], global steel emissions will need to decrease by 24% by 2030—and 91% by 2050—to avoid the worst effects of climate change and limit global heating to 1.5 °C. However, a lack of viable green alternatives for primary steel production has led to the perception of the steel industry as a hard-to-abate sector. Nevertheless, recent technological advances in steelmaking, coupled with cost reductions in renewable technologies, suggest that the steel sector has the potential to significantly reduce its greenhouse gas emissions and move towards deep decarbonization [2,3]. For example, renewably-sourced hydrogen can replace coking coal and methane in iron treatment to decarbonize steel production while supporting the growth of the international hydrogen industry. This transition presents Australia, the world's leading iron ore supplier, with significant opportunities and challenges in maintaining its competitive advantage while meeting the rising global demand for low-emission steel.

Hydrogen's versatility allows it to be utilized across various energy sectors, but its most significant potential lies in “no-regret” sectors such as primary steel production [4]. By concentrating on steel industry, we can maximize hydrogen's climate mitigation potential [4] as an essential reducing agent, rather than a less efficient fuel source. [5] projects the growth of hydrogen-based reduction in steel manufacturing within a zero-carbon scenario, with adoption commencing in 2030 and reaching 700 million tonnes by 2060. Similarly, [6] models the future of global steel production and anticipates a substantial increase in green hydrogen demand by the global steel industry. They expect a range of 2800–4400 TWh of hydrogen demand for steel manufacturing by 2050, which is about 10–17 times Australia's current annual electricity generation.

Low-emission steel manufacturing using hydrogen could facilitate Australia's goal of becoming a major player in the emerging hydrogen economy. As a net energy exporter with ample renewable energy resources and deep expertise in international trade [7], Australia seeks to leverage its competitive advantages to become a major player in the emerging hydrogen industry [7]. However, there are costs and technical challenges in direct hydrogen export to overcome before this potential can be realised [8]. A potential opportunity to help start this industry may be through the export of embodied hydrogen employed in the production of secondary and value-added products. In particular, green steel (*i.e.*, steel produced using hydrogen from renewable sources as the reducing agent) shows particular promise for the trade of embodied hydrogen from Australia [9,10]. Australia, as the world's largest iron ore producer, exported over 835 million tonnes, which constitutes approximately 36% of global production in 2019 [11]. The country's annual iron ore exports have exhibited consistent growth. In 2020, Australia exported 867 million tonnes of iron ore, which increased slightly to 874 million tonnes in 2021. This upward trend is expected to continue, with iron ore exports projected to reach 896 million tonnes during the 2022–2023 period [12]. Many iron ore production centres also host excellent renewable wind and solar resources [13,14]. Importantly, the presence of mining operations in these areas increases the economic potential for renewable projects by supplying the necessary shared infrastructure for energy generation, such as powerlines and transportation networks. Implemented successfully, the production of green steel can add value to Australian trade [5], reduce global greenhouse emissions, and future-proof Australian exports against international carbon-based tariffs.

In the analysis of current global iron and steel industrial decarbonization strategies, [15] examined several low-emission technologies, including hydrogen injection, solid biomass substitution, zero-carbon electricity substitution, scrap recycling, carbon capture and storage (CCS) retrofit, and various combinations thereof. The authors emphasized that there is no universal solution, and the practicality and cost-effectiveness of different approaches depend on factors such as geographical location, infrastructure, and local economies. Building on that note, our paper specifically aims to explore the potential for green steel production and export in Australia, with a focus on the competitive advantage provided by the country's renewable resources through an in-depth site-based system design and optimization. Additionally, the study underscores the importance of leveraging existing infrastructure to facilitate the roll-out of the green steel industry in Australia.

Furthermore, it is worth noting that a variety of emerging techniques are being developed into sus-tainable, industrial-scale solutions for green steel production. Key examples include hydrogen-based direct reduction [2], hydrogen plasma smelting reduction [16,17], molten oxide electrolysis [18], and electrowinning of iron in aqueous alkaline solution [19], among others. Of these alternatives, the hydrogen direct reduction method has reached the highest technology readiness level and is currently being employed on an industrial scale [20,21]. Meanwhile, bio-CCS has also been explored as a strategy to achieve carbon neutrality via the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route [22].

The production of green steel with direct hydrogen reduction involves different processing pathways compared to conventional steel-making [2,23]. In this method, the reduction of iron ore via smelting in a conventional blast furnace is replaced by a two-step process. First, the ore is reduced in a hydrogen-based shaft furnace, and then the reduced iron is cast in an electric arc furnace (EAF). For green steel, both processes require energy from renewable resources: green hydrogen for shaft furnace reduction and electricity for electric arc casting. Successful green steel projects necessitate a combination of quality renewable energy resources and abundant high-quality iron ore.

While there is a growing body of research on green hydrogen and its derivatives [24], studies specifically exploring green steel production remain limited. The economic analysis of the HYBRIT model is presented by [2], which demonstrates the production cost of steel using the hydrogen direct reduction (HDR) process route as dependent on the cost of electricity and different levels of scrap charge, utilizing a chemical process model. In contrast, [25] highlights the significant advantage of directly using ammonia in the steelmaking process, which eliminates the need for a separate, costly ammonia cracking process. This method, which can be implemented on an industrial scale, produces the same metallisation as hydrogen-based direct reduction and allows for easy adjustment of steel grade composition.

Previous studies have primarily focused on using grid electricity in techno-economic analysis to determine the levelized cost of steel. [26] analyze how expanding the renewable energy share in the European electricity grid affects the cost-efficient design of a hydrogen-based steelmaking process, demonstrating that the design is dependent on the mix of electricity sources in the grid. Similarly, [27] develop an open-source model for conducting a techno-economic assessment of a hydrogen-based steel manufacturing plant using grid electricity in Norway. This model analyzes the levelized cost of steel for two plant configurations with different electrolyzer capacities and finds that the high electricity cost is the largest challenge faced by the steel industry in transitioning to hydrogen-based steelmaking. Procuring electricity from day-ahead markets in the electricity market could be a viable option to reduce production costs by 15% compared to a fixed electricity price. [28] show that from 2050 onward, when the blast furnace (BF) based routes become unprofitable due to rising coal and carbon prices, HDR and hydrogen electrolysis become economically attractive due to the high share of renewable energy sources. The HDR route, which relies on grid electricity, can also play an essential role in stabilizing the grid and storing excess energy in a completely renewable energy system. The above studies assume fixed electricity prices or use historical grid electricity prices. It may be necessary to revisit the findings of grid connection studies in light of the more stringent European Union regulations [29], which mandate monthly and eventually hourly renewable generation matching for grid hydrogen to qualify as low emission.

Optimization studies investigating off-grid systems with on-site renewable resources are very limited in the literature. [30] explores the optimal energy system requirements for hydrogen direct reduction of iron with electric arc furnace steelmaking. Using the UK's iron and steel industry as a case study, the researchers highlight that a reliable electricity and hydrogen supply can be attained by utilizing wind power, solar power, combined cycle gas, hydrogen storage, and compressed air energy storage. [31] compares the ammonia and liquid hydrogen pathways for green steel manufacturing and assesses their respective impacts on the technical and economic performance of an Australia-Japan supply chain initiative. The commercial software HOMER Pro was used to determine the levelized cost of off-grid renewable electricity using a proprietary derivative-free algorithm. However, this study focused only on solar PV as a renewable generation technology and overlooked the potential contribution of wind power.

In the planning and decision-making processes for a large-scale green steel facility, it is crucial to take into account numerous factors that are specific to the plant's location. Although conventional levelized cost analyses can provide a rough estimate of general costs, there exist several cost and non-cost factors unique to the region where the plant is situated, including the availability of favourable wind and solar resources, and the presence of existing or planned infrastructure such as roads, ports, mining operations, and industrial facilities. In addition, remote locations can present challenges in connecting to a major grid, which emphasizes the importance of incorporating region-specific factors whenever possible. Our study focuses on large-scale green steel production, utilizing dedicated wind and solar resources to optimize renewable electricity and storage needs and minimize the cost of green steel, while also considering the availability of the regional infrastructure.

The aim of this research is to advance the current understanding of green steel production by conducting a comprehensive analysis of renewable resource availability at strategic locations in Australia. Specifically, the study seeks to enhance the comprehension of the planning and decision-making mechanisms for green steel export facilities by emphasizing the significance of both generic and location-specific factors. This involves assessing the availability of favourable wind and solar resources, current and anticipated infrastructure, as well as current and future operations in iron ore mining, while also addressing challenges presented by direct shipping ore (DSO) in the manufacturing of green steel. Moreover, the study introduces new analytical tools that enable international stakeholders to conduct a comprehensive examination of these factors. The insights gained from this research will be valuable to decision-makers and industry stakeholders worldwide, rather than being limited to the context of a specific nation. In particular, our work assesses the factors contributing to Australia's potential for green steel production for export and identifies key regions of interest for this nascent industry. Using locations from Geoscience Australia's mineral resources databases [32], we highlight regions of current and future iron ore production suitable for the production of green steel Regions of high potential for green steel production. These regions are cross-referenced against areas of high potential for hydrogen production identified by Geoscience Australia's Hydrogen Economic Fairways Tool (HEFT) [14,33].

After an initial screening, we selected two high-potential locations for further temporal analysis with hourly wind and solar data: the Pilbara region of North-Western Australia (WA) and the Eyre Peninsula in South Australia (SA). These two regions have been chosen as they present illustrative examples of green steel production potential from large-scale sustainable resource development supported by existing infrastructure. Both locations possess significant renewable resources and abundant iron ore reserves, and have recently been listed as prospective hydrogen hubs [34] by the Federal Government. Furthermore, each location has its own unique geological advantages: the Pilbara has access to large-scale, low-cost salt cavern storage, whereas the Eyre Peninsula has access to the National Electricity Market with frequent renewables curtailment.

Using a detailed Mixed Integer Programming (MIP) model designed to find the optimal mix of renewable energy sources for green steel production, we present results estimating the levelized cost of steel (LCOS) production in both regions Green steel production model. The results of the analysis quantify the benefits of the unique features of these regions and highlight the advantages of a well-optimized wind and solar generation mix — decreasing production costs by reducing renewable curtailment and the need for additional expensive energy storage. The following sections provide a detailed discussion of the models we developed to conduct the analysis.

Methods

In this section, we present a two-step analytical approach for conducting a comprehensive assessment of Australia's potential for green steel production.

Regions of high potential for green steel production

We cross-reference existing databases describing the extent of Australia's current iron ore deposits and production pathways [35] with an assessment of the regions of high potential for future hydrogen production [14].

Australia hosts significant iron ore deposits in all its states and territories except the Australian Capital Territory [32,35]. The vast majority of Australian iron ore production comes from the state of Western Australia, which contains approximately 92% of Australia's economic demonstrated resources [11]. The bulk of Western Australian iron ore is produced in a region in the North-West known as the Pilbara Craton. The Australian state with the second-highest concentration of iron ore deposits is South Australia. Most of its iron ore deposits are located on the Eyre Peninsula on the southern coast, bordered by the Great Australian Bight. The locations of significant iron ore deposits and their magnitudes are shown as circles in Fig. 1 [32]. Expanded views of the Pilbara and the Eyre Peninsula are given in Fig. 1 c) and d), respectively.

Fig. 1 also highlights regions across Australia that are economically favourable for green hydrogen production. As an illustrative input dataset, Fig. 1 a) shows the transportation infrastructure overlaid with the annual average solar capacity factor for Australia, indicating that the renewable resource is widely available, although economic potential varies due to differences in local infrastructure. Fig. 1 b) presents the resulting "Economic Fairways" identified using the HEFT, recently developed by Geoscience Australia and Monash University [14,36].

The HEFT analysis accounts for both the quality of the renewable energy source and plant economics when assessing the potential for hydrogen production. In this study, we assume that the hydrogen produced is consumed locally and that the plant is connected to the closest road (for construction and site access) and the nearest transmission line (as a backup power source). We consider three different sources of renewable energy – solar only, wind only, and a hybrid system with 50% wind and solar power.

The results of our analysis in Fig. 1 show a striking alignment between the distribution of high-potential regions for hydrogen production and existing centres of mining activity. At first glance, it may appear counter-intuitive that surface renewable resources (solar and wind) are associated with regions of mineral extraction. However, this correspondence stems not from geology but from available infrastructure. While Australia is blessed with ample areas of high-quality renewable resources, it is also vast and sparsely populated, with many regions lacking easy access to power and roads.

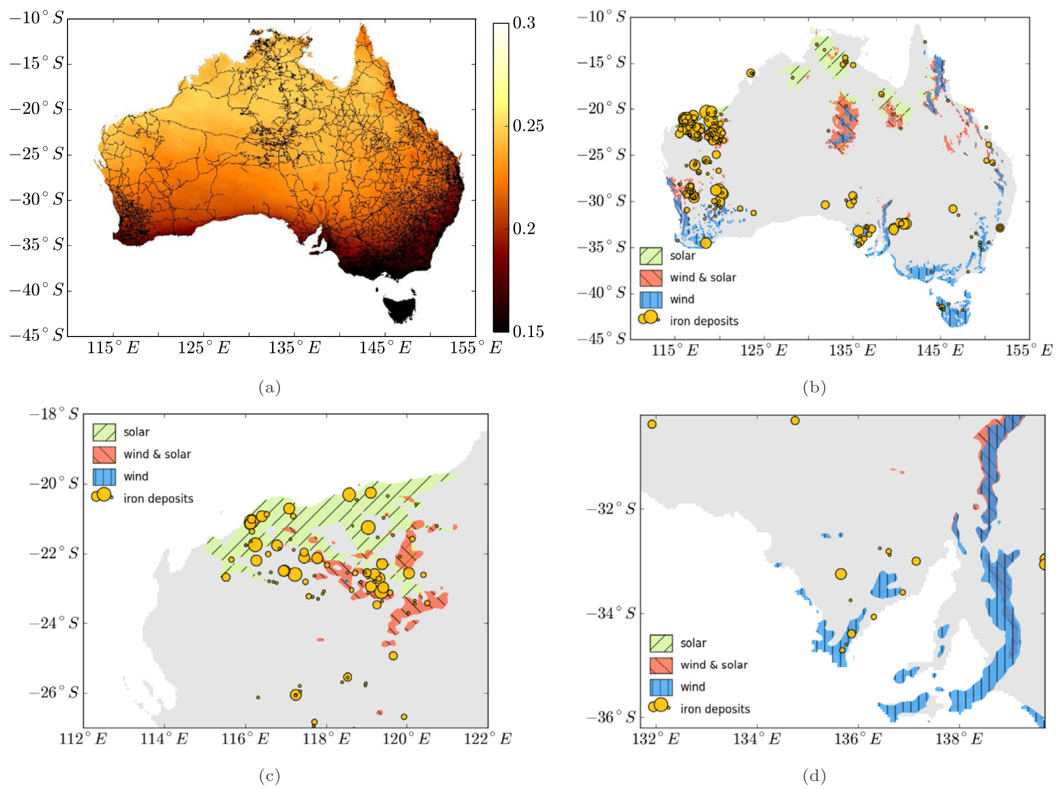

Fig. 1 — (a) Transportation infrastructure map overlain with annual average solar capacity factor for Australia. It illustrates that the resource is broadly distributed, but differences in local infrastructure lead to variations in economic potential. (b) High potential regions for the production of farm-gate and off-grid hydrogen from solar, wind, and hybrid sources, and locations of iron ore deposits in Australia. Deposit locations are based on [32], and the size of the symbol reflects the deposit size category. The lower figures (c) show expanded views of the Pilbara region of Western Australia and (d) the Eyre Peninsula in South Australia.

Large mining operations, such as iron ore mines, provide an economic incentive to develop electricity transmission and transportation infrastructure (roads and rail lines). Consequently, in Australia, the most economically favored sites for renewable energy production (solar power in particular) often lie close to centres of mining activity.

In 2020, the Pilbara region's commercially proved resource base was estimated to be 36,220 Mt (70% of Australia's total). The Pilbara ores, which are characterized by hematite–goethite, have a comparatively high grade (58–65% Fe) and gangue containing 3–4.8% Si, 1.4–2.4% Al_2O_3, and up to 0.1% P. Separating ferrous from non-ferrous minerals in such ores, however, is technically challenging. In general, the Pilbara produces direct shipping ores, which are crushed to lumps and fines before being shipped with little or no beneficiation. When beneficiation is used, it usually compensates for the mining of lower-grade iron ores, allowing blast furnace steelmakers to maintain target concentrate purities [37].

In comparison, South Australia's commercially proved resource base was estimated at 5755 Mt in 2020 (11% of the national share), with 89% of this being magnetite. Magnetite-dominated banded iron formation deposits are typical low-grade ore bodies with a Fe content of 15–40% [38]. On the other hand, the magnetic separation of magnetite allows for effective beneficiation. For example, magnetite operations in South Aus-tralia aim to generate high-purity concentrates of 65–70% Fe with gangue containing 2.3–5% Si, 0.15–1.9% Al_2O_3, and up to 0.02% P [38], which is ideal for hydrogen reduction shaft furnaces. Today, magnetite concentrates from Eyre Peninsula operations are being pelletized and utilized in the Whyalla steel mill or exported as sinter fines [39]. Compared with hematite, magnetite contains a somewhat greater amount of iron (72.36% vs. 69.94%). The exothermic reaction of magnetite during the sintering and pelletising processes enables energy and cost savings with less fuel consumption [40].

Although pellets can be created from either hematite (Fe_2O_3) or magnetite (Fe_3O_4) feedstock, they become Fe2O3 once pelletized because of the temperature-induced oxidation process [40]. Iron ore pellets are traded internationally, with prices subject to fluctuations in global demand. In the following sections, we consider the effects of regional variations on the cost of green steel production using local renewables from pelletized iron ore and the impact of price variability on the overall cost of green steel.

Green steel production model

Here, we further employ a site-based model to conduct a more detailed evaluation of the economics of green-steel production at an hourly resolution. In Results and Discussion, this model will be used to assess off-grid green steel production in the Pilbara region in Western Australia and the Eyre Peninsula in South Australia, as two strategic locations identified by the HEFT analysis.

Modelling of local renewable availability is facilitated by applying hourly wind and solar generation capacity factors retrieved from the Renewables.ninja model described by [41,42]. Onshore wind turbines (Vestas V80 2000) with a hub height of 150 m and solar photovoltaics (PV) with one axis tracking and the year 2019 are specified when retrieving the data. Figs. 2 and 3 illustrate the resource quality, hourly and seasonal variability of local wind and solar resources in the Eyre Peninsula in South Australia and the Pilbara in Western Australia. For both locations, wind and solar are largely complementary, with solar generating energy during the daytime and wind primarily at night. However, it is important to note that wind in WA and solar in SA present moderate seasonal variations, with wind in WA showing a greater shortfall from January to April and solar in SA showing greater seasonality from May to August. It is crucial to develop a flexible production system that is customized to accommodate localized renewable variations, which can range from hours to months.

To assess the potential for green steel production at specific sites considering the underlying temporal variability of local renewable resources, we have developed a Mixed Integer Programming (MIP) model called “MUREIL-Steel”. MUREIL-Steel is based on an earlier model, MUREIL-Ammonia, which is designed to assess the production potential of green ammonia [43,44]. Like MUREIL-Ammonia, MUREIL-Steel evaluates the impact of the temporal operational flexibility of electrolysers and the refining process on the optimal design of a green-steel production system based on hourly wind and solar data.

A schematic outline of the major components in the off-grid MUREIL-Steel model is presented in Fig. 4. The HDR process involves pre-heating iron ore and feeding it into a reduction shaft furnace. The iron ore is then transformed into direct reduced iron (DRI), which is further compressed into hot briquetted iron (HBI). A condenser pre-heats the hydrogen produced by an electrolysis unit before supplying it to the shaft as a reducing agent. HBI is melted in an electric arc furnace, where it is formed into liquid steel.

The model assumes that electricity for powering Polymer Electrolyte Membrane (PEM) electrolysers, the hydrogen direct reduction furnace, and the electric arc furnace for steel manufacturing can be supplied by onsite wind, solar PV, or a hybrid wind-solar PV system. This system may be supported by a 2, 4, or 8-h battery energy storage system (BESS) to manage renewable diurnal variation and a hydrogen buffer tank for seasonal variation. Cost-optimal designs are calculated among these generation and storage options to produce green steel with an output of 1000 tonnes per day. The MUREIL-Steel model searches for the optimal (i.e., least-cost) configuration of all components based on the simulated hourly operation of the plant, subject to any imposed production constraints (as illustrated in Fig. 5). The model also provides the capability to explore the trade-off between different system layouts.

Techno-economic parameters

The modelling seeks to quantify the benefit of system flexibility in green steel manufacturing. Matching variable electricity supply with electrolysis and smelting plants is a significant challenge. Of the available electrolyser technologies, PEM electrolysers possess the highest operational flexibility and turndown capability [45]. They are also expected to have the greatest potential for cost reductions [46]. For these reasons, we select PEM over other technologies for hydrogen production modelling. If the electrolyser is sized larger than required for operation at a 100% capacity factor, flexibility can be added to the system to cope with renewable variability while meeting the production target. Hydrogen from storage then opens up the possibility to offer positive reserve power by reducing the electrolyser load when renewable generation is low. Smelting plants typically are much less flexible than a PEM electrolyser for hydrogen production. We incorporate an intermediate low-pressure hydrogen storage system to buffer the variations in hydrogen production. Today, most PEM electrolysers operate with hydrogen outlet pressures between 30 and 40 bar [47]. Employing low-pressure hydrogen tanks at 100 bar could require the use of only a small compressor, potentially resulting in minimal electricity consumption for compression. For consistency, pressurised gaseous hydrogen storage in tanks is assumed for both locations.

Furthermore, solutions to maintaining high utilisation of the production plants with onsite renewables involve both short and long-term storage. We include lithium-ion battery storage to balance the diurnal variability of renewables, which will also add flexibility to the system. Flexible electric arc furnace operation is currently practical and in use to process scrap metal feedstock within Australia, *e.g.* [48]. The EAF can operate intermittently, providing the flexibility for steel mills to adjust energy consumption in response to factors such as electricity prices or on-site variations in renewable energy generation. However, the current model does not take into account variations in scrap charge or HBI storage, so the EAF operation is mainly determined by the supply of HBI from the inflexible HDR shaft. Further research will examine how scrap usage and HBI storage can enhance the flexibility of the system.

Financial input assumptions are also critical to techno-economic modelling. Key renewable generation technology capital expenses are taken from the Australian Energy Market Operator (AEMO) Integrated System Plan (ISP) 2022 [49] Inputs and Assumptions Workbook (under the “Step Change” scenario) as summarised in Table 1. We assume hydrogen tank storage at AU$600/kg (AU$18/kWh), which is in line with [50,51]. Most facilities are assumed to have an economic life of 25 years, whereas lithium-ion batteries are assumed to have a lifetime of 15 years. This assumption aligns with the 15-year warranty provided for Tesla's Powerpack 2 units of the Hornsdale project in South Australia [52]. The PEM stack lifetime is assumed to be 80,000 h of operation. The discount rate is assumed to be 10%, with a cost sensitivity analysis conducted in Fig. 10.

All generation scenarios utilized a specific energy consumption (SEC) of 3.48 MWh per tonne of liquid steel, as stated by [2]. For 24/7 operation on 100% hot briquetted iron,

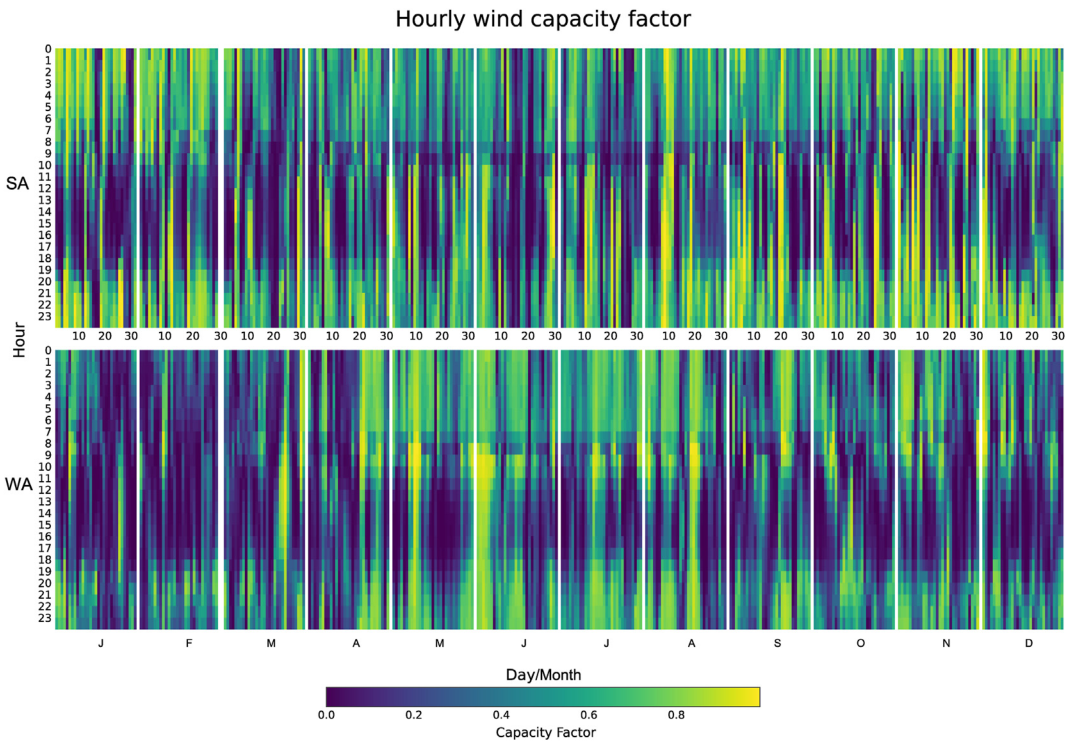

Fig. 2 – The input wind capacity factor (from a 1 MW onshore Vestas V80 2000 turbine at a hub height of 150 m) shows the temporal variation of the local wind resources in 2019. Compared to SA, WA has stronger wind seasonality from January to April. Data were retrieved from the Renewables.ninja model [41,42].

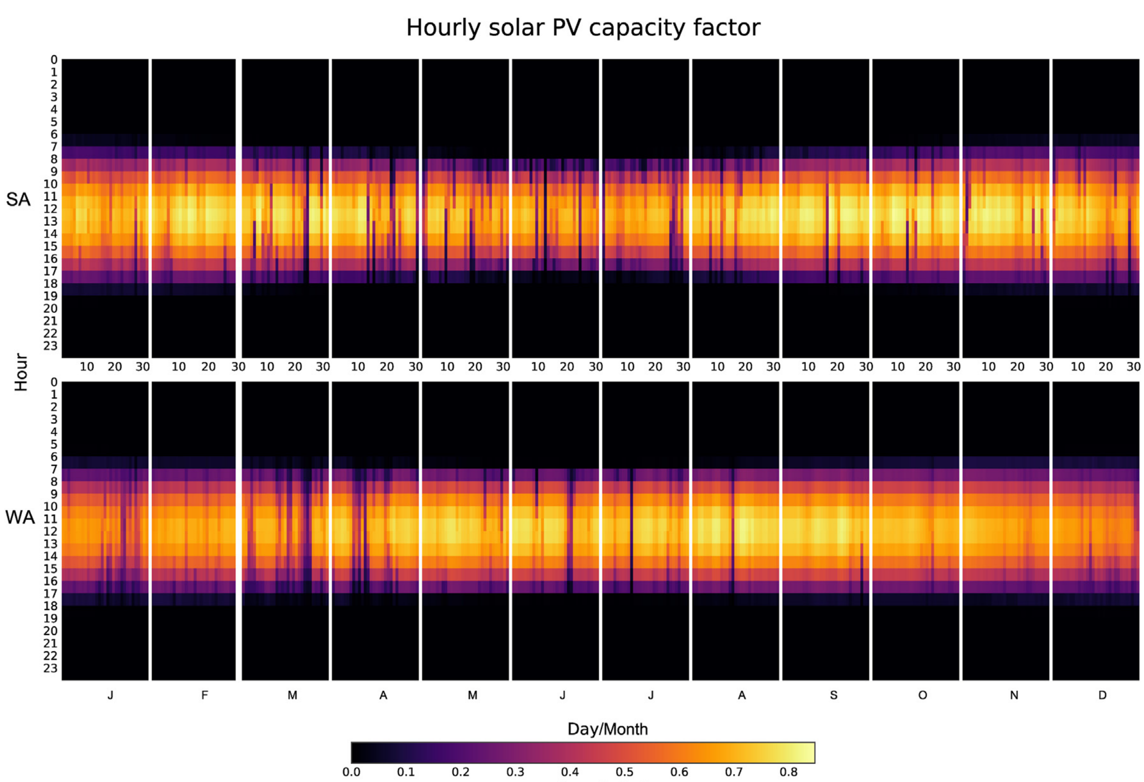

Fig. 3 – The input solar PV capacity factor (in a 1 MW system) with one axis tracking shows the temporal variation of the local solar resources across 2019. Compared to WA, SA has stronger solar PV seasonality (as indicated by the reduced brightness and broadness of the spectrum) from May to August. Data were retrieved from the Renewables.ninja model described by [41,42].

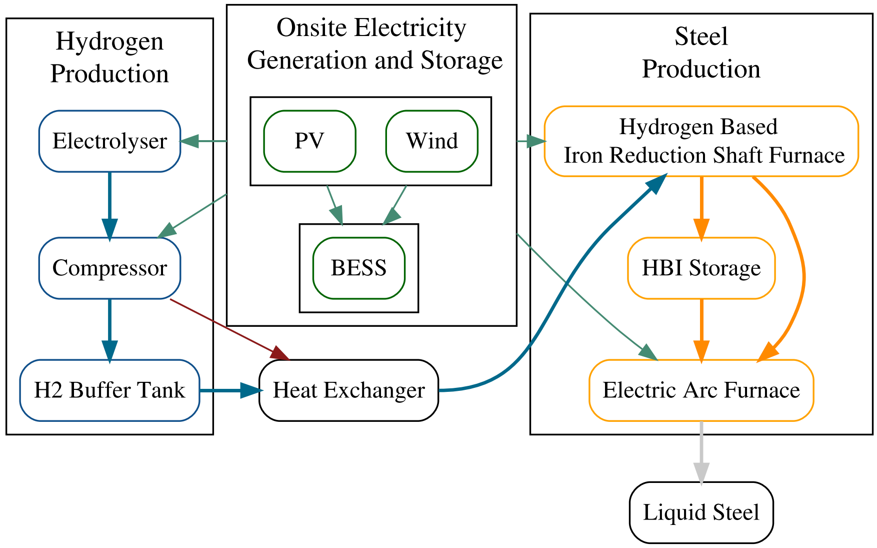

Fig. 4 – Schematic outlining the major components considered by the off-grid MUREIL-Steel model. Arrows indicate the flow of power (green), hydrogen (blue), thermal energy (red), iron/iron ore (yellow) and steel (grey). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

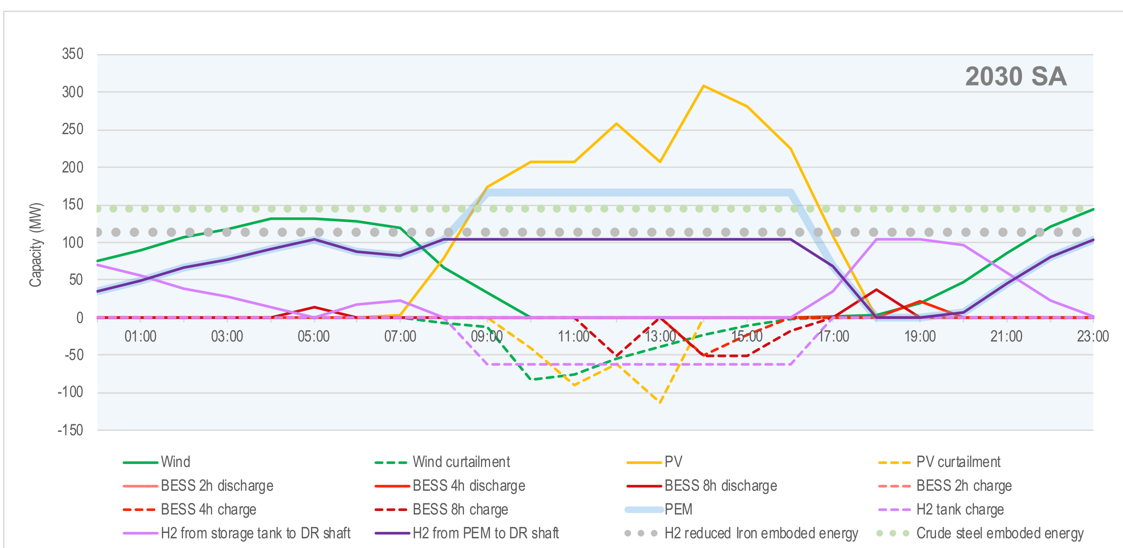

Fig. 5 – Example of simulated hourly operation of the h2DRI-EAF system powered by wind and solar with support of battery and hydrogen storage in 2030. The wind and solar capacity factor input was based on historical data on August 4, 2019 at Eyre Peninsula in South Australia.

producing one tonne of liquid steel requires approximately 1504 kg of iron ore pellets [2]. The operating temperature of the shaft furnace is 800 °C, and the metallization achieved in the shaft furnace is assumed to be 94% (i.e., from Fe_2O_3 to Fe, where Wustite (FeO) formation is neglected). This will require 51 kg of hydrogen as a reducing agent per tonne of iron without hydrogen losses [2]. The reaction is endothermic:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O(g)\ \Delta H_R = +99.5\ \text{kJ/mol}$$

The stoichiometric ratio of hydrogen feed to the shaft furnace is 1.5 [2]. Overall, it requires approximately 2.55 MWh per tonne of DRI (assuming 72% electrolysis efficiency), accounting for 73% of the total specific energy consumption [2].

The steel manufacturing process also requires 11 kg of alloys, 2 kg of graphite electrodes and 50 kg of lime for each tonne of liquid steel produced [2]. The cost of these consumables and other operational expenses are also listed in Table 1.

According to [2], electricity consumption for iron ore preheating and the shaft furnace is approximately 0.177 MWh per tonne of DRI. The electricity consumption of the shaft furnace is minimal due to the use of recovered heat from the condenser (Fig. 4). To compare, an electric arc furnace requires 0.753 MWh per tonne of liquid steel when processing pure DRI

Table 1 – Key cost assumptions employed in the MUREIL-Steel Model.

Component	Project Start		
	2025[a]	2030[a]	2050[a]
Capital expenditure (CAPEX)			
PEM electrolysers (efficiency wrt. LHV of 33.33 kWh/kg)	$1432/kW (57%)	$852/kW (59%)	$441/kW (66%) [49]
Wind	$1939/kW	$1848/kW	$1619/kW [49]
Solar PV	$906/kW	$796/kW	$552/kW [49]
Battery Energy Storage System (2 h) (85% round trip efficiency)	$716/kW	$548/kW	$278/kW [49]
Battery Energy Storage System (4 h) (85% round trip efficiency)	$1037/kW	$759/kW	$452/kW [49]
Battery Energy Storage System (8 h) (85% round trip efficiency)	$1717/kW	$1211/kW	$805/kW [49]
H2 tank (with compressor)		$18/kWh [50]	
Electric Arc Furnace		$285/tonne per annum [2][b]	
Hydrogen Direct Reduction Shaft Furnace		$355/tonne per annum [2][b]	
Operational expenditure (OPEX)			
Variable OPEX of wind, solar PV, BESS and PEM		0 [49]	
Non-fuel OPEX for steelmaking (lime, alloys, graphite electrodes, etc.)		$51/tonne crude steel [2]	
PEM Fixed OPEX		3% of CAPEX/year [49]	
Fixed OPEX of EAF and H2-DR shaft		3% of CAPEX/year [2]	
H2 tank Fixed OPEX		1% of CAPEX/year [50]	
Wind Fixed OPEX		$28/kW/year [49]	
Solar Fixed OPEX		$19/kW/year [49]	
BESS 2 h Fixed OPEX		$12/kW/year [49]	
BESS 4 h Fixed OPEX		$19/kW/year [49]	
BESS 8 h Fixed OPEX		$31/kW/year [49]	
Labour		$38.4/tonne crude steel[c] [9]	
Iron ore (DR-grade pellets)[d]		$152/tonne DRI [9]	

[a] Costs adjusted to 2022 AUD with foreign exchange rates of 1 EUR = 1 USD = 1.6 AUD.
[b] The Sweden's HYBRIT model - based on nameplate capacity, i.e., annual capacity at 100% operation.
[c] Assuming 73 full-time equivalent (FET) per Mt of DRI and 167 FET per Mt of steel at an hourly rate of $77 [9].
[d] Comprise 95% hematite and 5% inert substances.

without any scrap. It should be noted that the values provided are specific to the iron and steelmaking processes and do not encompass the energy demands required for other activities such as pelletising, secondary metallurgy, casting, and rolling. Pelletising, in particular, requires additional inputs of fuel and electricity [2,53].

With the energy requirements and plant operational constraints, the MIP model simultaneously optimizes the sizing of onsite wind, solar PV, lithium-ion battery, PEM electrolysers, hydrogen storage tanks, and the HDR-EAF system to achieve a daily production target of 1000 tonnes of liquid steel.

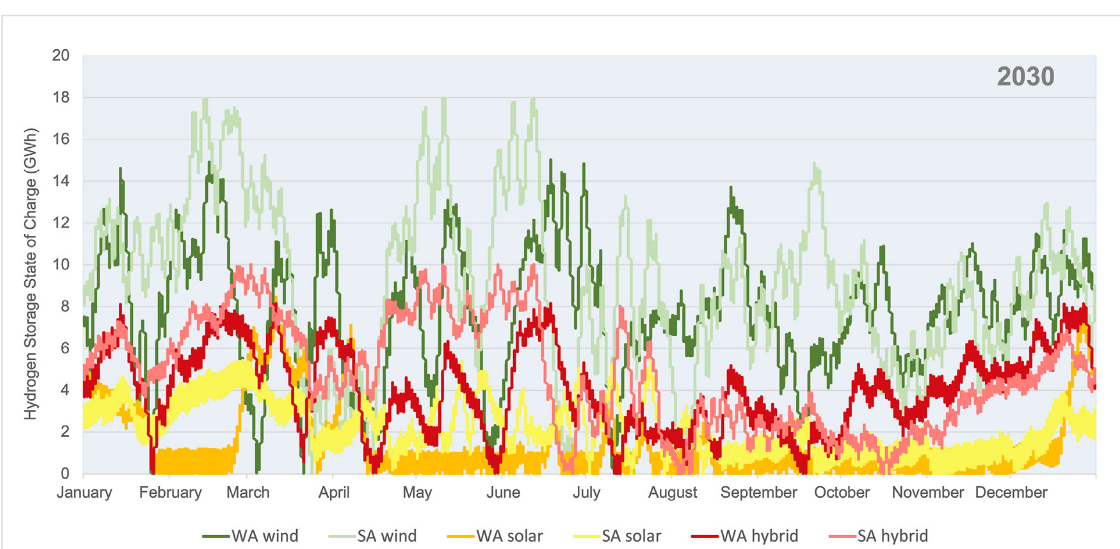

Fig. 6 – State of charge of hydrogen tanks for the simulated year of 2030 by energy source and region. Wind-only powered systems tend to require larger hydrogen storage, whereas solar-powered systems require less hydrogen storage.

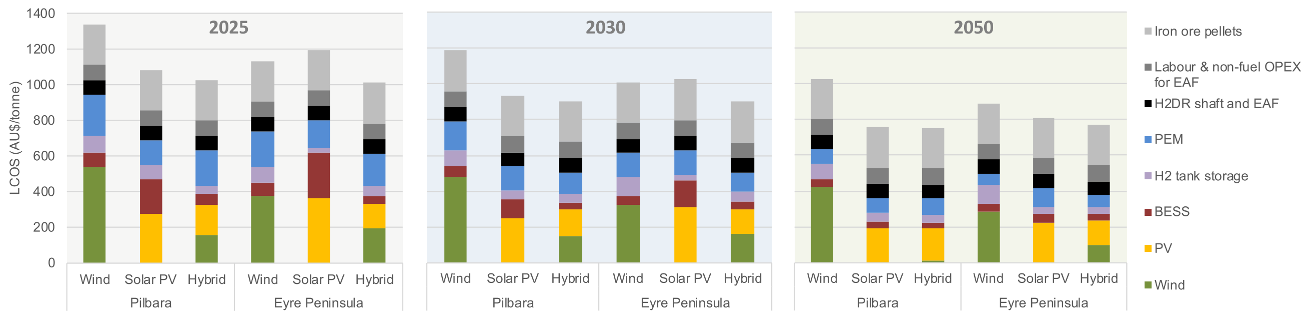

Fig. 7 — Levelized costs of steel production in the Pilbara (Western Australia), and the Eyre Peninsula (South Australia) with 100% Direct Reduced Iron (*i.e.*, no recycled steel).

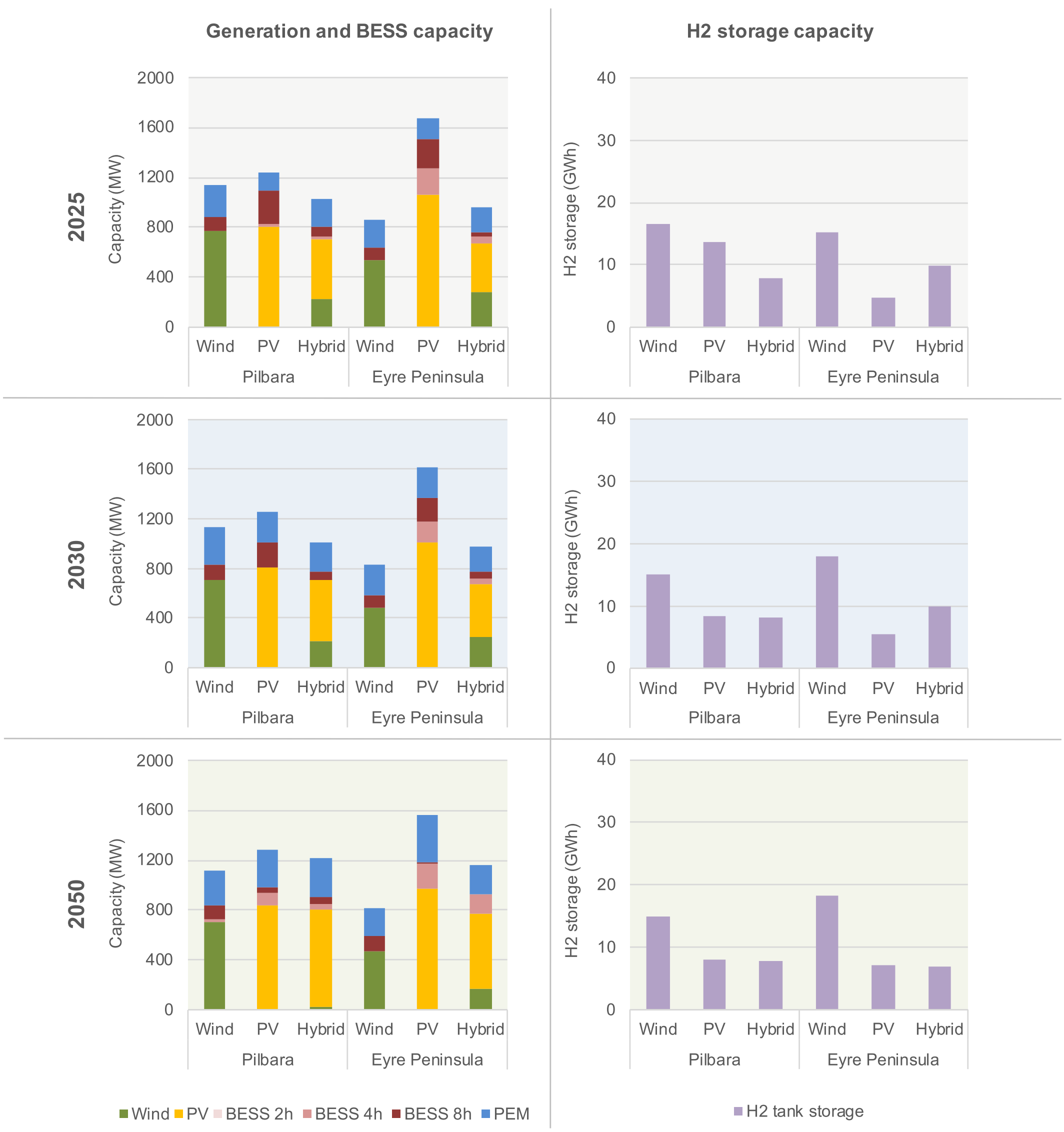

Fig. 8 — Renewable generation and storage plant capacity required to produce 1000 tonnes of steel per day.

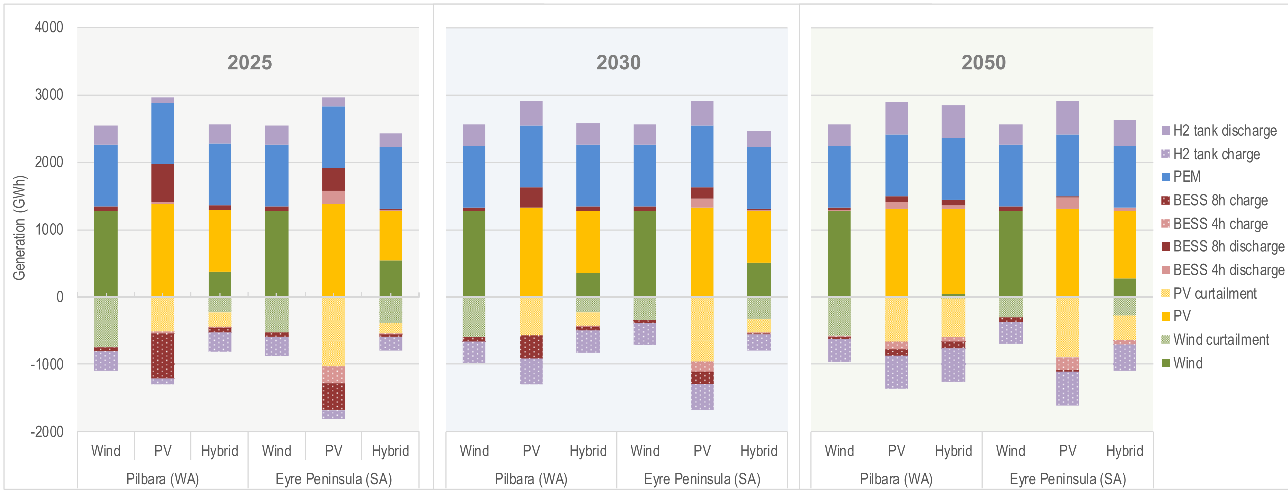

Fig. 9 – Aggregated annual generation, storage and renewable curtailment.

The levelized cost of liquid steel is then calculated based on plant costs of the optimized system components, operational expenditures, iron ore costs, and production volume, among other factors.

Results and discussion

Here, we use the MIP model to assess green steel production using diverse renewable energy sources in two predetermined strategic locations and present the modelling results. Specifically, we compare the modelling results of three scenarios: (i) wind power only, (ii) solar PV only, and (iii) a hybrid wind-solar PV system for plants situated in the Pilbara in Western Australia and the Eyre Peninsula in South Australia.

As a demonstration, Fig. 5 displays an example of one day out of the entire year of the modelled hourly interplay between the hybrid wind-solar PV generation system, BESS, PEM electrolysers, hydrogen tanks, the HDR shaft, and the EAF in the Eyre Peninsula on August 4, 2030 (using historical data from 2019). From Fig. 5, it is observed that the system predominantly uses solar energy for hydrogen production and system operation during the daytime, with excess energy stored in the BESS and hydrogen tank when solar energy is at its peak. Wind and solar energy are also most curtailed during this period. When the sun sets, the system depends on wind and storage systems for continuous operation. Fig. 6 illustrates the state of charge of hydrogen tanks for the whole simulated year of 2030, segregated by energy source and region, with measurements recorded in GWh. The results demonstrate that a solar PV-powered system requires a lesser amount of hydrogen storage due to the widespread use of battery storage, enabling it to balance diurnal variation effectively. Conversely, a wind-powered system has the highest hydrogen storage requirement. The hybrid system, which combines both wind and solar PV, necessitates moderate hydrogen storage due to a compromise between long-term seasonal storage and short-term daily storage needs.

The time-based simulation of system operation described above has important implications for future renewable energy and hydrogen projects. It highlights the significant influence of energy source selection on storage requirements and suggests that hybrid systems may be a viable alternative. By modelling system operation at an hourly resolution, we can estimate how changes in renewable energy technology may impact the overall cost of production and the distribution of costs. We accomplish this by comparing the current cost of energy generation and storage technologies with forecast prices for 2030 and 2050. Additionally, we evaluate the sensitivity of the model to variations in cost assumptions.

The levelized costs of steel production in 2025, 2030, and 2050 with various generation configurations are presented in Fig. 7. The figure shows the relative contribution of individual components to the lowest cost of steel production in the selected regions. Two additional figures showing the aggregated annual generation from each plant and the associated plant capacity to meet the daily production target of 1000 metric tonnes of crude steel are presented in Figs. 8 and 9, respectively.

The projected costs of green steel production, as shown in Fig. 7, are expected to decline significantly over time. This decline is attributed to improvements in power generation, energy storage, and hydrogen production technology. The balance between wind and solar power sources is greatly influenced by cost projections and the ability to manage variations in wind and solar resources. In 2025, differences in the cost of wind and solar power generation will result in significantly different ratios of both power sources, while by 2050, the optimal balance of wind and solar power will be similar at both locations due to the projected decline in solar power costs. Cost analysis further suggests that using wind power alone for steel production in the Pilbara region is prohibitively expensive due to significant overcapacity and curtailment caused by high seasonal variations in wind resources. In contrast, solar PV-powered systems are approximately 20% cheaper than wind-powered systems in the Pilbara in 2025 and 2030. However, they require a larger amount of battery storage to operate overnight. By 2050, when solar PV prices are expected to decline to $552/kW, a 40% reduction from $906/kW in 2025, overbuilding PV with increasing seasonal

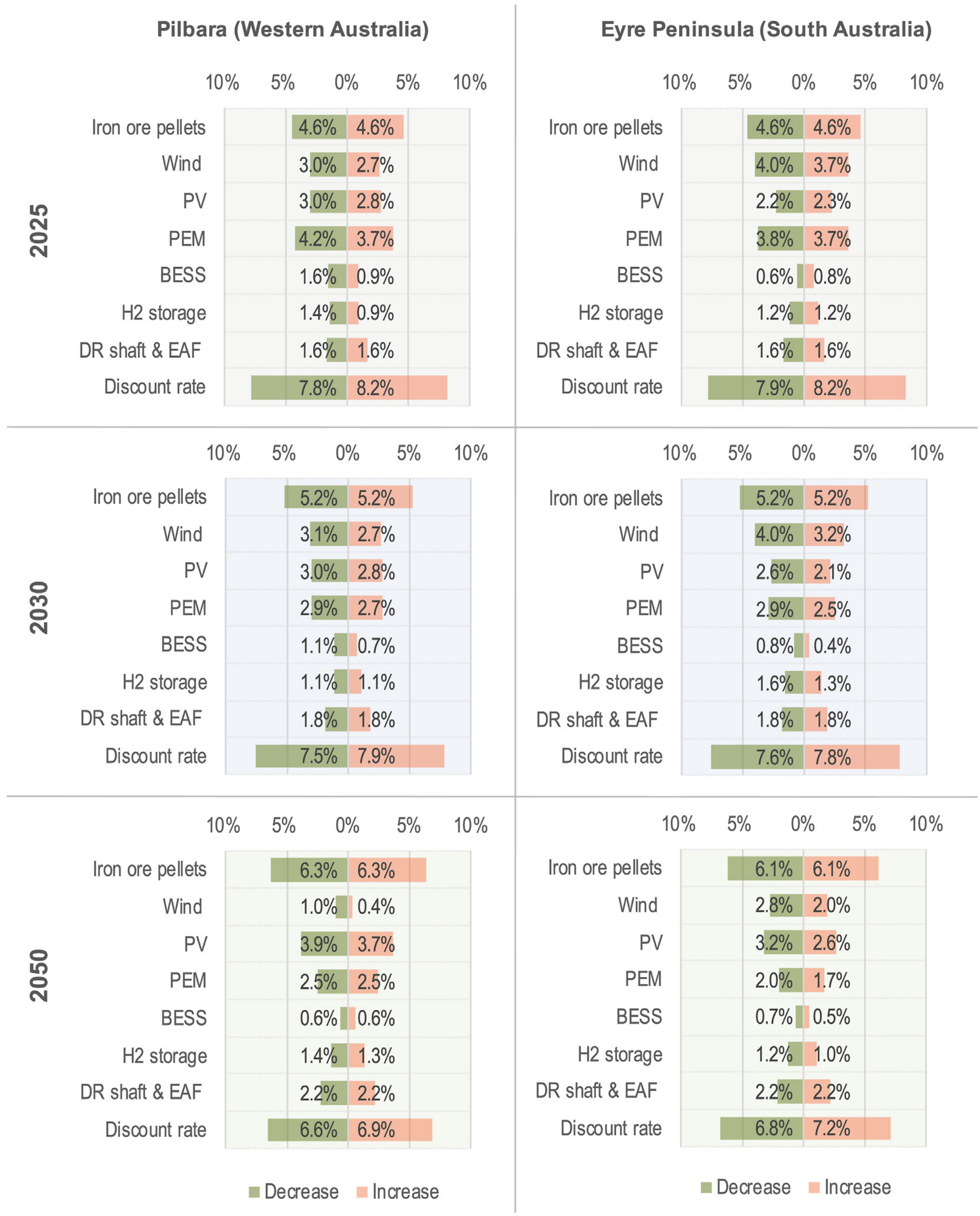

Fig. 10 – Tornado diagrams showing the sensitivity of the cost of green steel production to various input parameters in the hybrid wind-solar PV system considered with a 20% change (decrease and increase) in iron ore pellet price, technology CAPEX, and discount rate.

curtailment will be more cost-effective than storing the energy. Although battery costs are declining, their application is limited by their storage time.

Conversely, in the Eyre Peninsula, solar PV-powered steel production systems will be more expensive than wind-powered systems in 2025 and 2030 due to a strong seasonal shortfall in PV generation during the winter season. The optimization model employs a smaller PEM electrolyser and overbuilds solar PV, resulting in significant curtailment. Large 4- and 8-h battery systems are employed to balance solar diurnal variability as the most cost-effective option, and hydrogen storage plays a less important role than batteries. However, this situation will change by 2050 when solar PV and PEM electrolysers become more affordable. The overcapacity of solar PV and PEM electrolysers would be more economically viable when supplemented by hydrogen tank storage.

Most importantly, the model further highlights the benefits of an optimized mix of wind and solar energy sources, which results in increased plant capacity factors (Fig. 8), reduced renewable curtailment (Fig. 9), and lower overall production costs (Fig. 7) for both the Pilbara and the Eyre Peninsula. A relatively small amount of battery storage and hydrogen storage is sufficient for the hybrid wind-solar system. This is due to the enhanced system's ability to balance energy supply and demand from both smelting and hydrogen generation. These benefits are particularly pronounced in the Eyre Peninsula, where renewable energy generation costs are similar for each scenario; however, significant cost savings are achieved through reduced hydrogen and battery storage costs in the hybrid wind-solar system.

There are considerable uncertainties surrounding the various costs associated with green steel production, and a change in the cost of one component may affect the optimal configuration and operation of the green steel plant. To address this, a sensitivity study was conducted using the MUREIL model to examine the impact that changes in these prices might have on the final cost of green steel in the hybrid wind-solar PV system. In the sensitivity study, the costs associated with iron ore pellets, wind, solar PV, electrolysis, battery and hydrogen storage, and the DRI shaft and electric arc furnace were varied by ±20%, as was the discount rate. Each of the four scenarios was then rerun in the MUREIL steel model using the updated costs and rates, and the resulting steel price was compared to that obtained with the baseline cost.

Based on the results presented in Fig. 10, the sensitivity analysis indicates that the cost of producing green steel is most sensitive to the discount rate in the short term (2025 and 2030). This is expected due to the high initial investment costs associated with steel and hydrogen production, along with the extended timeframes of these projects. This finding highlights the potential for government policies to reduce financing costs, such as offering low-interest loans and implementing strategies to mitigate risks, which would ultimately incentivize investments in green steel projects.

Concerning individual plant components, green steel production is most sensitive to short-term fluctuations in wind, solar PV, and electrolyser costs. However, renewable energy costs are predicted to fall, and this decrease is expected to be accompanied by cost reductions in battery storage and hydrogen electrolysis [49,54]. These technological improvements will result in a net reduction in the cost of green steel by around 24% in the Eyre Peninsula and 27% in the Pilbara. The decrease in energy costs also implies that green steel will become increasingly sensitive to the price of pelletized iron ore. By 2050, the iron ore price will have a stronger influence on the cost of green steel production. This result illustrates the urgent need for research on new processing technologies for the direct reduction and beneficiation of low-quality ores today.

Future work could further explore the site-specific attributes of the Pilbara region and Eyre Peninsula, such as access to hydrogen geological storage and the National Electricity Market, in further reducing production costs. The MIP model showed that the 1000 t liquid steel per day plant capacity requires 6–15 GWh of hydrogen storage to balance seasonal renewable energy variability, which is well within estimates for some Australian salt formations [55,56] for large-scale hydrogen storage. Although geological storage was not explicitly considered in this study, reducing the cost of tank storage by 20% in the sensitivity analysis suggests the economic benefit of low-cost geological storage in the Pilbara region. For a wind-only power system, the need for support from low-cost geological storage would be significant due to the pronounced seasonal variation of the wind resource in the Pilbara region, as illustrated in Figs. 6 and 2. In contrast, grid connection in South Australia may be an attractive option, given the high penetration of renewable resources in the SA electricity market and extended periods of low, and often negative, electricity prices. By participating in the electricity spot market and operating flexibly, green steel projects could reduce production costs, maintain grid stability, and unlock wider system benefits through sector coupling.

Our analysis has focused on the domestic production of green DRI-EAF steel, but there are trade-offs to consider when determining the optimal roles of green hydrogen and green DRI in the global iron ore-steel value chain. For example, DRI exports could be processed in existing international EAF facilities, which would reduce local capital expenditure requirements. However, this would bypass the liquefaction process typically required for shipping liquid hydrogen, including its associated costs and energy requirements [57]. Additionally, transportation costs for DRI are higher than those for green steel. Under certain conditions, DRI can reoxidize and potentially self-ignite, but this risk can be reduced with appropriate storage and shipping precautions [58], or by compressing the DRI pore structure to produce hot briquetted iron, which has a significant lower ignition risk [59]. Further research is needed to consider the optimal role of international shipping within Australia's iron ore-steel value chain, taking these complexities into account.

Our analysis has also focused on the iron ore-green steel value chain through standalone projects. However, integrating DRI-EAF steelmaking within a hydrogen hub [7] could potentially improve competitiveness by hedging electrolysis and renewable energy generation production costs with other industries. For instance, optimal green hydrogen production potential (Fig. 1) could be leveraged to supply both domestic and international consumption.

Australia's competitiveness also depends on the international shift towards carbon trading, for instance through the European Union's Carbon Border Adjustment Mechanism (CBAM). The average global emission intensity of steel is 1.85 t CO2 per t [60]. A CBAM price of EU154, at current exchange rates (i.e., EU1 = US$1.05), would make our off-grid green steel production cost estimates (Fig. 7) competitive with conventional approaches by 2050. Depending on future markets and production cost reductions, there may soon be an opportunity cost to Australia for not producing green steel. This vulnerability also extends to Australia's hematite DSOs, given their reliance on BF-BOF steelmaking.

Global steel manufacturers are actively seeking innovative methods to use lower-grade iron ore in direct reduced iron processes due to the scarcity of high-grade iron ore. One alternative is to incorporate a melting phase and employ a basic oxygen furnace instead of an electric arc furnace for steel production, as BOFs offer more adaptability with regard to iron ore quality and contaminants [61]. Fluidized bed reactor (FBR) technology, such as HyREX [62], HYFOR [63], and Circored [64,65], allows for the direct use of fine ores. This eliminates the need for iron ore pelletization or agglomeration. Although these processes hold the potential to utilize lower-grade iron ore, challenges still remain, as employing DRI from lower-grade ores diminishes efficiency (and iron recovery) in steel smelting due to losses incurred from gangue removal.

The demand for green steel and hydrogen from both domestic and international markets would provide a crucial impetus for their production and use, giving investors and innovators the necessary market signals. Government policies that support the expansion of renewable energy sources and the establishment of a domestic hydrogen economy are crucial in creating an environment that is conducive to the production of green steel using local resources. In the short to medium term, a green premium would also be beneficial to jumpstart the green steel industry, which is still in its early stages of development. Since green steel production requires substantial investments in renewable energy infrastructure and is currently more expensive than traditional steel production, a premium would provide the necessary financial support. This support would help get the industry off the ground. High-end industries [66] such as automotive and aerospace may be better positioned to afford a green premium for steel production, as they often have higher margins and prioritize sustainable practices, making them more willing to invest in environmentally friendly alternatives. As green steel production technology and infrastructure continue to develop, the cost premium is likely to decrease, making it more accessible to a wider range of industries. In addition, construction companies seeking to obtain green building certifications and prioritize sustainable building practices may also be willing to pay a premium for green steel.

Transitioning to green steel production on a global scale will require a significant amount of land. In 2019, global production of fossil-fuel based crude steel amounted to 1875 million tonnes [20]. To replace just 1% of this with green steel, and utilizing the plant capacity depicted in Fig. 8, the least-cost option in 2030 would require a minimum of 25 GW of solar PV, 11 GW of wind, and 1047 square kilometers of land in the Pilbara region. Achieving the same objective would necessitate a minimum of 22 GW of solar PV, 13 GW of wind, and 1054 square kilometers of land in the Eyre Peninsula, based on the installed power density of onshore wind turbines (21 MW/km^2) [67] and utility-scale solar farms (50 MW/km^2) [68] in Australia. As the green steel industry grows and evolves, it will be equally important to consider the land use implications and work towards sustainable solutions that minimize the impact on natural habitats and ecosystems.

Conclusions

Green steel – produced using hydrogen and electricity from renewable energy sources – provides both the means to decarbonize steel manufacturing and facilitate the growth of the international hydrogen industry . This represents a critical contribution to the global effort in achieving net-zero emissions by 2050. Our study highlights Australia's competitive advantages in this space by leveraging its renewable energy and hydrogen resources, iron ore reserves, existing infrastructure, and mining expertise. Many current iron ore mining centres are also particularly suited for hydrogen production from renewable resources due to the enabling power and transportation infrastructure built to service existing mining operations. Our research emphasizes the considerable benefits of strategically positioning hydrogen production facilities (i.e., hydrogen hubs), iron ore mining operations, and steel manufacturing plants in close proximity to one another. This co-location approach can significantly reduce the costs associated with long-distance hydrogen transportation and extensive, long-term hydrogen storage.

Flexible green steel production, enabled by the hydrogen electrolysis and electric arc furnace system, presents significant economic opportunities for Australia. Here, we have presented case studies that provide a more detailed analysis of green steel production in the Pilbara region in northwestern Australia and the Eyre Peninsula in South Australia. Our study considers how the practical application of the HDR-EAF system will be influenced by the volatility and mix of renewable power sources and other technical concerns. The cost-optimal design of the system is largely driven by technology costs, plant operational constraints, and local renewable variability. The modelling results illustrate how an optimized mix of wind and solar can significantly reduce energy storage requirements and decrease the cost of green steel production overall. The results also indicate that while green steel costs are most strongly affected by renewable energy generation and storage costs today, they will become increasingly sensitive to the iron ore price in the long run.

In addition to these technical considerations, the success of the green steel industry will also depend on government support, including measures such as low-interest loans, regulatory incentives, and policies that promote the growth and development of the industry. For example, funding for research and development, infrastructure investment, and subsidies for early adopters can help to de-risk investment in green steel projects and accelerate their commercialization. Moreover, policies that support the scaling up of renewable energy and the development of a hydrogen economy can create a more conducive environment for the production of green steel. The successful development of domestic green steel production would require significant investments in renewable energy infrastructure and advanced technologies. However, this effort would not only support Australia's long-term economic growth but also strengthen its position in the global transition to a low-carbon economy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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