Contributing to regional decarbonization: Australia's potential to supply zero-carbon commodities to the Asia-Pacific

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Abstract
The Asia-Pacific has experienced prodigious growth in energy use and is by far the world's largest greenhouse-gas emitting region. Australia has played a leading role in meeting the region's energy and resource needs, becoming the world's largest exporter of coal, liquefied natural gas, iron ore, and alumina. Our analysis shows that these exports are tied to sizeable consequential emissions at the point of use or processing, accounting for about 8.6% of the total greenhouse gas emissions of the Asia-Pacific. The paper investigates three pathways by which Australia could instead export zero-carbon energy and products: direct exports of renewable electricity via sub-sea cables, exports of zero-carbon fuels such as green hydrogen, and the export of "green" metals processed from Australian ores using renewable energy. Carrying out robust, high-level calculations we find that Australia has the land and renewable energy resources to become a key exporter of these commodities. Realization of this potential relies on ongoing cost reductions, growing demand-side interest linked to meeting ambitious emission reduction targets in the region, and the development of cross-border frameworks for clean energy trade. If it were to achieve this goal, Australia could make a sizeable contribution to regional decarbonization via renewable-energy based exports.

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The Australian National University Grand Challenge: *Zero-Carbon Energy for the Asia-Pacific* transdisciplinary research project is a $10m investment between 2019 and 2023 that aims to help transform the way Australia trades with the world. It comprises five interrelated projects: Renewable Electricity Systems, Hydrogen Fuels, Energy Policy and Governance in the Asia-Pacific, Renewable Refining of Metal Ores, and Indigenous Community Engagement. The Grand Challenge's goals include developing zero-carbon export industries, creating new paradigms in benefit-sharing, and developing technologies, polices and approaches which can be applied in the Asia-Pacific and beyond.

1. Introduction

At the time the Kyoto Protocol was negotiated, the Asia-Pacific – a region spanning East Asia, Southeast Asia, South Asia, and Oceania – accounted for less than a quarter of global carbon dioxide (CO_2) emissions from fuel combustion. Rapid growth in fossil fuel use, especially in China and India, saw this increase to 49% by 2019 [1]. The International Energy Agency (IEA) expects that under stated policies the Asia-Pacific will account for almost two-thirds of global energy use growth over the coming two decades [1]. If this energy is emissions-intensive, the world will remain on a path towards more than 2°C of temperature increase relative to pre-industrial levels, contrary to the goals of the Paris Agreement [2,3]. Local air pollution problems would be exacerbated in cities such as Jakarta and Hanoi, resulting in large health and economic costs [4].

The Asia-Pacific has also become the world's largest producer and consumer of heavy materials such as steel and aluminium [5]. Ore processing and metal production are currently carried out in highly emission-intensive ways, with steel manufacturing relying heavily on coal as a fuel and reduction agent. Strong growth in demand for materials linked to long-term needs for investment in urban and other infrastructure [6] is expected as economies recover from the COVID-19 downturn over coming years. Australia's near neighbour, Indonesia, has the potential for substantial demand growth and may enter the group of the world's four largest national economies in the next several decades [7].

Australia is currently the world's largest exporter of both coal and liquefied natural gas (LNG) [8] and as of 2018 was ranked behind only Russia, the United States, and Saudi Arabia in terms of overall fossil fuel energy exports [9]. Australia is also the world's largest producer of iron ore and bauxite [10] and largest exporter of iron ore and alumina [11]. Australia's renewables sector is booming, with sizeable investments in solar and wind power projects. While Australia accounts for only about 0.3% of the world's population [12], it is a key country in terms of commodity supply and the ability to contribute to regional and global decarbonization.

In this paper we calculate the greenhouse gas emissions that occur as a consequence of the use and processing of key Australian export commodities in the form of coal, natural gas, iron, bauxite, and alumina. The great majority of these exports are to the Asia-Pacific (section 2). We find that consequential emissions tied to these Australian exports account for a significant fraction of the region's total emissions. These emissions dwarf Australia's domestic emissions.

The paper then explores three potential pathways for Australia to reduce its consequential emissions and play an important upstream role as a supplier of zero-carbon exports to the Asia-Pacific (section 3). Specifically, we analyze the potential to export renewable electricity via sub-sea cables, zero-carbon fuels such as green hydrogen, and "green" metals processed from Australian ores using renewable energy. We perform high-level calculations using generalized assumptions to quantify the ongoing renewable energy, land, and water requirements for Australia to become a sizeable exporter of zero-carbon electricity, liquefied hydrogen, aluminium, and steel (section 4 and Appendix). We also identity and discuss key economic challenges, required policy frameworks, and political and other dimensions of the potential new export model (sections 5 and 6).

The analysis indicates that adopting a new commodity export model centered on renewable energy and zero-carbon processed metals would allow Australia to make a sizeable contribution to decarbonization of the Asia-Pacific, assisting the efforts of major economies in the region to achieve emission reduction goals, including long-run net-zero emission targets. Australia also has the potential to serve as a demonstration of concept to other large commodity exporters that have the land and renewables endowments to decarbonize their exports. The results should thus be of broad interest outside the region.

This paper contributes to the literature on the potential for export decarbonization to assist in achieving regional and global emission reductions. It is well known that there are sizeable cross-border flows in emission-intensive products [13]. Prior papers have explored the possibility for coal export curtailment mechanisms to help in achieving emissions reductions [14,15]. The possibility for phase-outs of oil and natural gas exports has also been analyzed [16,17]. Gulberg [18] examined prospects for Norway to become a "green battery" for Europe through the provision of energy storage services via pumped hydro projects. However no prior study has estimated the potential emissions savings from a new zero-carbon export model for a major commodity exporter such as Australia or the land, energy, and water requirements for achieving such a model. Our paper does so at a time when efforts to reduce greenhouse gas emissions are ramping up and there is growing attention on the emissions embodied in traded products, as evidenced by the European Union's proposal for a carbon border adjustment mechanism [19].

The paper also contributes to the literature assessing new cross-border energy trade initiatives, whether low-carbon or otherwise. Prior literature has assessed projects such as the Association of Southeast Asian Nations (ASEAN) power grid [20,21] and the now-abandoned Desertec initiative [22]. Studies have also examined the viability of an electricity link between Australia and Asia [23,24]. Our focus is broader in that we analyze the potential for a new model of zero-carbon exports from Australia that would involve not only exports of zero-carbon electricity but also of hydrogen and commodities processed in Australia using zero-carbon energy (green steel and aluminium).

The methods employed in the paper to assess the consequential greenhouse gas emissions associated with key commodity exports and to calculate the land, energy, and water requirements for a new export model are new and involve simple but rigorous calculations using parameters from the extant literature. For example, average emissions factors for the production of iron ore and aluminium in China are obtained from recent studies [25,26]. These are used to calculate an approximate value for Australia's consequential emissions from exports of iron ore, bauxite, and alumina, the majority of which go to China. The methods are highly relevant for future analyses of export decarbonization for other commodity exporting countries.

2. Consequential emissions associated with key Australian exports

We first present calculations of the annual downstream CO_2 emissions, termed "consequential emissions", tied to several of Australia's principal commodity exports. These are scope 3 emissions occurring outside Australia that arise from combustion of exported Australian fuels plus the processing of exported ores and production of metals.

We base the analysis on Australia's thermal coal, natural gas, iron ore, and bauxite and alumina exports – referred to here as Australia's "benchmark exports" – in Australian financial year 2018–2019. Australia also exports other goods and services, but we restrict our focus to the above given the scale of the emissions associated with their use and/or processing and the potential for decarbonized alternatives to be exported in their place. To avoid double-counting, we do not calculate consequential emissions from Australia's metallurgical coal exports, as these are predominantly for steel production in the Asia-Pacific (using exported Australian iron ore).

In 2018–2019 Australia exported 210 million tonnes (Mt) of thermal coal, 75 Mt of LNG, 819 Mt of iron ore, 33.5 Mt of bauxite, and 17.6 Mt of alumina [11]. For each of thermal coal and LNG, the annual consequential greenhouse gas (GHG) emissions in megatonnes of carbon dioxide equivalent (MtCO$_2$-e yr^{-1}) from the combustion of exported fuels are given by:

$$G_{Fuel} = Q \cdot EC \cdot \left(EF_{CO_2} + EF_{CH_4} + EF_{NO_2} \right) \tag{1}$$

where Q is the quantity of the fuel, EC is an Australia-specific average per-quantity energy content factor, and EF is the average per-energy unit GHG emission factors during combustion. We calculate that the consequential GHG emissions associated with Australia's energy exports were about 511 MtCO$_2$-e yr^{-1} for thermal coal and 210 MtCO$_2$-e yr^{-1} for LNG in 2018–2019 (Table 1).

Table 1. Calculation of greenhouse gas emissions from thermal coal and LNG exports, 2018–2019.

Fuel	Quantity (Q) Mt yr^{-1}	Energy content factor (EC) GJ t^{-1}	Emission factor (EF) kgCO$_2$-e GJ^{-1}			Total GHG emissions (G) MtCO$_2$-e yr^{-1}
			CO$_2$	CH$_4$	N$_2$O	
Thermal coal	210	27.0	90	0.03	0.2	511
LNG	75	54.4	51.4	0.1	0.03	210

Note: Export quantities are from [11]. Average energy content factors are for thermal coal exports and LNG from [27]. Average emission factors are from [28].

Consequential emissions associated with Australia's iron ore exports are emissions that occur during the production of steel. We assume exported Australian iron ore to have an iron mass fraction of $F_{Fe\,ore} = 62\%$ [29] and use an average emissions intensity of crude steel production of $EI = 2.03$ MtCO$_2$ Mt^{-1}, the value for China in 2018 from [25]. In 2018–2019, 81% of Australian iron ore exports were to China in weight terms [11]. The CO$_2$ emissions from the processing of iron ore are then approximately:

$$G_{Fe\,ore} = M_{Fe\,ore} \cdot F_{Fe\,ore} \cdot EI = 1{,}033 \text{ MtCO}_2 \tag{2}$$

where $M_{Fe\,ore}$ is the mass of Australia's 2018–2019 iron ore exports.

Consequential emissions from Australia's bauxite and alumina exports occur during the processing of these commodities into aluminium overseas. Our calculations use a mass fraction of alumina in exported Australian bauxite of $F_{baux} = 50.27\%$ and a mass fraction of aluminium in alumina of $F_{Al_2O_3} = m_{Al_2O_3}/2m_{Al} = 52.93\%$, with $m_{Al_2O_3} = 102.0$ g mol^{-1}

and $m_{Al} = 27.98$ g mol^{-1} being the molar weights of alumina and aluminium respectively [30]. China accounted for 98% of Australia's exports of aluminium ores and concentrates by weight in 2018–2019 [31], so we use average emission intensities for Chinese aluminium production. Specifically, an average emission intensity of China's conversion of bauxite to aluminium of $EI_{Al_2O_3} = 12.97$ MtCO$_2$ Mt^{-1} of aluminium produced is used, the year-2018 value from [26]. From alumina to aluminium, we use an average emissions intensity for China of $EI_{baux} = 10.63$ Mt^{-1} of aluminium, also from ref [26]. Consequential CO$_2$ emissions from the processing of alumina and bauxite are then approximately:

$$G_{Al} = M_{baux}(F_{baux}F_{Al_2O_3})EI_{baux} + M_{Al_2O_3}F_{Al_2O_3}EI_{Al_2O_3} = 215 \text{ MtCO}_2 \qquad (3)$$

where M_{baux} and $M_{Al_2O_3}$ are the mass of Australia's 2018–2019 bauxite and alumina exports, respectively.

Total consequential emissions from Australia's benchmark exports are thus approximately 1,968 MtCO$_2$-e yr^{-1}, the sum of the consequential emissions for each of the commodities. Using greenhouse gas emissions data from CAIT [32], this equals about 4% of global annual greenhouse gas emissions, including emissions from land use change and forestry. Consequential emissions from Australia's benchmark exports vastly exceed Australia's domestic emissions (Figure 1). Australia thus has the potential to make a disproportionately sizeable contribution to regional and global emission reductions via decarbonizing its exports. Further details for the calculation are provided in the Appendix.

The vast majority of Australia's benchmark commodity exports are to countries in the Asia-Pacific. As of 2018, in weight terms the Asia-Pacific was the destination for:

- 93.5% of Australia's total coal exports [31]. We use this share as data are not available for thermal coal only.
- 99.7% of Australia's LNG exports [33].
- 99.8% of Australia's iron ores and concentrates exports [31].
- 99.6% of Australia's aluminium ores and concentrates exports [31].

Using the above shares we calculate that about 98% of the consequential emissions from Australia's benchmark exports occur in the Asia-Pacific (about 1,931 MtCO$_2$-e yr^{-1}). This equals about 8.6% of annual GHG emissions of the Asia-Pacific, calculated using GHG emission data from [32]. If Australia's domestic emissions are considered in addition to consequential emissions associated with the benchmark exports, the nation's activities contribute (either directly or indirectly) about 5% of global greenhouse gas emissions and 11% of emissions in the Asia-Pacific. See the Appendix for additional details.
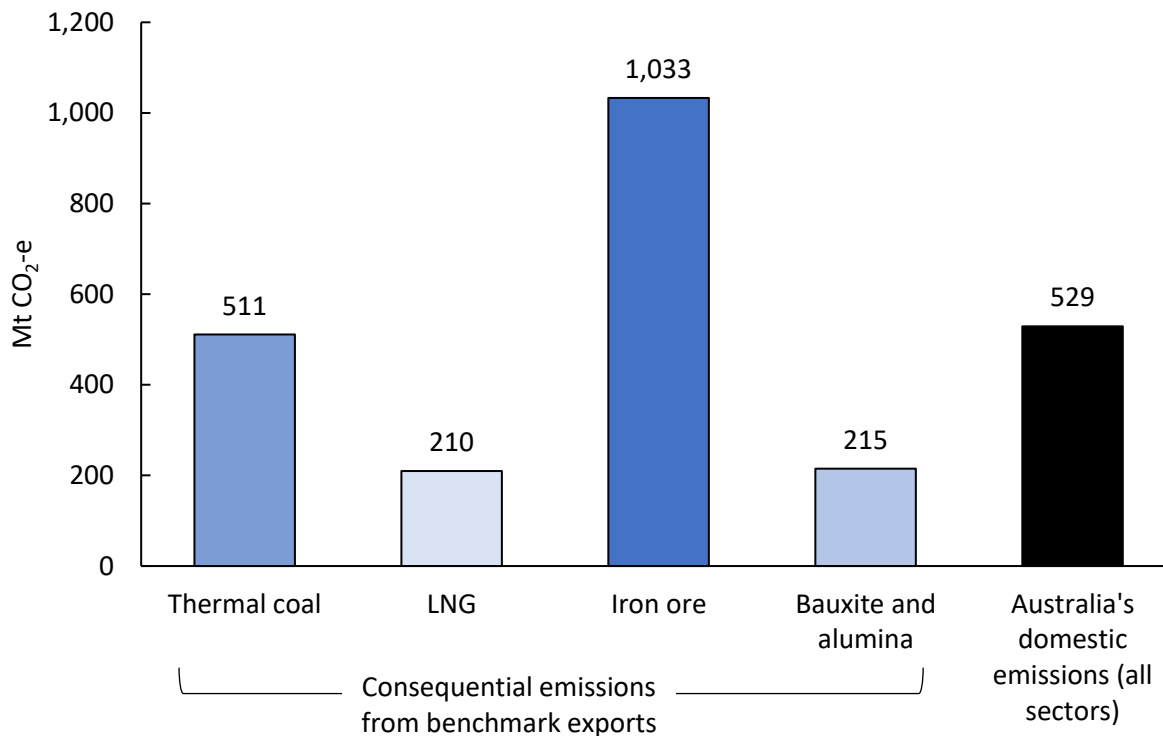
Figure 1. Consequential emissions associated with key Australian resource exports, 2018–2019.
Data are for the 2018–2019 Australian financial year. Consequential emissions are greenhouse gas emissions from the combustion of exported thermal coal and LNG plus the overseas refining of iron ore and bauxite and alumina. Emissions from metallurgical coal exports are not shown to avoid double counting (as these exports are used in steel production overseas). Domestic emissions [34] are also shown.

3. Pathways to zero-carbon energy trade

Australia is one of the world's best-endowed countries in renewable energy, blessed with sunshine, wind, and a large landmass. The country has recently been installing solar and wind generation capacity at the fastest per capita rate – more than 200 watts yr^{-1} – of any developed nation [35] and has the highest installed solar photovoltaic (PV) generation capacity per capita in the world [36]. Northern Australia experiences some of the best insolation in the world, exceeding 6.5 kWh m^{-2} day^{-1} in some locations (Figure 2). Yet much of Australia's solar and wind endowment remains untapped.

Given the suitable solar and wind conditions, multi-gigawatt solar and wind power plants in the most prospective locations in northern Australia could generate some of the cheapest electricity in the world using technologies that are already available and that are also improving over time [37,38]. Australia's iron ore and bauxite deposits are co-located with some of the best of these solar and wind resources, so new local processing opportunities are emerging [39]. Land is plentiful, and there are numerous sites that could be used for off-river pumped-hydro storage [40].
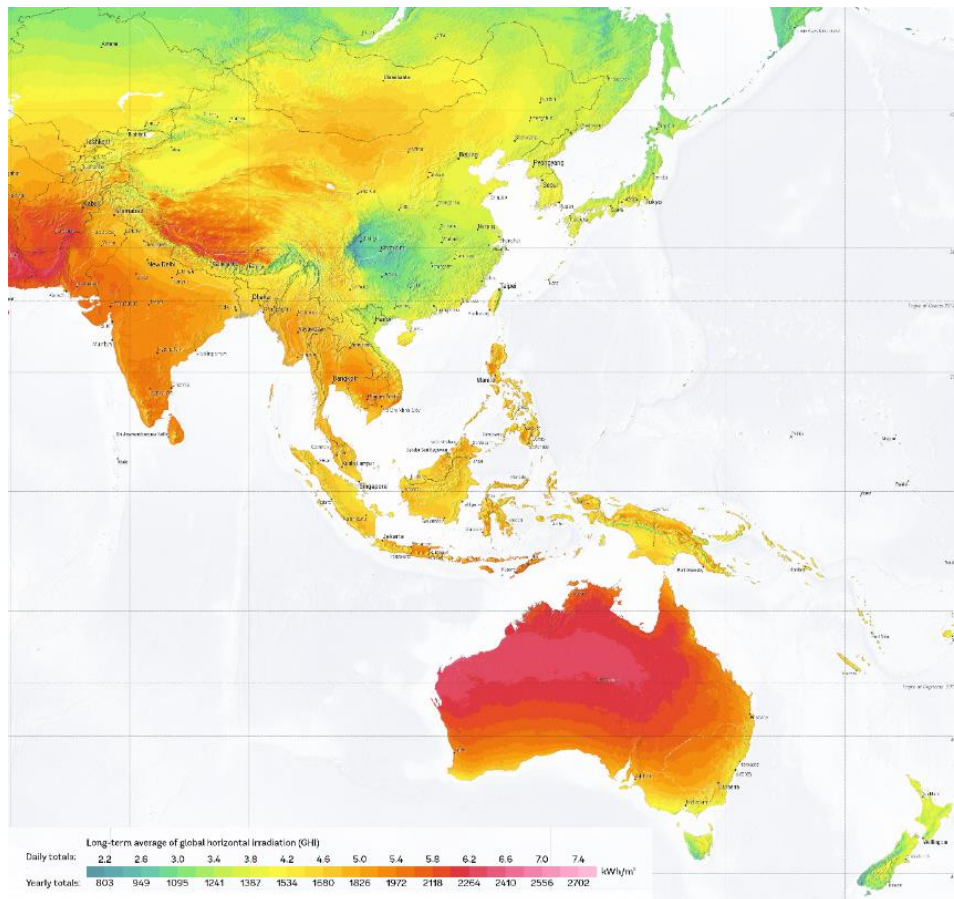
Figure 2. Global solar horizontal irradiation in the Asia-Pacific.
Source: World Bank [41].

There are three pathways via which Australia could become an exporter of zero-carbon energy (direct or embodied):

1. Direct exports of renewable electricity via sub-sea cables.
2. Exports of zero-carbon fuels such as green hydrogen, produced using electrolysis powered by renewable electricity.
3. Exports of products processed in Australia using renewable energy. Australia's large iron and bauxite endowments make processed ores, steel, and aluminium among the most promising.

Each is becoming increasingly viable over time. Inter- and trans-continental electricity trade is benefitting from the maturation of high-voltage direct current (HVDC) cable technology. Such cables are capable of transporting electricity at ±1,100 kilovolts over 3,000 km with losses of only about 10% [42] and can be laid sub-sea, alongside telecommunications cables. The private sector is currently pursuing the export of green electricity from Australia via a proposed Australia-Asia PowerLink [43], a multi-billion dollar project that would send power from Australia's Northern Territory to Singapore and potentially Indonesia via subsea cables of approximately 4,200 km. These cables would be multiples of the length of what is currently the world's longest subsea power cable, the North Sea Link power connection between the United Kingdom and Norway (720 km). The Australia-Asia PowerLink was given "major project status" by the Australian Government in 2020, and approval has recently been granted by the

Indonesian government for the cables to be laid through Indonesian waters [44]. While highly ambitious, analysis has supported the project's technical feasibility [45].

There is also growing interest in exporting hydrogen. Despite currently having a round-trip efficiency (electricity-hydrogen-electricity) of only about 30%, hydrogen has the advantage of transport flexibility given that it can be transported by ship, with no need to rely on fixed cable infrastructure. The governments of Japan, South Korea, and China have each expressed strong interest in hydrogen for transport, industrial, and other applications, with Japan's Basic Hydrogen Strategy [46] setting out ambitious adoption targets towards becoming a "hydrogen society". Ongoing research into and development of hydrogen storage and transport technologies aims to address problems associated with the small size of the hydrogen molecule and the low energy density and boiling point of the gas [47].

Hydrogen could be shipped in liquefied form [48] or could alternatively be converted to ammonia prior to shipping [49]. Green ammonia could be deployed to directly decarbonize the US\$50bn yr^{-1} global ammonia fertilizer market [50], co-fired for industrial and other energy needs, or reconverted back to hydrogen at the final market [51]. There is an established shipping trade in ammonia, and several private-sector projects are pursuing the export of green hydrogen derivatives including ammonia from Australia [52,53,54,55]. One, the Asian Renewable Energy Hub, was also granted major project status in 2020. The production of ammonia currently contributes about 1% of annual global CO_2 emissions [56]. Australia has the second-largest pipeline of announced green hydrogen projects in the world [57].

Steel is an essential component of the physical capital on which modern economies are built. Iron and steel production contributes about 7% of annual global greenhouse gas emissions [58], with almost three-quarters of the world's steel produced in the Asia-Pacific in 2020 [59]. China's overall stock of steel in use is expected to approximately double by 2050 [60], and strong steel demand growth is expected in India and elsewhere [61]. While progress in commercially-competitive decarbonized steel production is ongoing [62], direct electrolytic reduction processes have been demonstrated at lab scale [63] and pilot plants that use hydrogen to reduce iron ore are being developed in Europe and elsewhere [64,65]. As one example of interest in Australia, there is a private-sector plan to invest in direct-reduced iron production and an electric-arc furnace for green steel in South Australia [66].

Aluminium has wide applications in transport, construction, and consumer goods due to its light weight and resistance to corrosion. About two-thirds of the world's aluminium production is in the Asia-Pacific, with global and regional demand expected to boom over coming decades [67]. Aluminium smelting is electricity-intensive, directly and indirectly contributing about 1% of global greenhouse gas emissions [68]. Electricity from emission-free sources is able to reduce the bulk of these emissions. Further emissions avoidance requires the replacement of carbon electrodes by inert electrodes, a process in pilot development [69]. The use of renewable energy for the calcination of alumina to eliminate emissions in the Bayer process is also an active area of research [70].

4. Analysis of a new export scenario

Our analysis examines the feasibility of an export scenario for Australia that involves matching its major energy exports and its iron ore, bauxite, and alumina exports with equivalent flows of exports of zero-carbon energy and processed metals. It is based on a scenario in which Australia is assumed to:

1. Export the same quantity of energy in green forms as it exported in thermal coal and LNG in 2018–2019, and
2. Process currently-exported iron ore, bauxite, and alumina (as measured in 2018–2019) into green steel and green aluminium prior to export.

We assume that, in energy terms, 80% of the energy exports would be liquefied hydrogen and 20% would be electricity exported via sub-sea cables. Green metals would be produced using renewable electricity and green hydrogen as energy and reduction sources, respectively. The amount of energy required for hydrogen production is estimated based on currently achievable efficiencies and includes the energy required to desalinate water as a feedstock and liquefy the hydrogen for storage and transport. The energy and hydrogen required for metals processing is calculated using industry averages and/or estimated thermodynamic requirements.

In our scenario, the energy required for the zero-carbon exports would be provided by renewable electricity: half by wind power and half by solar PV. We assume that the solar and wind plants would be co-located in northwest Australia, an area with some of the best renewable resources in the world. We use capacity factors of 32% for solar PV and 44% for wind, as relevant for numerous sites in the region [41,71]. The calculations and assumptions are presented in detail in the Appendix and the results described here. The scenario does not include the conversion of current in-country aluminium and steel production to zero-carbon methods.

4.1 Export quantities

We begin by calculating the export quantities of green electricity, hydrogen, steel, and aluminium equivalent to Australia's 2018–2019 exports of thermal coal, LNG, and iron ore, bauxite, and alumina. These are shown in Table 2, with detailed calculations in the Appendix. Under the scenario, Australia would export about 540 TWh yr^{-1} of direct electricity to Asia and about 65 Mt yr^{-1} of green hydrogen, the latter produced using about 4,200 TWh yr^{-1} of electricity. The direct electricity exports would require about 62 GW of cable capacity, meaning at least five cables with capacity equal to what is currently the world's largest (12 GW) and longest (3,300 km) overland HVDC cable, in China [42]. Cross-border electricity transmission infrastructure remains limited in Southeast Asia, so this would may be near to Australia's maximum feasible electricity exports over coming decades given the constraints on transmitting electricity around the region.

The new export model would involve about 510 Mt yr^{-1} of green steel exports and 18 Mt yr^{-1} of green aluminium exports. These are sizeable flows and would involve a substantial ramping up of Australian production of these metals. However, using data from the IEA [1] Sustainable Development Scenario, Table 2 shows that these would still remain minority contributions to Asia-Pacific output of these metals in 2040.

Table 2. Australian export quantities under an ambitious zero-carbon export scenario.

Product	Unit (yr^{-1})	Quantity	Australia's current production (all forms)	Production in the IEA Sustainable Development Scenario (SDS), 2040	
				Asia-Pacific	World
Electricity	TWh	540	264	19,886	38,774
Hydrogen	Mt	65	0	46	100
Steel	Mt	510	6	1,376	1,993
Aluminium	Mt	18	2	106	181

The scenario involves Australia exporting green electricity and green hydrogen (liquefied) to equal the energy content of current thermal coal and natural gas exports, plus green steel from exports of iron ore and green aluminium from exports of bauxite and alumina. 2018–2019 data are used. See the Appendix. Production data [11,72] include non-green sources. The SDS data are from the IEA [1]. Asia-Pacific hydrogen production in 2040 is not reported by the IEA. To create a proxy, we multiplied the IEA's expected Asia-Pacific share of global primary energy use in 2040 by the IEA's expected world hydrogen production under the SDS.

4.2 Energy and land requirements

The energy requirement for the new export model would be sizeable. Much would be for hydrogen production given the electricity-intensive nature of the electrolysis and liquefaction processes. In total we estimate that about 7,000 TWh yr^{-1} of solar PV and wind electricity generation would be needed, about 27 times Australia's current annual electricity generation [72] of 264 TWh yr^{-1}. If wind and solar farms are co-located with a 50:50 solar-to-wind generation mix, this would involve a land area of about 168,000 km^2 – about 2% of Australia's land mass (Figure 3). To provide a comparator, this is equivalent to about 4% of the area currently used for livestock grazing [73].

4.3 Water requirements

Each kilogram of hydrogen produced by electrolysis would require about 9 L of water [74]. In contrast, the fuel cycle of conventional natural gas consumes less than 0.33 L kg^{-1} of gas produced and for shale gas the water requirement is roughly 1 L kg^{-1} [75]. In total we calculate that the new export model would require about 865 GL yr^{-1} of water for hydrogen production, equivalent to about 80% of the current water usage of the entire Australian mining industry [76]. Water use would need to be subject to tight environmental safeguards, as would all other aspects of the new export model.

Water requirements could in part be met by desalinated seawater, with desalination plants co-located with hydrogen production in coastal areas. Desalination would add to costs, but the additional energy requirements are relatively small: the energy required for desalination with reverse osmosis is 4 Wh L^{-1} or 36 Wh kgH$_2$$^{-1}$ [77], less than a thousandth of the energy needed to generate 1 kg of H$_2$ with electrolysis. In total, desalination would require about an additional 3.5 TWh yr^{-1} of electricity. Australia already has a number of desalination plants and the know-how for their planning and operation.
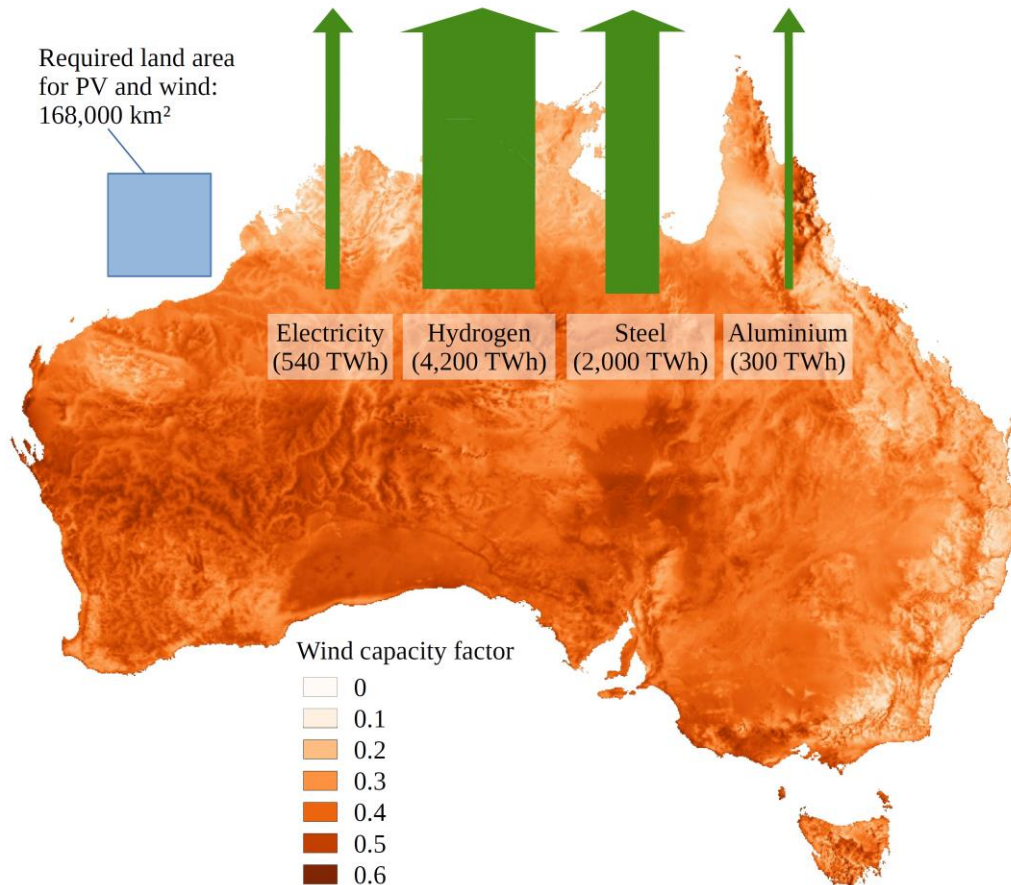
Figure 3. Land and electricity requirements under an ambitious zero-carbon export scenario.
Arrow widths are proportional to the electricity generation requirements shown. The wind capacity factor is from the World Bank [71]. The land area is shown to three significant figures and the electricity requirements to two significant figures. See the Appendix for additional details on the calculations.

4.4 Off-river pumped hydro energy storage
The electricity produced by wind and solar PV installations varies diurnally and with the weather. Some energy storage will be needed to guarantee the reliability of electricity export supply and optimize the economics of downstream processes [78]. Based on scaling up previous calculations for a 100% renewable National Electricity Market (NEM) [79], exporting 540 TWh yr^{-1} of electricity would require about 2,100 GWh yr^{-1} of energy storage. This calculation recognizes that heads (h) in the northwest of Australia for pumped hydro are of the order of 200 m and assumes that an average depth (d) of reservoirs of 20 m. The density of water (ρ) is 1,000 kg m^{-3}, gravity (g) is 9.8 m s^{-1}, and hydroelectricity generation efficiency (ε) is assumed to be 90%. The land area for energy storage requirements for direct electricity exports can then be obtained by rearranging:

$$E(GWh) = \varepsilon.r.Area.d.g.h/(3.6*10^{12}) \tag{4}$$

On this basis we calculate a total required area for upper reservoirs of about 215 km^2. An equivalent area would be needed for lower reservoirs, meaning a total of about 430 km^2 for off-river pumped-hydro storage reservoirs. Mapping confirms that this area would be

available near key solar and wind sites, and with water storages that can typically be supplied by natural rainfall [40]. Additional energy storage would be required for a decarbonized national electricity grid, however much of this would not be activity-specific. Aluminium producers, for example, rely largely on grid-wide reliability. Electricity grids in Australia currently meet a high reliability standard, and estimates of the cost of balancing intermittent energy supplies on the Australian electricity grid are relatively modest [38].

5. Economic dimensions

There are various economic requisites for the realization of the zero-carbon export scenario analyzed in this paper. Strong demand for zero-carbon commodities is vital, underpinned by the need for countries to make progress towards meeting emissions reduction targets [80]. Momentum for a low-emissions future in the Asia-Pacific is building. In September 2020 China announced a commitment to reach carbon neutrality by 2060, a change that requires a fundamental shift in its economic model. In October 2020 the leaders of Japan and South Korea each committed to reducing national emissions to net zero by 2050. Ambitious long-run emissions reduction targets have also been announced by the leaders of Asia-Pacific countries including Indonesia (net zero by 2060), India (net zero by 2070), Singapore (net zero as soon as viable in the second half of the century), and New Zealand (net zero other than methane by 2050). Policy settings and trade models are yet to be adequately calibrated to the achievement of these goals, however.

In addition to the need for climate action, Asia-Pacific countries have pressing needs to address local air pollution problems. Coal appears to have entered a process of structural decline, with the IEA [1] anticipating a 2% reduction in use in the Asia-Pacific by 2040 under stated policies and a 62% reduction under a Sustainable Development Scenario. The IEA net-zero by 2050 scenario involves about a 90% decline in coal use by 2050 [81]. Australia's exports of coal have indeed already begun to decline, falling by 7% in energy content terms by 2020 from the year-2015 peak [8]. In 2020 China restricted imports of coal from Australia during a period of political tensions.

An advantage for Australia is having substantial experience in the large-scale production and export of primary commodities. Lessons from the LNG industry's development, for example, are highly applicable. One is the importance of foreign capital inflows for project development. Another is the value of secure long-term contracts with take-or-pay arrangements [82]. Such contracts reduce the risk faced by project developers, placing downward pressure on financing costs and helping to get projects started. There is also a potential role for public underwriting of first-mover projects, such as by back-up off-take commitments [83].

Solar PV and wind are now the cheapest forms of electricity in Australia, with a levelized cost of electricity (LCOE) in the order of US$30 MWh^{-1} at the best sites [84,85]. Costs are expected to continue to decline. In a 2020 reverse auction run by the Australian Capital Territory, for example, the 14-year agreed feed-in tariff came in at below $US30 MWh^{-1} in real present-value terms, well below levels seen in early auctions under the scheme [86]. In Australia's neighbours, solar and wind conditions are less favorable and the cost of land is higher. For instance the LCOE for utility-scale solar PV power in Indonesia is typically calculated to be more than double that at the best sites in Australia, and wind power in Indonesia is much less competitive from a cost viewpoint [87,88].

Given their proximity and relative cost differentials, Indonesia and Singapore are two of the most attractive markets for direct electricity exports from Australia. The year-2019 average cost of electricity generation in Indonesia was US$98 MWh^{-1} and the wholesale electricity price in Singapore about US$72 MWh^{-1} (Figure 4). Provided that transmission and other project costs can be minimized, this means there are potential gains from cross-border trade given Australia's low LCOE for solar and wind power generation. A recent study by ref [85] concluded that, at around US$70/MWh, the levelized cost of supplying Singapore using electricity from large-scale solar farms in Australia is currently similar to the levelized cost of natural gas-fired electricity generated in Singapore inclusive of domestic carbon tax payments. This does not include the cost of energy storage to smoothen the supply profile from Australia, however. Importantly, solar, cable, and storage technologies continue to improve, boosting the competitiveness of clean electricity export projects over local fossil fuel projects over time. Singapore also intends to increase its carbon tax rate.

A combination of economics and politics will determine the markets in which hydrogen fuels can compete with the higher technical efficiency of electricity. The cost of green hydrogen is falling, although is yet to reach parity with higher-emitting alternatives. The CSIRO [89] expects that production costs at the best sites could fall to as low as US$1.6 kg^{-1} by 2025. Australia's Technology Investment Roadmap [90] states a goal of producing at below US$1.4 kg^{-1}. With industry scale-up it is also possible that the cost of green hydrogen may fall to below US$1 kg^{-1} by 2050 [91]. This is expected to be helped by declines in electrolyzer costs of around 55–75% over the next two decades [1] as learning effects are realized and standardization and automation of electrolyzer manufacturing occurs [92]. Hydrogen produced from fossil fuels with emissions captured and stored is not likely to be subject to the same pace of cost reduction [1]. A recent study by Vartiainen et al. [93] estimated that the potential levelized cost of green hydrogen production in Western Australia is among the lowest in the world, alongside sites in South Africa and Chile.

Japan's 2017 Basic Hydrogen Strategy targets a delivered cost of hydrogen of US$1.3 kg^{-1} by 2050. Achieving this cost level at the import destination requires maturation and cost reductions in hydrogen liquefaction, storage, and transport. Liquefaction or ammonia conversion currently [74] costs around US$1 kgH$_2$$^{-1}$, and international transport of hydrogen remains at a nascent stage. The IEA [94] concluded that by 2030, green hydrogen imports to Japan from Australia could cost around US$4.2 kg^{-1}, undercutting the cost of local supply by about US$1 kg^{-1}. Further declines are anticipated over time if the industry is ramped up.

The production of green steel using hydrogen direct reduction has been estimated to involve additional costs of about one-third relative to greenfield investments in basic oxygen furnace steel production [95], although this premium would be lower if using the lowest-cost renewable energy resources. Like green hydrogen, the competitiveness of green steel is likely to strengthen with technological improvements and industry scale-up. For aluminium, the most important energy requirement is low-cost and reliable electricity. Provided there is adequate investment in energy storage and transmission [96], Australia will have a strengthening comparative advantage in this input. Australia's grid-based wholesale electricity prices have already started to decline as a result of the entry of solar and wind generators [97].
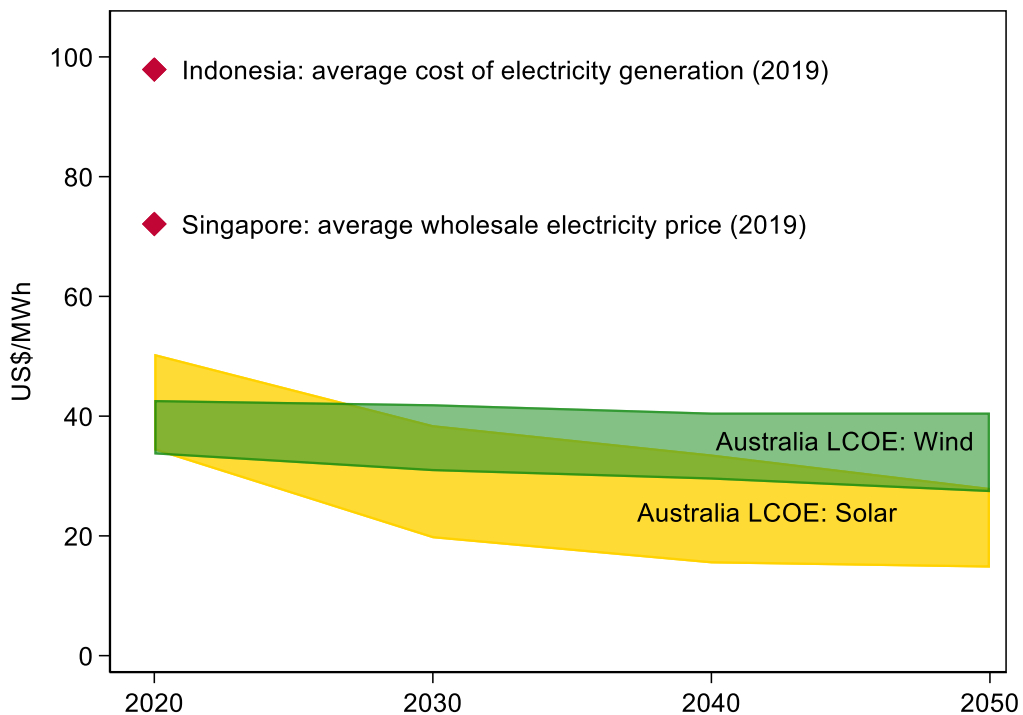
Figure 4. Australia's projected levelized cost of electricity (LCOE) for standalone solar PV and wind generation relative to the average cost of electricity generation in Indonesia and the average wholesale electricity price in Singapore in 2019.
The LCOEs show the low-to-high range of CSIRO [84] projections. The average cost for Indonesia is the *biaya pokok penyediaan listrik* (BPP) [98]. The mean of the average monthly uniform Singapore energy price [99] is used. An Australian-US dollar exchange rate of 0.7 is used. Exchange rates for Indonesia and Singapore are from the St. Louis Fed [100].

Scale-up of green hydrogen and green metals production is dependent on importers being initially willing to pay a price premium, justifiable on the basis that importing countries are able to avoid local pollution costs and make progress toward meeting greenhouse gas emission reduction targets by importing such products. Carbon pricing and emissions regulations provide direct incentives for such premia to be paid. There is growing application of carbon pricing in the Asia-Pacific, with Japan, South Korea, China, Singapore, and New Zealand already having carbon prices [101]. Other countries are considering adoption of carbon pricing. For example, in 2020 Vietnam's National Assembly passed a revised Law on Environmental Protection that opens the way for a future carbon trading scheme [102]. A reform option for countries in the region is the use of border carbon tax adjustments to ensure an incentive for exporters to pursue zero-carbon processes, as is currently being considered by the European Union.

A key parameter for capital-intensive zero-carbon opportunities is the cost of capital. Interest rates in Australia and elsewhere have fallen to record lows, with Australia's cash rate target falling to only 0.1% yr^{-1} as of November 2020 and remaining at that level throughout 2021 [103]. The post-COVID context thus provides a ripe setting for private-sector investment in capital-intensive industries. A downside for Australia is that northern Australia has a hot climate and does not have a large existing labor force. These factors add to costs, although

Australia also has ample zero-carbon production and utilization opportunities near larger population centers in the south and east. An underlying incentive will exist to source zero-carbon commodities from Australia when the savings on energy and transport costs exceed other additional costs.

6. Political and policy dimensions

The export scenario analyzed in this paper would involve a change in the way Australia trades with the world, especially as electricity exports require fixed cross-border energy transmission infrastructure. Australia is seen as a relatively safe and reliable trading partner and has close trade links with countries throughout the Asia-Pacific, although there are current frictions in its relationship with China. Investment links with the Asia-Pacific are somewhat less well developed, with only about one-fifth of the current stock of foreign capital in Australia coming from the region, principally Japan and China [104]. Investment from Indonesia remains low, with large potential to grow. A scale-up of investment from the region is likely to be politically viable provided that projects are able to demonstrate success and national benefits. Capital from domestic sources and from countries outside the region is also already being attracted to low-carbon opportunities in Australia.

Demand for Australian renewable energy will depend in part on the post-COVID politics of self-sufficiency in the Asia-Pacific. Tendency to focus on domestic energy supplies and supply chains is on the rise [105], although energy self-sufficiency is not a realistic or cost-effective option for energy-poor countries such as Singapore. At the same time, increasing awareness and concerns over local air quality and climate change risks, competition to provide better physical environments to attract financial and human capital, and the growing number of corporations and sub-national jurisdictions engaging in climate change mitigation efforts is fostering bottom-up momentum for clean energy. Many large private firms are seeking to switch to zero-carbon sources of energy under the RE100 and other initiatives.

Given that Australia is already a major fuel exporter, a move to hydrogen exports may not carry major political economy implications [106]. The same is not true for metals. The global steel market is highly competitive, and whether Australia will be capable of a large ramp-up of its production remains an open question. Other countries in the region also have their own opportunities to switch to zero-carbon processing methods [107], although for many this would involve higher energy costs than it would for Australia. It will be important to ensure that international supply chains in zero-commodities do not become overly distorted as a result of geopolitical competition; ideally low-emission production processes would occur in the lowest-cost and most suitable locations. Using zero-carbon energy to carry out additional local beneficiation of iron ore and produce intermediate products such as direct reduced iron also serves as an opportunity for Australia.

Zero-carbon energy exports from Australia will also face substantial competition from other fuels and suppliers. Natural gas has generally become more affordable over time due to supply-side expansion and a reduction in transport costs, although its emissions implications place it at a long-run disadvantage relative to zero-carbon energy. Countries in the Middle East, South America, and elsewhere also have vast opportunities in clean energy. However few have Australia's proximity to key Asia-Pacific economies nor its sizeable co-located endowments in renewable energy and mineral ores.

Who bears the costs of a new zero-carbon trade model is an important issue. In part, the need for green investment is already embedded in any development scenario consistent with the Paris Agreement. For example, the IEA's Sustainable Development Scenario requires almost all electricity to be from zero-carbon sources by 2070, as well as substantial decarbonization of other sectors [108]. Zero-carbon exports from Australia also allow the avoidance of sizeable costs, including the costs of developing additional coal mines and natural gas fields and the health and other costs associated with fossil fuel emissions. Some communities, including in coal-mining regions, may see their opportunities decline with the rise of zero-carbon exports. These regions could be the focus of targeted infrastructure and other investments to support a reorientation toward lower-emission activities [109].

Substantial investment in cross-border electricity transmission infrastructure will be required under the analyzed export model [110,111]. Such infrastructure is subject to "hold-up" problems, creating a role for government-led risk reduction efforts, potentially including co-investment. Political agreements between Australia and near-neighbors could help, with careful design of investment frameworks needed to ensure they will deliver equitable outcomes and prioritize low-carbon opportunities [112]. There are now ways to design international law to better protect investors from expropriation while allowing governments the flexibility necessary for the energy transition [113,114]. Internationally compatible emissions accounting and certification schemes will also be needed to lower the regulatory burden for green products to receive price premia [115].

Efforts to boost trust and connectivity in the Asia-Pacific will be important, particularly for the development of fixed network infrastructure such as cross-border electricity grids [23,24,116]. Ideally Australia's state and federal governments would also align industry policy and governance frameworks with the development of new zero-carbon export industries. The Australian Government's first experiment with international green industrial policy, the negotiation of an Australia-Singapore Green Economy Agreement in 2021 [117], is a positive step. Australia's National Hydrogen Strategy [118] also has a strong focus on exports, and state governments have adopted hydrogen strategies. In September 2020 Australia released a Technology Investment Roadmap [90] that prioritizes clean hydrogen, energy storage, and low-carbon steel and aluminium. In October 2021 Australia also announced a net zero by 2050 emissions target. However, concerns remain about the emphasis in Australian policy on carbon capture and land sector offsets rather than making the most of Australia's renewable energy potential. The opportunity to actively contribute to overseas emissions reductions via the decarbonization of exports has also yet to be embraced at a government level.

Aboriginal people hold exclusive possession native title over much of northwest Australia, placing an impetus on the renewable energy industry to negotiate access and develop agreements that will benefit Aboriginal landholders. To date, many Indigenous communities have not received substantial benefits from Australia's mining boom [119]. There is an opportunity for a more inclusive model to be adopted for the case of utility-scale renewables [120]. The creation of opportunities for Indigenous people is central to sustainable development.

7. Conclusion

This paper is the first to quantify the energy, land, and water requirements for the realization of a new zero-carbon export model for Australia. The calculations show that Australia could feasibly contribute to as much as an 8.6% reduction in the Asia-Pacific's greenhouse gas emissions by switching to the export of zero-carbon electricity, green hydrogen, green aluminium, and green steel. Doing so would require about 2% of Australia's land mass, a large but feasible area. The energy requirements would be sizeable, however could be feasibly accommodated based on low-cost solar and wind generation. The water requirements would also be feasible based on the desalinization of seawater powered by zero-carbon energy.

The COVID-19 crisis has led to a reset in thinking on industry policy and how to best position national, regional, and global economies to deliver sustainable development outcomes. While 2020 saw a sharp contraction in trade flows and interconnectivity [121], a continued return to global economic growth is expected [122], with the dominance of the Asia-Pacific in energy and materials demand likely to continue to grow [1]. Improvements in solar, wind, hydrogen, and other technologies have provided Australia a new advantage in zero-carbon products at a time when they are increasingly needed to meet the region's emission reduction goals. There are other zero-carbon export opportunities for Australia in addition to those considered here, including exports of lithium, cobalt, copper, and nickel via supply chains that could be decarbonized over time [123].

This paper lays out the broad parameters of a new zero-carbon export model for a key commodity exporter. The energy, land, and water requirements to achieve large-scale exports of zero-carbon energy and metals from Australia are calculated using high-level methods. Future research may be able to build on this analysis by assessing the feasibility of switches to zero-carbon exports by other commodity exporters – in the Middle East, North America, South America, Africa, or elsewhere. Additional attention is also needed on required cost pathways for the emission-free shipping and storage of products such as green hydrogen. The ability to decarbonize international supply chains for agricultural and other commodities is also an important priority for ongoing research.

Appendix – Calculations

Australia's benchmark exports and associated consequential emissions

Details of the calculations are provided in the paper. Underlying data are provided in Tables S1 and S2.

Table S1. Australian benchmark export quantities, 2018–2019

	Total[a] (Mt)	Asia-Pacific share (%)
Thermal coal	210	93.5[b]
LNG	75	99.7[c]
Iron ore	819	99.8[d]
Bauxite	33.5	99.6[e]
Alumina	17.6	99.6[e]

[a] Source: [11].
[b] Share of exports of all coal, briquettes, ovoids and similar solid fuels manufactured from coal. Source: [31].
[c] Source: [33]
[d] Share of exports of iron ores and concentrates. Source: [31].
[e] Share of exports of aluminium ores and concentrates. Source: [31].

Table S2. Consequential emissions tied to Australian benchmark exports, 2018–2019 ($MtCO_2$-e)

	Total[a]	Asia-Pacific[b]
Thermal coal	511	478
LNG	210	209
Iron ore	1,033	1,031
Aluminium ores	215	214
Total	1,968	1,931

[a] Emissions are calculated using the average energy content factors and emissions factors provided in the paper.
[b] Asia-Pacific values are calculated by multiplying the first column by the Asia-Pacific shares in Table S1.

To calculate the shares of the emission totals in Table S2 in total greenhouse gas emissions of the world and the Asia-Pacific, we use data for emissions (all sectors) from CAIT [32]. The data are for 2018. BP [8] data indicate that energy-sector emissions for the Asia-Pacific increased by 1.7% in 2019, while global emissions were stable. We thus scaled up total Asia-Pacific year-2018 total emissions by 0.8% to approximate the 2018–2019 emissions level. Consequential emissions tied to Australia's benchmark exports of 1,931 $MtCO_2$-e are then equal to about 8.6% of Asia-Pacific emissions in 2018–2019.

Australia's domestic emissions equalled 529 $MtCO_2$-e yr^{-1} [34] in 2018–2019. If these are added to the 1,931 $MtCO_2$-e yr^{-1} of consequential emissions from the benchmark exports to the Asia-Pacific, Australia's total emissions contribution equals about 11% of regional emissions. Including both domestic emissions and consequential exports tied to the benchmark exports, Australia's total contribution to global greenhouse gas emissions was about 5%.

Renewable electricity requirements for the new export scenario

Australia's exports of thermal coal and LNG in 2018–2019 were calculated to have a combined energy equivalent of $E_{export} = 9{,}733$ PJ based on energy content factors of 27 and 54.4 PJ Mt^{-1} for thermal coal and LNG, respectively [27].

In replacing these thermal coal and LNG exports with renewable energy we assumed that 80% of the new energy exports will be in the form of renewable hydrogen and 20% in the form of electricity. This is because there are limits to the extent to which Australia will be able to export electricity to Asia due to the absence of a well-connected ASEAN Power Grid. Liquefied hydrogen, on the other hand, can be transported by ship and is better suited to making it to Northeast Asian markets. The majority of existing proposals for clean energy export projects in Australia are also for exports of hydrogen derivatives.

The electricity required to replace $F_{HVDC} = 20\%$ of the energy content of Australia's annual thermal coal and natural gas exports with HVDC electricity, E_{HVDC}, was calculated as:

$$E_{HVDC} = F_{HVDC} \cdot E_{export} = 540 \text{ TWh yr}^{-1}.$$

The mass of hydrogen needed to replace $F_{H_2} = 80\%$ of Australia's annual energy exports is approximately:

$$M_{H_2} = \frac{F_{H_2} \cdot E_{export}}{LHV_{H_2}} = 65 \text{ Mt yr}^{-1},$$

where $LHV_{H_2} = 120$ PJ Mt^{-1} is the lower heating value of hydrogen. We then calculated the electricity required to produce this hydrogen assuming a specific energy requirement of $e_{H_2} = 55$ TWh/MtH$_2$ for the electrolysis of water [89, 124] and a further $e_{LH_2} = 10$ TWh/MtH$_2$ to liquefy the hydrogen for storage and export [125]:

$$E_{H_2} = M_{H_2} \cdot (e_{H_2} + e_{LH_2}) = 4{,}200 \text{ TWh yr}^{-1}.$$

Likewise, we calculated the amount of hydrogen needed to process Australia's iron ore exports into green steel. During the process the iron oxide (primarily hematite) in iron ore is reduced by hydrogen, producing iron and water:

$$Fe_2O_3 + 3\,H_2 \rightarrow 2\,Fe + 3\,H_2O$$
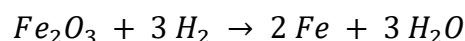
The reaction requires 3 moles of hydrogen for each mole of iron oxide. In addition, the process is endothermic and requires 98 kJ mol$_{Fe_2O_3}{}^{-1}$ of heat [126], which can also be provided by the combustion of hydrogen, equivalent to 0.405 mol$_{H_2}$ mol$_{Fe2O3}{}^{-1}$. In total, 3.40 mol$_{H_2}$ mol$_{Fe_2O_3}{}^{-1}$ or $S = 0.0432$ kg$_{H_2}$ kg$_{Fe_2O_3}{}^{-1}$ is required for metal processing.

The mass of iron oxide in the iron ore is given by:

$$M_{Fe_2O_3} = M_{Fe\ ore} \cdot F_{Fe\ ore} \cdot \frac{m_{Fe_2O_3}}{2\,m_{Fe}},$$

where $F_{Fe\ ore} = 62\%$ is the assumed iron content of Australian iron ore. $m_{Fe_2O_3} = 159.0$ g mol^{-1} and $m_{Fe} = 55.5$ mol^{-1} are the molar weights of iron oxide and iron, respectively.

The amount of hydrogen needed to process Australia's annual iron ore exports to green steel is then approximately:

$$M_{H_2 \rightarrow Fe} = M_{Fe_2O_3} \cdot S = 31 \text{ MtH}_2 \text{ yr}^{-1},$$

which would require approximately:

$$E_{Fe} = M_{Fe} \cdot \left(e_{H_2} + e_{LH_2} \right) = 2{,}000 \text{ TWh yr}^{-1}$$

of electricity, assuming the same electricity requirements for the electrolysis of water and liquefaction of hydrogen for storage and export as above.

Aluminium production requires energy for the processing of bauxite to alumina and the smelting of alumina to aluminium. Processing of bauxite to alumina in Australia requires about $e_{Al_2O_3} \approx 9$ t^{-1} or 2.5 t^{-1} of energy per tonne of alumina [127].

The mass of aluminium produced from the exported bauxite alumina and bauxite converted to alumina is given by:

$$M_{Al} = (M_{baux} F_{baux} + M_{Al_2O_3}) F_{Al_2O_3}$$

Modern smelters [128] require electrical energy of about $e_{Al} = 13.56$ t^{-1} of aluminium produced. As a result, the energy to convert current annual Australian bauxite and alumina exports into aluminium is estimated as:

$$E_{Al} = M_{baux} F_{baux} e_{Al_2O_3} + \left(M_{baux} \cdot F_{baux} + M_{Al_2O_3} \right) F_{Al_2O_3} e_{Al} = 300 \text{ TWh yr}^{-1}.$$

To the nearest thousand TWh yr^{-1}, the total electricity to replace Australia's annual thermal coal and LNG energy exports with renewable alternatives and process Australia's annual iron ore exports to green steel and bauxite and alumina exports to green aluminium is then:

$$E_{tot} = E_{HVDC} + E_{H_2} + E_{Fe} + E_{Al} = 7{,}000 \text{ TWh yr}^{-1}.$$

In the long run Australia has the potential to export other zero-carbon products and may even be able to exceed the quantities calculated here. We use the above benchmark export approach to provide a framing of the size of the opportunity. The calculations do not consider the renewable electricity required to power mining operations or transport.

Required capacity of solar and wind energy. We assumed that half the electricity required for Australia's green exports will be generated using solar, $F_{solar} = 50\%$, and half using wind, $F_{wind} = 50\%$. We further assumed that these power generation plants will be located in northwest Australia, which has some of the best renewable resources in the world.

We used a capacity factor, $CF_{solar} = 32\%$, for large, single-axis tracking solar energy systems, and $CF_{wind} = 44\%$, from 2020–2021 estimates of renewable energy generation in Australia [84]. The required capacity of solar and wind energy installations is then approximately:

$$C_{solar} = \frac{E_{total} \cdot F_{solar}}{CF_{solar}} = 1{,}264 \text{ GW}$$

$$C_{wind} = \frac{E_{total} \cdot F_{wind}}{CF_{wind}} = 919 \text{ GW}$$

This is equal to 1.8 times the world's solar power capacity and 1.3 times the world's wind capacity as of 2020 [129].

Estimated land required for renewable energy capacity. The area needed to harvest the solar and wind resources under the modelled export scenario was calculated by dividing the required annual energy by the expected annual energy output density of the renewable energy system.

For a typical large-scale solar system we assume a power conversion efficiency of $\eta_{PV} = 18\%$ based on a 20% module efficiency [130] and 10% plant losses. We also assume an average annual solar energy density (i.e. global horizontal irradiation summed over a year) of $\rho_{sun}^{in} = 2{,}300 \text{ GWh yr}^{-1}\text{ km}^{-2}$ in northwest Australia, calculated using data from the Global Solar Atlas [41]. The annual energy output density is then given by:

$$\rho_{PV}^{out} = \eta_{solar}\rho_{sun}^{in}$$

The average wind power density in northwest Australia is about 307 W m^{-2}, derived from an average wind speed of about 8 ms^{-1} ascertained from the Global Wind Atlas [71]. This yields an average annual wind energy density (average wind energy density summed over a year) of $\rho_{wind}^{in} = 2{,}693 \text{ GWh yr}^{-1}\text{ km}^{-2}$. For a wind farm with a turbine efficiency, $\eta_{turbine} = 50\%$, the annual energy output density (energy per land area) can be calculated as:

$$\rho_{turbine}^{out} = \eta_{turbine} \cdot \frac{\pi}{200} \cdot \rho_{wind}^{in}.$$

The factor $\pi/200$ reflects a typical value for large-scale wind farm turbine spacing, which we assumed here to be 5d × 10d, where d is the turbine blade length, to allow for turbulence losses downstream from the prevailing winds.

The land area covered by solar panels to generate 50% of the required renewable energy is then approximately:

$$A_{solar} = \frac{E_{total} \cdot F_{solar}}{\rho_{PV}^{out}} = 8{,}570 \text{ km}^2.$$

The land area required for wind farms to generate the other 50% is approximately:

$$A_{wind} = \frac{E_{total} \cdot F_{wind}}{\rho_{Pwind}^{out}} = 168{,}000 \text{ km}^2.$$

We assume that solar and wind can be co-located. Land is required for balance of systems, maintenance roads, and other structures. We assume these will be absorbed into the land area between the widely separated wind turbines and the solar installations.

The above calculations thus indicate that around $168,000 \text{ km}^2$ in the northwest of Australia would be required for renewable energy generation to replace the 2018–2019 benchmark exports. This is about 2% of Australia's land mass.

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