energies

Article

Potential Domestic Energy System Vulnerabilities from Major Exports of Green Hydrogen: A Case Study of Australia

Andrew J. Curtis and Benjamin C. McLellan *

Graduate School of Energy Science, Kyoto University, Kyoto 606-8501, Japan; curtis.andrew.k05@kyoto-u.jp
* Correspondence: b-mclellan@energy.kyoto-u.ac.jp

Abstract: Australia has clear aspirations to become a major global exporter of hydrogen as a replacement for fossil fuels and as part of the drive to reduce CO_2 emissions, as set out in the National Hydrogen Strategy released in 2019 jointly by the federal and state governments. In 2021, the Australian Energy Market Operator specified a grid forecast scenario for the first time entitled "hydrogen superpower". Not only does Australia hope to capitalise on the emerging demand for zero-carbon hydrogen in places like Japan and South Korea by establishing a new export industry, but it also needs to mitigate the built-in carbon risk of its export revenue from coal and LNG as major customers, such as Japan and South Korea, move to decarbonise their energy systems. This places hydrogen at the nexus of energy, climate change mitigation and economic growth, with implications for energy security. Much of the published literature on this topic concentrates on the details of what being a major hydrogen exporter will look like and what steps will need to be taken to achieve it. However, there appears to be a gap in the study of the implications for Australia's domestic energy system in terms of energy security and export economic vulnerability. The objective of this paper is to develop a conceptual framework for the implications of becoming a major hydrogen exporter on Australia's energy system. Various green hydrogen export scenarios for Australia were compared, and the most recent and comprehensive was selected as the basis for further examination for domestic energy system impacts. In this scenario, 248.5 GW of new renewable electricity generation capacity was estimated to be required by 2050 to produce the additional 867 TWh required for an electrolyser output of 2088 PJ of green hydrogen for export, which will comprise 55.9% of Australia's total electricity demand at that time. The characteristics of comparative export-oriented resources and their interactions with the domestic economy and energy system are then examined through the lens of the resource curse hypothesis, and the LNG and aluminium industries. These existing resource export frameworks are reviewed for applicability of specific factors to export-oriented green hydrogen production, with applicable factors then compiled into a novel conceptual framework for exporter domestic implications from large-scale exports of green hydrogen. The green hydrogen export superpower (2050) scenario is then quantitatively assessed using the established indicators for energy exporter vulnerability and domestic energy security, comparing it to Australia's 2019 energy exports profile. This assessment finds that in almost all factors, exporter vulnerability is reduced, and domestic energy security is enhanced by the transition from fossil fuel exports to green hydrogen, with the exception of an increase in exposure of the domestic energy system to international market forces.

Keywords: energy security; hydrogen; exports; resource curse; carbon neutrality

check for updates

Citation: Curtis, A.J.; McLellan, B.C. Potential Domestic Energy System Vulnerabilities from Major Exports of Green Hydrogen: A Case Study of Australia. *Energies* **2023**, *16*, 5881. https://doi.org/10.3390/en16165881

Academic Editors: Raffaele Marotta and Lorenzo Ferrari

Received: 13 June 2023
Revised: 5 August 2023
Accepted: 7 August 2023
Published: 8 August 2023

1. Introduction

As with fossil fuel deposits [1], renewable energy resources, such as rivers with hydroelectrical potential, accessible geothermal resources, large open spaces with high solar radiation levels, or available land with high wind speeds, are also not evenly distributed worldwide. Countries with a high population density and high energy demand, such as Japan and South Korea, which already experience energy supply challenges due to a lack of domestic fossil fuel reserves [2] are similarly challenged with access to sources of renewable electricity generation which is a significant limitation in their efforts to achieve a zero-carbon society [3]. The importation of hydrogen produced by means that do not contribute to anthropogenic climate change is emerging as a key method for countries deficient in renewable energy resources to decarbonise their domestic energy systems [3,4]. Through the process of electrolysis, hydrogen produced from low-cost and plentiful renewable electricity in a supplier country can be used as a vector to transport that renewable energy internationally, without the need for contiguous land borders or undersea cables.

In recent years, Australia has had well-publicised aspirations to become a hydrogen-exporting renewable energy superpower [5–8]. These aspirations have crystalised into clear government policy, with the National Hydrogen Strategy released in 2019 jointly by the federal and state governments, supported by the National Hydrogen Roadmap [7] prepared by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Following a change in federal government in May 2022 from the centre-right Liberal–National coalition to the centre-left Labor party [9], the hydrogen strategy has been re-affirmed, and with it the objective of Australia being a global leader by 2030 in hydrogen for export and for domestic industry decarbonisation [10]. Not only does Australia hope to capitalise on the emerging demand for zero-carbon hydrogen in places like Japan and South Korea by establishing a new export industry, it also desperately needs to mitigate the built-in carbon risk (an exporter's vulnerability to loss of export revenue as customers take climate change action and reduce fossil fuel consumption; related to the CO_2 emissions intensity of exported fuels) of its export revenue from coal and liquefied natural gas (LNG) as major customers, such as Japan [3] and South Korea [11], move to decarbonise their energy systems. The Australian Government's focus on these two countries as its hydrogen export customers is abundantly clear in the CSIRO's National Hydrogen Roadmap [7], the National Hydrogen Strategy from the Coalition of Australian Government (COAG) [8] and the Opportunities for Australia from Hydrogen Exports report prepared for the Australian Renewable Energy Agency (ARENA) [12], and is emphasised even further by the National Hydrogen Strategy document being available for download in English, Japanese and Korean language versions.

1.1. Hydrogen Sources

An informal colour-coding system of hydrogen has been developed as a shorthand means of describing its means of production and CO_2 footprint [13]. While the colour label "green" has been used for many decades for environmentally friendly technologies, in the case of hydrogen it has been used to specifically refer to hydrogen produced from electrolysis with renewable energy, generally via electrolysis. These hydrogen colours still lack consensus (e.g., sometimes biomass is considered to be green, other times it is considered to be brown; yellow may refer to grid-electricity-based electrolysis, nuclear-based or solar-based hydrogen production, or catalytic water-splitting), and can be considered mostly a marketing gimmick. Scientifically, hydrogen can be produced by various routes—each of which has different implications for the carbon footprint of the produced hydrogen and for other environmental and economic factors. The general potential supply chains are shown in Figure 1.

It should be noted that hydrogen cannot typically be considered a primary energy source—unless it is extracted from geological deposits. It is more accurately defined as an energy carrier—although it is sometimes considered a form of energy storage and also requires storing itself, often in compounds such as ammonia or as metal hydrides. Through using renewable energy to electrolyse water and produce hydrogen, "green" hydrogen is a medium to make it possible for energy-import-dependent countries to essentially import renewable electricity from sources worldwide.

Australia currently hosts the Hydrogen Energy Supply Chain (HESC) demonstration project in Victoria's Latrobe Valley [14], developed and operated with a number of major Japanese energy players, producing hydrogen from brown coal (without CCS). The HESC project is currently capable of producing "brown" hydrogen and has begun making trial shipments of liquefied hydrogen (LH_2) to Japan. Future commercial expansion of this project proposes capturing carbon dioxide (CO_2) from the hydrogen production process and injecting it into offshore geological sequestration sites. This would then make any hydrogen produced "blue". Brown coal for the HESC project is currently sourced from the Loy Yang mine, however the Loy Yang A Power Station is scheduled to cease operation in 2035 [15]. As brown-coal-fired electricity generation is phased out in Victoria, this resource will be available without any other use. While this project represents an interesting source of potentially zero-carbon hydrogen supply, the project itself will have no material interaction with the Australian energy system since it will not compete with power stations for fuel, and the hydrogen produced is intended to be solely for export.

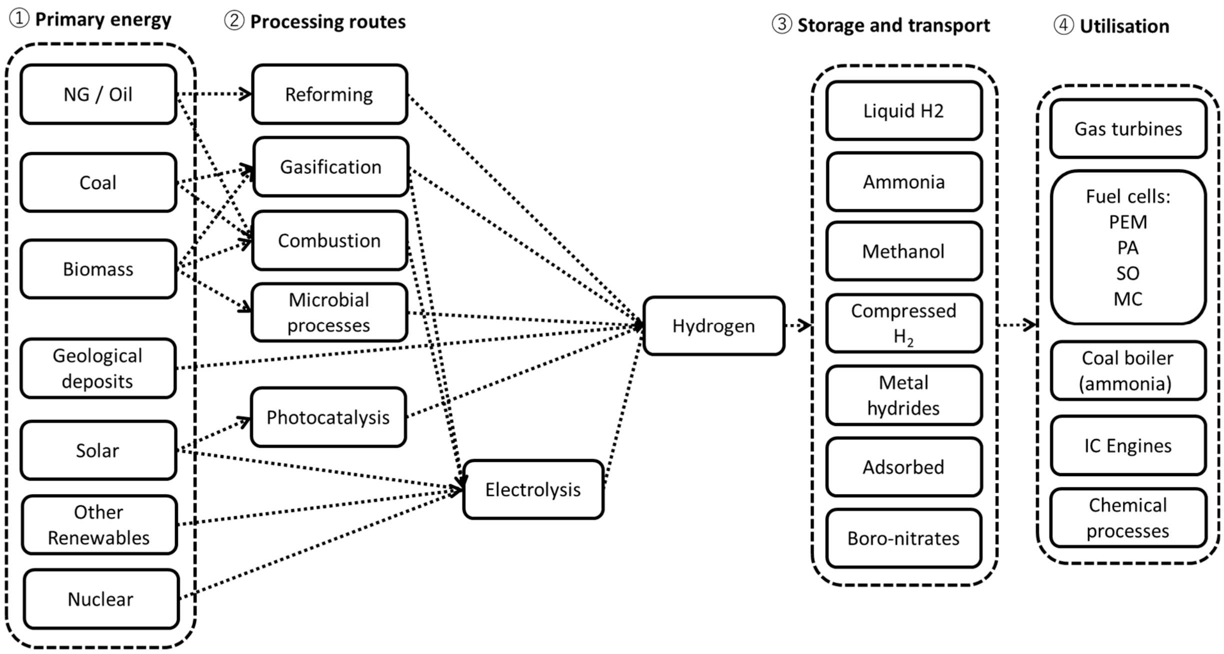

Figure 1. Hydrogen production, supply chains and end uses.

Hydrogen from fossil fuels without CCS does not achieve the intended purpose of displacing CO_2 emissions from fossil fuels. In the absence of a commercial nuclear power industry for the foreseeable future, "pink" hydrogen production in Australia is not considered. Other production routes are unlikely to be commercially scalable options for the foreseeable future [13].

Since the purpose of this paper is to explore interactions of hydrogen exports with the Australian energy system, we will focus solely on "green" hydrogen produced from renewable electricity. The interlinkages of hydrogen exports and the domestic energy system are shown in Figure 2.

1.2. Electrolyser Technology

The two main commercially available and technically mature electrolysis technologies applicable to the production of green hydrogen are alkaline electrolysis (AE) and polymer electrolyte membrane (sometimes also called proton exchange membrane) (PEM). Historically, AE has been the more widely deployed [16] and has a lower capital cost. However, PEM has a number of operational benefits, and while it currently has a higher capital cost, the PEM share of electrolyser capacity globally has been increasing [16]. Many forecasts for future green hydrogen production [7,17–19] use PEM with future cost reduction due to the scale assumed. CSIRO [7] data for current and expected AE and PEM electrolyser efficiencies in Table 1 show that while there is a difference; the uncertainty range for potential improvement for each technology is greater than the difference between them in both the current case and the expected best case.

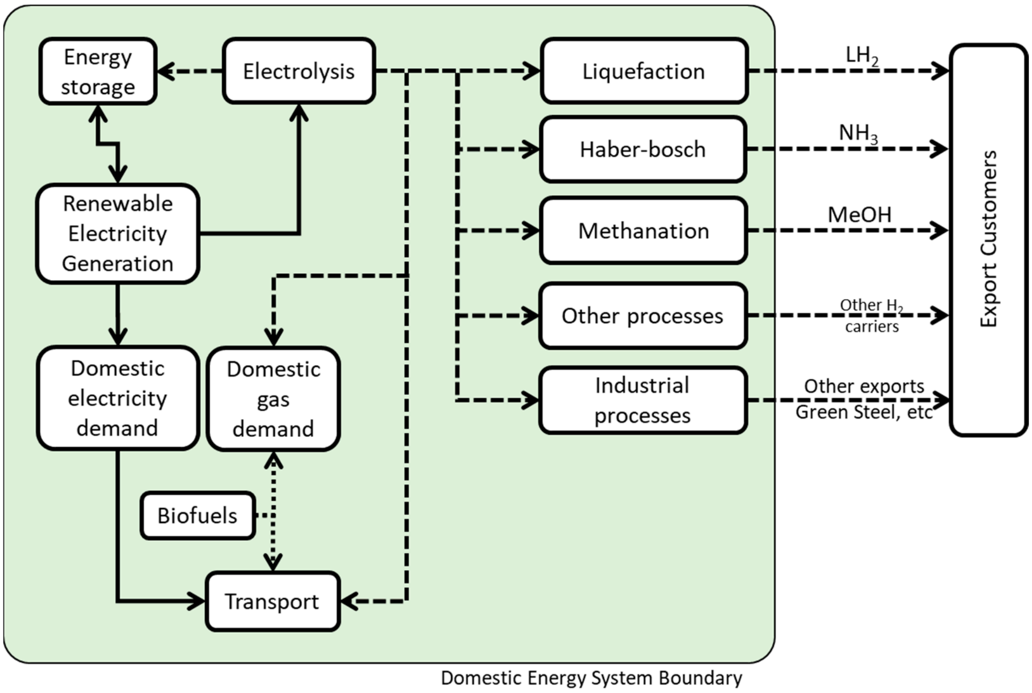

Figure 2. Domestic energy system with hydrogen exports in the hydrogen export 2050 scenario.

Table 1. Comparison of electrical efficiency of mature electrolyser technologies.

Technology	Current (kWh/kgH_2)	Best Case (kWh/kgH_2)
PEM	54	45
AE	58	49

Therefore, for the purposes of this paper, since we are mainly interested in the electricity consumption of hydrogen production, there is not a material difference between the selection of either AE or PEM technology, and we adopt PEM as the base case, which is also used as the reference case in future scenarios by CSIRO and the Australia Energy Market Operator (AEMO). To examine the sensitivity of results with this assumption, electricity consumption if AE were to be deployed would be 7% greater than PEM on the basis of current technology, or 9% in the future "best case".

1.3. Hydrogen Carrier

Green hydrogen is a carrier for renewable electricity. However, hydrogen in a gaseous state, even when compressed, is only really suitable for pipeline or truck transport due to low energy density. For the international shipping of hydrogen in large quantities, a carrier method is required to improve energy density and transportability. Rasool et al. [20] and Wang et al. [21] have both conducted a detailed cost evaluation of potential hydrogen carriers among mature technologies for the international export shipping of Australian green hydrogen, liquefied hydrogen (LH_2), compressed hydrogen (CH_2), ammonia (NH_3), methanol (MeOH) and methane, potentially as green e-LNG (liquefied methane synthesised from hydrogen produced by electrolysis using renewable electricity). CSIRO [7] points to LH_2 and NH_3 as the most viable, while in AEMO's hydrogen superpower scenario [17], NH_3 is selected as the base case hydrogen carrier, being, according to AEMO's assessment, the lowest cost and most widely deployed at the present time. From the customer side, METI [3] (Japan) also uses NH_3 as their base case hydrogen carrier.

In this context, it is useful to understand the properties of these two potential methods of hydrogen transport by ship compared to LNG. A comparison is provided in Table 2. Although the calorific value of LH_2 is well above that of LNG and NH_3, due to a much lower density, the energy density of LH_2 is the lowest of all. The greatest technical challenge is in the liquefaction temperature, which is considerably lower for LH_2 than LNG, while for NH_3, it is much higher.

Table 2. Properties of LNG, LH_2 and NH_3 compared.

Fuel	Calorific Value (LHV) MJ/kg	Density kg/m^3	Energy Density MJ/m^3	Temperature (Liquid State)
LNG	45	450	20,250	−162 °C
LH_2	120	71	8520	−283 °C
NH_3	19	680	12,920	−33 °C

LH_2 production, transport and storage is not new; however, domestic production has been primarily for industrial uses. There is still considerable room for research and development in scaling up LH_2 production and improving the efficiency of processes for large-scale production as an energy transport vector for international shipping. The ship transport of LH_2 is a new technology—the first ocean-going LH_2 carrier "Suiso Frontier" [14] began operation in 2021 as a part of the Japan–Australia HESC project. As can be expected with any demonstration technology scale-up, LH_2 shipping trials have not been without technical challenges, including a brief uncontrolled hydrogen flame-out event on board [22].

Conversely, NH_3 exports and shipping are already well-established with 65 NH_3 tanker vessels transporting 19.8 Mt of NH_3 exports worldwide in 2021 [23]. For the immediate industrial deployment of the international trade of hydrogen by ocean freight at large scale, NH_3 appears to be the most feasible carrier at the present time.

Whichever vector is used, the energy density deficit compared to LNG will necessitate an increase in shipping activity if the direct energy replacement of LNG is considered. For every one ship of LNG, 2.4 shiploads of LH_2 or 1.6 shiploads of NH_3 of an equivalent volume would be required to deliver the same energy.

1.4. Hydrogen Export Literature Review

A number of papers have been published recently that take a country-specific approach in examining the prospect of zero-CO_2 hydrogen production and exports, including Rasool et al. [20] and Wang et al. [21], who each examined the cost profile of different hydrogen carrier methods for export from Australia; Gallardo et al. [24], with a techno-economic analysis of the case for export from Chile using low-cost solar electricity in the Atacama Desert region; Burdack et al. [25], with a similar techno-economic analysis of potential green hydrogen exports from Colombia; Kavavand et al. [26], who provided a similar analysis for the case of green hydrogen and NH_3 exports from Iran using wind and solar electricity; and Galvan et al. [27], who proposed a plan for green hydrogen exports from South America, adding up to 20% electricity demand in conjunction with an electricity generation transition to renewable sources. Armijo and Philibert [28] presented a case study of green hydrogen and NH_3 production in Chile and Argentina, initially supplying local needs, then expanding to export operations, Khan & Al-Ghamdi [29] examined the potential benefits and challenges for hydrogen exports from Gulf Cooperation Council member states, and Bhandari [30] provides a study of potential for green hydrogen production in Niger. Hjeij et al. [31] developed an index for rating the hydrogen export competitiveness of countries, and Downie [32] has developed a high-level framework for the geopolitical leverage of states exporting renewable electricity, including through media such as green hydrogen. With regard to exporter-side domestic impacts, one of the few studies focussing on this aspect [33] developed the idea of domestic implications for export-oriented hydrogen producers in terms of water availability and land use in low-income countries, including Morocco, Mexico and South Africa. The idea of a domestic hydrogen market operating in synergistic conjunction with hydrogen export operations is discussed in a few papers [28,31] while the idea of a domestic hydrogen market acting as an incubator for an export industry takes a major place in the main Australian hydrogen strategy narrative, as set out in AEMO [17], CSIRO [19], COAG [8] and ARENA [12] reports. However, the potential for hydrogen exports to dominate and adversely impact the exporters' domestic hydrogen market is absent. Further references to energy security, impacts on domestic energy markets generally and the distortion of local electricity pricing in these papers examining the hydrogen export case are lacking. Any mentions of energy security refer only to importing countries [25,32,34].

The current academic and policy body of knowledge on hydrogen exports thus reflects the typical focus, in which energy security is primarily a concern for energy-import-dependent countries [31]. This confirms the gap in existing work on the topic of hydrogen exports and the importance of this paper in developing a framework for domestic energy security specific to the emergence of large-scale green hydrogen exports to contribute to filling this gap.

1.5. Methodology and Structure

Having established the research need, the methodology and structure of this paper are set out as follows: In this paper, we will take the CSIRO "Hydrogen Export" scenario [19] as a plausible case for a fully developed green hydrogen export industry and use it as the reference against which to develop this framework. In Section 2, we expand on what the hydrogen export scenario means domestically for Australia's energy system and also validate that scenario against major trading partners' hydrogen strategies. In Section 3, we examine comparative resource cases for factors applicable to green hydrogen export, including a review of literature on the "resource curse" or "paradox of plenty" phenomenon and test if those conditions might apply to hydrogen exports. In addition, we a review other research conducted on the known domestic energy system impacts from exporting industries with strong links to the domestic energy system, such as LNG and aluminium, and filter these existing frameworks for potentially comparable factors and effects, considering the extent to which these energy intensive export-focussed sectors are embedded in Australia's domestic energy system.

In Section 4, we apply some of the energy-exporter-focussed focussed approaches developed in our earlier work [1,35] to evaluate exporter vulnerability and domestic energy security before (2019) and after (2050) the realisation of the hydrogen export scenario. In Section 5, we present the compiled conceptual framework for domestic energy system impacts of green hydrogen exports developed in this study. Conclusions and policy recommendations are contained in Section 6.

1.6. Limitations of This Study

This study is limited to the domestic energy system and related internal economic effects of a country becoming a major hydrogen exporter. This study specifically focusses on "green" hydrogen, which is produced via electrolysis from renewable electricity, and does not address fossil-fuel-derived hydrogen as the share of the latter in the global market for decarbonised energy is expected to decline, and from a producer perspective, the linkages to the domestic energy system are expected to be negligible as hydrogen producers also move away from fossil-fuel-based electricity generation domestically. While the extent of renewable energy generation required to reach the extent of hydrogen production identified in various studies is assessed at a high level. This assessment is provided for context, and an analysis of the construction program required and potential challenges to achieving it are excluded from this study.

2. What Would Being a Hydrogen Export Superpower Look like for Australia?

2.1. Electricity Generation Requirements

"Hydrogen superpower" appeared as a forecast scenario in AEMO's "2021 Inputs Assumptions and Scenarios Report" for Australia's National Electricity Market (NEM) [17], in which "NEM-connected renewable energy exports via hydrogen become a significant part of Australia's economy". The hydrogen superpower scenario has been updated and expanded in AEMO's latest Integrated System Plan (ISP) issued in June 2022 [36]. CSIRO and Climateworks prepared a detailed modelling report [19] for AEMO as an input to the next ISP update, and covers all of Australia, not just the NEM states (Queensland, New South Wales, Victoria, Tasmania and South Australia). COAG's 2019 report "Australia's National Hydrogen Strategy" [8] sets out a similar, highly ambitious scenario titled "Hydrogen—Energy of the Future", with modelling inputs provided by the consulting firm Deloitte [18]. Key data of these various hydrogen exporting scenarios are summarised in Table 3. We have only converted between Mt and PJ and have intentionally omitted any conversions between electrical consumption and hydrogen production not included in the source reports since there is a slight difference between assumptions about conversion efficiency, technology applied, and improvement over time. There is, however, a reasonable convergence in the scale of the 2050 case from each source report. Of these scenarios, the most recent and most comprehensive (covering all Australia, and with 10-year steps) is the "Hydrogen Export" scenario prepared by CSIRO and Climateworks [19] for AEMO, which we will adopt as the reference case for further analysis in this paper.

Table 3. Australia green hydrogen export scenarios.

Scenario and Parameter	2030	2040	2050
COAG (2019) "Hydrogen—Energy of the Future" scenario [8,18]			
Green H_2 produced (Australia)	0.5 Mt (60 PJ)	-	18 Mt (2160 PJ)
Electricity for Green H_2 production (Australia)	19 TWh	-	912 TWh
AEMO (July 2021) "Hydrogen Superpower" scenario [17] (all figures NEM only)			
Total Green H_2 produced (domestic + export)	1.0 Mt (120 PJ)	5.0 Mt (600 PJ)	15.0 Mt (1800 PJ)
Green H_2 exported	0.6 Mt (73 PJ)	3.4 Mt (408 PJ)	12.3 Mt (1474 PJ)
Total electricity demand, including Green H_2 production	-	614 TWh	-
Electricity for Green H_2 production (% of total electricity demand)	57 TWh	285 TWh (46.4%)	795 TWh
Electricity for Green H_2 exports (% of total electricity demand)	41 TWh	221 TWh (36.0%)	774 TWh
AEMO (June 2022) "Hydrogen Superpower" scenario [36] (all figures NEM only)			
Total Green H_2 produced (domestic + export)	0.9 M t (107 PJ)	-	17.0 Mt (2038 PJ)
Green H_2 exported	0.7 Mt (84 PJ)	-	11.5 Mt (1376 PJ)
Total electricity demand, including Green H_2 production	294 TWh	-	1278 TWh
Electricity for Green H_2 production (% of total electricity demand)	51 TWh (17.3%)	-	900 TWh (70.4%)
Electricity for Green H_2 exports (% of total electricity demand)	49 TWh (16.7%)	-	768 TWh (60.1%)

Table 3. *Cont.*

Scenario and Parameter	2030	2040	2050
CSIRO and Climateworks for AEMO (Dec 2022) "Hydrogen Export" scenario [19]			
Total Green H_2 produced (domestic + export)	1.9 Mt (233 PJ)	6.3 Mt (757 PJ)	20.2 Mt (2426 PJ)
Green H_2 exported	1.7 MT (204 PJ)	5.4 Mt (648 PJ)	17.4 Mt (2088 PJ)
Total electricity demand, including Green H_2 production	455 TWh	790 TWh	1550 TWh
Electricity for Green H_2 production (% of total electricity demand)	112 TWh (24.6%)	339 TWh (42.9%)	1008 TWh (65.0%)
Electricity for Green H_2 exports (% of total electricity demand)	98 TWh (21.6%)	290 TWh (36.7%)	867 TWh (55.9%)

The "Hydrogen Export" scenario proposes additional renewable electricity generation dedicated to green hydrogen production for exports of 98 TWh in 2030, 290 TWh in 2040, and 867 TWh in 2050, by which time over half (55.9%) of Australia's electricity production (1550 TWh) is dedicated to producing green hydrogen for export. Considering Australia's electricity generation in 2019 was 264 TWh (including distributed and behind-the-meter generation, such as rooftop solar) [37]. This clearly constitutes a significant industrial undertaking when combined with the replacement of fossil fuel generation (212 TWh in 2019, 80.3% of total), excluding a domestic electricity consumption increase from increased electrification in the industry and society, and underlying economic growth.

Table 4 and Figure 3 set out an indicative example we have prepared based on this "Hydrogen Export" scenario of the extent of new renewable electricity generation required solely for hydrogen production. This example assumes the mix of renewables as 40% onshore wind, 40% solar and 20% offshore wind. Energy storage in the form of batteries and pumped hydro would also need to be deployed however these are not shown since even though they function as generators on the discharge cycle, they are not net electricity generators and do not add energy to the system, that is, they only store it for later release. The capacity factors for each technology are taken from Aurecon's 2020 report for AEMO [38].

Table 4. New generation required solely for hydrogen production for export.

		2030	2040	2050
Hydrogen production	PJ	204	648	2088
Electricity generation	TWh	98	290	867
Onshore Wind				
Share of export green H_2 generation	%	40%	40%	40%
Share of export green H_2 generation	TWh	39	116	347
Capacity factor	%	43.0%	46.0%	46.0%
Installed capacity required	GW	10.4	28.8	86.1
Offshore Wind				
Share of export green H_2 generation	%	20%	20%	20%
Share of export green H_2 generation	TWh	20	58	173
Capacity factor	%	51.0%	57.0%	57.0%
Installed capacity required	GW	4.4	11.6	34.7

Table 4. *Cont.*

		2030	2040	2050
Solar				
Share of export green H_2 generation	%	40%	40%	40%
Share of export green H_2 generation	TWh	39	116	347
Capacity factor	%	30.5%	31.0%	31.0%
Installed capacity required	GW	14.7	42.8	127.7

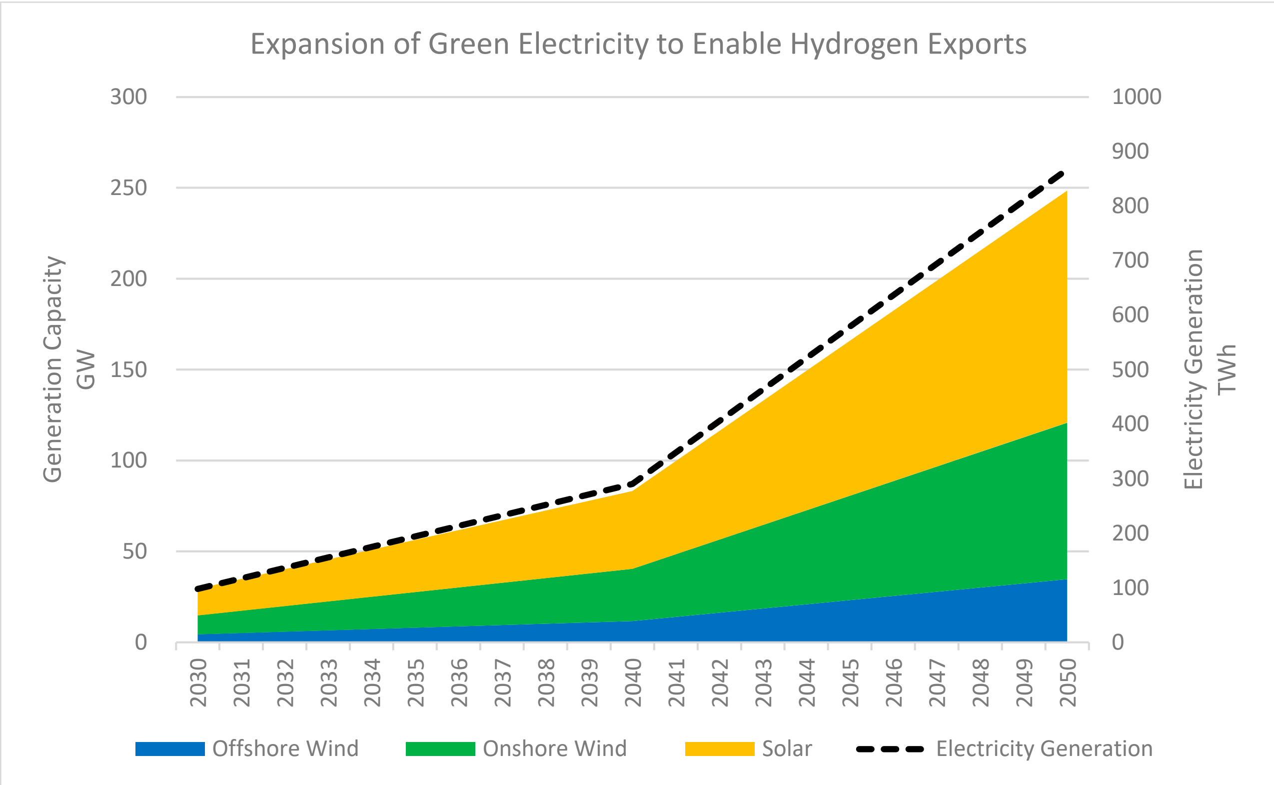

Figure 3. Expansion of green electricity required solely for hydrogen production for export.

The following construction program will be required to achieve these new generation capacity figures that are solely dedicated to green hydrogen production:

2020–2030

- Two to three new wind farms per year of 200 MW per site;
- The first two 2 GW offshore wind farms begin operation by 2030;
- Three to four new solar farms per year of 400 MWp per site.

2030–2040

- Nine new wind farms per year of 200 MW each year;
- A new 2 GW offshore wind farm every 3 years;
- Seven new solar farms per year of 400 MWp per site.

2040–2050

- Twenty-nine new wind farms per year of 200 MW each year;
- A new 2 GW offshore wind farm every 14 months;
- Fourteen new solar farms every 18 months of 400 MWp per site.

2.2. Hydrogen Export Quantity Validation with Major Trading Partners

The hydrogen export reference scenario anticipates 2088 PJ (17.4 Mt) of hydrogen exports by 2050. The feasibility of this figure (or not) can be validated by considering the announced hydrogen strategies of Japan and South Korea, two of Australia's major LNG customers.

According to the Ministry of Trade, Economy and Industry, Japan plans to import 3 Mt of zero-carbon hydrogen by 2030, increasing to 20 Mt by 2050 [3]. South Korea plans to reach 1.96 Mt of green hydrogen imports by 2030 [39]; assuming the same growth rate as Japan, they would reach 13.1 Mt by 2050.

We have estimated the potential share of Japan's and South Korea's hydrogen import market that Australia can reasonably achieve based on Australia's current share of their LNG imports since green hydrogen (in whichever carrier form) will increasingly be used to replace LNG imports [3] as a primary energy source in power generation and for industrial use. Australia's share of LNG supply [40] to Japan and South Korea is shown in Table 5. Japan and South Korea were Australia's number two and number three LNG export customers in 2021, taking 34.1% and 12.3% of total LNG exports, respectively. China was Australia's number one LNG export customer, taking 39.4% of Australia's total LNG exports. However, here, we concentrate on Japan and Korea due to their clearly articulated and ambitious hydrogen strategies, which are also largely reliant on imports.

Table 5. Australia's LNG trade to Japan and South Korea (2021).

2021 LNG Trade	Japan	South Korea
Total LNG imports from all sources (Mt)	74.35	46.92
LNG imports from Australia (Mt)	26.77	9.69
Share of LNG from Australia	36%	21%
Share of Australia's LNG exports	34.1%	12.3%

If Japan and South Korea were to maintain the same share of supply from Australia for hydrogen as is currently the case for LNG, then Australia's exports of green hydrogen (in whatever carrier form) would be 7.2 Mt to Japan and 2.7 Mt, respectively, and a total of 9.9 Mt by 2050. If we assume a similar proportionality again to 2021 LNG trade, of which 53.6% is to other energy-import-dependent countries (China, Singapore, etc.), then a total of 21.3 Mt of hydrogen exports is estimated. In this context, the scale of CSIRO's hydrogen export scenario seems reasonably aligned with potential importer demand.

2.3. Hydrogen Export Price Validation with Major Trading Partners

The Japanese Government's expectations for hydrogen price reduction are set out by METI [3]—30 JPY/Nm^3 by 2030 and not more than 20 JPY/Nm^3 by 2050 (approx. 20 USD/GJ and 13 USD/GJ, respectively, using the JPY/USD exchange rate of 140.12 as at 24 May 2023). For context, The Japanese average LNG price (delivered to the destination port) in January 2023 was approximately 17 USD/GJ [41]. In September 2019 (before the major disruptions to global energy markets of the Russia–Ukraine war and the COVID-19 pandemic), it was approximately 11 USD/GJ [42].

From the supply side, in Advisian's report for the Australian Government's Clean Energy Finance Corporation (CEFC), the cost of hydrogen CIF (inclusive of Cost, Insurance and Freight) for Japan in 2050 is forecast to fall to approximately 25 USD/GJ [43]. The gap between the 2050 price delivered to Japan anticipated by the Japanese Government and Australian sources is considerable, and further work will be necessary to achieve a convergence by reducing capital costs, technical efficiencies and operating costs of renewable electricity generation, hydrogen production, conversion processes to carriers, and end use technologies to enable the required development of this sector.

2.4. Operating Mode Considerations

When considering the operation of electrolysers, COAG [8] suggests the coupling of hydrogen production for export with electrical grid operations control in a kind of demand-management role for balancing excess renewables and frequency control. While this is possible from a technical perspective, Advisian [43] points out that export-oriented hydrogen production projects will seek to maximise their capacity factor to reduce production cost per unit hydrogen for capital investment in plant and suggested a hydrogen electrolyser capacity factor figure of at least 75%. CSIRO [7] enumerates 2018-based LCOH in Australian dollars per kilogram of hydrogen for various capacity factor cases, as shown in Table 6, converted to USD. Although the magnitude of these figures does not include cost reduction from scale-up and technological development in the decades ahead, the relative difference based on capacity factor is not expected to change substantially.

Table 6. LCOH (2018) at the electrolyser for various capacity factor cases.

Case	Capacity Factor	LCOH (USD/kg)
Grid connected renewables	85%	4
Dedicated renewables	35%	7
Excess renewable generation	10%	17

The case for "dedicated renewables" assumes the use of co-located wind and solar energy, while the "excess renewables" case assumes that hydrogen generation is optimised to only use otherwise curtailed excess grid-connected renewable electricity generation (mainly solar day-time peaks).

The conclusion we draw here is that any export-oriented hydrogen production plants will most likely operate at maximum capacity factor to ensure the most efficient use of invested capital and will not have an economic interest in providing the grid balancing of variations in renewable generation, unless otherwise incentivised through specific policies. Optimisation for the much lower capacity operation of hydrogen electrolysers for grid balancing is an entirely different function, hence a different business case for investment altogether, and would only be viable if the revenue received from that role compensates for lost revenue from higher-capacity factor operation for maximum hydrogen production.

3. Comparative Resources

As established in Section 1.4 of this paper, there is a gap in the existing literature on hydrogen exports regarding the domestic implications on the exporting country. In this section we provide a brief comparative examination of the resource curse hypothesis, LNG exports and aluminium exports, to establish some aspects of a conceptual framework for the domestic economic and energy system impacts of a future large-scale green hydrogen export industry.

3.1. Resource Curse Framework: Applicability to Hydrogen Exports?

There is a considerable body of literature examining the potential for extraction and the export of natural resources to yield negative economic results. In this section, we reference the common features of the "resource curse" framework and examine each one to determine whether exports of hydrogen could be considered as worse, better, or the same. The aim is to establish a comparative framework for resource curse risk compared to fossil fuels and mineral resources, to which the framework has historically been applied. We have not attempted to provide a full literature review of the resource curse hypothesis, which would be extensive, but rather have selected two representative papers as the reference point for comparison. Badeeb et al. [44] conducted a wide-ranging critical literature review of the resource curse hypothesis and compiled the various causal factors, while Leonard et al. [45] develop a framework for the application of the resource curse hypothesis to renewable energy.

Hydrogen may be treated as a natural resource, being ultimately derived from solar, wind and hydro energy; however, it also has characteristics of a manufacturing industry, with high levels of capital investment in each stage of production, and as the resource is essentially inexhaustible, there is potentially no "post-resource" phase. In practical terms, there are of course limitations. For example, the required critical materials needed for green hydrogen supply chain technologies including renewable electricity generation, energy storage and electrolysis (e.g., lithium, graphite, platinum and rare-earth metals) [46], the limits to land and other inputs. The investment cycle and the potential for insufficient long-term investment could also be considered as a potential resource-ending cause.

We have extracted the causal factors from each of these papers into Table 7 below and applied an assessment of how each factor would apply to hydrogen exports, with a simple rating system, as follows:

0 The factor is not applicable to hydrogen exports;
1 The factor is applicable to hydrogen exports, but the impact is mitigated compared to the classic resource curse;
2 The factor is applicable to hydrogen exports the same as with the classic resource curse;
3 The factor is applicable to hydrogen exports with a more severe impact than for the classic resource curse.

As can be seen in Table 7, most of the established causal factors in the resource curse hypothesis are applicable to green hydrogen production and exports. Those related to land use and technology dependence are rated higher than traditional extractive export industries, while those related to limitations to ongoing production are rated lower. Factors of governance and equitable distribution of benefits, economic management, and institutional quality are likely to be largely unchanged for green hydrogen compared to non-renewable resource extractive activities. However, such factors are also strongly related to pre-existing conditions in the exporting country.

The ratings in Table 7 indicate a tendency for resource curse effects of a similar extent to mineral or fossil fuel extraction export activities. The factors listed are intended to be a representative list to provide an indication of the relevance of the resource curse hypothesis to export-scale green hydrogen production, which would benefit from further detailed analysis.

3.2. LNG Exports Framework: Lessons for Hydrogen?

The similarities between LNG and hydrogen exports (whether as NH_3 or LH_2) are clear from an energy user perspective; hydrogen can be directly blended with natural gas in existing natural gas networks [52,53], and LNG-fired gas turbines are increasingly capable of partial or full conversion to hydrogen firing [54,55]. These similarities on the user side lead us to consider similarities on the production side and, in particular, how the reference case for Australia's transition from a gas producer for solely domestic consumption to a major global LNG exporter might provide insights for potential domestic energy system impacts from the transition to a major hydrogen-exporting superpower.

3.2.1. Competition between Domestic Use and Export for Gas, and Possibly Hydrogen?

Simshauser and Nelson [56] discussed potential impacts on the domestic gas supply system shortly before the commencement of LNG export operations from Queensland the following year (2016), and their analysis has proven remarkably accurate, forecasting unserved load immediately on the commencement of LNG exports (domestic demand exceeds supply). Notwithstanding the pre-existing balance in supply and demand and extensive export-oriented development of coal seam gas (CSG) production wells, the introduction of an export pathway immediately enabled the diversion of domestic gas supply to higher-paying LNG export customers, exacerbated by an insufficient, new CSG supply for the step change in demand from LNG export facilities [35]. Even domestic industrial gas customers willing to pay international net-back LNG prices struggled to obtain long terms contracts for gas supply due to the dominance of LNG export demand.

Table 7. Resource curse causal factors and expected relevance to green hydrogen exports.

Causes	Reference	Relevance to Hydrogen	Rating
1. Extracted not produced (high capital investment and low labour input)	Badeeb [44] Leonard [45]	A. Although renewable, the energy source for green hydrogen depends on high capital investment in wind and solar and electrolysis, with relatively little labour required, similar to LNG production. B. Foreign investment and foreign debt may be required, as well as offshoring of profits and control. C. Limited opportunities for local employment in manufacturing of specialised equipment.	2 2 2
2. Price volatility	Badeeb [44] Leonard [45]	A. Green hydrogen is an energy commodity comparable to fossil fuels in market price mechanisms.	2
3. Limited resource	Badeeb [44]	A. Unlimited resource of renewable electricity. B. Limitations to availability of critical minerals required for renewable electricity and electrolysers [47,48]. C. Potential water scarcity can be addressed by the treatment of wastewater or the desalination of seawater, which require additional capital equipment but adds negligible energy requirements (0.14% and 0.05%, respectively) [49].	0 1 1
4. "Dutch disease" currency exchange rate and labour pull effects	Badeeb [44] Leonard [45]	A. Increase in export revenues affecting exchange rate and causing domestic manufacturing to become less export-competitive, thus shrinking the sector. This may be mitigated by potentially indefinite production (no crash at the end of resource deposit life) and permanent realignment of the economy (see issues in 4.D, 9.A, 13.A). B. Diversion of talent from other sectors (labour pull) into renewable/hydrogen construction projects away from other sectors due to higher salaries, similar to effects seen on fossil fuel projects.	1 2
5. Economic mismanagement	Badeeb [44]	A. Hydrogen-exporting countries are potentially just as susceptible to economic mismanagement in the same manner as the classic resource curse hypothesis suggests.	2
6. Rent seeking	Badeeb [44]	A. Equitable distribution of green-hydrogen-export windfall revenues within a country or concentration of benefits by elites does not appear to change for hydrogen compared to fossil fuels or minerals.	2
7. Corruption and institutional quality	Badeeb [44]	A. Hydrogen-exporting countries are potentially just as susceptible to corruption and issues of institutional quality in the same manner as the classic resource curse hypothesis suggests.	2

Table 7. *Cont.*

Causes	Reference	Relevance to Hydrogen	Rating
8. Damage to the natural environment	Leonard [45]	A. Renewable energy installations (particularly solar) will require significant land coverage, for as long as hydrogen production continues, affecting local ecology. Since wind and solar resources are less concentrated than deposits of fossil fuels, a larger land area is affected in producing electricity for green hydrogen than for fossil fuels. B. Since hydrogen production is not limited by finite resource life, operations may continue perpetually, and there is potentially no future planned date for site rehabilitation and restoration. C. Renewable electricity generation and hydrogen production would have less (negligible) potential for the contamination of ground water (CSG issue) [50] and water table dropping (coal mining issue) [51].	3 3 0
9. Diversion of investments away from human capital	Leonard [45]	A. Skilled and higher paid renewable energy construction jobs would attract workers from other sectors, unchanged compared to fossil fuels or mineral extraction.	2
10. Diversion of land	Leonard [45]	A. As per 8.A, more land will be diverted per PJ exported for green hydrogen compared to fossil fuels.	3
11. Economic dependence	Leonard [45]	A. If any one sector of the economy (oil/gas/minerals extraction or green hydrogen) grew proportionally too large, there is the potential for economic dependence and vulnerability. As with fossil fuels, this effect is highly dependent on the size and diversity of the rest of the economy, which may be reduced by “Dutch Disease” effects.	2
12. Technology/expertise dependence	Leonard [45]	A. As a nascent industry, there are a relatively small number of gatekeepers of key renewable energy and hydrogen production technologies upon which producing countries will be dependent. By comparison, mineral/fossil fuel extraction technology and expertise are well established worldwide.	3
13. Income inequality	Leonard [45]	A. Skilled and higher paid renewable energy construction jobs would attract workers from other sectors, while other sectors suffer the effects of “Dutch Disease”, similar to fossil fuel extraction activity.	2

Turning our attention to the emerging domestic and export-oriented green hydrogen market, the CSIRO's HyResource reference website [57] provides a comprehensive list of hydrogen projects under development in Australia. We have filtered this list for proposed commercial-scale projects (excluding those for research and demonstration) for the production of green hydrogen, and in Appendix A, we show those projects proposing either production for domestic use, export, or both. Of the 56 green hydrogen projects listed, 25 (45%) are designated solely for the domestic supply of green hydrogen in its various carrier forms, 13 (23%) are explicitly for export only, while 18 projects (32%) have intentions to export and provide local supply. The domestic only projects tend to be much smaller scale than the export-oriented projects.

The potential parallels with the commencement of LNG exports in Queensland are clear; once export facilities are in place, local hydrogen users will be in direct competition with international customers for supply, and pricing will be linked to international markets. There would be potential for "unserved load" or local investments in hydrogen utilisation becoming stranded assets without access to a supply of hydrogen that their original business case was based on before local hydrogen supply pricing became linked to export markets.

On this basis, it is clear that approximately one-third of the green hydrogen projects under development in Australia will potentially have locally developed hydrogen-using infrastructure that will sooner or later become export-exposed in a similar manner to the LNG export start-up. This represents a material risk to the business case of any such domestic project unless instruments, such as fixed-price long-term supply contracts or regulated domestic supply reservations are implemented. While it may appear preferable from a social licence perspective, the inclusion of domestic offtakes in a project that will become predominantly export-oriented is a clear energy security risk, unless regulatory instruments are applied to protect domestic users.

3.2.2. Competition between Domestic Use and Export-Oriented Electrolysers for Electricity?

In addition to the direct effects from Queensland LNG export start-up on eastern Australia's domestic gas system, in our earlier work [35], we also established the secondary effects experienced in the electricity system considering pre-LNG CSG ramp gas as a generation fuel. In the case of future green hydrogen production for export, the linkage to the NEM is much more direct for two reasons:

First, unlike LNG exports that are concentrated in central Queensland with influence in the electricity system flowing indirectly to other states, under the hydrogen export scenario, green hydrogen exporting plants are potentially located in each NEM state, directly impacting each of the interconnected state grids.

Second, according to the CSIRO hydrogen export 2050 scenario, 882 TWh will be used for green hydrogen production for export out of a total electrical consumption of 1570 TWh, hence 56% of all NEM electricity will be taken for the production of internationally traded green hydrogen. By comparison, in 2019, only 10.8% of NEM-state electricity was sourced from gas in LNG-export-exposed networks.

Consequently, the potential for international green hydrogen pricing to set the highest price for NEM electricity offtake is considerably more pronounced than it already is with LNG exports.

3.3. Aluminium Exports Framework: Lessons for Hydrogen?

In this section, we examine the aluminium production and export industry for potential similarities to contribute to our conceptual framework for green hydrogen export impacts on the domestic energy system. As an internationally traded commodity with significant electricity production input, aluminium is a comparable resource to export-scale green hydrogen.

3.3.1. Significance of Electricity in Aluminium Smelting

The two key inputs into the smelting of aluminium are alumina and electricity, accounting for 29% and 21% of input costs, respectively [58], and for this reason, aluminium is sometimes referred to as "congealed electricity" [59] or "solid electricity" [60] because of the concentration of electrical energy required for smelting. Aluminium production from mined ore (bauxite) to raw ingots is substantially more energy intensive (212 GJ/t) than for the manufacturing of steel from iron ore (23 GJ/t) [61], although it is the final stage of smelting, which contributes 25% of that energy input as electricity (approximately 15 MWh/t).

Historically, the 1970s oil shocks led to considerable relocation of aluminium smelting to countries with domestic low-cost electricity generation. For example, Japan's domestic aluminium smelting industry peaked at 1.12 million tonnes in 1974 (world #2) [62], until being impacted heavily by the effects of the 1970s oil shocks since Japan's electricity generation at the time was 71% reliant [63] on imported oil and oil products for fuel. Japan's sole remaining aluminium smelter is still in operation, Nippon Light Metal Co. Ltd. (Tokyo, Japan), Kambara Complex [64], and only survives because its electricity supply is almost entirely from its privately owned hydro power stations, which have protected the plant from electricity price increases due to imported fossil fuels. Just as Japanese aluminium smelter production was declining, the Boyne Smelter in Queensland, the Tomago Smelter in New South Wales and the Portland Smelter in Victoria were being constructed in the late 1970s and early 1980s in eastern Australia, attracted by access to low-cost electricity from local coal reserves [58].

3.3.2. Aluminium as a Means of Exporting Low-Cost Electricity

In 2021, Australia produced 1.56 Mt of aluminium, of which 1.43 Mt (91.7%) was exported, with 1.41 Mt (98%) of those exports was as unprocessed ingots [65]. In the same year, Australia imported 0.41 Mt of aluminium, 0.33 Mt (82%) of which was in semi-fabricated forms, such as extrusions, wire, sheet, plate and foil [65].

Due to the high energy intensity of aluminium, approximately 15% of Australia's electricity production is used in aluminium smelting [58]. Based on the abovementioned figure of 15 MWh/t of electricity used in aluminium production, this exported portion of production consumed approximately 21.45 TWh. For comparison, this would equate to 133 PJ of LNG consumed in modern combined cycle gas turbine power stations at 58% efficiency generating electricity for aluminium smelting. Considering the electricity density of aluminium, aluminium production and export can be seen as a method of exporting low-cost electricity to countries that do not smelt their own aluminium due to higher energy prices.

3.3.3. Aluminium Producer Interactions with the Domestic Electricity System

Effects on Electricity Pricing

The development of Bayswater Power Station in New South Wales is closely connected with the development of the Tomago smelter, as was the Loy Yang A Power Station in Victoria with the Portland Smelter [66,67]. In both cases, state governments led with the construction of additional coal-fired generation capacity to enable the development of the smelters (which had a shorter construction time than the power station but whose power they required to operate) and agreed to discounted long-term electricity supply contracts for smelters to attract investment and industrial development [58]. These and other smelters operating in Australia have subsequently used their market power as a major existing incumbent industrial employer and electricity user to obtain further price reductions significantly below market electricity supply prices, with the threat of ceasing operations and transferring production to other locations with a lower cost of electricity. This pattern is found to occur worldwide [58]. When generators are privately owned, this loss is mitigated by increasing the price of electricity charged to other users. When generators are state-owned, the loss is subsidised from government funds. In either case, multinational aluminium corporations are consistently subsidised by the host community.

Grid Stability

Aluminium smelters are technically and commercially optimised to run continuously at full output. In situations of extreme demand and insufficient electricity supply, aluminium smelters can be disconnected from the grid to restore system balance and prevent blackouts [68]; however, the damage to smelting equipment can be severe for even a few hours of lost electricity supply, so an aluminium smelter would not be considered as an interruptible industrial load in terms of grid operations, and such, an operation would only be performed in extreme circumstances of imminent grid blackout. The operation of aluminium smelters does provide a measure of grid stability due to their continuous stable operation and significant load, although this is only an incidental benefit.

3.3.4. Aluminium Smelting and Applicable Factors to a Hydrogen-Exporting Framework

Australia's aluminium smelting industry can therefore be seen to have some similarity with green hydrogen in its electrical intensity of production and primary export focus. Table 8 lists various specific commercial and technical impacts of aluminium-smelting operations on the domestic electricity system and considers their application to green hydrogen production to contribute to the framework for analysing the domestic impacts of a green hydrogen industry.

Table 8. Aluminium smelting domestic impacts and applicability to a future green hydrogen export industry.

Aluminium Industry Domestic Impacts	Reference	Green Hydrogen Application
1. Electricity price Aluminium production located globally based on lowest cost of electricity. Investors threaten relocation offshore to leverage electricity price reductions/subsidies.	Oil shock effects driving Japan's smelter shut down, growth in Australia's industry in 1980s [62,65]. Electricity supply contract renegotiation in Australia [58].	A. Lowest cost of green electricity will be a primary driver for location of projects. B. Potential for hydrogen producers to relocate production for lower $/MWh, greater risk than for aluminium as technology development continues to reduce green electricity costs for newer installations.
2. Capacity Factor Smelters are commercially optimised for continuous operation at full output.	Smelters operate baseload and are willing to accept take-or-pay electricity contracts [58].	Highest capacity factor operations provide the best return for invested capital in hydrogen production. Grid electricity is preferred over dedicated renewable generation [38].
3. Grid Interaction Smelters are technically optimised for continuous full capacity operation.	Aluminium production assets are severely affected by electricity supply [69] interruptions.	Electrolysers are much less sensitive to electricity supply disruptions than smelters and can operate as interruptible loads in case of supply demand imbalance on the grid [7].

4. Evaluation of the Hydrogen Superpower Scenario

Energy exporters are rarely the focus of energy security or vulnerability studies, and thus, to assess these requires the development and adaptation of new approaches or tools. Using the evaluation tools we have established in previous work for energy exporter vulnerability [1] and domestic energy security [35], the present (pre-2019 pandemic) state of Australia's energy system and energy exporting economy is subsequently compared to the hydrogen export scenario set out in Section 2 of this paper.

4.1. Energy Exporter Economic Vulnerability Metrics

The economic vulnerability of energy exports can be evaluated using the six metrics set out in our earlier work [1], as follows:

External vulnerability factor metrics

M1—Customer Energy Import Dependence;

M2—Customer Energy Mix Diversity;
M3—Export Customer Diversification.

Internal vulnerability factor metrics

M4—Energy Exports Significance to GDP;
M5—Resource-to-Production Ratio;
M6—Carbon Intensity of Energy Export Blend.

Our objective in this paper is to compare the current status (pre-2019 pandemic data reference point) with the future case of a fully implemented hydrogen-exporting-superpower scenario by 2050 as has been examined in Section 2 of this paper. In each case, forecasts for 2050 fossil fuel exports are reduced to zero as oil and gas are considered largely depleted except for some gas for domestic use, and coal is no longer tradeable in any meaningful quantity, consistent with the IEA Net Zero by 2050 scenario [70]. Green hydrogen (in its various carrier forms) is, by 2050, Australia's primary energy export.

The evaluation of external metrics M1–M3 for 2050 is based on a forecast case we have assumed as follows, based to the extent possible on currently policy settings for the 2050 time horizon.

From 2019 to 2050, for metrics M1–M3, we have assumed a single change in the top five export customers, Japan, China, India, South Korea and Taiwan, with Singapore replacing Taiwan at number 5 in 2019. In the case of Japan, South Korea and Taiwan, we have assumed their aggressive decarbonisation plans [3,71,72] are achieved, and in each case, petroleum imports are ceased by 2050, being replaced by the almost complete electrification of energy use. In Japan's case, the present 14% renewables and 9% nuclear contribution to electricity generation increases to 38% renewables and 22% nuclear, ensuring 60% domestic energy supply. In South Korea, we assume that the current share of 30% nuclear is maintained, and renewables expand to 20% of total energy supply, allowing for 50% energy self-reliance. For Taiwan, we have assumed the aggressive decarbonisation strategy based on offshore wind and solar achieves 70% energy self-reliance, hence their reduction in imports from Australia and removal from the top five export customers. The energy self-reliance of India and China increases in line with nuclear and renewable energy development trends, with a reduction by 50% in dependence on imported energy. Singapore, added as number five in 2050, is assumed to increase its very small local renewable generation by a factor of 10, but still remains 96% dependent on energy imports, 60% of which we assume as being supplied from Australian renewable electricity (green hydrogen/direct cable).

M1—Customer Energy Import Dependence

The energy import dependence ratio of each export customer is multiplied by the share of energy exports to that customer, and then the total is divided by the exporter's total energy exports, as shown in Equation (1). The share of energy imports to the total primary energy supply is a recognised indicator for energy security [73,74], and import-dependent countries will have a tendency to reduce their share of energy imports to improve domestic energy security. As a result, a high level of customer import dependence represents a vulnerability for the exporter, while a lower score indicates the mix of customers is less dependent on energy exports and are therefore less likely to try to reduce their import dependence further, thus being a less vulnerable situation for an exporter.

Equation (1)—M1—Customer Energy Import Dependence

$$M1 = \frac{Q_A \times (E/TPES)_A + Q_B \times (E/TPES)_B + \cdots + Q_n \times (E/TPES)_n}{Q_{total\ exports}} \quad (1)$$

where

Q = quantity of energy exports to country A, B, n, or the total energy export (in PJ);
E = energy imports by country A, B, n (in PJ);

TPES = total primary energy supply of country *A*, *B*, *n* (in PJ).

The significant reduction in M1 seen in Table 9 is driven primarily by the actions of the largest export customer Japan (46% of Australia's energy exports) realising their decarbonisation strategy, which includes increasing the share of domestic renewable electricity generation from 14% in 2019 to 38% by 2050 and increasing nuclear power generation from 9% to 22% over the same time period [3]. A similar change is also modelled for South Korea (third largest export customer, with 13% of Australia's energy exports) based on their policies to hold nuclear generation at 30% and increase domestic renewables from 2% to 20% [39]. As a result, by 2050 both Japan and Korea are considerably less likely to further reduce energy imports, hence Australia's reduction in export vulnerability.

Table 9. M1—Customer Energy Import Dependence (Australia) 2019 and 2050.

	2019	2050
M1	0.744	0.413

M2—Customer Energy Mix Diversity

Diversity of energy sources is a widely recognised indicator for energy security [73,75], with a greater diversity providing greater energy security. Energy importers can be expected to pursue actions to diversify their energy mix and to reduce the import of existing fuels in their primary energy mix. Hence, a lower customer energy mix diversity represents a higher vulnerability to loss of export revenue. The Herfindahl–Hirschman Index (HHI) index, which is widely used to assess energy mix diversity [73], is applied here to quantify the energy mix diversity of individual export customers, as set out in Equation (2). Thus, for the current evaluation, a higher score represents less customer energy mix diversity and higher vulnerability for the exporter.

The exporter's total export portfolio position weighted by the export energy share of each customer is thus calculated using the following equation:

Equation (2)—M2—Customer Energy Mix Diversity

$$M2 = \frac{(Q \times HHI_{TPES})_A + (Q \times HHI_{TPES})_B + \cdots + (Q \times HHI_{TPES})_n}{Q_{total\ energy\ exports}} \tag{2}$$

where

Q = quantity (in PJ) of energy exports to country 1, 2, . . ., *n*, or the total energy export quantity;
HHI_{TPES} = HHI diversity index for total primary energy supply for country 1, 2, n = (x_{coal})2 + (x_{gas})2 + (x_{oil})2 + ($x_{nuclear}$)2 + (x_{hydro})2 + (x_{wind})2 + (x_{solar})2 + ($x_{biomass}$)2 + ($x_{geothermal}$)2;
$X_{fuel\ type\ \mathrm{A}}$ = consumption of fuel type A/TPES.

The calculation result for M2, as shown in Table 10, is strongly influenced by Japan's long term decarbonisation strategy for 2050 [3], being Australia's primary energy export customer as noted earlier. Japan's strategy sees reduced fossil fuel use and increased shares of nuclear, geothermal, biomass, solar, onshore wind and offshore wind energy, with an increase in their energy mix diversity shown by a reduction in $\mathrm{HHI}_{\mathrm{TPES}}$ from 0.273 to 0.226. South Korea's own energy strategy, which includes an increase from 2% to 30% in total renewables, including onshore and offshore wind, solar and biomass, increases their energy mix diversity, as shown by a reduction I HHITPES from 0.320 to 0.182, although the overall effect on M2 is less since South Korea's overall share of Australia's energy exports is only 13% compared to Japan's 46% share. An exception is Singapore, which has a limited domestic renewable energy potential, in which reducing fossil fuels makes the country more concentrated in externally sourced energy, relying on imported green hydrogen and a direct electricity cable connection. The overall weighted diversity index result for M2 is an increase in customer energy mix diversity, hence the reduced exporter vulnerability. Since green hydrogen is largely seen to replace coal and LNG consumption, the direct effect from green hydrogen exports on the change in M2 from 2019 to 2050 is negligible.

Table 10. M2—Customer Energy Mix Diversity (Australia) 2019 and 2050.

	2019	2050
M2	0.329	0.228

M3—Export Customer Diversification

Exporter vulnerability is reduced as the diversity of energy export customers is increased, with a greater number of smaller customers affording greater protection against the loss of exports to any one customer [76,77]. The same approach is applied to the importer side with respect to the diversity of suppliers as a measure of energy security [73,75]. The HHI index is applied to quantify export customer diversification. In the current international energy supply market (2019 case), the index is adjusted by the use of a factor representing each export customer's actions to reduce CO_2 emissions, where stronger commitments cause greater vulnerability to current fossil fuel exports. The calculation method is shown in Equation (3).

Equation (3)—M3—Export Customer Diversification

$$M3 = \left[CER_{\,1} \times (X_{1\ FF})^2 + \left(100 - CER_{\,1}\right) \times (X_{1\ ZCF})^2\right] + \cdots + \left[CER_{\,n} \times (X_{n\ FF})^2 + \left(100 - CER_{\,n}\right) \times (X_{1\ ZCF})^2\right. \quad (3)$$

where

CER = the export customer country's CO_2 emissions reduction rating index (0–100), adopted from the Climate Change Performance Index [78];

x_{FF} = fossil fuels exported to country 1, 2, n, as a fraction of total energy (PJ) exports;

x_{ZCF} = zero-carbon fuels exported to country 1, 2, n, as a fraction of total energy (PJ) exports.

For this metric, a greater diversity of customers yields a lower score, which is desirable for the exporter to reduce vulnerability that would be associated with having only one or two large customers. The Climate Change Performance Index (CCPI) [78], used as an input to the CER, rates poor performance with a low score. For the exporter, countries with a high CER score represent heightened vulnerability to future fossil fuel exports. For zero-carbon fuels, the CER weighting factor is applied in reverse (100-CER) since commitment to the CO_2 emissions of export customers for zero-carbon fuels will reduce the vulnerability to export concentration to those customers. Using this approach that differentiates between fossil fuels and zero-carbon fuels, we are able to dynamically assess vulnerability with this metric as a country's energy export mix transitions away from fossil fuels, along with changing importer CO_2 emission reduction commitments.

In 2050, we assume that Australia has largely ceased exporting fossil fuels, with those exports replaced by green hydrogen, and fossil fuels are only exported to countries with limited, if any, emission reduction policies. Accordingly, fossil fuel exports to Japan, South Korea and Singapore (Australia's first, third and fifth largest energy exports customers, respectively) are completely replaced by green hydrogen, which has the effect of flipping the weighting factor of each country to 100-CER. This is the primary driver for the reduction in M3, as shown in Table 11.

Table 11. M3—Export Customer Diversification (Australia) 2019 and 2050.

	2019	2050
M3	10.171	6.335

The result is a significantly reduced vulnerability to Australia as it transitions to green hydrogen exports in line with customer policy settings for CO_2 emissions reduction manifested in import demand.

M4—Energy Exports Significance to GDP

The basic indicator of a country's vulnerability to the dominance of any one economic activity is captured in this metric, which is widely applied to the general economic vulnerability of developing countries [79], as well as in the case of oil exporters [76] and, similarly, to the cost of energy imports as a fraction of GDP, which is a widely applied energy security metric [73]. While an increase in revenue from energy exports is generally desirable, it also has the effect of increasing a country's economic vulnerability if the share of energy export revenue to GDP is increased. The method of calculation is set out in Equation (4).

Equation (4)—M4—Energy Exports Significance to GDP

$$M4 = \frac{R_{fuel\ A} + R_{fuel\ B} + \cdots + R_{fuel\ n}}{GDP} \tag{4}$$

where

R = revenue;
GDP = gross domestic product;

The composition and results for M4 are shown in Table 12, all units are in billions of USD, converted from Australia dollars at AUD 1.00 = USD 0.65 (the prevailing exchange rate at the time of writing). Although the value of energy exports will increase by 20.6% from 2019 to 2050, with green hydrogen revenue entirely replacing fossil fuel exports, M4 will decline from 2019 to 2050 under the hydrogen export superpower scenario. This is in part due to the cessation of coal, oil and LNG exports; however, it is more strongly influenced by the growth of Australia's domestic services economy.

Table 12. Energy export significance to GDP metric, including the 2050 hydrogen exports scenario.

Year	2019	2050
GDP [80]	1490	5300
Coal export revenue [81]	14.7	0.0
LNG export revenue [82]	30.9	0.0
Oil export revenue [82]	8.3	0.0
Hydrogen export revenue [18]	0.0	65.0
Total energy export revenue	53.9	65.0
M4	**0.036**	**0.012**

M5—Resource-to-Production Ratio

An energy exporter's vulnerability to achieve sustainable income from resource exports is heavily dependent on the remaining life of resource deposits. This is a particular concern for countries producing and exporting fossil fuels. However, some countries' deposits of some resources (black coal in Australia, for example) are so vast that the actual related vulnerability is negligible, hence the resource-to-production ratio input figure is capped at 100 years to return a vulnerability score of zero. The calculation method is set out in Equations (5) and (6).

Equation (5)—M5—Resource-to-Production Ratio

$$M5 = \frac{100 - RPR_{aggregated}}{100} \tag{5}$$

where

RPR = the resource-to-production ratio for each energy resource type (years), with an upper limit to RPR of 100. i.e., for RPR $\geq$ 100; M5 = 0.

Equation (6)—RPR Detailed Method

$$RPR_{aggregated} = \frac{S_{coal} \times \left({}^{Q_{coal}}/_{P_{coal}}\right) + S_{gas} \times \left({}^{Q_{gas}}/_{P_{gas}}\right) + S_{oil} \times \left({}^{Q_{oil}}/_{P_{oil}}\right) + S_{greenH2} \times 100}{X} \quad (6)$$

where

$RPR_{aggregated}$ = resource-to-production ratio (aggregated);
Q = total demonstrated resource of each energy resource type, in petajoules;
P = annual production rate of energy resource type, in petajoules per year;
S = export quantity from each energy type, in petajoules per year;
X = total export quantity from all energy types, in petajoules per year.

The aggregate RPR is the RPR of each resource weighted by its share of total energy exports (in PJ). By using total demonstrated (including sub-economic) resources estimates instead of economically recoverable reserves, the results return a strategic insight and are insulated from short-term price volatility and technology changes. Since the production of green hydrogen is sustainable indefinitely and not dependent on the exploitation of a finite resource, the ratio of Q/P is not relevant, and instead, the maximum allowable figure of 100 is applied. As Australia's export energy transition progresses and share of fossil fuels diminishes while the share of green hydrogen increases, $RPR_{aggregated}$ tends toward 100, and the score for M5 (representing exporter vulnerability) tends toward zero.

The inputs and results for B are shown in Table 13. In 2019, the weighted calculation of M5 returns a value of 0.0 due to the overwhelming presence of coal exports (72% of all energy exports by energy value), along with 95% of all resources. Since hydrogen is derived from renewable electricity, the resource is unlimited, hence M5 again scores 0.0. The data for gas and oil resource estimates are sourced from the Australian Petroleum Production and Exploration Association (APPEA), while coal resource estimates are sourced from Geoscience Australia (GA) [81].

Table 13. Resource-to-Production ratio metric, including the 2050 hydrogen exports scenario.

Year	2019	2050	Reference
Resource			
Gas	86,399	0	APPEA [82]
Oil	13,749	0	APPEA [82]
Coal	1,959,417	1,798,446	GA [81]
Hydrogen	0	very high	CSIRO [19]
Production			
Gas	4938	0	APPEA [82]
Oil	719	0	APPEA [82]
Coal	12,596	0	GA [81]
Hydrogen	0	2088	CSIRO [19]
M5	**0.0**	**0.0**	

The results show that a transition from exporting fossil fuels from limited life deposits to exporting green hydrogen provides significant benefits for exportation by reducing their vulnerability to the loss of export revenue due to resource depletion, although the effect for Australia is obscured by coal resources in excess of 100 years of production.

M6—Carbon Intensity of Energy Export Blend

As energy-import-dependent countries worldwide pursue their own decarbonisation, exporter dependence on fossil fuel exports is an important vulnerability. Fuels with higher CO_2 emissions intensity are at greater risk of demand reduction and loss of markets sooner.

The weighted CO_2 emissions intensity of the exporter's energy exports blend, calculated as shown in Equation (7), is therefore a measure of vulnerability to loss of export revenue. Increasing shares of zero-carbon fuels, such as green hydrogen, reduce an exporter's exposure to loss of revenue from customer-side energy transition away from fossil fuels.

Equation (7)—M6—Carbon Intensity of Energy Export Blend

$$M6 = \frac{(S_{coal} \times f_{coal}) + (S_{gas} \times f_{gas}) + (S_{oil} \times f_{oil}) + \left(S_{zero\ carbon\ fuels} \times f_{zero\ carbon\ fuels}\right)}{X} \quad (7)$$

where

S = export quantity from each energy type, in PJ;
X = total export quantity from all energy types, in PJ;
f = CO_2 emissions adjustment factor for each energy type, as per Table 14.

Table 14. Fossil fuel emissions factors.

Energy Type	Emissions Factor (t CO_2/TJ)	"f" CO_2 Emissions Adjustment Factor
Coal	96.3	1.00
Crude oil	73.3	0.76
Natural gas	56.1	0.58
Green hydrogen	0.0	0.00

The composition and result for M6 is shown in Table 15. Australia's current highly vulnerable position of high carbon intensity of energy exports is replaced by effectively 100% due to green hydrogen, hence a score for M6 of 0.0 in 2050. The policy implication for Australia is that an early transition away from exporting fossil fuels as an early mover to supply emerging green hydrogen markets in Japan and Korea, as set out earlier in this paper, considerably reduces exporter vulnerability.

Table 15. Carbon intensity of energy exports, including the 2050 hydrogen exports scenario.

Year	**2019**	**2050**
Gas exports (PJ)	3686	0
Oil exports (PJ)	518	0
Coal exports (PJ)	10,629	0
Hydrogen exports (PJ)	0	2088
Total exports (PJ)	14,833	2088
M6	**0.86**	**0.00**

Export Vulnerability Metrics Scaled and Compared

We have applied a scaling and normalisation method consistent with our original approach for these metrics [1], and the comparison is shown in Figure 4 (data in Table 16). The upper values for each metric are normalised to 1.0, except for M5, which scored 0.0 for both 2019 and 2050. Overall, it is clear that the energy transition away from fossil fuels and toward domestic zero-carbon generation sources supplemented by exportable green hydrogen has a positive impact in every metric, on the condition that the exporter, in this case Australia, adapts their energy exports to meet the demand for zero-carbon energy.

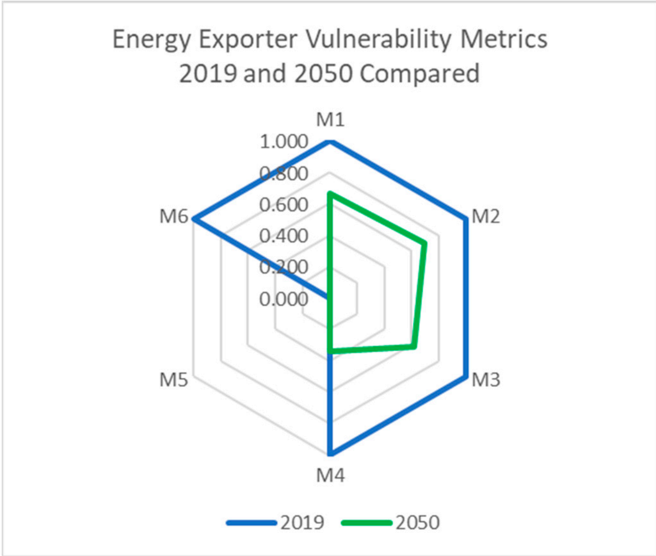

Figure 4. Energy exporter vulnerability metrics, compared between 2019 and 2050.

Table 16. Energy exporter vulnerability metrics, compared between 2019 and 2050 (data for Figure 4).

	2019	2050	2019	2050
		Raw Scores		Normalised and Scaled
M1	0.744	0.413	1.000	0.555
M2	0.329	0.228	1.000	0.693
M3	10.171	6.335	1.000	0.623
M4	0.036	0.015	1.000	0.423
M5	0.000	0.000	0.000	0.000
M6	0.860	0.000	1.000	0.000

4.2. Energy Exporter Domestic Energy Security Metrics

The exporter's energy security impacts on the hydrogen exports superpower scenario examined in this paper are evaluated using the two new metrics set out in our earlier work [35]. For these two metrics, the possible range of scores is 0.0 to 1.0, and a higher score means higher domestic energy security (higher is more desirable).

Ex.PESS—Exporter's Primary Energy Self-Sufficiency

Energy security theory widely holds that higher primary energy self-sufficiency is a desirable objective [73,75]. In the case of energy exporters, the calculation method of primary energy self-sufficiency needs some additional consideration to avoid an incorrectly favourable result weighted by energy production dedicated to exports that does not contribute to domestic supply, hence input values for domestic energy self-sufficiency for each energy type are capped at 100%. This new calculation method is set out in Equation (8).

Equation (8)—Ex.PESS—Exporter's Primary Energy Self-Sufficiency

$$Ex.PESS = \frac{(TES \times DSS)_{electricity} + (TES \times DSS)_{oil} + (TES \times DSS)_{gas} + (TES \times DSS)_{greenH2}}{TPES} \quad (8)$$

where

Ex.PESS = Exporter Primary Energy Self-Sufficiency;
TES = total energy supply in each category;
DSS = domestic supply self-sufficiency, capped at 100%, being the maximum rate of production that can be applied for domestic use;

TPES = total primary energy supply (sum of all TES categories: electricity, oil, gas and green hydrogen);

In the 2050 hydrogen export superpower scenario [19], hydrogen is introduced as a new energy source, being entirely generated from domestic renewable electricity. The use of imported oil and oil products, principally as transport fuels, is expected to be ceased before 2050 since under this scenario, new internal combustion engine vehicles will not be available beyond 2035. Any use of imported fossil fuels (primarily diesel) in electricity generation is also replaced with various local renewables and hydrogen. Australia thus becomes 100% self-sufficient in energy sources for its domestic electricity supply. Domestic gas is almost entirely converted to biogas, hydrogen blending and synthetic methane from green hydrogen. The inputs and calculation result for Ex.PESS in 2019 and 2050 for the hydrogen export superpower scenario are shown in Table 17. The policy implication of a major transition for Australia to become a green hydrogen export superpower by 2050 in this metric is the benefit of displacing imported oil used in 2019 primarily as a transport fuel and also a small portion for power generation with abundant, locally produced renewable electricity and green hydrogen, thus enhancing Australia's energy security.

Table 17. Exporter's Primary Energy Self-Sufficiency, including the 2050 hydrogen exports scenario.

	2019		2050	
	TES	**% DOM**	**TES**	**% DOM**
Oil	2307	31.4%	0	-
Electricity source	2404	98.6%	5652	100.0%
Gas	922	100.0%	790	100.0%
Hydrogen	0	-	2088	100.0%
Ex.PESS (aggregate)		**0.71**		**1.00**

Ex.DES—Exporter Domestic Energy System Exposure to Export Impacts

When an energy exporter's domestic energy system is linked to export activities, energy security can be impacted through the influence of international market forces on pricing and demand. This metric quantifies the extent to which an energy exporter's domestic energy system is exposed to these export impacts, with the calculation method as shown in Equation (9).

Equation (9)—Ex.DES—Exporter Domestic Energy System Exposure to Export Impacts

$$Ex.DES = \frac{(Ex.DES_{gas} \times TES_{gas}) + \left(Ex.DES_{electricity} \times TES_{electricity}\right) + (Ex.DES_{greenH2} \times TES_{greenH2})}{TES_{gas} + TES_{electricity} + TES_{greenH2}} \quad (9)$$

where

$Ex.DES_{(\text{energy type})}$ = 1 minus the ratio of domestic energy supply of that energy type that is physically linked to an export market;

$TES_{(\text{energy type})}$ = total energy supply of the given energy type.

We show the composition and calculation results for Ex.DES in 2019 (historical data) and 2050 (forecast scenario) in Table 18. Due to the widespread deployment of export-focussed electrolysers connected to the electricity grid in each state, 100% of grid electricity becomes physically linked to an export pathway, and hence heavily exposed to pricing and demand from international markets. Since 2050, 867 TWh (55.9%) of Australia's electricity production of 1550 TWh is taken by green hydrogen production for export. The extent of hydrogen supply in 2050 that is connected to export-oriented hydrogen production facilities is difficult to forecast at this time; we have reviewed and filtered CSIRO's HyResource database [57] for planned hydrogen producing projects (see Appendix A) and established that of the 43 projects planned to supply the domestic market, 18 of them (42%) are associated with an export-oriented facility, hence we have therefore applied the figure of 42% as the share of domestic hydrogen supply that is physically export-exposed. The policy implication for Australia is a reduction in energy security as the domestic energy system becomes entirely export-linked and majority export-focussed, only mitigated by domestic-focussed gas projects with no LNG export linkage and local hydrogen production. The export-linkage of the electricity system has the potential to cause domestic electricity pricing to become set not by domestic supply-demand forces, but rather by international demand for green hydrogen, unless protective policy measures are put in place.

Table 18. Exporter domestic energy system exposure to export impacts, including the 2050 hydrogen exports scenario.

	2019	2050
Gas (domestic use) (PJ)	922	790
Electricity (domestic use) (PJ)	950	5652
Hydrogen (domestic use) (PJ)	0	338
Ex.DES (gas)	0.37	1.00
Ex.DES (electric)	0.59	0.00
Ex.DES (hydrogen)	0.00	0.42
Ex.DES (aggregate)	**0.48**	**0.14**

5. Framework Summary

The elements of conceptual framework for domestic impacts from the green hydrogen export superpower scenario established in this paper are summarised in Figure 5 and shown to be linked to the applicable stage of the energy system value chain. By associating each framework element to a phase in the green hydrogen production and export supply chain, the direct application of each is further clarified.

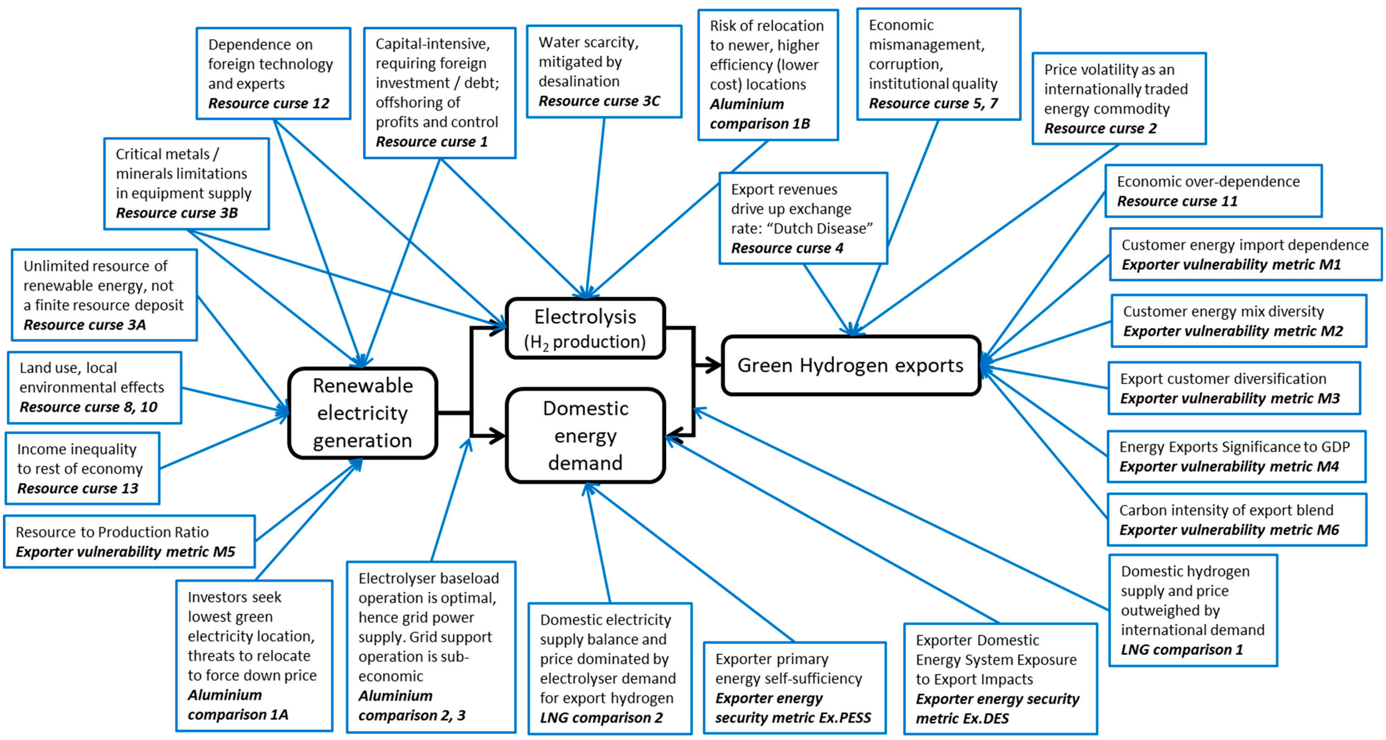

Figure 5. Conceptual framework for domestic impacts of the green hydrogen export superpower scenario.

As set out in Section 2, the extent of renewable electricity generation required to supply hydrogen production is of such a large scale that policymakers, regulators, project developers and community stakeholders will benefit from an increased awareness of factors related to the renewable electricity phase as an input to optimise projects and mitigate negative outcomes for related communities. Elements of the framework related to domestic energy demand are essential considerations for grid operators, regulators, governments, and other major industrial electricity users who will potentially be in competition with hydrogen export customers for electricity supply. Elements of the framework related to the green hydrogen exports phase are most applicable to state and national government policy makers and related advisors as well as think-tanks to the extent that establishing a robust and relevant policy framework reflecting these elements of domestic vulnerability sets clear expectations for an emerging industry of the investment conditions that are sustainable for the producing country and state.

6. Discussion and Implications

The conceptual framework and its application in this study for understanding the domestic energy system implications of a prospective green hydrogen exporter, such as Australia, are quite unique in the academic literature. As mentioned in Sections 1.4 and 4, a majority of earlier works on energy security and vulnerability has been focussed on energy. There are a few notable exceptions, which are compared here. Firstly, a study, using Egypt as an example of sunbelt countries, considered the impact of exporting hydrogen and other renewable-electricity-derived energy carriers on the domestic energy situation, but from a techno-economic perspective [83]. They show potential benefit to reduce domestic energy system costs under some scenarios.

Secondly, and of most relevance to the current study, a study specifically examines the implications for security justice from Australia's coal-generated hydrogen exports to Japan [34]. They highlight two of the traditional energy security factors—availability and affordability—within their six-dimension framework for analysing this transition. Though they consider that hydrogen might reduce vulnerability through the increased diversification of energy sources and support for renewables, they do not consider the overall vulnerability of Australia due to exports at present versus the future with the explicit consideration of the technical, economic and carbon policy interconnections. They also focus heavily on fossil-based hydrogen, making the comparison with the present work less direct. Therefore, the following discussion relies primarily on our current work and extracts some further implications.

In Table 19, we show the summarised quantitative evaluation of Australia's energy export economic vulnerability and domestic energy security, comparing 2019 as the base case with the 2050 hydrogen export scenario.

As seen in Table 19, exporter vulnerability due to importer efforts to reduce import dependence (M1) and to diversify energy sources (M2) is reduced by switching to green hydrogen exports from 2019 to 2050 since it is found that by 2050, these actions will have already been implemented by importing countries as they increase the extent and diversity of domestic zero-carbon energy sources. Exporter vulnerability due to carbon risk in export fuels (M3) is dramatically reduced since fossil fuel exports to countries taking action to decarbonise are replaced by green hydrogen imports. Vulnerability is expected to have decreased due to a lower ratio of energy exports to GDP (M4), even though both increase, since GDP is forecast to increase at a faster rate, although this result may not necessarily be widely applicable to other countries, depending on their economic structure. Vulnerability in terms of resource-to-production ratio (M5) is unchanged for Australia at a level of negligible exposure, exchanging over 300 years of coal reserves in 2019 for unlimited renewable energy supply hydrogen exports. However, for current fuel fossil exporters with less than 100 years of known resources, or none at all, a transition to green hydrogen exports using unlimited renewable electricity could provide a material reduction in vulnerability. A current fossil fuel exporter's vulnerability due to carbon exposure (M6) is found to be substantially reduced by reducing or eliminating fossil fuel export in favour of green hydrogen.

Table 19. Summary of change in exporter internal vulnerability and domestic energy security from 2019 to 2050 (hydrogen export scenario).

	2019	2050	Comment
Exporter Internal Vulnerability			
M1	0.744	0.413	Less vulnerable (improved)
M2	0.329	0.228	Less vulnerable (improved)
M3	10.171	6.335	Less vulnerable (improved)
M4	0.036	0.012	Less vulnerable (improved)
M5	0.00	0.00	Unchanged (negligible vulnerability)
M6	0.860	0.00	Less vulnerable (improved)
Exporter Domestic Energy Security			
Ex.PESS	0.71	1.00	More secure (improved)
Ex.DES	0.48	0.14	Less secure (deteriorated)

Further, we have found that primary energy self-sufficiency, as measured by Ex.PESS, is increased as all energy needs are met in 2050 from domestic renewable energy, providing an improvement in the exporting country's energy security situation. However, the exporter's domestic energy system exposure to international market effects (as measured by Ex.DES) is found to significantly increase, representing a deterioration in the exporting country's energy security situation in that dimension as the entire electricity grid and a significant part of the domestic hydrogen supply is directly linked to export demand and pricing.

7. Conclusions and Further Research

Amid the excitement surrounding the possibility of developing a new zero-carbon export industry in the form of green hydrogen, countries with excess renewable energy potential capable of supporting large-scale green hydrogen production should carefully consider the domestic implications, as established in this study, to design development plans and policies to appropriately maximise the benefits from this new export industry while limiting the risk of negative impacts to domestic customers and domestic energy security.

We have established that the hydrogen export scenario proposed by CSIRO and Climateworks for AEMO in their 2022 report [19] is broadly consistent in terms of export quantity with projected demand expressed by potential import customers, Japan and South Korea, although there is still some way to go in technological development in both production and end use equipment before convergence on the buyer's and the seller's price is reached.

From the analysis of frameworks for resource curse hypothesis, LNG exports and aluminium exports in the preceding sections, a conceptual framework for domestic implications and energy security risks is compiled and shown in Figure 5. Our initial examination of relevance of the resource curse hypothesis has provided indications of many similarities with extractive resource export industries while also revealing some differences. Further research and analysis on this topic are recommended to establish a more comprehensive understanding of potential resource curse risks to emerging hydrogen exporters to enable preventative action in policies and development planning. From the comparison with the LNG export framework, we note that a high export price for hydrogen can result in domestic hydrogen supply being diverted to export markets and driving up the domestic electricity price. From the comparison with the aluminium export frameworks, we note that a low export price for hydrogen can result in established hydrogen producers threatening to relocate production to another country if the electricity price paid is not reduced, requiring cross-subsidy from other customers accepting increased prices, or in the form of government subsidies.

From this study, opportunities for further research have been identified in the following areas:

- A deeper study of the relevance of detailed aspects of the resource curse hypothesis to large-scale green hydrogen exports can be continued from the initial review provided in this paper.
- As the extent of energy infrastructure construction (renewable electricity generation, transmission lines, hydrogen electrolysers and conversion plants for exportable carriers) required for the anticipated transition has been demonstrated, questions immediately arise on the shortages of critical minerals to manufacture the equipment required. Further research on potential supply shortages and alternative materials is proposed.
- The potential opportunities and benefits for reducing import customer energy demand by the relocation of energy-intensive activities closer to low-cost renewable energy resources, in a similar manner to the relocation of aluminium production from Japan to Australia, such as green steel production, rather than transforming renewable electricity into hydrogen, then into a carrier, for shipping to a distant customer.

Author Contributions: Conceptualization, A.J.C.; Methodology, A.J.C.; Formal analysis, A.J.C.; Data curation, A.J.C.; Writing—original draft, A.J.C.; Writing—review & editing, B.C.M.; Supervision, B.C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data is publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

Glossary

AE	Alkaline electrolysis
AEMO	Australian Energy Market Operator
APPEA	Australian Petroleum Production and Exploration Association
CEFC	Clean Energy Finance Corporation (Australia)
CO_2	Carbon dioxide
COAG	Coalition of Australian Government (National and State Governments body)
CSG	Coal Seam Gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
e-LNG	Liquefied natural gas produced from synthesised methane using hydrogen produced from electrolysis
GA	Geoscience Australia
HESC	Hydrogen Energy Supply Chain Project (Australia Japan cooperation)
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
MeOH	Methanol
NEM	Australia's National Electricity Market
NH_3	Ammonia
PEM	Polymer electrolyte membrane (sometimes also called proton exchange membrane)

Appendix A

Commercial scale green hydrogen development projects categorised by intended offtake (domestic, export or both) [57] are listed in Table A1.

Table A1. Summary of commercial scale hydrogen projects by intended offtake.

Project	State	Domestic	Export
Abel Energy Bell Bay	Tasmania	✓	✓
Arrowsmith Hydrogen	Western Australia	✓	
Australian Renewable Energy Hub (Pilbara)	Western Australia	✓	✓
Bristol Spring Solar Hydrogen	Western Australia	✓	
Cape Hardy Green Hydrogen	South Australia		✓
Central Queensland Hydrogen Energy	Queensland	✓	✓
Collie Battery and Hydrogen Industrial Hub Project	Western Australia	✓	
Darwin Green Liquid Hydrogen Export	Northern Territory	✓	✓
Darwin H2 Hub	Northern Territory		✓
Desert Bloom Hydrogen	Northern Territory	✓	✓
Altona Renewable Hydrogen Plant	Victoria	✓	
Edify Green Hydrogen (Townsville)	Queensland	✓	✓
Energys Renewable Hydrogen Production Facility	Victoria	✓	
Fortescue Green Hydrogen and Ammonia Plant Bell Bay	Tasmania	✓	✓
Swanbank Future Energy and Hydrogen Precinct	Queensland	✓	
Fortescue Geelong Hydrogen Hub	Victoria	✓	✓
Geraldton Export-scale Renewable Investment (GERI)	Western Australia	✓	✓
Gibson Island Green Ammonia	Queensland	✓	
Good Earth Green Hydrogen and Ammonia (Moree)	New South Wales	✓	
Goondiwindi Hydrogen	Queensland	✓	
Grange Resources Renewable Hydrogen (Port Latta)	Tasmania	✓	
Great Southern (Georgetown)	Tasmania	✓	
Origin Green Hydrogen Export	Queensland	✓	✓
Green Springs (off-grid)	Northern Territory	✓	✓
H2-Hub (Gladstone)	Queensland	✓	✓
Woodside H2TAS	Tasmania	✓	✓
Han-Ho H2 Hub	Queensland		✓
Hay Point Hydrogen Export	Queensland		✓
HIF Carbon Neutral eFuels Manufacturing Facility	Tasmania	✓	
Hunter Energy Hub (AGL + Fortescue)	New South Wales	✓	✓
Hunter Valley Hydrogen Hub (Origin + Orica)	New South Wales	✓	
Hydrogen Brighton	Tasmania	✓	
Hydrogen Launceston	Tasmania	✓	
Hydrogen Park Murray Valley	Victoria	✓	
Hydrogen Park South Australia	South Australia	✓	
Hydrogen Portland	Victoria	✓	✓
HyEnergy	Western Australia		✓
Melbourne Hydrogen Hub	Victoria	✓	
Murchison Hydrogen Renewables	Western Australia		✓
Neoen-ENEOS Export	South Australia		✓

Table A1. *Cont.*

Project	State	Domestic	Export
Ord Hydrogen	Western Australia	✓	✓
Origin ENEOS Gladstone	Queensland		✓
Origin Bell Bay Green Hydrogen and Ammonia	Tasmania	✓	✓
Pacific Solar Gladstone Hydrogen	Queensland		✓
Port Bonython Hydrogen Hub	South Australia		✓
Port Pirie Green Hydrogen	South Australia		✓
Project Haber	Western Australia	✓	
SM1 Port Augusta	South Australia	✓	
South Australian Government Hydrogen Facility	South Australia	✓	
Sumitomo Rio Tinto Green Hydrogen Yarwun	Queensland	✓	
SunHQ Hydrogen Hub	Queensland	✓	
Tiwi H2	Northern Territory		✓
Torrens Island Green Hydrogen Hub	South Australia	✓	
Western Green Energy Hub	Western Australia		✓
Whaleback Energy Park	Tasmania	✓	✓
Yuri Renewable Hydrogen to Ammonia	Western Australia	✓	

Total number of hydrogen-producing projects shown in the CSIRO HyResource database [57]: 56.

Domestic supply only: 25 projects (45%);

Export supply only: 13 projects (23%);

Both export and domestic supply: 18 projects (32%);

Projects supplying the domestic market: 43 (of which 18 (42%) are export-linked).

References

1. Curtis, A.; McLellan, B. Framework for Assessment of the Economic Vulnerability of Energy-Resource-Exporting Countries. *Resources* **2023**, *12*, 27. [CrossRef]
2. BP Statistical Review of World Energy 2021. 2021. Available online: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed on 7 September 2021).
3. Ministry of Economy Trade and Industry Japan Agency for Natural Resources and Energy. *Outline of Strategic Energy Plan*; Agency for Natural Resources and Energy: Tokyo, Japan, 2021.
4. Japan to Invest 15 tril. Yen in Hydrogen Supply for Decarbonization. 2023. Available online: https://mainichi.jp/english/articles/20230606/p2g/00m/0na/019000c (accessed on 6 June 2023).
5. Smith, M.; Hargroves, K. Energy superpower-or sustainable energy leader? *CSIRO ECOS* **2007**, *2007*, 20–26. Available online: http://www.ecosmagazine.com/?act=view_file&file_id=EC140p22.pdf (accessed on 11 June 2023).
6. Garnaut, R. *Australia: Energy Superpower of the Low-Carbon World*; University of Adelaide: Adelaide, Australia, 2015.
7. Bruce, S.; Temminghoff, M.; Hayward, J.; Schmidt, E.; Munnings, C.; Palfreyman, D.; Hartley, P. National Hydrogen Roadmap—Pathways to an Economically Sustainable Hydrogen Industry in Australia. 2018. Available online: https://www.csiro.au/en/research/environmental-impacts/fuels/hydrogen/Hydrogen-Roadmap (accessed on 17 May 2023).
8. COAG Energy Council Hydrogen Working Group. Australia's National Hydrogen Strategy. Available online: https://www.dcceew.gov.au/sites/default/files/documents/australias-national-hydrogen-strategy.pdf (accessed on 17 May 2023).
9. Labor Has Won the Election and These Are Their Policies. 2022. Available online: https://www.abc.net.au/news/2022-05-22/labor-won-federal-election-albanese-policies/101088720 (accessed on 29 June 2023).
10. Department of Climate Change Energy the Environment and Water (Australia). National Hydrogen Strategy Review. Available online: https://www.dcceew.gov.au/energy/publications/australias-national-hydrogen-strategy (accessed on 29 June 2023).
11. International Energy Agency. Korea Hydrogen Economy Roadmap 2040. 2020. Available online: https://www.iea.org/policies/6566-korea-hydrogen-economy-roadmap-2040 (accessed on 17 May 2023).
12. ACIL ALLEN. Opportunities for Australia from Hydrogen Exports—Report for ARENA. 2018. Available online: https://acilallen.com.au/uploads/projects/149/ACILAllen_OpportunitiesHydrogenExports_2018pdf-1534907204.pdf (accessed on 24 May 2023).

13. Brown, F.; Roberts, D. Green, Blue, Brown: The Colours of Hydrogen Explained. *CSIROscope*. 27 May 2021. Available online: https://blog.csiro.au/green-blue-brown-hydrogen-explained/ (accessed on 18 May 2023).
14. The Hydrogen Energy Supply Chain Project. Available online: https://www.hydrogenenergysupplychain.com/ (accessed on 26 May 2023).
15. AGL. AGL Loy Yang Power Station. Available online: https://www.agl.com.au/about-agl/how-we-source-energy/loy-yang-power-station (accessed on 26 May 2023).
16. International Energy Agency. 2022. Available online: https://www.iea.org/reports/electrolysers (accessed on 26 May 2023).
17. Australian Energy Market Operator. *2021 Inputs, Assumptions and Scenarios Report Final Report*; Australian Energy Market Operator: Melbourne, Australia, 2021.
18. Deloitte. Australian and Global Hydrogen Demand Growth Scenario Analysis COAG Energy Council—National Hydrogen Strategy Taskforce, 2019. Available online: https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf (accessed on 17 May 2023).
19. Reedman, L. Multi-Sector Energy Modelling 2022: Methodology and Results Final Report. 2022. Available online: https://publications.csiro.au/rpr/pub?pid=csiro:EP2022-5553&expert=false&sb=RECENT&q= (accessed on 25 May 2023).
20. Rasool, M.A.; Khalilpour, K.; Rafiee, A.; Karimi, I.; Madlener, R. Evaluation of alternative power-to-chemical pathways for renewable energy exports. *Energy Convers. Manag.* **2023**, *287*, 117010. [CrossRef]
21. Wang, F.; Swinbourn, R.; Li, C. Shipping Australian sunshine: Liquid renewable green fuel export. *Int. J. Hydrogen Energy* **2023**, *48*, 14763–14784. [CrossRef]
22. Australian Transport Safety Bureau. Gas Control Equipment Malfunction on Board the Gas Tanker Suiso Frontier at Western Port, Hastings, Victoria on 25 January 2022. Available online: https://www.atsb.gov.au/publications/investigation_reports/2022/mair/mo-2022-001 (accessed on 23 May 2023).
23. Hatfield, O. Country Traded Ammonia Logistics and Storage, Present and Future. 2021. Available online: https://www.ammoniaenergy.org/paper/country-traded-ammonia-logistics-and-storage-present-and-future/ (accessed on 23 May 2023).
24. Gallardo, F.I.; Ferrario, A.M.; Lamagna, M.; Bocci, E.; Garcia, D.A.; Baeza-Jeria, T.E. A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan. *Int. J. Hydrogen Energy* **2021**, *46*, 13709–13728. [CrossRef]
25. Burdack, A.; Duarte-Herrera, L.; López-Jiménez, G.; Polklas, T.; Vasco-Echeverri, O. Techno-economic calculation of green hydrogen production and export from Colombia. *Int. J. Hydrogen Energy* **2023**, *48*, 1685–1700. [CrossRef]
26. Kakavand, A.; Sayadi, S.; Tsatsaronis, G.; Behbahaninia, A. Techno-economic assessment of green hydrogen and ammonia production from wind and solar energy in Iran. *Int. J. Hydrogen Energy* **2023**, *48*, 14170–14191. [CrossRef]
27. Galván, A.; Haas, J.; Moreno-Leiva, S.; Osorio-Aravena, J.C.; Nowak, W.; Palma-Benke, R.; Breyer, C. Exporting sunshine: Planning South America's electricity transition with green hydrogen. *Appl. Energy* **2022**, *325*, 119569. [CrossRef]
28. Armijo, J.; Philibert, C. Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina. *Int. J. Hydrogen Energy* **2020**, *45*, 1541–1558. [CrossRef]
29. Khan, M.I.; Al-Ghamdi, S.G. Hydrogen economy for sustainable development in GCC countries: A SWOT analysis considering current situation, challenges, and prospects. *Int. J. Hydrogen Energy* **2023**, *48*, 10315–10344. [CrossRef]
30. Bhandari, R. Green hydrogen production potential in West Africa—Case of Niger. *Renew. Energy* **2022**, *196*, 800–811. [CrossRef]
31. Hjeij, D.; Bicer, Y.; Al-Sada, M.B.S.; Koç, M. Hydrogen export competitiveness index for a sustainable hydrogen economy. *Energy Rep.* **2023**, *9*, 5843–5856. [CrossRef]
32. Downie, C. Geopolitical leverage in the energy transition: A framework for analysis and the case of Australian electricity exports. *Energy Res. Soc. Sci.* **2022**, *93*, 102826. [CrossRef]
33. Cremonese, L.; Mbungu, G.K.; Quitzow, R. The sustainability of green hydrogen: An uncertain proposition. *Int. J. Hydrogen Energy* **2023**, *48*, 19422–19436. [CrossRef]
34. Hancock, L.; Ralph, N. A framework for assessing fossil fuel 'retrofit' hydrogen exports: Security-justice implications of Australia's coal-generated hydrogen exports to Japan. *Energy* **2021**, *223*, 119938. [CrossRef]
35. Curtis, A.; McLellan, B. Exposing the Blind Spots in Domestic Energy Security of Major Energy Exporters. (unpublished work).
36. Australian Energy Market Operator. 2022 Integrated System Plan for the National Electricity Market. 2022. Available online: https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2022-integrated-system-plan-isp (accessed on 1 June 2023).
37. Commonwealth of Australia. Australian Energy Statistics 2020. 2020. Available online: https://www.energy.gov.au/publications/australian-energy-update-2020 (accessed on 8 May 2023).
38. Aurecon. 2020 Costs and Technical Parameter Review Consultation Report for Australian Energy Market Operator (AEMO). 2020. Available online: https://www.aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/aurecon-cost-and-technical-parameters-review-2020.pdf?la=en#page=59&zoom=100,91,64 (accessed on 26 May 2023).
39. Austrade. Korean Hydrogen Market Update. 2022. Available online: https://www.austrade.gov.au/news/publications/korean-hydrogen-market-update-2022 (accessed on 26 May 2023).
40. International Gas Union. World LNG Report 2022. 2022. Available online: https://www.igu.org/resources/world-lng-report-2022/ (accessed on 26 May 2023).

41. The Institute of Energy Economics Japan. IEEJ Newsletter No. 242. 2023. Available online: https://eneken.ieej.or.jp/en/jeb/230221.pdf (accessed on 27 May 2023).
42. The Institute of Energy Economics Japan. IEEJ Newsletter No. 171. 2019. Available online: https://eneken.ieej.or.jp/en/jeb/191021.pdf (accessed on 27 May 2023).
43. Advisian. *Australian Hydrogen Market Study—Sector Analysis Summary (Report for CEFC)*; Advisian: Adelaide, Australia, 2021.
44. Badeeb, R.A.; Lean, H.H.; Clark, J. The evolution of the natural resource curse thesis: A critical literature survey. *Resour. Policy* **2017**, *51*, 123–134. [CrossRef]
45. Leonard, A.; Ahsan, A.; Charbonnier, F.; Hirmer, S. The resource curse in renewable energy: A framework for risk assessment. *Energy Strategy Rev.* **2022**, *41*, 100841. [CrossRef]
46. Lotrič, A.; Sekavčnik, M.; Kuštrin, I.; Mori, M. Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. *Int. J. Hydrogen Energy* **2021**, *46*, 10143–10160. [CrossRef]
47. Viebahn, P.; Soukup, O.; Samadi, S.; Teubler, J.; Wiesen, K.; Ritthoff, M. Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. *Renew. Sustain. Energy Rev.* **2015**, *49*, 655–671. [CrossRef]
48. Zimmermann, T.; Rehberger, M.; Gößling-Reisemann, S. Material flows resulting from large scale deployment of wind energy in Germany. *Resources* **2013**, *2*, 303–334. [CrossRef]
49. Madsen, H.T. Water Treatment for Green Hydrogen: What You Need to Know. 2022. Available online: https://hydrogentechworld.com/water-treatment-for-green-hydrogen-what-you-need-to-know (accessed on 25 May 2023).
50. Ward, S. The Coal Seam Gas (CSG) Industry in Queensland. 2014. Available online: https://www.ehaqld.org.au/documents/item/725 (accessed on 3 May 2023).
51. Zhao, L.; Ren, T.; Wang, N. Groundwater impact of open cut coal mine and an assessment methodology: A case study in NSW. *Int. J. Min. Sci. Technol.* **2017**, *27*, 861–866. [CrossRef]
52. Wulf, C.; Linßen, J.; Zapp, P. Review of power-to-gas projects in Europe. In *Energy Procedia*; Elsevier Ltd.: Amsterdam, The Netherlands, 2018; pp. 367–378. [CrossRef]
53. Paul, S. Australia Starts Piping Hydrogen-Gas Blend into Homes. 2021. Available online: https://www.reuters.com/business/energy/australia-starts-piping-hydrogen-gas-blend-into-homes-2021-05-19/ (accessed on 31 May 2023).
54. Siemens Energy. Zero Emission Hydrogen Turbine Center. Available online: https://www.siemens-energy.com/global/en/priorities/future-technologies/hydrogen/zehtc.html (accessed on 31 May 2023).
55. General Electric. Hydrogen Fueled Gas Turbines. Available online: https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines (accessed on 31 May 2023).
56. Simshauser, P.; Nelson, T. Australia's coal seam gas boom and the LNG entry result. *Aust. J. Agric. Resour. Econ.* **2015**, *59*, 602–623. [CrossRef]
57. CSIRO. HyResource—Australian Hydrogen Projects List. Available online: https://research.csiro.au/hyresource/projects/facilities/ (accessed on 31 May 2023).
58. Turton, H. The Aluminium Smelting Industry Structure, Market Power, Subsidies and Greenhouse Gas Emissions. 2002. Available online: https://australiainstitute.org.au/wp-content/uploads/2020/12/DP44_8.pdf (accessed on 17 May 2023).
59. Brooks, G. The Trouble with Aluminium. 2012. Available online: https://theconversation.com/the-trouble-with-aluminium-7245 (accessed on 22 May 2023).
60. Geoscience Australia. Aluminium. Available online: https://www.ga.gov.au/education/classroom-resources/minerals-energy/australian-mineral-facts/aluminium (accessed on 31 May 2023).
61. Rankin, J. Energy Use in Metal Production. 2012. Available online: https://publications.csiro.au/rpr/download?pid=csiro:EP12183&dsid=DS3 (accessed on 22 May 2023).
62. Usui, E. The Status of the Aluminium Industry in Japan. 1998, pp. 15–24. Available online: http://www.icaa-conference.net/ICAA6/Aluminium%20Alloys%20Volume%201/15-24.pdf (accessed on 18 May 2023).
63. International Energy Agency. Energy Balance Data (Japan). Available online: https://www.iea.org/sankey/#?c=Japan&s=Balance (accessed on 9 November 2022).
64. Nippon Light Metal Company Ltd. Kambara Complex. Available online: https://www.nikkeikin.com/company/seizou/ (accessed on 18 May 2023).
65. Aluminium Council of Australia. Australia Aluminium Production. Available online: https://aluminium.org.au/australian-aluminium/ (accessed on 30 May 2023).
66. Gill, M. Déjà vu All over again—Electricity-Hungry Aluminium Smelters Continue to Push for More Coal-Fired Power Stations. *Inside Story*. 16 August 2018. Available online: https://insidestory.org.au/deja-vu-all-over-again/ (accessed on 7 June 2023).
67. Thornton, K. The Electricity Commission of New South Wales and Its Place in the Rise of Centralised Coordination of Bulk Electricity Generation and Transmission 1888–2003. University of Newcastle, 2015. Available online: https://nova.newcastle.edu.au/vital/access/services/Download/uon:21089/ATTACHMENT01?view=true (accessed on 7 June 2023).
68. Kelly, M. Tomago Aluminium Expects to Play a Bigger Role in Propping up the Energy Grid. 2023. Available online: https://www.newcastleherald.com.au/story/8213869/there-is-a-limit-tomago-braces-for-more-shut-down-orders-due-to-grid-instablilty/ (accessed on 29 May 2023).
69. Potter, B. Alcoa's Portland Smelter Faces Uncertainty after Blackout. 2016. Available online: https://www.afr.com/politics/alcoas-portland-smelter-faces-uncertainty-after-blackout-20161202-gt2hmm (accessed on 7 June 2023).

70. International Energy Agency. Net Zero by 2050—A Roadmap for the Global Energy Sector, 2050. Available online: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf (accessed on 1 June 2023).
71. Republic of Korea Ministry of Trade Industry and Energy. *Third Energy Master Plan*; Ministry of Trade Industry and Energy: Sejong, Republic of Korea, 2020.
72. National Development Council. Taiwan's Pathway to Net-Zero Emissions in 2050. 2022. Available online: https://www.ndc.gov.tw/en/Content_List.aspx?n=B154724D802DC488 (accessed on 12 June 2023).
73. Kruyt, B.; van Vuuren, D.P.; de Vries, H.J.M.; Groenenberg, H. Indicators for energy security. *Energy Policy* **2009**, *37*, 2166–2181. [CrossRef]
74. Martchamadol, J.; Kumar, S. An aggregated energy security performance indicator. *Appl. Energy* **2013**, *103*, 653–670. [CrossRef]
75. Murakami, T.; Motokura, M.; Kutani, I. An Analysis of Major Countries' Energy Security Policies and Conditions—Quantitative Assessment of Energy Security Policies. *IEEJ Energy J.* **2011**, *6*. Available online: https://eneken.ieej.or.jp/data/3719.pdf (accessed on 1 January 2023).
76. Dike, J.C. Measuring the security of energy exports demand in OPEC economies. *Energy Policy* **2013**, *60*, 594–600. [CrossRef]
77. Kanchana, K.; McLellan, B.C.; Unesaki, H. Energy dependence with an Asian twist? Examining international energy relations in Southeast Asia. *Energy Res. Soc. Sci.* **2016**, *21*, 123–140. [CrossRef]
78. Burck, J.; Hagen, U.; Bals, C.; Hohne, N.; Nascimento, L.; Essop, T. Climate Change Performance Index 2021 Results. Available online: https://ccpi.org/download/the-climate-change-performance-index-2021/ (accessed on 1 September 2021).
79. Cariolle, J. The Economic Vulnerability Index 2010 Update, 2011. Available online: https://www.researchgate.net/publication/261035539_The_Economic_Vulnerability_Index_2010_Update (accessed on 21 January 2019).
80. The World Bank. Australia GDP Data. Available online: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD?locations=AU (accessed on 1 January 2023).
81. Australia Government. Value of Australian Mineral Exports. Available online: https://www.ga.gov.au/digital-publication/aimr2020/value-of-australian-mineral-exports (accessed on 1 January 2023).
82. Production, A.P.; Association, E. APPEA Key Statistics 2021. Available online: https://www.appea.com.au/wp-content/uploads/2021/06/2021-APPEA_Key-Statistics-1.pdf (accessed on 1 January 2023).
83. ElSayed, M.; Aghahosseini, A.; Caldera, U.; Breyer, C. Analysing the techno-economic impact of e-fuels and e-chemicals production for exports and carbon dioxide removal on the energy system of sunbelt countries—Case of Egypt. *Appl. Energy* **2023**, *343*, 121216. Available online: https://www.sciencedirect.com/science/article/pii/S0306261923005809 (accessed on 28 July 2023). [CrossRef]