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ZCWP03-19 AUSTRALIA'S FUTURE AS A ZERO-CARBON ENERGY EXPORTER: An analysis of the recent reports on Australian hydrogen for export

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Summary

The global energy system will have to undergo a significant transformation over the next two decades to reduce greenhouse gas emissions and avoid dangerous climate change. Hydrogen could be an important enabler of deep decarbonisation in the energy sector and beyond, as it can be used as a low-carbon energy vector. Countries around the world are beginning to investigate the challenges and opportunities that will arise with the emergence of a global hydrogen economy.

In this paper, we analyse the different ways that Australia could produce clean hydrogen for exports, based on existing hydrogen generation technologies. We compare "low-carbon" hydrogen generated from fossil-fuels coupled with carbon capture and storage and "zero-carbon" hydrogen from electrolysis powered by renewable energy. Employing quantitative estimations, we compare the ability of the technologies to rapidly scale to meet the clean hydrogen export demand, and compare CO_2 emissions over the next 20 years. Additionally, we consider the social licence issues and policy risks associated with hydrogen generation and use in Australia.

This analysis is critical to ensure that: investment is efficiently directed into appropriate technologies; the hydrogen industry is not unnecessarily exposed to carbon price risk (risking international competitiveness); and public investment is not at risk of being lost in stranded assets.

Key findings are that:

- ***Australia would need to implement carbon capture and storage (CCS) at an unrealistically rapid pace over the next 20 years to meet the projected hydrogen export opportunity with fossil-fuel based "low-carbon" hydrogen production***. The CCS storage capacity required to meet the hydrogen export demand from Australia is similar to the combined capacity of all CCS facilities operating worldwide by 2040, and is an order or magnitude larger than the capacity currently under active development to store emissions from hydrogen generation in Australia.

- ***Based on the current rate of growth of renewable energy capacity, it is feasible that Australia will be able to meet the projected hydrogen export demand with "zero-carbon" technologies based on renewable electricity and electrolysis.*** Importantly, this estimate does not rely on any significant technology improvements, and only a marginal increase in electrolyser efficiency over the next 20 years.

- ***"Low-carbon hydrogen" production utilising carbon capture and storage will lead to a rise in carbon dioxide emissions estimated to be roughly equal to 1% of Australia's climate change emission targets by 2040.*** CCS technology is not 100% efficient as some CO_2 will escape into the atmosphere, and additional CO_2 is emitted due to the extra energy needed to compress, transport and store CO_2 underground.

- ***Social licence issues and policy risks associated with hydrogen are increased in "low-carbon" hydrogen production via fossil-fuel based sources, compared to inherently "zero-carbon" renewable energy methods.***

Introduction

The 2018 IPCC report issued a stark warning: greenhouse gas (GHG) emissions must be reduced to 45% of their 2010 level by 2030 to limit global warming to 1.5°C and avoid the worst effects of climate change [1, p. 14]. The International Renewable Energy Agency (IRENA) has indicated that such deep decarbonisation will require a transformation in the way we use energy: not only switching to largely renewable electricity sources, but also decarbonising industrial energy use [2, p. 22].

The energy transformation is already underway, driven by the rapid uptake of renewable electricity generation. Capacity has more than doubled in the last decade and renewable energy generation provided over 10% of the total energy consumed globally in 2017 [3]. With continued aggressive expansion, renewable electricity generation could account for almost 65% of global energy by 2050, surpassing traditional fossil fuel electricity production [2]. However, converting to renewable electricity sources alone will not be enough. Renewable electricity is very different from traditional fossil fuel energy sources: it is by nature intermittent, and it is not easily stored or exported. As the proportion of renewable energy on the electricity grid increases, so does the need for grid balancing, such as storage and high voltage grid interconnects. Additionally, not all sectors can directly replace fossil fuel use with electricity. Currently a third of the emissions due to global energy use have no commercially viable alternative to fossil fuels [4]. These include heavy freight, aviation, and industries like iron and steel, cement, chemicals and aluminium. To truly decarbonise, we need to find carbon-free energy vectors and fuels that can replace fossil fuels in a range of sectors.

Hydrogen is a particularly interesting candidate for an alternative fuel as it has a high energy density and contains no carbon. Hydrogen can be burnt directly for heat, or to run a turbine, or combined with oxygen in a fuel cell to produce electricity, with only water as a by-product. For this reason, it could play a role in decarbonising a wide range of energy uses, including domestic heating and cooking, transportation, and heavy industrial processes. Hydrogen can be generated from a range of power sources: electricity, fossil fuels, biofuels, and directly from sunlight. If it is generated from fully renewable sources it contains no embedded carbon, and provides a pathway for a fully decarbonised energy system. In particular, hydrogen could play an important role in storing renewable energy, offering the possibility of exporting renewable resources and mitigating the variability of renewable energy.

Due to the versatility of hydrogen, it has been identified as a possible "*missing link in the energy transition*" [4, p. 7] by the International Renewable Energy Agency. Likewise, the Hydrogen Council envisage a "*global hydrogen economy"* emerging by 2050, where hydrogen plays a critical role in enabling high levels of renewables penetration, decarbonisation of industry and transport, as well as export and international energy distribution [5, p. 7]. Countries around the world are beginning to respond, actively scoping out the potential of hydrogen: as both an export and import opportunity.

Australia is among the countries preparing for a hydrogen-rich future and State [6] and Federal agencies [7][8][9] have commissioned reports on the emerging hydrogen economy. In particular, the Chief Scientist and the Council of Australian Governments Energy Council are developing the National Hydrogen Strategy for release in 2019. These reports indicate that with an effective National Strategy, Australia could transition from a reliance on carbon intensive energy exports to a new role as a hydrogen exporter.

National Reports on Hydrogen

In the second half of 2018, three national hydrogen reports were released looking at the opportunities afforded by the emerging hydrogen economy from the Australian perspective. The main findings are summarised below, with a focus on the outcomes that are critically investigated in this paper.

All three reports highlight that the global demand for hydrogen is being driven by countries looking to decarbonise and meet their Paris greenhouse gas (GHG) emission targets. They also agree that Australia has a significant competitive advantage in developing a hydrogen export industry due to its vast renewable energy resources, skilled workforce, land availability, existing trade relationships and lack of security issues.

The consulting firm ACIL Allen was contracted by the Australian Renewable Energy Agency (ARENA) to identify opportunities for Australia in the rise of global demand for 'clean' hydrogen. The report, ***Opportunities from Australia for Hydrogen Exports*** [9], examines drivers for hydrogen market demand; potential markets for hydrogen; and Australia's net competitive advantage relative to other hydrogen exporters. It highlights that the emerging hydrogen market is being driven by the need to decarbonise the global economy. Three demand scenarios are identified based on the IEA's Sustainable Development Scenarios [10], low, medium and high demand, assuming different levels of global engagement with the decarbonisation process. The report identifies the key markets for Australian hydrogen as China, Japan, Republic of Korea, and Singapore. Additionally, it names competitors for the emerging hydrogen market as Norway, Iceland, USA, and Brunei. The report provides detailed demand modelling, based on global and national growth projections, and the predicted cost of hydrogen produced in Australia. The predicted cost of hydrogen employed in the model is based on calculations by CSIRO and published in a report described below.

Table 1: Predicted hydrogen exports from Australia [H_2 kTpa].

YEAR	***2025***	***2030***	***2040***
Low	26.5	242.1	621.3
Med	136.5	502.1	1350.4
High	344.8	1088.4	3180.4

The key result from the ACIL ALLEN report is the predicted demand for Australian exports of hydrogen [9, p. 47], reproduced in Table 1. To compare the results of the ACIL Allen report, we list the predicted global hydrogen demand for energy (in PJ) in that report [9, p. iii, Table ES1], along with independent predictions from the Hydrogen Council [5, p. 20, Exhibit 5] and IRENA [4, p. 32, Fig. 14] in Table 2. The ACIL Allen predictions agree well with those from IRENA, while the predictions from the Hydrogen Council are roughly an order of magnitude higher.

Table 2: Comparison of predicted global H_2 demand for energy [PJ]

<table>
<tr><th>Source</th><th>ACIL ALLEN</th><th>Hydrogen Council</th><th>IRENA</th></tr>
<tr><th>YEAR</th><th>2040</th><th>2050</th><th>2050</th></tr>
<tr><td>Low</td><td>1898</td><td rowspan="3">58000*</td><td rowspan="3">7700</td></tr>
<tr><td>Med</td><td>4183.2</td></tr>
<tr><td>High</td><td>9860.8</td></tr>
</table>

**We have subtracted feedstock demand, following [7, p. 32, Fig. 14].*

The CSIRO *National Hydrogen Roadmap* aims to "*provide a blueprint for the development of the hydrogen industry in Australia, by informing investment so the industry can scale in a coordinated manner*" [8]. This report focuses on the technologies needed for commercial scale hydrogen production for each aspect of the value chain, both for export and for use domestically in Australia:

- Production: renewable electrolysis, steam reforming of methane, coal and biomass gasification, and other zero-carbon emerging technologies such as artificial leaf, microbial hydrogen production and solar thermochemical cycles.
- Storage: compression in tanks, underground, and in pipelines –"line packing", liquefaction, and emerging material based storage
- Transport: trucks, trains, pipelines, and ships
- Usage: fuel cells, turbines, hydrogen vehicles, residential heat and industrial feedstock

The different technologies are described, and a series of recommended actions are identified for each part of the value chain, covering the commercial, policy/regulatory, RD&D and social sectors. The report also models the cost of the different hydrogen technologies, based on an analysis of the current state of the hydrogen industry (2018). It then uses this model to identify key cost drivers and areas for investment, and predicts a "best case scenario" cost by 2025 if these investments were made. A key component of the CSIRO Roadmap is the predicted Levelised Cost of Hydrogen (LCOH) for different technologies in Australia[8, pp. 79–91].

The Hydrogen Strategy Group, led by the Chief Scientist Dr Alan Finkel, prepared a briefing paper for the Council of Australian Government's Energy Council, titled: ***Hydrogen for Australia's future****.* This paper draws on the analysis provided by the reports described above to summarise the potential role of hydrogen and the opportunity for Australia. It advocates strongly for the development of a national hydrogen strategy, and lays out a vision for "*a future in which hydrogen provides economic benefits to Australia".* Additionally, it highlights the role of government in regulating the safety, trade, planning and pricing of hydrogen, and in supporting necessary research and development as well as community engagement and education.

The three reports have been invaluable for positioning hydrogen on the national agenda and are an important step towards sparking public discourse and encouraging a coordinated government response. All three reports highlight the need for a national hydrogen strategy to support the development of a competitive Australian hydrogen industry that is futureproof and delivers economic benefits and emissions reductions to Australia. The call has clearly been heard as the Chief Scientist announced the development of a National Strategy in late 2018.

The reports provide predictions of the economic opportunities and the levelised cost of hydrogen produced using different technologies. However, the reports do not analyse the feasibility of meeting the projected demand for Australian hydrogen using different production methods. Different hydrogen generation techniques represent significantly different investment pathways for a hydrogen export industry, and the choice will impact the techno-economic, policy and social risks of the emerging industry. We analyse the reports with the goal of critically evaluating the opportunities and risks inherent in the current hydrogen generation technologies.

Current hydrogen generation technologies

The CSIRO report, which provides the technological data for the ARENA and COAG reports, identifies two main generation methods for low-carbon hydrogen: thermochemical routes relying on fossil fuels, coupled with carbon capture and storage; and electrochemical routes relying on electricity powered by renewable energy[8].

Thermochemical routes use a carbon-based feedstock that is reacted with water at high temperatures to produce hydrogen and carbon monoxide or dioxide. Currently, the most advanced technology is steam methane reforming (SMR), with natural gas as the feedstock, sometimes referred to as "blue" hydrogen. The CSIRO report did not consider SMR a likely candidate for large-scale hydrogen production because of questions over the price and long-term supply of gas[8, p. 22]. Instead, coal was identified as a more attractive feedstock for hydrogen production by means of coal gasification, referred to as "brown" hydrogen. Both of these methods produce carbon dioxide (CO_2) as a by-product and need to be coupled with carbon capture and storage (CCS) to be considered "low-carbon" technologies. In CCS, carbon dioxide from a polluting source is collected and pumped into underground cavities for long-term storage.

Electrolysis is the process of splitting water into hydrogen and oxygen using electricity. There are two main commercial types of electrolysers: alkaline and proton exchange or polymer electrolyte membrane (PEM). Currently, alkaline electrolysis dominates the market; however, PEM is likely to be the technology of choice in the future as it has the potential to be more efficient, more durable, and can react more quickly to changes in the electricity supply[11]. Hydrogen generation with electrolysis does not produce any CO_2 emissions, and has the potential to be a truly "zero-carbon" technology if the electricity used in the process is itself generated from renewable sources. This is sometimes referred to as "green" hydrogen.

In the analysis below, we evaluate the feasibility of the two different pathways to large scale hydrogen production in Australia: low-carbon vs zero-carbon pathways. Employing quantitative estimations we compare the ability of the technologies to rapidly scale to meet the clean hydrogen export demand from Australia forecast by ACIL Allen, and reproduced in Table 1. Additionally, we compare the potential for additional CO_2 emissions that would result from the production of low- and zero- carbon hydrogen, as capacity is ramped up over the next 20 years.

Thermochemical hydrogen generation plus CCS

Thermochemical hydrogen production is well established, however CCS is a relatively new technology in Australia. For this reason, we focus our analysis on the projected carbon sequestration capacity that would be needed to generate low-carbon hydrogen from fossil fuels at the required scale for export.

Australia has very large "storage resources": the geological formations or depleted oil and gas fields that can be used to sequester CO_2[12]. Many of the identified sites are co-located with fossil fuel reserves. There are currently three large-scale CCS projects under development in Australia[12].

The most advanced CCS facility in Australia is the Gorgon Carbon Dioxide Injection Project. This project aims to sequester 3.4-4 Mt pa of CO_2 generated from the Barrow Island gas processing plant [13]. Unfortunately, the project has met with significant difficulties: gas has been processed since the end of 2016 at the Barrow Island plant, but CCS has not yet commenced owing to technical problems [14]. As a consequence, Barrow Island has been one of the largest CO_2 emitters in WA since 2016 according to the Clean Energy Regulator, and is under investigation by the EPA [15].

CarbonNet is a new CCS facility in Victoria, expected to come online in the 2020s, with a capacity of 1-5 Mt CO_2 pa[12]. This site has been identified as a feasible location to demonstrate brown hydrogen generation with CCS and is the focus of the *Hydrogen Energy Supply Chain* pilot project, which aims to deliver hydrogen from brown coal gasification for transport to Japan[8].

The South West Hub, located in Western Australia, is projected to begin operations in 2025. The facility aims to capture 2.5 Mt CO_2 pa from industrial and power generation plants, with a possible expansion to 5-8 Mt CO_2 pa.

CarbonNet is the only facility in Australia that is being developed to store emissions from hydrogen generation, however all three projects represent an important first step in demonstrating large-scale CCS in Australia.

To calculate the CO_2 storage capacity required to sequester the emissions from blue (SMR using natural gas) and brown (coal gasification) hydrogen generation, we calculate the mass of CO_2 produced, and how much can be captured and stored. The emission intensity (i.e. the amount of CO_2 emitted per ton of hydrogen produced) depends on the generation technology and the feedstock used. Table 3 shows a range of emission intensity estimates for both blue and brown hydrogen production. The data is taken from a 2018 review paper which collated data on CO_2 emissions from major industrial hydrogen manufacturing processes [16]. The values used in this work are also shown.

Table 3. CO_2 emission intensities from thermochemical hydrogen generation **[CO_2kg/H_2kg]**

	BROWN HYDROGEN (COAL GASIFICATION)	***BLUE HYDROGEN (SMR WITH NATURAL GAS)***
Average global range	19-24	8.7-10.4
This work	21.5	9.5

Carbon capture and storage technology is not 100% efficient: some CO_2 will escape into the atmosphere, and additional CO_2 is emitted due to the extra electricity needed to compress, transport and store CO_2. The percentage of CO_2 that is captured and stored depends on the technology being used and the type of carbon emitting process, however, it is usually between 80-90% of the total CO_2 emissions[16].

The required storage capacity is estimated by multiplying the amount of hydrogen required (taken from the high and low demand scenarios reported in Table 1) by emission intensity and the CCS efficiency, taken to be 85%.

Figure 1 shows the estimated CO_2 storage capacity that would be needed per annum if Australia were to meet the hydrogen demand using only thermochemical fossil-fuel based production, coupled with CCS. Data is shown for blue and brown hydrogen. The different sections of the bars represent the low, medium, and high hydrogen export demand scenarios. The required capacity is compared to the capacity of existing CCS facilities worldwide (red line), as well as the best-case projected capacity of CCS projects currently under development in Australia (black line) [12].

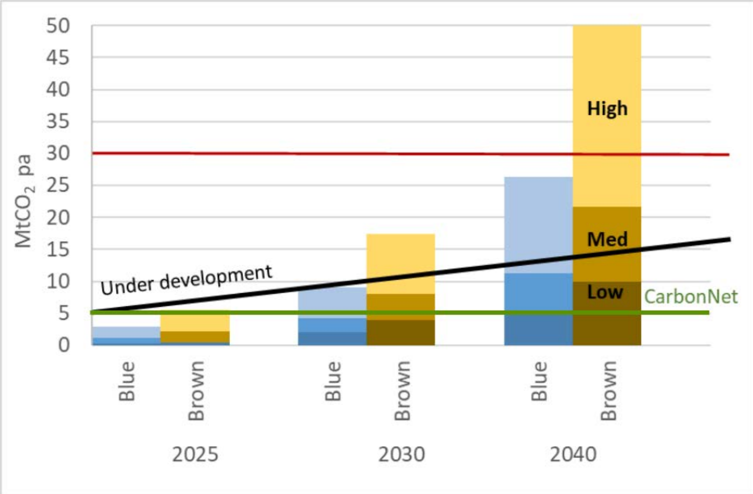

Figure 1*: Bar graph shows* CO_2 *storage capacity per annum required to sequester the emissions from blue and brown hydrogen generation from 2025-2040. The different sections of the stacked bar graph represent the three demand scenarios: low, medium, and high, as defined by the ACIL Allen demand modelling, (values reproduced in Table A1). The current global capacity of operational CCS is indicated by the red line. The blue line shows the best-case projected capacity of CCS projects currently under development in Australia.*

The data shows the CCS storage capacity required to meet the high demand scenario is similar to the combined capacity of all global operating CCS facilities by 2040, and is an order or magnitude larger than the capacity under active development to store emissions from hydrogen generation in Australia. This suggests that ***Australia would need to very rapidly increase the scale of local CCS over the next 15-20 years to sequester the emissions from fossil fuel based thermochemical hydrogen generation****.* Given the lack of experience with operating large scale CSS facilities in Australia, and the long lead time for developing facilities, this could be considered to be unfeasible.

Electrolysis

In this section, we employ a simple analysis to answer the question: is it feasible to meet the demand for Australian hydrogen exports using electrolysis powered by renewable energy? We consider the case where renewable energy assets and electrolysers are separately connected to the national electricity grid. We do not consider the case of electrolysers being powered by dedicated, off-grid renewable sources as these systems are not yet deemed to be economically competitive [4, p. 30]. This is largely due to the fact that the cost of hydrogen produced by electrolysis is sensitively dependent on the capacity factor of the electrolysers [8, p. 14]. Electrolysers driven solely by variable renewable sources will only be operating a fraction of the time, increasing the relative cost of the capital investment per unit of hydrogen produced. Here we note that further techno-economic analysis is needed to understand the cost drivers for hydrogen generation with renewable electricity, both on and off-grid, as the cost of renewable energy and electrolysers fall over the next few decades.

To understand if the hydrogen demand could be met zero-carbon technologies, we calculate the amount of electricity that would be needed to meet projected demand for Australian hydrogen using PEM electrolysers. The specific energy consumption of PEM electrolysers is given in MWhr/t H_2, and is estimated with reference to the CSIRO Hydrogen Roadmap [8], as well as a recent study predicting progress in PEM electrolysers (Fig E.1 in ref [11], Conversion from kWh/m^3 to kWh/kg = 11.13). The values are shown in Table 4.

***Table 4**: Estimated specific energy consumption for Electrolysis [MWhr/t H_2]*

Estimates from CSIRO report [8]	***highest***	***lowest***	***low limit***
	58	54	45
Estimates from Schmidt 2017 [11]	***2016***	***2020***	***2030***
	60	56.8	53.4
Values used in this work	***2025***	***2030***	***2040***
	57	53	50

We estimate the additional electricity that would be needed to generate the required hydrogen in the low, medium, and high demand scenarios, by multiplying the estimated specific energy consumption of PEM electrolysis in Table 3 with the expected hydrogen demand values in Table 1. The projected electricity demand in the National Energy Market (NEM) for all other uses apart from hydrogen generation, is taken from the Australian Energy Market Operator [17]. The results are given in Table 5.

Table 5: Estimated electricity demand [TWh pa]

YEAR	***2025***	***2030***	***2040***
Low H_2 demand scenario	1.5	13	31
Medium H_2 demand scenario	8	27	68
High H_2 demand scenario	20	58	159
National electricity market	180	180	190
Projected renewable energy generation	149	213	341

Scenario 1: Fixed growth of renewable capacity

Here we compare amount of electricity that would be needed to meet the projected demand for hydrogen using PEM electrolysers with projections of renewable energy capacity in Australia over the next 20 years. This scenario assumes that *the installation rate of new renewable energy systems is equal to the 2018 rate, and remains constant despite the growth in demand for electricity for zero-hydrogen production*. This is a simplistic assumption that does not take into account demand drivers, however it allows us to judge whether the renewables industry would be able to scale as needed to meet the needs of an emerging zero-carbon industry in Australia.

A recent analysis by ANU researchers has demonstrated that if the current growth rate of renewable energy capacity continued, Australia would be able to generate 100% of its current electricity demand by renewable means by 2030 [18]. We use the same methodology and assumptions to calculate the projected renewable energy generation per annum out to 2040 for a fixed growth rate.

For our analysis, the current installed renewable energy capacity in 2017 is taken from the Clean Energy Council [19]. The projected growth in renewable energy capacity is calculated assuming an additional 5.6 GW is installed each year, composed of 2 GW of large scale solar PV, 1.6 GW of small scale solar PV, and 2 GW of wind energy. These figures are based on actual and proposed renewable energy installations in 2018 reported by the Clean Energy Regulator [20], and employed by ref [18]. The corresponding capacity factors were taken to be 21%, 15% and 40%, as reported in ref [18]. Multiplying the installed capacity (in GW) by the number of hours in a year and the capacity factor, gives the projected renewable energy generation per annum, listed in Table 5.

Figure 2 compares the total amount of electricity required (shaded area), with the projected renewable energy capacity (red line). The grey shaded area indicates the electricity needed for the NEM, while the green shaded areas represent the electricity needed to meet the low, medium and high hydrogen demand scenarios. In this analysis, we assume that fossil-fuel generators meet the balance of the electricity demand, and are gradually phased out as more renewable electricity sources become available.

Figure 2 shows that the electricity demand from the NEM could be met with renewables by 2027, in agreement with ref [18] if the rate of renewable capacity increase remains constant. Generating hydrogen for export with electrolysis in the high demand scenario would require us to nearly double the electricity supply in Australia by 2040, in agreement with the ACIL Allen findings[9, p. 49]. This additional electricity demand is projected to delay the point at which fossil fuels can be phased out of the Australian market at the current rate of renewable energy installation: from 2027 to 2040 for high demand. However, Fig. 2 suggests that ***it is feasible to provide this additional electricity with renewable energy by 2040, if the growth of the renewable energy capacity continues at its current rate***. Notably, this projection does not rely on any significant technology breakthroughs, and only a marginal increase in electrolyser efficiency over the next 20 years.

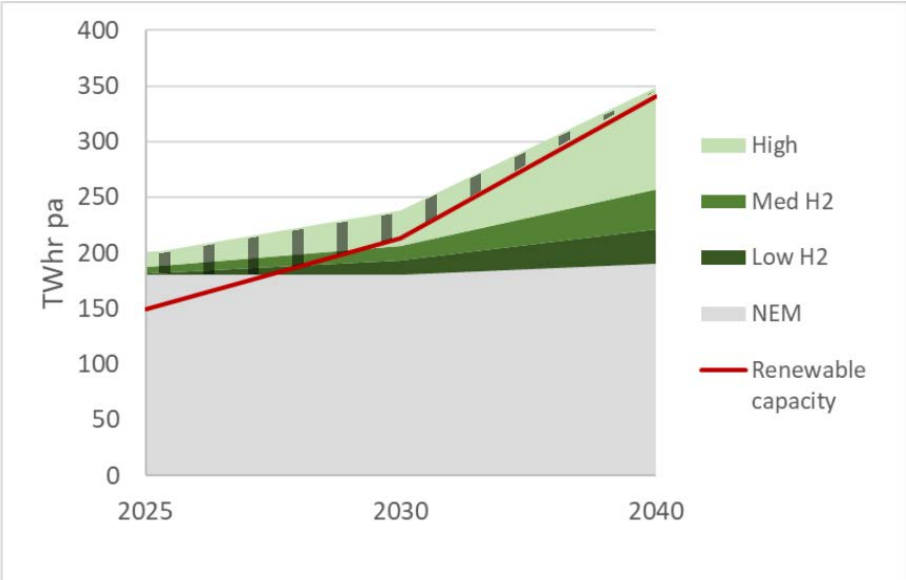

Figure 2*: Total estimated electricity demand per annum, decomposed into the electricity needed to power the NEM (grey), and electrolysers to supply green hydrogen (green) in the low, medium and high demand scenarios, as defined by the ACIL Allen demand modelling, (values reproduced in Table A1).The projected electricity generation from renewable energy per annum is shown for comparison (red). The balance of demand is met with fossil-fuel based electricity sources. The striped area indicates additional fossil-fuel based electricity capacity that would be needed to meet the hydrogen demand at the current rate of renewable energy installation.*

The expansion of the electricity market will require significant infrastructure development, in addition to renewable energy installations, to accommodate the growth of the electricity network. Additionally, as the percentage of variable renewable energy generators increases, storage and grid upgrades will be necessary to balance the grid (e.g. high voltage DC connection, pumped hydro, batteries, and demand management) [21], [22]. Hydrogen generation from electrolysis could play a role in grid stabilisation, providing grid firming services and a way to store electricity [8, p. 35][4, p.

41]. Electrolysers can act as variable loads, soaking up excess electricity when large amounts of renewable energy is being produced, and scaling back hydrogen production when demand exceeds supply. Recent work has suggested that converting renewable energy to hydrogen during periods of surplus electricity production could be economically viable within the next decade [23]. Stored hydrogen could also be used to compensate for seasonal changes in renewable energy production. However, further analysis is needed to understand the economic viability of hydrogen production as a method for electricity storage and grid balancing.

Scenario 2: Growth of renewable capacity accelerates to meet demand

Here we assume that the ***increase in demand for electricity due to zero-carbon hydrogen production is met by the increased growth of the renewables sector*** and estimate the capacity and land requirements of the required renewable energy plants. We assume that the renewable energy demand, shown in green in Figure 2, is met with new-build installations, divided equally between large-scale solar (>5MW capacity), and wind.

The required capacity of new-build renewable energy installations (in Watts) is calculated by dividing the estimated electricity demand in Watt-hours (Table 5) by the number of hours in a year and the capacity factor of the renewable technologies. The corresponding capacity factors were taken to be 21% for solar and 40% for wind, as in ref [18]. Results are shown in Table 6.

Table 6: Renewable energy capacity required to meet demand [GW]

YEAR	***2025***		***2030***		***2040***	
	Wind	***Solar***	***Wind***	***Solar***	***Wind***	***Solar***
Low	0.21	0.41	1.8	3.5	4.4	8.4
Med	1.1	2.1	3.8	7.2	9.6	18
High	2.8	5.3	8.2	16	23	43

In order to meet the renewable electricity demand for green hydrogen with new-build wind and solar plants, large-scale solar PV would have to be installed at a rate of 2.5 GW/year, and wind at just over 2.3 GM/year. This is comparable with the current rate of capacity installation for both technologies, which is 2GW/year. ***The results indicated that the Australian renewable sector would not need to expand growth greatly to keep pace with the demand for electricity for zero-carbon hydrogen production.***

To estimate the amount of land required for the new-build renewable energy installations, we calculate the energy output per annum per unit area for an average wind farm and solar power plant. See ref [24] for further details on the calculations below.

The average yearly wind energy density in Australia is calculated assuming an average wind speed of 8ms^{-1} [25]. The conversion factor for a turbine is determined by a geometrical factor $\frac{\pi}{100}$, determined by how closely turbines can be packed together, and the turbine efficiency, taken to be $\eta = 50\%$. The average yearly solar energy density in Australia is taken from ref [26]. The overall conversion efficiency of a solar farm is taken to be around 14%, based on $\eta = 16\%$ efficient solar modules and a plant performance factor of $PF = 85\%$.

Table 7 Results for renewable installations in Australia

	Wind	Solar
Conversion efficiency	$\eta \times \frac{\pi}{100} = 1.6\%$	$\eta \times PF = 13.6\%$
Average yearly energy input density [kWhpa/m^2]	2917	2000
Average yearly energy output density [kWhpa/m^2]	20-66	221-286

The average yearly energy output density for each technology is estimated by multiplying the average yearly energy input density with the conversion efficiency. The values are shown in Table 7. The area of land required for renewable energy installations is then given by dividing the required yearly electricity demand (Table 5) by the average yearly output density. Results are shown in Table 8.

Table 8: Area of land required for renewable energy installations [km^2]

YEAR	2025		2030		2040	
	Wind	**Solar**	**Wind**	**Solar**	**Wind**	**Solar**
Low	16	2.7	137	23	333	57
Med	83	14	285	49	723	124
High	210	36	618	106	1703	292

The total area needed for the high demand scenario is roughly 2000 km^2, which represents the minimum footprint of the power plants, and does not include additional land to allow access and the balance of systems to be installed. Assuming that roughly double the area would be needed for auxiliaries results in a ***required area of less than 0.03% of Australia's land mass, or less than a third of the size of Greater Sydney.***

Comparison of carbon dioxide emissions

As mentioned above, carbon capture and storage technology is not 100% efficient as some CO_2 will escape into the atmosphere, and additional CO_2 is emitted due to the extra electricity needed to compress, transport and store CO_2. The CO_2 emissions released due to blue and brown hydrogen generation coupled with CCS are calculated from the emission intensity (the amount of CO_2 released per unit of hydrogen) of the different processes.

The emissions intensity values depend on the details of the hydrogen generation process and the CCS technology, and were taken from a recent review paper that compared values from many sources [6]. The values used in this work were 1.8 (kg CO_2/ kg H_2) for brown hydrogen (coal gasification) and CCS, and 1.3 for blue hydrogen (SMR) and CCS. Note that this is significantly higher than the values quoted in the CSIRO report of 0.71 for brown hydrogen (coal gasification) and CCS 0.76 for blue hydrogen (SMR) and CCS [5, p. 67, Table 31]. It is notable that the emission intensity for brown hydrogen and CCS, based on an internal CSIRO calculation, is lower than that of blue hydrogen and CCS even though, stoichiometrically, there is more carbon in coal than in natural gas. It is not clear how the CSIRO values were arrived at.

As shown in Figure 2, it is also possible that the installation of renewable energy will not keep pace with the demand for renewable electricity. The analysis above suggests that additional fossil-fuel based electricity will be required to meet the hydrogen demand between 2025 and 2040 if the rate of renewable capacity installation remains constant at 2018 levels, (indicated by the striped area shown on Fig. 2, and given in Table 9). The CO_2 emissions released due to the additional fossil fuel generation are calculated from the emission intensity of coal fired power stations, taken to be 0.9 kg CO_2/ kW from ref [27].

Producing hydrogen from fossil fuels directly, from standard thermochemical processes with CCS, is much more efficient and releases less CO_2 than generating hydrogen from fossil fuel-based electricity. For this reason, it is interesting to compare emissions from the two different scenarios discussed above: where the hydrogen demand is met by electrolysis as we continue to add renewables to the grid at the current rate of capacity installation; and where the demand is met with fossil-fuel based thermochemical methods and CCS.

Table 9: Excess fossil-fuel electricity generation due to H_2 demand [TWh pa]

YEAR	*2025*	*2030*	*2040*
Low H_2 demand scenario	1	0	0
Medium H_2 demand scenario	8	0	0
High H_2 demand scenario	20	25	0

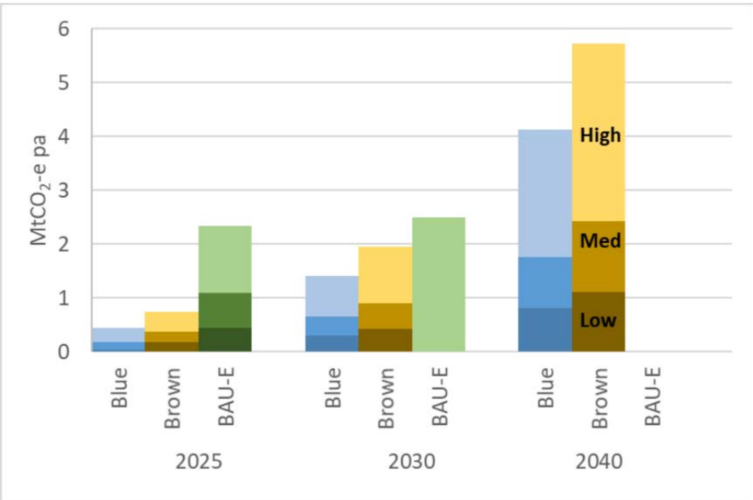

Figure 3: CO_2 emissions per annum resulting from hydrogen generation by different methods. BAU-E: hydrogen produced by electrolysis in a "business-as-usual" scenario, where emissions are due to the fact that the installation rate of renewable energy is fixed at the current rate, which does not keep pace with the demand for renewable electricity. The balance of electricity demand not provided by renewable energy is met with fossil-fuel based electricity (see Figure 2), and blue and brown hydrogen coupled with 85% efficient carbon capture and storage. The different sections of the stacked bar graph represent the three demand scenarios: low, medium, and high, as defined by the ACIL Allen demand modelling, (values reproduced in Table A1).

Figure 3 CO_2 emissions per annum resulting from hydrogen generation by different methods, including hydrogen produced by electrolysis in a "business-as-usual" scenario, where emissions are due to the fact that the installation rate of renewable energy is fixed at the current rate, which does not keep pace with the demand for renewable electricity. These additional emissions peak in 2030 and fall to zero thereafter, as renewable penetration on the grid reaches 100%.

It is worth noting explicitly that CO_2 emissions from hydrogen produced by electrolysis could be considerably lower (or zero) if the rate of new renewable energy installations increases with the demand for electricity.

Conversely, the emissions from coal gasification with CCS would continue to rise with the growth of the hydrogen market, to up to 5.5 $MtCO_2$ per annum by 2040 for the high demand scenario. The emission estimates for fossil-fuel based thermochemical generation are roughly double those provided by ACIL Allen [9, p. 55, Table 5.6], due to the lower emission intensity data used in that work, taken from ref [8, p. 67, Table 31]).

The simple analysis presented above suggests that the large-scale blue or brown hydrogen production will result in significant ongoing emissions representing roughly 1.2% of Australia's climate change emission target (441 $MtCO_2$-e per annum by 2030). Producing zero-carbon green hydrogen with renewable electricity produces no emissions. However, if the rate of renewable energy installation remains constant at 2018 levels, there may be a short term increase in emissions due to the fact that the installation of renewable energy will not keep pace with the demand for renewable electricity. Even in this case, ***the best route to reduce emissions by 2040 is to promote continued growth of the renewable energy industry, expansion of the grid with 100% renewable penetration, and investment in electrolysers for hydrogen generation.***

Social licence, policy and economic impact of hydrogen production in Australia

Social Licence

For the hydrogen industry to successfully develop in Australia, for domestic consumption and/or export, the support of the Australian public must be secured. Social license to operate must be obtained and subsequently maintained by the hydrogen industry. Absence of public support, especially when expressed in protests and conflicts, may lead to political constraints on projects and potential regulatory restrictions, which can cause project failures, economic losses and reputational damage to the industry [28]. This was recently experienced by the coal seam gas industry in the Northern Rivers region of New South Wales, where social license withdrawal occurred (spurred by local perceptions of sustainability, rural economies and questions about the local benefit provision) [29]. This recent example demonstrates that the importance of obtaining and maintaining social license to operate should not be underestimated. To give the Australian hydrogen industry the highest chance of success, appropriate time and resources need to be invested into education and genuine participatory processes.

Perceptions of safety

The CSIRO's *National Hydrogen Roadmap* mentions social license in passing and only in reference to the public's 'normalisation of risk' and perceived safety issues regarding hydrogen [8]. In particular, the need to combat the perception that hydrogen may be more dangerous than petrol or natural gas. The report also mentions the risk of over regulation of safety standards which could increase project costs. The Hydrogen Strategy Group's report specifically addresses safety for hydrogen, stating that preliminary analysis by the Energy Pipelines Cooperative Research Centre indicates that the overall risk of hydrogen is similar to natural gas, despite their different combustion characteristics [30].

Environmental concerns and support for green hydrogen

Preliminary research undertaken by the University of Queensland, and included in the COAG report, shows that the publics' concerns about large-scale hydrogen production and use go beyond safety. Results showed that the environment was an important factor [7]:

> *"Participants expressed mixed feelings about producing hydrogen from fossil fuels with CCS rather than renewables, with cost and environmental impacts being critical to acceptance of either."*

This public sentiment is crucial and highlights the public's concern over climate change and the environment. It also foreshadows that there may be large-scale public opposition to hydrogen production methods that rely on fossil fuels and unproven CCS technologies. The CSIRO report confirms that "When compared with other hydrogen production pathways, thermochemical production coupled with CCS is likely to carry additional social license challenges." [8, p. 25]. This is due to the capital intensity of these projects, concerns over continued use of fossil fuels, and questions over long term CCS viability [8, p. 25].

This initial research into public attitudes towards hydrogen is an important first step and needs to be built upon and investigated further. In particular, a recent report by ITP Energised Group calls for additional research on "the technical, economic and social risks associated with hydrogen infrastructure" [6, p. 11]. It is positive that the Australian government has recently announced that the Future Fuels Cooperative Research Centre has a goal to explore social license for hydrogen [7] and it will be important to ensure that the focus remains broad and covers all elements of the industry from production to end use. Furthermore, if hydrogen produced from fossil fuels and coupled with CCS is included in the development of the Australian hydrogen industry, then public perceptions regarding CCS also need to be incorporated. This may add an extra layer of social risk to the hydrogen industry given the skeptical public perceptions [31] held towards CCS by the Australian public. Research into CCS has found there is strong support for renewable technology and that investments into CCS at the expense of renewables is not well tolerated [32]. The government needs to be cognisant of this support for renewables when considering the investment of large sums of public money in new energy technologies [32].

Policy impacts on competitiveness of Australian hydrogen

Finally, the global hydrogen market is going to be driven largely by the need to decarbonise. Accordingly, many countries have introduced carbon pricing schemes, making zero-carbon products more attractive than low-carbon products. All three reports circumvent the issue of carbon pricing. The CSIRO report states that their modelling assumes other countries have carbon pricing. The other two reports skirt the issue making statements such as there needs to be a "legislative requirement or long-term pricing signal" for CCS; that we should "verify and reward clean hydrogen production"; and we need a "clear policy direction".

Global carbon pricing policies

There are currently 53 carbon pricing initiatives worldwide, either implemented or scheduled for implementation. In 2018 these initiatives will cover 11 $GtCO_2$-e, representing 19.8% of global GHG emissions, across 46 national and 25 subnational jurisdictions [33]. Most countries have proposed national action plans under the Paris Agreement through the mechanism of Nationally Determined Contributions to 2030: it is unequivocal that the world is moving to decarbonise the global economy.

It is fundamental that while Australia moves to capitalise on new opportunities in a decarbonised global economy, that we should invest with intelligence and foresight to create resilient future industries. To fully benefit from the opportunities of a future hydrogen export market, Australia needs to foster a resilient hydrogen industry. Resilience in this case means supporting a hydrogen industry that is protected from foreseeable cost increases, such as a price on carbon. To future proof the Australian hydrogen industry, hydrogen produced by renewable energy should be prioritised, to eliminate the carbon price risk to the commodity. Failing to acknowledge this risk, by manufacturing hydrogen with fossil fuels and relying on unproven CCS technologies, exposes Australian hydrogen to an increased risk of becoming internationally uncompetitive. This concern is not sufficiently addressed in any of the reports.

Key Asian hydrogen export markets

For the four major export markets for Australian hydrogen, China, Japan, the Republic of Korea and Singapore, as cited in ACIL Allen's report *Opportunities for Australia from hydrogen exports*, a price for carbon exists or is set to be introduced:

- China has a national emissions trading scheme (ETS) due to begin in 2020, and a number of current pilot ETSs: Beijing pilot ETS, Chongqing pilot ETS, Fujian pilot ETS, Guangdong pilot ETS, Hubei pilot ETS, Shanghai pilot ETS, Shenzhen pilot ETS, Tianjin pilot ETS;
- Japan has a carbon tax (Tax for Climate Change Mitigation), which started in 2012 and covers 68% of the economy's emissions;
- The Republic of Korea launched its national ETS (Korea ETS) in 2015 and covers 68% of emissions, which was the first national cap-and-trade system in operation in East Asia; and
- Singapore is set to introduce a carbon tax in 2019, which will be between S$10–20/t$CO_2$-e (US$7–14/tCO_2-e) [33]. The revenue raised will help to fund industrial emission reduction measures.

Australian hydrogen being sold into these markets will face scrutiny on the carbon emissions associated with the production and transport of the hydrogen. It will be a socially fractious outcome if the Australian government takes on the liability of this carbon risk, as it has done for the carbon liability of the CCS component of the Gorgon gas plant in Western Australia [34], with potential implications to increase Australia's sovereign risk.

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