Crawford School of Public Policy
Centre for Climate & Energy Policy

# Green hydrogen production costs in Australia: implications of renewable energy and electrolyser costs

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**Abstract**

A crucial question in the development of a hydrogen industry is whether green hydrogen, made using renewable energy, will be able to be produced at a cost that makes it attractive compared to hydrogen produced from fossil fuels. The main factors are the cost of electricity and the cost of electrolysers, together with capacity utilisation rates. Over recent years the cost of electricity from solar PV and wind have fallen dramatically, and further reductions are expected. Cost reductions are also being realised for electrolysers. In this note, we compile recent cost estimates and projections to provide plausible ranges for the production cost of green hydrogen. We find that the cost of green hydrogen could readily be at or below A$3/kg in the near future, and that the 'stretch goal' of A$2/kg mentioned in Australian strategy documents is likely to come into reach, possibly rapidly.

**Keywords:**
Renewable energy; hydrogen; electrolysis; economic analysis; projections; levelised cost of electricity

**JEL Classification:**
Q41, Q42, Q47

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# I. Introduction

Australia is one of several countries considering the creation of a hydrogen production, use and export industry. Hydrogen can be produced from fossil fuels or through electrolysis of water. The latter offers the possibility of hydrogen produced without emissions of carbon dioxide. This 'green' hydrogen has been more expensive to produce than fossil fuel-based hydrogen, but its costs are declining. The two main factors determining the cost of hydrogen production from electrolysis are the cost of electricity and the cost of electrolysers.

The cost of renewable electricity has fallen rapidly over recent years, and is expected to fall further. In many parts of the world, wind and solar power is already the cheapest form of energy for any new built generating capacity. Its average cost is cheaper than electricity from natural gas in many places including Australia and is often cheaper than wholesale prices on the grid (IEA 2020, IRENA 2020, Graham et al 2020).

Lower costs of electricity generation from carbon dioxide-free sources have fundamental implications for the choice of energy in many applications. Electrification of many processes and applications has become commercially attractive. Production of hydrogen from fossil fuel-based processes currently dominates global hydrogen production, but hydrogen production based on renewable energy is becoming more competitive (IEA 2019). To date fossil fuel based hydrogen production has been cheaper than via the electrolysis route; however, hydrogen from fossil fuels is highly emissions-intensive unless coupled with carbon capture and storage, and even then there are significant remaining carbon dioxide emissions (Jotzo, Beck and Longden 2019).

This note takes stock of the development of renewable energy costs since 2010 and projections to 2050, and shows what different electricity cost levels and costs of electrolysers (coupled with different capacity factors) imply for the costs of producing hydrogen through electrolysis. It specifically looks at international and Australian projections. It is intended to help inform current analysis in Australia about the likely future cost competitiveness of green hydrogen. There is uncertainty about how costs for electricity and electrolysers will develop in the future, and the estimates presented here are not meant as a prediction of the future.

We do not provide estimates for future costs of hydrogen from fossil fuel based processes. We also do not account for the (implicit or explicit) cost of any remaining carbon dioxide emissions, nor analyse the competitiveness of hydrogen with other energy carriers and energy sources (such as natural gas or direct use of electricity in different applications and places).

## II. Renewable energy supply costs

Typical up-front capital costs for solar PV installations fell by 79% from 2010 to 2019 and by 24% for onshore wind generators (IRENA, 2020). This means lower average costs of generating electricity over the lifetime of assets (Figure 1).

The levelised cost of electricity (LCOE) for large scale solar PV installations in 2020 is between A$41-60/MWh in Australia according to CSIRO estimates ('GenCost', Graham et al., 2020), and A$49-64/MWh internationally according to the IRENA auction database.[1] The equivalent numbers for onshore wind are A$48-60/MWh (Graham et al., 2020) and A$46-64/MWh (IRENA, 2020). The LCOE is a measure of average electricity generation costs over the lifetime of a generating plant.

The expected future trend is for further reductions in costs from solar PV with a projected mean LCOE in 2030 at A$33/MWh, which drops to A$26/MWh in 2040. Onshore wind is projected at a mean LCOE of A$46/MWh and A$43/MWh for 2030 and 2040, respectively. However, offshore wind has seen recent dramatic reductions in recent costs that have been reflected in the global average auction price dropping from A$181/MWh for 2020 to A$117/MWh for 2023, with prices in the lower ranges (5$^{th}$ percentile) between A$77/MWh and A$101/MWh for 2020 to 2023 (IRENA, 2020).

The mean cost projection for 2030 across both PV and onshore wind is A$40/MWh, and the lowest estimate was A$25/MWh (Figure 1c). In the analysis that follows we refer in particular to mean cost estimates and projections. This is a highly conservative approach for two reasons.

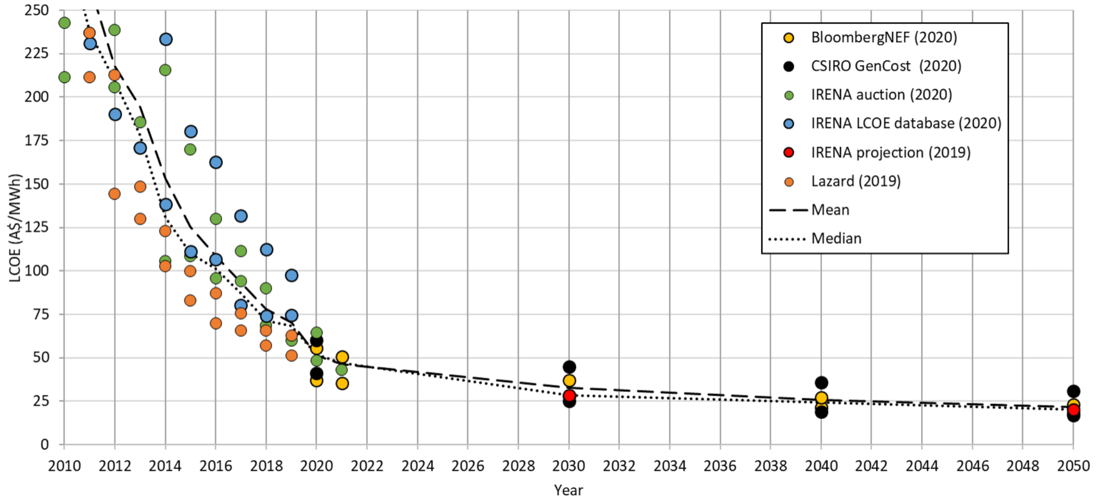
[1] All monetary values in this note are given in AUD. Many estimates are in USD in the original materials, currency conversions are all at 1 AUD = 0.70 USD.

One, production of hydrogen using electrolysis would almost always make use of the cheapest available electricity generation options. Therefore it is the lower range of present and projected future costs that is relevant, not the higher-cost installations e.g. in locations that are not optimally suited for renewable energy generation.

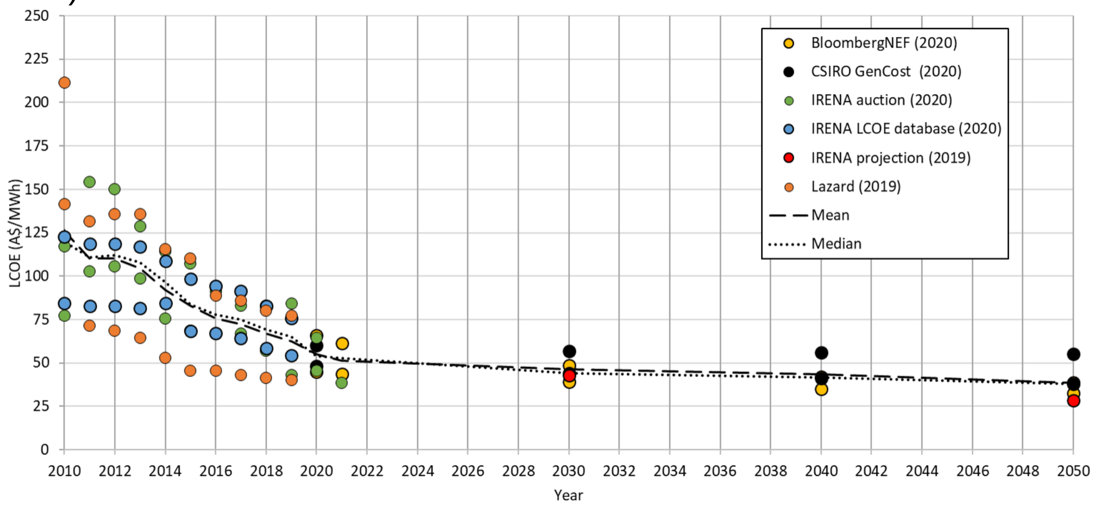
Two, the history of renewable energy projections has been to underestimate capacity and overestimate investment costs (Carrington and Stephenson 2018, Gilbert and Sovacool 2016). One factor that suggests that reality may once again lead to lower costs than currently projected is that capital is now available at very low cost, and interest rates are likely to remain low on account of a global recession. Note that the IRENA LCOE calculation applies an interest rate of 7.5% for the OECD and China over a lifetime of 25 years.

**Figure 1 – Levelised cost of electricity 2010-2020 and projections to 2050**

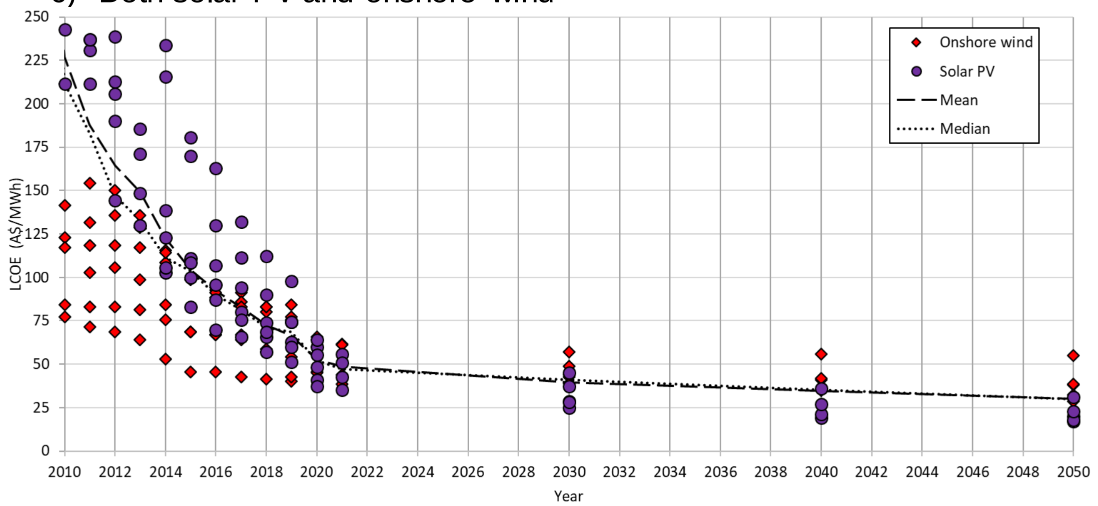
a) Solar PV




b) Onshore wind




c) Both solar PV and onshore wind




Sources of these data are: Bloomberg NEF (2020), Graham et al., (2020), IRENA (2020), IRENA (2019a,b), Lazard (2019). Values in USD have been converted to AUD.

## III. Production costs of hydrogen via electrolysis

The cost of electricity is a major cost component in production of hydrogen via electrolysis. The other defining cost components are the efficiency and capital cost of electrolysers, in combination with the capacity utilisation of electrolysers. Other costs, such as labour, land and water, are a minor determinant of the production cost of hydrogen (IEA, 2019).

IEA (2019) provides a breakdown of capital costs by electrolyser type. For alkaline electrolysers they are between A$714-2000/kW (today) and A$571-1214/kW (2030). For polymer electrolyte membrane (PEM) electrolysers they are between A$1571-2571/kW (today) and A$928-2143/kW (2030). However, lower capital costs have been reported. In 2017, Nel reported an alkaline electrolyser cost of A$1000/kW for 2015 and a projection of a little over A$700/kW for 2020. The Norwegian company reported that large electrolyser facilities were already at capital expenditure parity with medium sized steam methane reforming (SMR) plants (Løkke, 2017). Electrolyser manufacturing costs could fall substantially as demand for electrolysers increases.

These factors combine to determine a cost of producing hydrogen. This relationship is plotted in Figure 2, based on estimations by IEA (2019).[2] To estimate this relationship, the IEA used an electrical efficiency at 69%, an interest rate of 8%, and a lifetime of 25 years. We developed a simple equation that accurately captures the IEA estimations for hydrogen production costs using electrolysis. The equation that estimates a hydrogen production cost (PC) for a given electricity cost (E) is:

$$PC = \beta_0 + \beta_1 E$$

where $\beta_0$ is an intercept and $\beta_1$ is a parameter that defines the impact of electricity costs.

Modifying the intercept accounts for variations in the cost of capital (CC) and the operating capacity factor (CF). The impact of the parameter for electricity costs is shown as increasing costs per kilogram along the x-axis. For every A$10/MWh decrease in electricity costs there

[2] As per Figure 18 of IEA (2019).

is a decrease in hydrogen production costs of A$0.47/kg. Other cost components are held constant and captured in the intercept as they do not have a large impact on the estimates.

We show costs for electrolyser costs at A$1000/kW and A$500/kW, respectively. The higher cost point proxies presumed costs of Alkaline electrolysers today and possible cost levels of PEM electrolysers in the near future, while the lower cost point proxies costs that might be able to be achieved over the next decade. We note that there is significant uncertainty about future capital costs including the possibility of rapid and large cost reductions.

The capacity utilization factors for electrolysers will depend on the energy sources. An electrolyser run from stand-alone renewable energy sources firmed with deep storage, or using the grid as backup, will be able to be run at high capacity rates, possibly exceeding 90% (though grid connection will generally mean some use of fossil fuel based electricity and thus carbon dioxide emissions in production of hydrogen). An electrolyser run off a wind farm could operate at capacity factors close to 45%, and a standalone solar farm at around 30%. These capacity factors are consistent with the grading of high quality onshore wind and solar PV by the Australian Energy Market Operator (AEMO, 2020). We use these capacity factors in our analysis below.

On the basis of electrolyser costs, applicable capacity factors, and LCOE projections, the following production costs for green hydrogen may be plausible for 2030. For a capacity factor of 30%, which is consistent with solar PV, the 2020 estimates range from A$3.12-3.82/kg. This uses the mean electricity cost for solar PV in 2020, which was A$51/MWh (Fig. 1a and Appendix 1). For the mean cost of solar PV in 2030 (A$33/MWh), hydrogen costs range from A$2.25-2.95/kg. The lower range projections for PV electricity for 2030 are around A$25/MWh, implying hydrogen costs of A$1.89-$2.56/kg for the relevant range of electrolyser cost scenarios.

For a capacity factor of 45%, which is consistent with high quality onshore wind generation, hydrogen costs range from A$3.10-3.60/kg (2020) and A$2.70-3.20/kg (2030). This uses the mean cost of wind electricity shown in Fig. 1b. The lower range projections for wind electricity for 2030 are around A$40/MWh, implying hydrogen costs of A$2.40-$2.90/kg for the full range of electrolyser cost scenarios.

At a capacity factor of 90 per cent, hydrogen could be produced at below A$3/kg if electricity costs were below A$50 per MWh at either of the two electrolyser cost assumptions; whereas for hydrogen at A$2/kg electricity would need to be below A$30s per MWh. For comparison, average on-grid spot market prices in New South Wales and Queensland during July 2020 were A$46/MWh. Note that the partial use of grid-based electricity would mean that hydrogen from such electrolysis plants was not fully 'green' given the current configuration of the grid involves fossil fuels.

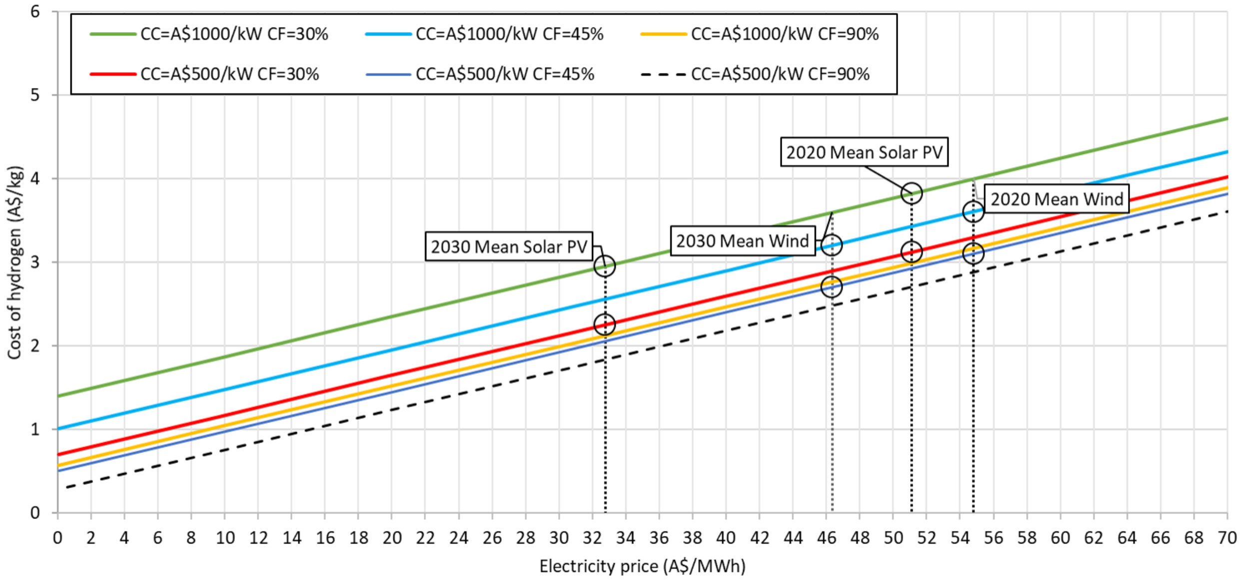
At what cost levels green hydrogen becomes competitive with alternatives is a complex question that we do not investigate in this paper. Cost competitiveness with other fuels and fuel carriers eg natural gas, diesel and electricity storage depends strongly on the specific application, location and any carbon dioxide penalties.

Cost competitiveness with fossil fuel based hydrogen production can be gauged from cost data and projections. Such comparisons need to take into account that the costs of carbon capture and storage (CCS) in hydrogen production are uncertain and could vary greatly between processes and sites, and the fact that there are remaining carbon dioxide emissions even after CCS which could be subject to carbon penalties or which could suppress demand in jurisdictions where green hydrogen is the standard.

CSIRO (2019) puts the base case cost for hydrogen produced from steam methane reforming (SMR), the most commonly used fossil-based method, at A$2.27-2.77/kg and the cost of production from black coal gasification at A$2.57-3.14/kg. The maturity of the SMR and coal gasification technologies suggests any further gains would be incremental (with projections between A$1.88-2.30/kg for SMR and A$2.02-$2.47/kg for black coal gasification) and would be dependent on energy input prices remaining constant and reasonable proximity of carbon dioxide storage sites. Lignite (brown coal) gasification could result in prices between $A2.14-2.74/kg, but would not come on line commercially until the 2030s. CSIRO also points out that SMR and coal gasification costs are highly sensitive to input prices for gas and coal – a factor that causes Wood MacKenzie (2020) to project substantial increases in costs of SMR production costs over time. CSIRO's figures are broadly consistent with IEA (2019) which estimates approximately A$2.00-2.14/kg for SMR with CCS in "the most promising regions" for production; BNEF (2020) puts hydrogen from SMR with CCS in a range between approximately A$2.00-4.80/kg between 2019 and 2050, with little reduction in the lowest-cost product by 2050.

By contrast, productions costs for green hydrogen are certain to fall over time, and may fall substantially, as detailed in our analysis above and indicated by various relevant projections (eg Wood Mackenzie, BNEF and Hydrogen Council 2020). In its recently issued hydrogen strategy, the European Commission states that "In regions where renewable energy is cheap, electrolysers are expected to be able to compete with fossil-based hydrogen in 2030." (European Commission 2020).

**Figure 2 – Production cost of hydrogen at different electricity costs and electrolyser costs**



## IV. Australian cost estimates

The projected cost of producing hydrogen through different technologies could be a decisive factor in determining technology investment choices made in Australia (Commonwealth of Australia, 2019). A key premise of Australia's Technology Roadmap that is under development is that "driving down the cost of deploying low emissions technologies to a point where they are competitive with existing alternatives will deliver meaningful reductions in global emissions" (DISER, 2020).

Figure 3 shows a comparison of price points for green hydrogen production based on the CSIRO's GenCost electricity generation cost projections for Australia applied in the IEA cost model with assumptions about electrolyser costs and capacity factors as in the previous section, and cost estimates from the CSIRO Hydrogen Roadmap (Bruce et al 2018).

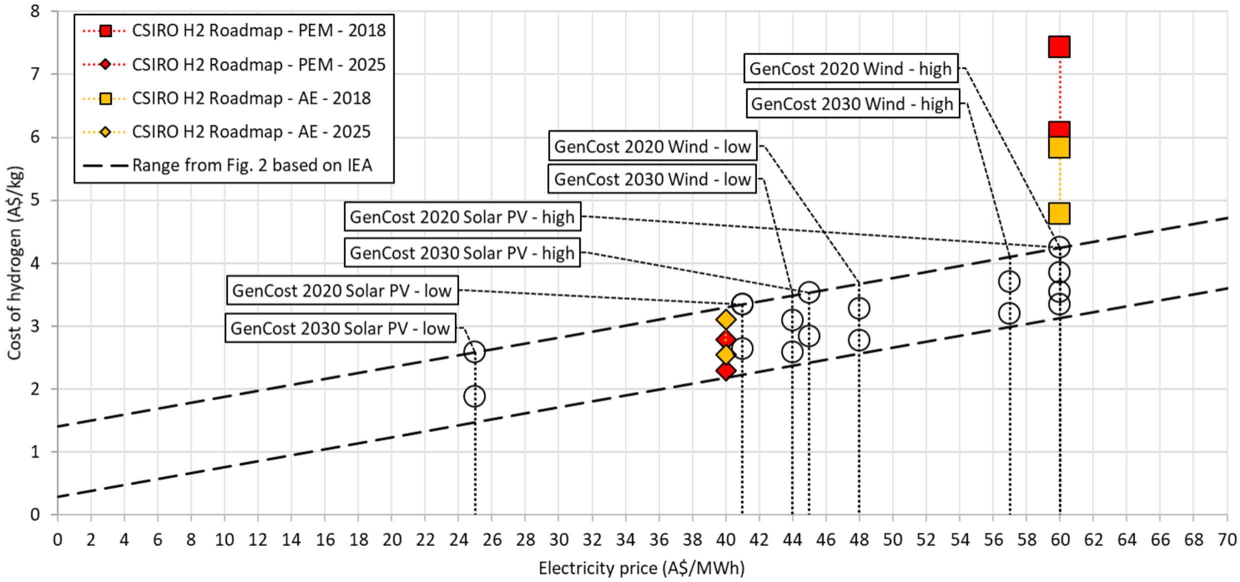
The hydrogen production cost estimates for 2018 in the CSIRO National Hydrogen Roadmap range from A$4.78/kg to A$7.43/kg (Bruce et al., 2018). For 2025, the CSIRO Roadmap estimates are between A$2.29/kg and A$3.10/kg. Applying the CSIRO GenCost estimates for 2020 to the IEA cost relationship (shown in Fig. 2 and equation 1) results in estimates between A$2.64/kg and A$4.24/kg. On the basis of GenCost electricity cost projections for 2030, the resulting hydrogen production cost estimates are between A$1.89/kg and A$3.71/kg. These estimates are derived on the basis of GenCost low and high electricity cost projections, electrolyser capital costs of A$500/kW and A$1000/kW respectively, and capacity factors of 30% for PV electricity and 45% for wind. They are detailed in Figure 3.

The lower end of these cost estimates will likely be more relevant in practice as hydrogen production would be run on the lowest cost renewable energy generation opportunities. We also once again emphasize the uncertainty regarding future cost estimates, and the possibility of large and rapid cost reductions as the industry scales up.

The main difference in the CSIRO National Hydrogen Roadmap estimates for 2018 is that much higher capital costs for electrolysers are assumed. For PEM, the capital costs assumed by CSIRO in the Australian Hydrogen Roadmap are A$3496/kW for 2018 and A$968/kW for 2025. Alkaline electrolysers are assumed to be A$1347/kW for 2018 and A$1012/kW for 2025. As detailed above, other projections and current day cost estimates have electrolysers at lower costs.

The upshot is that Australia-specific cost estimates confirm the conclusions from international cost estimates: green hydrogen production at or below A$3/kg will be possible soon or could already be possible, and green hydrogen production costs in the vicinity of A$2/kg may well come within reach in coming years.

**Figure 3 – Production cost of hydrogen – comparison of price points based on GenCost estimates in the IEA cost model and CSIRO Hydrogen Roadmap**



## V. Conclusion

Given rapid past reductions in renewable energy supply costs and the prospect of sustained reductions in electrolyser capital costs, the production of green hydrogen at costs of below A$3/kg is likely to be possible, and a reduction of production costs over the next decade to approach A$2/kg is plausible. Australia is well placed to achieve low-cost green hydrogen production due to its low-cost renewable energy supply and the potential to achieve large economies of scale.

Our analysis here does not assess the competitiveness of hydrogen with other fuels and energy carriers. Nor does it address green hydrogen's likely cost competitiveness with fossil-fuel based hydrogen production, though some recent assessments (BNEF 2020, Wood Mackenzie 2020) point to a convergence with fossil-fuel based alternatives as green hydrogen costs come down and factors such as the rising cost of natural gas (and potentially pricing in of environmental externalities) push the price of SMR up. Nevertheless, the data suggest that there are significant opportunities for green hydrogen as an emissions-free fuel in domestic use, including for the production of commodities for export, and possibly also for export.

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**Appendix 1. Levelised cost of electricity in 2020 and projections to 2050 (A$/MWh)**

| | Solar PV | | | |
|---|---|---|---|---|
| | **Minimum** | **Mean** | **Median** | **Maximum** |
| **2020** | 37 | 51 | 52 | 64 |
| **2021** | 35 | 46 | 47 | 56 |
| **2030** | 25 | 33 | 29 | 45 |
| **2040** | 19 | 26 | 24 | 36 |
| **2050** | 17 | 22 | 20 | 31 |
| | **Wind** | | | |
| | **Minimum** | **Mean** | **Median** | **Maximum** |
| **2020** | 45 | 55 | 54 | 66 |
| **2021** | 39 | 51 | 53 | 61 |
| **2030** | 39 | 46 | 44 | 57 |
| **2040** | 35 | 43 | 42 | 56 |
| **2050** | 29 | 39 | 38 | 55 |
| | **Combined** | | | |
| | **Minimum** | **Mean** | **Median** | **Maximum** |
| **2020** | 37 | 53 | 52 | 66 |
| **2021** | 35 | 49 | 47 | 61 |
| **2030** | 25 | 40 | 41 | 57 |
| **2040** | 19 | 35 | 35 | 56 |
| **2050** | 17 | 30 | 30 | 55 |

Note: these data are summaries of the data points in Figure 1a-c, refer to text for more details.