Dynamics of the transition to renewable hydrogen

Reza Fazeli[1*], Fiona J. Beck[1], Matt Stocks[1]

Email: reza.fazeli@anu.edu.au

[1] The Australian National University, College of Engineering and Computer Science

Abstract

Hydrogen gained a lot of attention as an energy carrier to achieving the goal of net-zero emissions targeted by many governments and businesses around the world. Yet, the high production cost of zero-emission 'renewable' hydrogen, produced from electrolysis powered by renewable electricity, is hindering its adoption. In this paper, we examine the dynamics of the transition to renewable hydrogen and the role of uncertainties in projections of techno-economic factors on the transition. We propose an integrated framework, linking techno-economic and Monte-Carlo-based uncertainty analysis with quantitative hydrogen supply-demand modelling, to examine hydrogen production by different technologies, and the GHG emissions from feedstock supply and the production process. We find that without taking into account the cost of carbon emissions, hydrogen production will likely be dominated by fossil fuels for the next few decades, while implementing a price on carbon emissions can significantly expedite the transition to renewable hydrogen and cut the cumulative emissions significantly.

Introduction

Interest in hydrogen is growing both internationally and domestically as industry and governments around the world investigate decarbonization strategies. However, progress towards decarbonization targets will depend on how the hydrogen is produced. While there are no carbon emissions at point of hydrogen use, the production and transportation of hydrogen can contribute to significant carbon emissions depending on the technologies used [1].

The high production cost of 'zero-emission' or 'renewable' hydrogen – in the range of 3.2-7.7 USD$/kg H_2 [2] – is hindering its adoption. However, continued declines in the cost of renewable electricity and the significant improvement in the capital cost of electrolysers (60% since 2010 [3]) are now paving the way for lowering the cost of renewable hydrogen [4].

In addition, during the past two years interest in hydrogen has been rising around the world. Many countries (including Australia, South Korea, Japan, along with the European Union) have announced, drafted or published national hydrogen strategies that incorporated support measures for clean hydrogen[5]. Many of these strategies have included both renewable and fossil-fuel based hydrogen with CCS in their definition of clean hydrogen, and some have explicitly stated that fossil-fuel based hydrogen will be acceptable during the transition phase as the hydrogen market expands [6].

There has been a growing interest in assessing the competitiveness of renewable hydrogen over the coming decades to replace carbon-intensive fossil fuels in a range of applications. Several recent studies provide a techno-economic analysis of renewable hydrogen production [4], [7]–[11]. However, few studies captured the impacts of uncertainties in techno-economic factors. To have a better understanding of the dynamics of the transition pathways, system dynamics and agent-based simulation models have been developed to examine interactions between agents (governments, consumers, car manufacturers). These models are valuable in showing how simple relationships can result in complex dynamics, as demonstrated by previous attempts to foster alternative fuel transitions; and they can provide insights into the conditions under which heterogeneous actors might foster a transition through consumption, investment, policy, and cooperation decisions. Examples in the field of hydrogen transitions include [12]–[14]. However, they overlooked the impact of uncertainties on transition to hydrogen economy.

In this paper, we examine the role of uncertainties in projections for techno-economic factors on the transition from fossil based to renewable hydrogen, focusing on low-temperature electrolysers. We propose an integrated framework, linking techno-economic and Monte-Carlo based uncertainty analysis with quantitative hydrogen supply-demand modelling to examine hydrogen production by different technologies and the associated greenhouse gas (GHG) emissions from feedstock supply and the production process.

This work provides an understanding of the role of uncertainty in key techno-economic factors (the system cost of electrolysers, the price of feedstocks, the efficiency and lifetime of electrolyser stacks and the discount rate) on the transition to renewable hydrogen. Section 2 describes methods, assumptions for the reference case, and uncertainty ranges for key factors.

Results are presented and discussed in section 3. The concluding remarks are presented in Section 4.

2. Methods & assumptions

An integrated framework linking techno-economic and Monte-Carlo based uncertainty analysis with quantitative hydrogen supply-demand modelling is used to assess the impact of uncertainty in key inputs on the development of hydrogen production in Australia. Three production pathways are considered: steam methane reforming (SMR) of natural gas, and electrolysis of water using alkaline (AEL) or PEM electrolysers.

2.1. Methods

A simple supply-demand dynamic simulation model was developed to study the evolution of hydrogen production capacity by technology required to satisfy the given demand (Supply-demand balancing loop illustrated in Figure 1). The development of hydrogen production capacity depends on the expected profitability of new capacity which relies on the levelized cost of hydrogen (LCOH) for different production technologies.

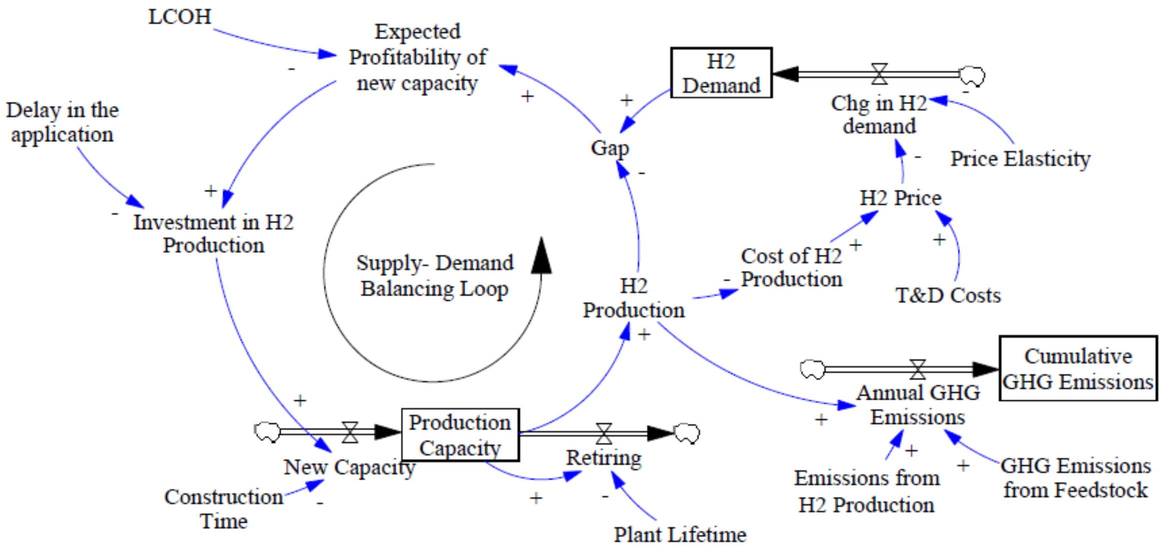

Figure 1: Dynamic simulation model of hydrogen production

There are two types of delay that can affect the transition. The first one is the delay associated with the processing of permit applications for the investment in hydrogen production facilities, while the second one is related to the construction time. The delay in the application permit was assumed to be 1 year, while the construction time of 3 years for SMR plant and half a year for electrolysis were obtained from IEAGHG, [16]. The expected profitability of new capacity was determined by the LCOH, which is estimated from the present value of all expenses during the plant's lifetime and the present value of hydrogen generation, as:

$$LCOH = \frac{\sum_{t=0}^{N} \frac{C_t + O_t + F_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{H_t}{(1+r)^t}} \qquad (1)$$

where C_t represents the capital investment in year t, O_t the annual fixed operation expenditure (OPEX), F_t the annual feedstock cost (Natural gas or electricity), H_t the annual hydrogen production (kg H_2), r the real discount rate, and N the plant lifetime.

The LCOH for renewable hydrogen is dependent on several factors that are inherently uncertain. The capital investment represents total system cost which is dominated by the CAPEX of electrolyser and balance of plant. The electrolyser stack lifetime determines how often the electrolyser electrodes need to be replaced, which represents a significant capital replacement cost. In this study, we choose solar PV as the most promising source of electricity for renewable hydrogen production for both the reference case and the uncertainty analysis.

The factors that affect the LCOH for SMR based hydrogen production are the capital cost and the gas price. The capital investment costs for SMR are well understood and is assumed not to change in real terms as this is a mature technology [19], whereas the price of gas is variable and considered as an uncertainty in our analysis. The assumption for the discount rate is particularly important for renewable technologies because they tend to have high CAPEX and low OPEX [20]. We used a representative real discount rate of 5.9% based on [21]. From Bruce et al., [22], the plant lifetime of 40 years is considered for all technologies.

From the discussion above, seven key factors have been identified that significantly impact the cost of LCOH, and that are inherently uncertain over the time horizon of the study. These are the capital cost of the renewable energy plant, the capacity factor of the RE which determines how often the electrolyser will run, the system cost of electrolyser, efficiency and stack lifetime of electrolyser, the gas price, and the discount rate.

We begin by defining a reference case based on recent reports from the IEA [19], [2], and the report prepared by the Australia’s Commonwealth Scientific and Industrial Research

Organization (CSIRO) [22]. Finally, the ranges of uncertainty for the seven key factors have been defined in section 2.3., are used for the uncertainty analysis.

2.2 Techno-economic factors

Table 1 presents the techno-economic assumptions for four hydrogen production technologies used to calculate the LCOH in the reference case, throughout the time horizon of the analysis (2020-2050). The projection of energy supply is bound to be speculative to some degree, as it is impossible to know with certainty how technology will evolve. However, for SMR, the capital cost is not expected to change considerably [19]. Parameters are taken from projections are obtained from [19], [2], [22], as indicated in the table. The exchange rate of 1 USD = 1.45 AUD was applied according to the Australian Tax office [23].

Table 1: Techno-economic assumptions for hydrogen production technologies from [19], [2], [22]

	Unit	2020	2030	2050
SMR (Natural gas based)				
CAEPEX[1]	AUD$/kW H_2	1320	1320	1320
Annual OPEX[1]	% of CAPEX	4.7%	4.7%	4.7%
Specific Consumption[1]	kg NG/Kg H_2	3.16		3.16
Gas Price[3]	AUD$/GJ	8		8
Max Capacity factor[1]	%	95%		95%
Lifetime[3]	years	40		40
Nominal Capacity[3]	ton H_2/day	210		210
Alkaline electrolyser (AEL)				
CAPEX[2]	AUD$/kW	1620	910	580
Annual OPEX[1]	% of CAPEX	2.2%		1.5%
Electrical efficiency[2]	% LHV	66%	67%	75%
Stack lifetime[2]	hours	75000	95000	125000
Capacity of Reference size plant[3]	MW	10		10
PEM electolyser				
CAPEX[2]	AUD$/kW	1800	1470	750
Annual Opex[1]	% of CAPEX	2.2%		1.5%
Electrical efficiency[2]	% LHV	58%	65%	70%
Stack lifetime[2]	hours	60000	75000	125000
Capacity of Reference size plant[3]	MW	10	10	10

[1] IEA, [2]

[2] IEA, [19]

[3] Bruce, et al., [22]

2.3. Uncertainty range of projections for key inputs

Figure 2 shows the range and reference values for five of the seven factors that have been identified as key to affect the transition to renewable hydrogen production: (a) the capital cost of AEL and (b) PEM electrolysers, (c) the capital cost of Solar PV, (d) the price of natural gas, (e) the electrical efficiency (% LHV) for AEL, (f) the electrical efficiency (% LHV) for PEM, (g) the stack lifetime of the AEL and (h) PEM electrolysers. In order to explore the effect of uncertainties on the transition, the ranges of projections for key inputs are defined, based on several sources, including [19], [2], [22], [18], [25]–[29]. The representative real discount rate of 7% was selected based on Bruce, et al., 2018, while the range of 5%-7% was selected based on [22], [21], [30].

Since there is no consensus on the most probable projections of techno-economic factors, a uniform distribution function was applied for key inputs at specific years (2020, 2030, and 2050). Linear interpolation was used to generate simulation input values between the specified years in each run. Multivariate sensitivity simulations were performed using the Vensim Monte Carlo function, while parameter values were sampled from within the bounds of the random uniform distributions.

As explained earlier, the uncertainty in regulations and policies is a critical factor affecting the transition to renewable hydrogen. Different policies can imply a cost on carbon, which remains controversial and surrounded by considerable uncertainty, and to date have not been enacted on a national scale. The IEA have defined an implicit carbon price in their 450ppm Scenario (consistent with achieving 2 C climate change goal) ranging between US\$43–US\$63/tCO2 in 2025 and US\$125–US\$140/tCO2 in 2040 [31]. In this study, the impact of implementing a carbon price consistent with the IEA 450 ppm scenario is investigated, assuming a carbon price at the higher end of the IEA estimate and remaining constant during the period 2040-2050.

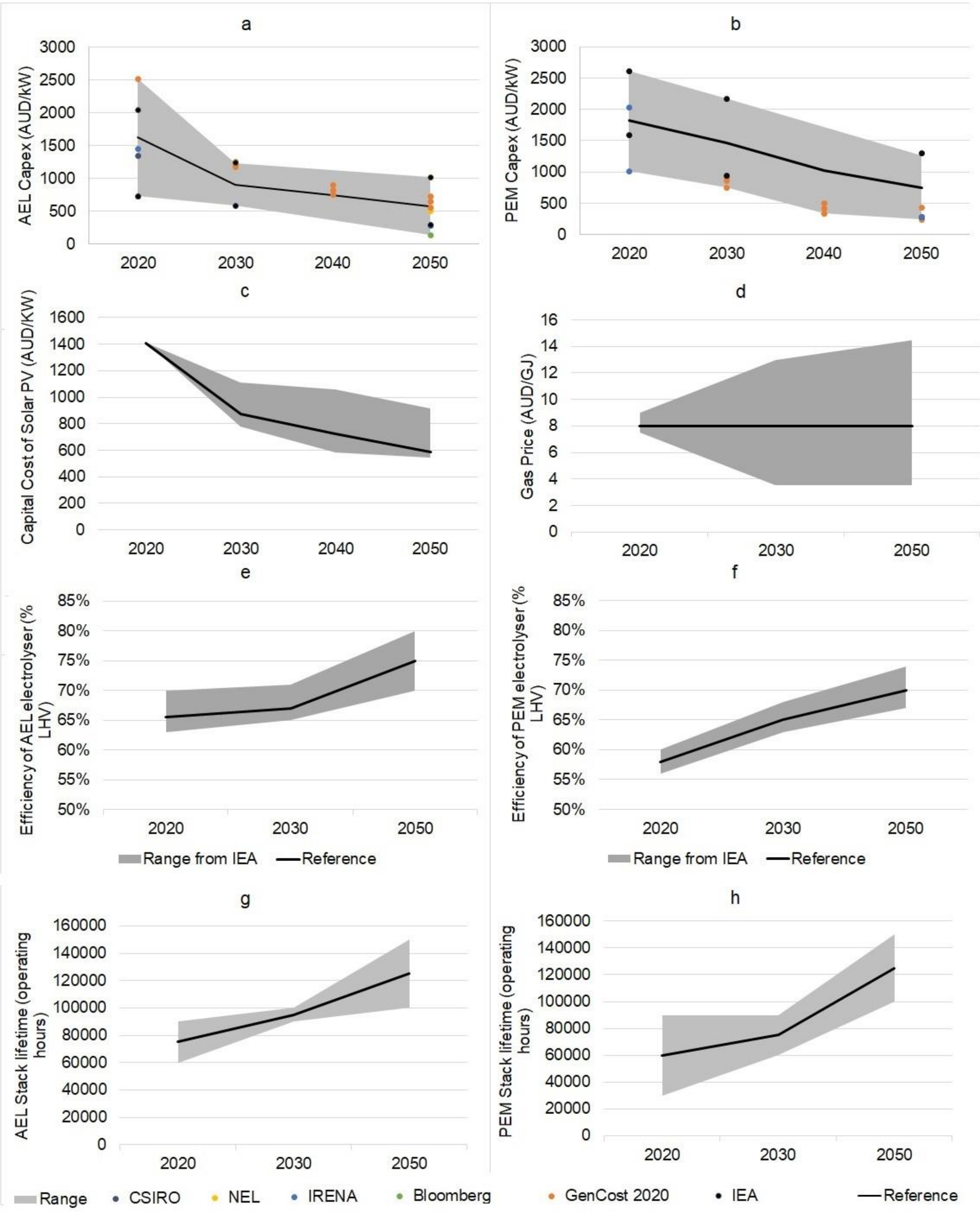

Figure 2: Range of projections for five factors; (a) the capital cost of AEL and (b) PEM electrolysers, (c) the capital cost of Solar PV, (d) the price of natural gas, (e) the electrical efficiency for AEL, and (f) for PEM, (g) the stack lifetime of AEL and (h) PEM electrolysers

3. Results

Figures 3 show the development of the LCOH for four hydrogen production technologies without the carbon price for using SMR and AEL electrolyser process from 2020 to 2050, with confidence bounds showing its spread of values at each period. The black line shows the median values of the LCOH, and the green region represents the central 50% of scenarios (i.e., ranges 25-50% and 50-75%).

The LCOH for SMR production show a relatively small variation, which is expected since this is a mature technology. In 50% of scenarios, it falls between 1.51 - 2.25 AUD/kg H_2 in 2030 and between 1.57 - 2.44 AUD/kg H_2 in 2050, mainly driven by gas price uncertainty.

It is clear that the levelized cost of renewable hydrogen production varies a great deal due to the uncertainty in the projection of the system cost of electrolyser and the cost of power generation with solar PV. The LCOH of renewable hydrogen produced with alkaline electrolysers falls between 3.24 - 4.24 AUD/kg H_2 in 2030 and between 1.94 - 2.8 AUD/kg H_2 in 2050 for half the scenarios.

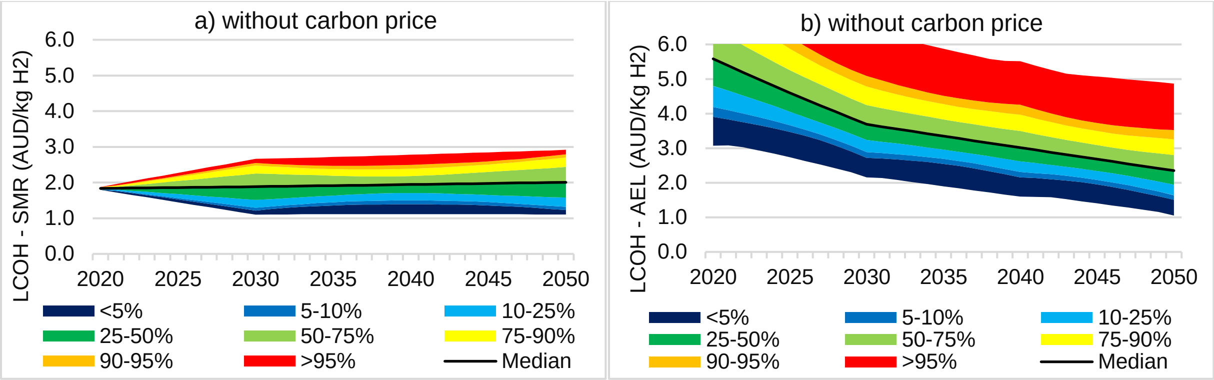

Figure 3: The confidence bounds for the LCOH for different technologies without and with carbon pricing

After estimating the LCOH for different technologies using the Monte-Carlo approach, the LCOH is used as an input in the dynamic simulation model to explore the impact of uncertainties in LCOH on the transition from fossil-fuel based to renewable hydrogen.

Figure 4 shows the number of simulations for which a transition to renewable hydrogen either does (green) or does not (grey) occur for a given year. These results clearly illustrate the importance of taking uncertainties into account when modeling the transition to renewable hydrogen. For the most optimistic combination of techno-economic factors chosen, the transition can occur as early as 2030. However, this is very unlikely, as only 0.068% of simulations predict this result. Indeed, Figure 4 shows that in only 35% of scenarios, a transition can occur before 2050 without a carbon price. Conversely, application of a carbon price rises the percentage of scenarios with transition to renewable hydrogen markedly to 35% in 2030 and over 98% in 2050.

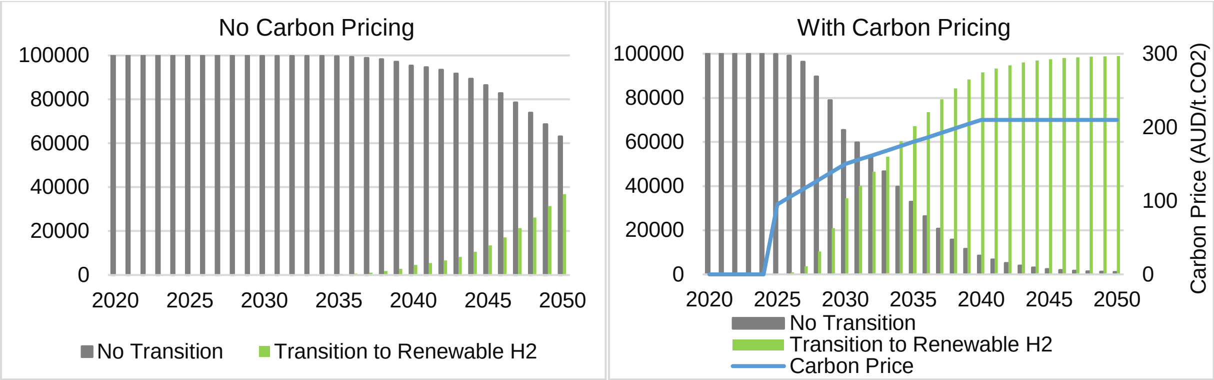

Figure 4: Accumulated number of scenarios without/with transition to renewable H_2

Figure 5 compares cumulative emissions without and with carbon pricing from 2020 to 2050, with confidence bounds showing the spread over time. Without a carbon price, cumulative emissions from the expansion of the hydrogen demand will exceed 650 Mt CO_2e in 2050 in 75% of scenarios, and in only 5% will they be less than 505 Mt CO_2e (left figures). To put this in perspective, Australia's annual emissions for the year 2018 were reported to be 537.4 Mt CO_2-e [32]. On the other hand, with a robust carbon price, cumulative emissions are reduced to 110 Mt CO2-e for the median scenario, and there is only a 5% chance that cumulative emissions exceed 365 Mt CO_2e in 2050, if the transition to renewable hydrogen is delayed.

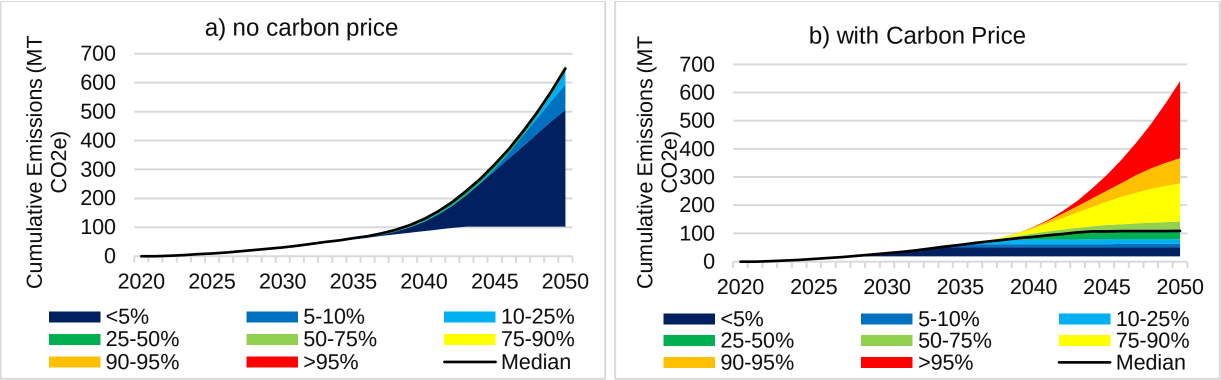

Figure 5: The confidence bounds for cumulative emissions from hydrogen production and feedstock supply without and with carbon price

Conclusions

Hydrogen is expected to play a key role in achieving decarbonization targets globally. However, even though there are no carbon emissions at point of hydrogen use, the production can contribute to significant carbon emissions. In this study, an integrated framework has been developed, linking techno-economic and Monte-Carlo based uncertainty analysis with quantitative hydrogen supply-demand modelling to examine the impact of uncertainties in projections of key parameters in hydrogen transition in Australia, and assess the associated GHG emissions from feedstock supply and the production process.

Uncertainty analysis also reveal that the hydrogen production in Australia is likely to be dominated by fossil fuel based SMR production in the absence of a carbon price. As a result, the cumulative emissions from hydrogen production can reach 650 MT CO_2-e by 2050, which is very significant considering Australia's annual emissions of 537 Mt CO_2-e in 2018. However, the application of a price on carbon emissions can expedite the transition to renewable hydrogen, and reduce cumulative emissions to 110 MT CO_2-e by 2050.

Acknowledgements

We are grateful for funding under the Australian National University Zero-Carbon Energy for the Asia-Pacific Grand Challenge project, and comments from colleagues.

References

[1] L. V. White *et al.*, "Towards emissions certification systems for international trade in hydrogen: the policy challenge of defining boundaries for emissions accounting," *Energy*, vol. 215, p. 119139, 2020, doi: 10.1016/j.energy.2020.119139.

[2] IEA, "Global average levelized cost of hydrogen production by energy source and technology, 2019 and 2050," Paris, France, 2020. [Online]. Available: https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050 .

[3] Hydrogen Council, "Path to Hydrogen Competitiveness A Cost Perspective," 2020. [Online]. Available: www.hydrogencouncil. com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.

[4] T. Longden, F. Jotzo, M. Prasad, and R. Andrews, "Green hydrogen production costs in Australia: implications of renewable energy and electrolyser costs," 2020, [Online]. Available: https://energy.anu.edu.au/files/2020 09 01 - ZCEAP - CCEP Working Paper - Green hydrogen production costs.pdf.

[5] IRENA, *Green hydrogen: A guide to policy making*. 2020.

[6] T. Longden, F. J. Beck, F. Jotzo, R. Andrews, and M. Prasad, "'Clean' hydrogen? An analysis of the emissions and costs of fossil fuel based versus renewable electricity based hydrogen," *Submitted*, 2021.

[7] J. Overbeek, "Cost-effective Hydrogen Production A comparison of uncertainties in the levelized cost of," Utrecht University, 2020.

[8] J. Yates *et al.*, "Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis," *Cell Reports Phys. Sci.*, p. 100209, 2020, doi: 10.1016/j.xcrp.2020.100209.

[9] M. R. Shaner, H. A. Atwater, N. S. Lewis, and E. W. McFarland, "A comparative technoeconomic analysis of renewable hydrogen production using solar energy," *Energy Environ. Sci.*, vol. 9, no. 7, pp. 2354–2371, 2016, doi: 10.1039/c5ee02573g.

[10] B. Lee, J. Heo, N. H. Choi, C. Moon, S. Moon, and H. Lim, "Economic evaluation with uncertainty analysis using a Monte-Carlo simulation method for hydrogen production from high pressure PEM water electrolysis in Korea," *Int. J. Hydrogen Energy*, vol. 42, no. 39, pp. 24612–24619, 2017, doi: 10.1016/j.ijhydene.2017.08.033.

[11] G. Glenk and S. Reichelstein, "Economics of converting renewable power to hydrogen," *Nat. Energy*, vol. 4, no. 3, pp. 216–222, 2019, doi: 10.1038/s41560-019-0326-1.

[12] M. Schwoon, "Learning by doing, learning spillovers and the diffusion of fuel cell vehicles," *Simul. Model. Pract. Theory*, vol. 16, no. 9, pp. 1463–1476, 2008, doi: https://doi.org/10.1016/j.simpat.2008.08.001.

[13] J. Struben and J. D. Sterman, "Transition Challenges for Alternative Fuel Vehicle and Transportation Systems," *Environ. Plan. B Plan. Des.*, vol. 35, no. 6, pp. 1070–1097, Jan. 2008, doi: 10.1068/b33022t.

[14] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, and E. I. Asgeirsson, "Comparative analysis of hydrogen, biofuels and electricity transitional pathways to sustainable transport in a renewable-based energy system," *Energy*, vol. 83, pp. 614–627, 2015, doi: https://doi.org/10.1016/j.energy.2015.02.071.

[15] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *Int. J. Hydrogen Energy*, vol. 42, no. 52, pp. 30470–30492, 2017, doi: https://doi.org/10.1016/j.ijhydene.2017.10.045.

[16] IEAGHG, "Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant With CCS," Cheltenham, 2017.

[17] Deloitte, "Australian and Global Hydrogen Demand Growth Scenario Analysis," 2019. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/au/Documents/ future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf .

[18] IRENA, "Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal," Abu Dhabi, 2020.

[19] IEA, "The Future of Hydrogen," Paris, 2019. [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen.

[20] J. Aldersey-Williams and T. Rubert, "Levelised cost of energy – A theoretical justification and critical assessment," *Energy Policy*, vol. 124, no. February 2018, pp. 169–179, 2019, doi: 10.1016/j.enpol.2018.10.004.

[21] AEMO, “2020 Integrated System Plan for the National Electricity Market,” 2020. [Online]. Available: https://aemo.com.au/-/media/files/major-publications/isp/2020/final-2020-integrated-system-plan.pdf?la=en .

[22] S. Bruce *et al.*, “National Hydrogen Roadmap,” 2018.

[23] ATO, “Exchange rate,” 2020. [Online]. Available: https://www.ato.gov.au/Tax-professionals/TP/Rates-for-financial-year-ending-30-June-2020/ .

[24] D. Feretic and Z. Tomsic, “Probabilistic analysis of electrical energy costs comparing: production costs for gas, coal and nuclear power plants,” *Energy Policy*, vol. 33, no. 1, pp. 5–13, 2005, doi: https://doi.org/10.1016/S0301-4215(03)00184-8.

[25] P. Graham, J. Hayward, J. Foster, and L. Havas, “GenCost 2020-21: Consultation draft,” 2020. [Online]. Available: https://www.csiro.au/~/media/News-releases/2020/renewables-cheapest/GenCost2020-21.pdf?la=en&hash=B2BC98D5AC4BED8BA6135BDF7E205CF49304870E.

[26] Core Energy, “Delivered Wholesale Gas Price Outlook 2020-2050 Residential & Commercial and Gas Generation Segments,” 2019. [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2019/core-energy-delivered-wholesale-gas-price-outlook-2020-2050_report.pdf?la=en&hash=4D53CA4DD239E0A075336D0B572462C7.

[27] BNEF, “Renewable Energy Auctions Database,” 2019.

[28] D. Peterson, J. Vickers, and D. DeSantis, “Hydrogen Production Cost From PEM Electrolysis,” 2020.

[29] B. Simonsen, “The pathway towards fossil parity for renewable hydrogen,” 2020. [Online]. Available: https://online.paretosec.com/static/files/PREC18/Nel Hydrogen.pdf.

[30] A. Blakers, B. Lu, and M. Stocks, “100% renewable electricity in Australia,” *Energy*, vol. 133, pp. 471–482, 2017, doi: https://doi.org/10.1016/j.energy.2017.05.168.

[31] IEA, “World Energy Model,” Paris, France, 2020. [Online]. Available: https://www.iea.org/reports/world-energy-model .

[32] Department of Environment and Energy, “Australia’s National Greenhouse Accounts Quarterly Update of Australia’s National Greenhouse Gas Inventory: September 2019,” 2020. [Online]. Available: https://www.industry.gov.au/sites/default/files/2020-02/nggi-quarterly-update-sep-2019.pdf .