Recognizing the role of uncertainties in the transition to renewable hydrogen

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Abstract

Achieving the goal of net zero emissions targeted by many governments and businesses around the world will require an economical zero-emissions fuel, such as hydrogen. Currently, 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 role of uncertainties in projections of techno-economic factors on the transition from hydrogen produced from fossil fuels to renewable hydrogen. 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. The results show that the uncertainty around the cost of electrolyser systems, the capacity factor and gas price are the most critical factors affecting the transition to renewable H_2. 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, resulting in cumulative emissions from hydrogen production of 650 MT CO_2-e by 2050. However, implementing a price on carbon emissions can significantly expedite the transition to renewable hydrogen and cut the cumulative emissions significantly.

Keywords:

Energy Systems Analysis; Transition Analysis; Uncertainty Analysis; System Dynamics; Monte-Carlo; Renewable Hydrogen.

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

1. Introduction

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].

Currently, hydrogen is almost entirely supplied from natural gas and coal which is responsible for 830 Mt CO_2-e per year [2]. Hydrogen can also be produced with no embedded emissions using electrolysis powered by renewable energy, but this is not yet directly cost competitive with hydrogen produced from fossil fuels.

Carbon capture and storage (CCS) technologies can be applied to fossil fuel based hydrogen production plants to capture the carbon emissions. While CCS is a relatively mature technology, the cost are uncertain and can be high, and the emission reduction potential varies widely depending on the technologies used and what is subsequently done with the captured carbon dioxide [3]. Of the four commercial scale hydrogen facilities in the world operating with CCS[4], three use the captured CO_2 for enhanced oil recovery which can result in significant re-emission of the CO_2 into the atmosphere [5]. In addition, the fugitive emissions associated with processing of fossil fuel feedstocks can be significant and cannot be captured by CCS applied at the hydrogen plant.

The high production cost of 'zero-emission' or 'renewable' hydrogen – in the range of 3.2-7.7 USD$/kg H_2 [6] – is hindering its adoption. However, continued declines in the cost of renewable electricity1 and the significant improvement in the capital cost of electrolysers (60% since 2010 [7]) are now paving the way for lowering the cost of renewable hydrogen

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[1] In 2018, solar energy was contracted at a global average price of 56 USD/MWh, compared with 250 USD/MWh in 2018. Onshore wind prices also fell during that period, from 75 USD/MWh in 2010 to 48 USD/MWh in 2018 [51]. New record-low prices were marked in 2019 and 2020 around the world: solar PV was contracted at USD 13.12/MWh in Portugal [52] and USD 13.5/MWh in the United Arab Emirates [53]; onshore wind was contracted at USD 21.3/MWh in Saudi Arabia [54] while in Brazil, prices ranged between USD 20.5 USD/MWh and 21.5 USD/MWh [44].

[8]. In addition, during the past two years interest in hydrogen has been rising around the world. Many countries (including Australia, South Korea, Japan, France, Germany, Italy, the Netherlands, Norway, Portugal and Spain, along with the European Union) have announced, drafted or published national hydrogen strategies that incorporated support measures for clean hydrogen[9]. 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 [3].

Several international reports have projected a large global demand for hydrogen in the next three decades [10], [11]. Transitioning early from high-emissions, fossil-fuel based hydrogen to low and zero emissions hydrogen is critical to avoiding large emissions from hydrogen production, which could undermine global decarbonization efforts. However, there are considerable uncertainties in the projections of techno-economic factors affecting the timing of the transition [12]–[15].

It has been well understood that studying the possible transition pathways for a hydrogen energy system is complex [16]. The long-term nature of technological changes is associated with considerable uncertainties, different viewpoints, and conflicting priorities. In addition, Fuss and Szolgayová [17], found that the uncertainty associated with the technological progress of renewable energy technologies leads to a postponement of investment, which can slow the expected reduction in the cost of those technologies. Both modelling approaches and narrative storyline scenarios have been widely applied to examine the possible future of hydrogen energy.

More than half of the merchant hydrogen currently produced is from steam methane reforming (SMR) using natural gas as a feedstock. This is a mature industrial process with well-established costs and there are limited opportunities for technological improvements or CAPEX cost reductions. The largest source of uncertainty in the future cost of SMR produced hydrogen comes from fluctuations in the price of natural gas feedstock, which dominates the OPEX [18].

In contrast, there are significant expectations for cost reductions in both the CAPEX and OPEX of renewable hydrogen production. Renewable electricity costs have fallen rapidly, demonstrating price reductions of around 80% for solar and roughly 40% for wind energy over the last decade, and this is likely to continue [19]. While alkaline electrolysers are a well-established technology, they have had limited implementation in niche applications, and are likely to reduce in cost as production is ramped up and economies of scale come into effect [2]. In addition, proton exchange membrane (PEM) electrolysers are being developed based on a solid polymer electrolyte, which could overcome the drawbacks of alkaline electrolysers, such as slow response [20]. Further advances in electrolyser technologies such as improved efficiency and lifetime of the stack will also reduce the levelized cost of renewable hydrogen [21].

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 [8], [14], [15], [22]–[24].

However, few studies captured the impacts of uncertainties in techno-economic factors. Carlson et al. [25] applied uncertainty analysis using a Monte-Carlo simulation method to assess the PEM fuel cell stack and system cost with emphasis on power density and cell design parameters. Thus, their analysis does not capture the uncertainties around the OPEX (fixed and electricity cost), and the levelized cost of hydrogen production. Later, Lee, et al., [23] focused on hydrogen production from high pressure PEM water electrolysis targeting a hydrogen production capacity of 30 Nm3/hour in Korea. They developed the cumulative probability curve for a unit H_2 production cost, considering the range of ±10 to ±50% for key economic parameters such as H_2 production equipment, construction, electricity, and labor. The selected range is rather arbitrary, while some important factors such as the stack lifetime have not been studied. In addition, a triangular distribution was selected for the Monte-Carlo simulation which could potentially weaken the comprehensiveness of combinations with extreme values are less likely to be explored.

Overbeek [14] compared the levelized cost of hydrogen (LCOH) production of several hydrogen production methods with the focus on the impacts of uncertainties in techno-economic data. While the selected parameters and ranges are based on recent studies, the analysis didn’t investigate how the uncertainty in the techno-economic parameters would affect the shift between hydrogen production technologies and its effect on emissions trajectories.

Yates, et al., [15], applied the Monte Carlo approach to determine the LCOH based on a wide range of input assumptions to identify key cost drivers, necessary for competitive stand-alone dedicated PV powered hydrogen electrolysis. The scope of the analysis was rather limited, since they did not assess the impacts of uncertainty associated with the cost of renewable hydrogen production with fossil fuel-based technologies and therefore the significance of uncertainty on the transition to renewable hydrogen was not studied.

Several studies have focused on the transition from fossil fuels to hydrogen produced from different sources using the “Bottom-up” energy system models (e.g., MARKAL and MESSAGE) to evaluate the desirability of hydrogen within the context of overall decarbonization. They analyze trade-offs with the wider energy system, and so provide greater techno-economic consistency than sectoral approaches, and many have simplistic representations of technology dynamics, while overlooking the effect of uncertainties associated with the technological development [26], [27].

The demand for hydrogen in different applications depends on hydrogen production cost and the cost of alternative fuels. In addition, hydrogen demand needs to be developed to help drive down costs, and a wide range of delivery infrastructure needs to be built [28]. This is complex and has not yet been addressed. In the absence of a comprehensive hydrogen demand projection, several studies used scenario analysis and expert elicitation to estimate the potential for hydrogen markets. Currently, hydrogen accounts for 4% of global final energy consumption, which can increase to 6% in 2050 according to the International Renewable Energy Agency (IRENA [29]). Bloomberg New Energy Finance estimates a theoretical global maximum demand for hydrogen in 2050 of 1,370 million metric tons per year (Mtpa) and a potential demand of 696 Mtpa under a strong policy scenario [28]. The Shell Sky scenario estimates that hydrogen demand does not start growing dramatically until 2040 but reaches 800 Mtpa in 2070 [30]. Ruth et al., [11] assessed the techno-economic potential of the H_2@Scale concept, which is a U.S. Department of Energy initiative led by the Office of Energy Efficiency and Renewable Energy’s Hydrogen and Fuel Technologies Office. They estimated a serviceable consumption potential of 106 Mtpa, approximately 11 times larger than the 2015 U.S. merchant hydrogen production of 10 Mtpa of hydrogen. While these estimates vary significantly and do not include an analysis of the dependence of demand on price, they are useful in assessing the possible transition pathways and providing insights on the development needed on the hydrogen production side.

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 [31]–[33]. However, they overlooked the impact of uncertainties on the transition to hydrogen economy.

Reviewing the literature, there is a need for a better understanding of the impact of uncertainty in projections of techno-economic factors on the transition of hydrogen production from fossil fuel based to renewable hydrogen. Uncertainties are important as they can lead to different timelines for a transition, which in turn results in significantly different projected GHG emissions from hydrogen production over the next few decades. As the global economy grapples with the need to decarbonize rapidly to avoid catastrophic climate change, it is critical to understand the emissions implications of an expansion of fossil fuel-based hydrogen industries to meet the projected demand growth.

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.

Australia is selected as a case study, as it has the potential to become a major hydrogen producer, given the abundance of natural gas reserves, and considerable potential in renewable electricity generation [18]. In November 2019, the Australian government released a National Hydrogen Strategy, which aims to position Australia's hydrogen industry as a major global player by 2030 [34]. We do not consider 'low emission' hydrogen production options utilising CCS because of questions around the potential for CCS to reduce overall emissions, as well as the difficulty in accurately estimating the costs of different CCS technologies.

While there is no consensus on the demand for hydrogen in the next few decades, we focus on the uncertainties on the supply side of hydrogen supply chain and used the demand curve developed by Deloitte, 2019 [10] for hydrogen production by Australia. We use data from major energy organizations (for example, International Energy Agency (IEA), Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), International Renewable Energy Agency (IRENA), and the Australian Energy Market Operator (AEMO) to define realistic ranges for techno-economic factors affecting the production of hydrogen from different technologies.

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. Currently, alkaline electrolysis dominates the market however PEM may become 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 [21].

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.

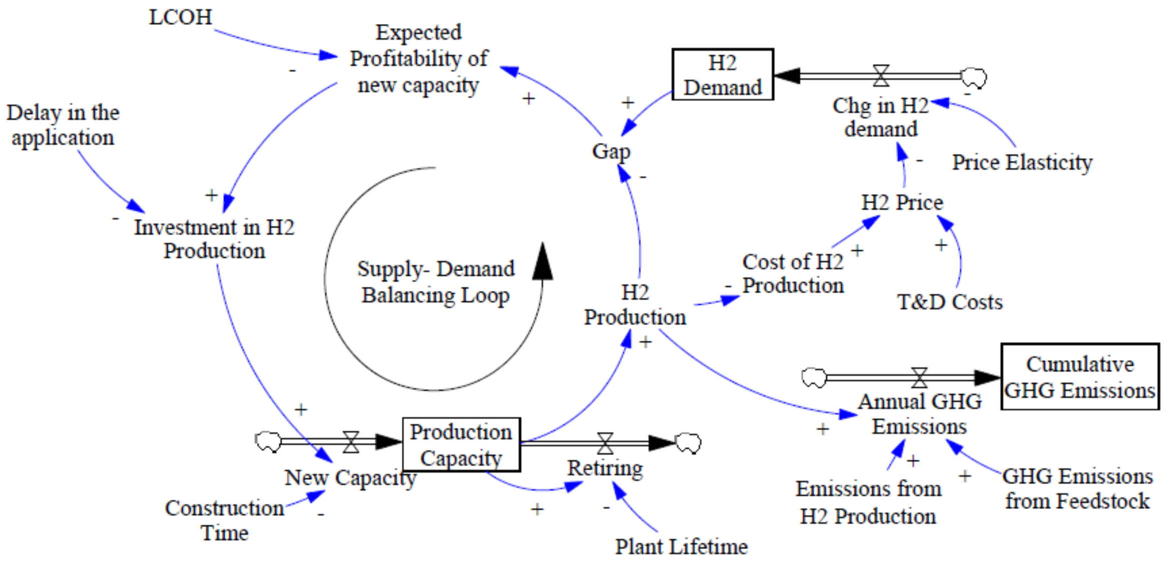

Figure 1: Dynamic simulation model of hydrogen production

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, [35].

A recent report by Deloitte, commissioned by the Australian Hydrogen Strategy Task force was used to define the annual hydrogen demand. Deloitte provided an analysis of hydrogen demand in Australia and globally and Australia's position in the hydrogen export market against potential competitors [10]. Four scenarios were developed to explore a wide range of demand by 2050, with over 304 Mtpa of hydrogen demand globally under the 'energy of the future' scenario to just over 90 Mtpa in the 'electric breakthrough' scenario. The annual hydrogen demand used in this work was consistent with the 'targeted deployment' scenario, under which countries are projected to adopt a targeted approach to maximize the economic value and benefits of hydrogen deployment. Under this scenario, the global demand could reach to 172.5 Mtpa, while total hydrogen production by Australia is projected to be 8 Mtpa H_2 by 2050 [10]. A price elasticity of 0.58 is used to adjust the demand based on the changes in H_2 price following the Deloitte [10].

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 Ct represents the capital investment in year t, Ot the annual fixed operation expenditure (OPEX), Ft the annual feedstock cost (Natural gas or electricity), Ht 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 (roughly 78% of the stack capital cost for AEL and 59% for PEM electrolyser, according to [36]). For renewable hydrogen there are no ongoing fuel costs, and the cost of electricity depends on the capital cost of the renewable energy generation plant, and the associated capacity factor (the percentage of actual electrical output out of the total possible output of a generation asset), which will be discussed in more detail in section 2.3. The factors that affect the LCOH for SMR based hydrogen production are the capital investment 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 [2], 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 [37]. We used a representative real discount rate of 5.9% based on [38] and the plant lifetime of 40 years for all technologies [18].

From the discussion above, seven key factors have been identified that significantly impact the cost of LCOH and hence the transition to renewable hydrogen production, 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 [2], [6], and the report prepared by CSIRO [18]. The significant role of the electricity source in determining the LCOH of renewable hydrogen production using electrolysis is then considered. Finally, the ranges of uncertainty for the seven key factors have been defined in section 2.4., 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 or use 30-40 years ahead 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 [2]. Parameters are taken from projections are obtained from [2], [6], [18], as indicated in the table. The exchange rate of 1 USD = 1.45 AUD was used according to the Australian Tax office [39].

Table 1: Techno-economic assumptions for hydrogen production technologies from [2], [6], [18]

	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, [6]

[2] IEA, [2]

[3] Bruce, et al., [18]

2.3. Source and cost of electricity

A key factor in the cost-competitiveness of hydrogen production from electrolyser is the cost of electricity. Various sources can be considered to supply the required low emissions electricity, namely: renewable electricity supplied from a 100% renewable grid (GC_Renewable); on-site, stand-alone solar (Solar); on-site, stand-alone wind (Wind); and co-located solar/wind (Solar/Wind). Figure 2 compares the current LCOE (levelized costs of energy) and capacity factor of five electricity sources and the development until 2050. Renewable electricity options are compared to direct grid connection (GC).

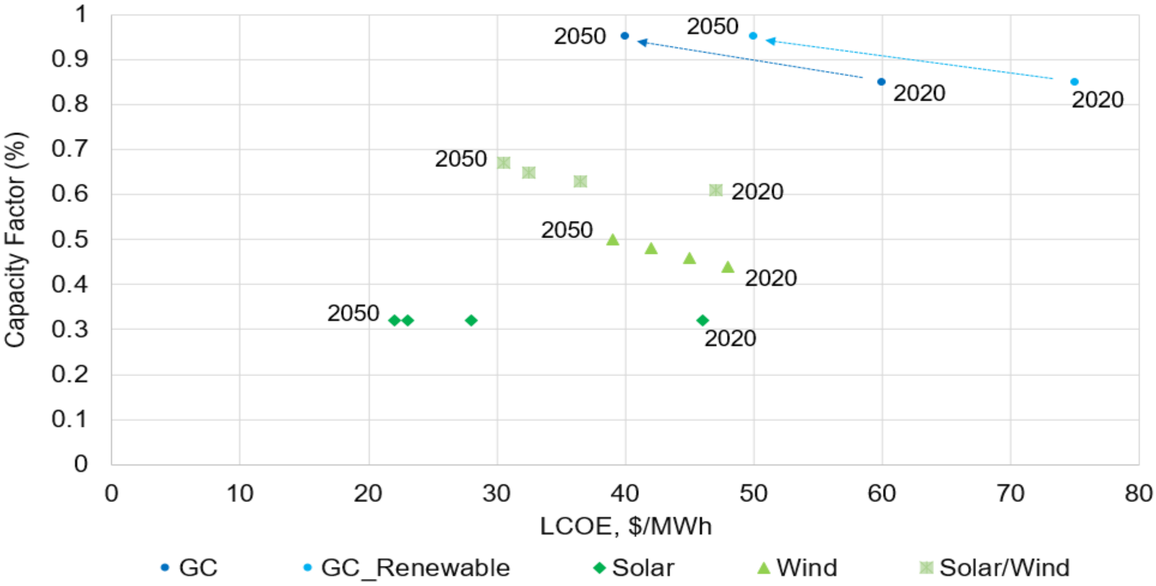

Figure 2: The levelized cost of energy (LCOE) and capacity factor for different electricity sources [18], [40], [41]

In this study, we did not consider oversizing the stand-alone renewable energy capacity to increase the capacity factor of the electrolyser, therefore the ratio between the capacity of the on-site renewable power generation and the electrolyser capacity was 1.

We calculate the LCOH using the reference parameters provided in Table 1, by employing the estimated the LCOE for different electricity source, based on the information obtained from [41]. Other costs are taken from the AEL reference case in Table 1. Figure 3 illustrates the considerable improvement in the LCOH for all options, as a result of falling renewable electricity prices. On-site solar PV offers the lowest LCOH in 2050, and the most significant potential to reduce the production cost of renewable hydrogen. For this reason, we choose solar PV as the most promising source of electricity for renewable hydrogen production for both the reference case and the uncertainty analysis.

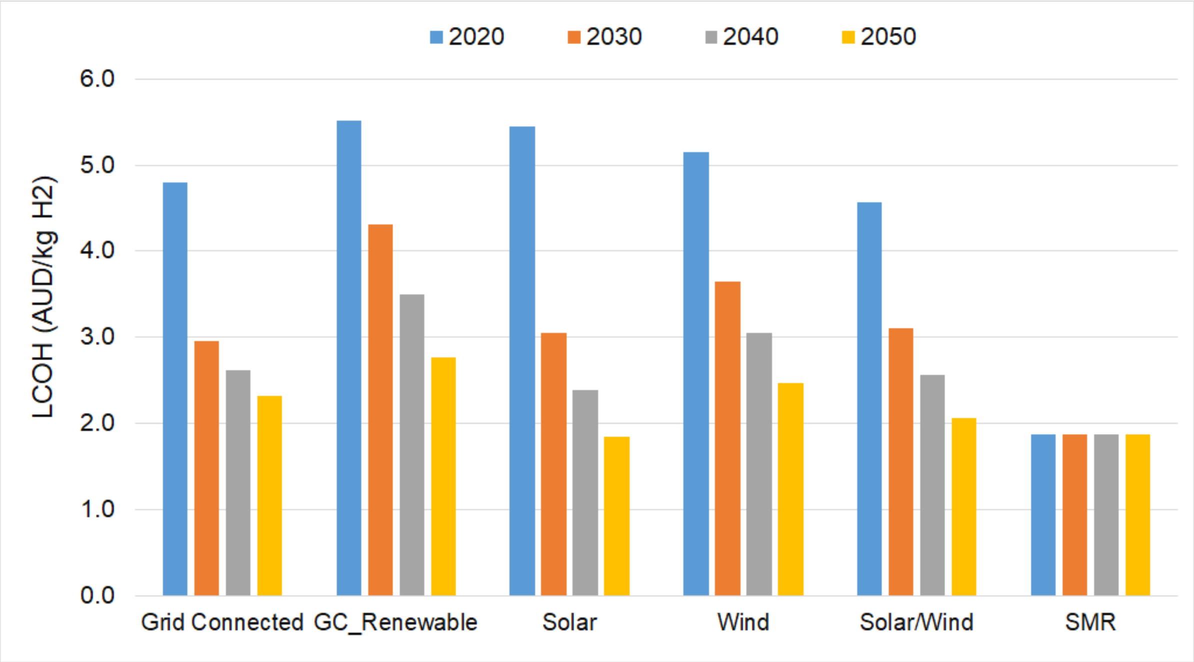

Figure 3: LCOH for hydrogen production from AEL electrolyser with different sources of electricity compared with SMR

2.4. Uncertainty range of projections for key inputs

The uncertainty analysis is implemented following the three steps proposed by Feretic and Tomsic, [42]:

1. Determine the range of uncertainty for key parameters that have the greatest impact on the levelized cost of hydrogen production
2. Develop a probability distribution for each key input variable
3. Generate a probability distribution using Monte Carlo analysis for each key performance and cost parameter.

Figure 4 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 [2], [6], [18], [36], [41], [43]–[46].

Figures 4a and 4b show the ranges and reference values for the capital cost of AEL and PEM electrolysers, while Figure 4c shows the ranges of expected reduction in the capital cost of solar PV, defined based on three projections in [41] with the assumptions for the reference case based on the central scenario in [41]. From the same source, the capacity factor of the one-axis tracked Solar PV ranges between 0.19 and 0.32 [41] in Australia. The Australian Energy Market Operator has engaged Core Energy & Resources to provide annual projections of wholesale delivered gas prices from 2020 to 2050 [43]. Figure 4d shows the ranges in the projections of gas price for gas powered generators (GPG) and the selected values for the reference case, which are defined based on [18]. The representative real discount rate of 7% was selected based on Bruce, et al., 2018 [18], while the range of 5%-7% was selected based on [18], [38], [40].

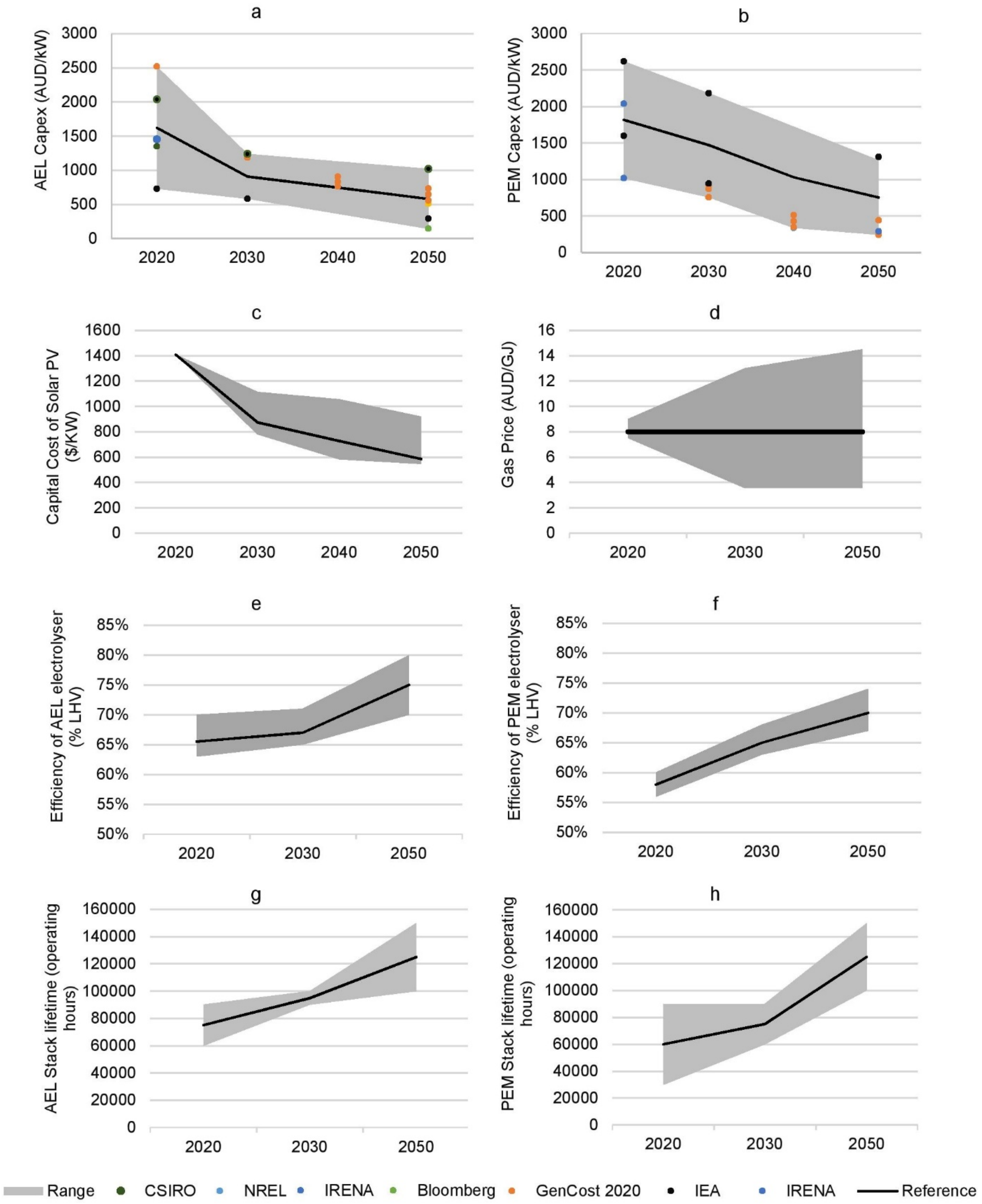

Figure 4: Range of projections for five factors; (a) the capital cost of AEL and (b) PEM electrolysers, (c) the capital cost of Solar PV, (d) the price of natural gas, (e) the electrical efficiency for AEL, and (f) for PEM, (g) the stack lifetime of AEL and (h) PEM electrolysers

Since there is no consensus on the most probable projections of techno-economic factors, a uniform distribution function was applied for key inputs (capital cost and capacity factor of electrolysis, price of feedstocks, discount rate and lifetime of electrolysis stacks) 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 (illustrated in Figure 4). A key methodological challenge for conducting a Monte Carlo analysis is to find the number of simulation runs (hereafter referred to as scenarios) that can sufficiently explore the search space. To address this concern, we investigated the findings with different numbers of scenarios (from 10,000, to 200,000). Figure S1 in the supplementary shows the percentage of scenarios that results in transition to renewable hydrogen for different numbers of total simulation runs. It can be observed that increasing the number of scenarios above 100k, does not significantly change the results. Thus, the analysis presented below is based on 100k scenarios, as it allows for a good representation of possible outcomes. The outputs of the simulations are represented as sensitivity graphs, where confidence bounds show the spread of values at each period.

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/tCO_2 in 2025 and US\$125–US\$140/tCO_2 in 2040 [47]. 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.

3. Results and discussion

A Monte Carlo analysis was performed by varying the 7 key parameters (the capacity factor and capital cost of solar PV, the capital cost of the electrolyser, the stack lifetime, the efficiency, the price of natural gas and discount rate) randomly within the ranges defined in section 2.4, and calculating the resulting LCOH. Figures 5 show the development of the LCOH for four hydrogen production technologies without the carbon price (left panel) and with carbon price applied (right panel) 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. When a carbon price is implemented, from 2025 onwards, the range for the LCOH for SMR changes to 3.00 and 3.74 AUD/kg H_2 in 2030 and between 3.65 and 4.52 AUD/kg H_2 in 2050.

It is clear that the levelized cost of renewable hydrogen production varies a great deal due to the uncertainty in the projection of key inputs. The LCOH for PEM and AEL follow similar patterns, with a larger uncertainty range driven mainly by large uncertainty ranges for 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. By comparison, the LCOH for PEM has a wider variation and half the scenarios fall between 4.25 - 6.0 AUD/kg H_2 in 2030 and between 2.33 - 3.38 AUD/kg H_2 in 2050. The main difference between the ranges for AEL and PEM is due to the larger uncertainty in the projection of PEM system costs compared to alkaline technologies (Figure 5b). Since the electricity used in the electrolyser is provided by on-site solar PV, the carbon price does not affect the LCOH for AEL and PEM. It is worth noting that both the top 5% and bottom 5% have a wide variation, as they show extreme cases with optimistic and pessimistic projections for the techno-economic factors affecting the production of renewable hydrogen.

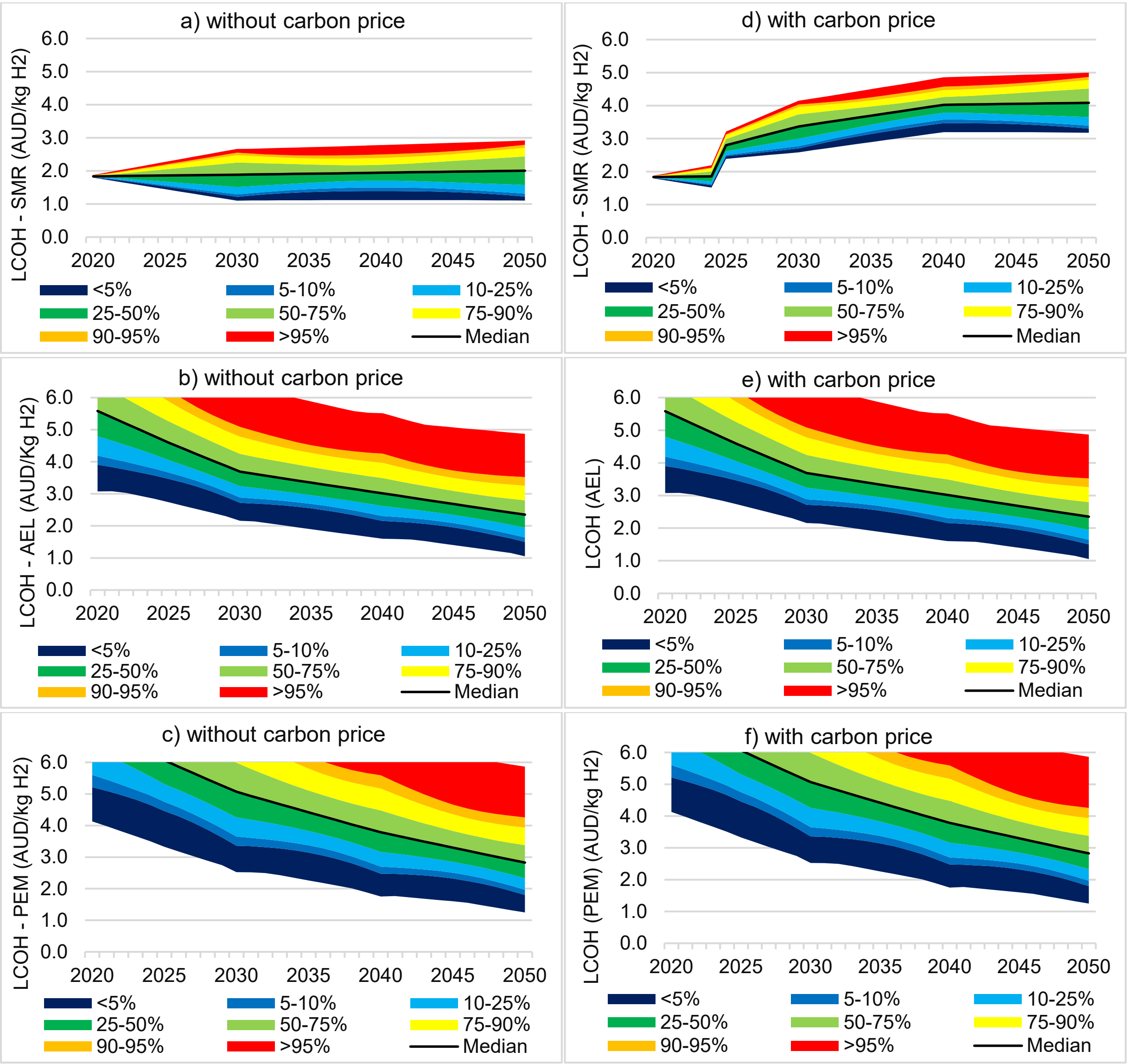

Figure 5: The confidence bounds for the LCOH for different technologies without and with carbon pricing

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. We define the transition to renewable hydrogen as the point at which renewable hydrogen becomes cost-competitive with the SMR hydrogen production process and thus, the investment in renewable hydrogen begins.

Figure 6 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 6 shows that in only 35% of scenarios, a transition can occur before 2050 without a carbon price. Conversely, application of a carbon price increases the percentage of scenarios with transition to renewable hydrogen markedly to 35% in 2030 and over 98% in 2050.

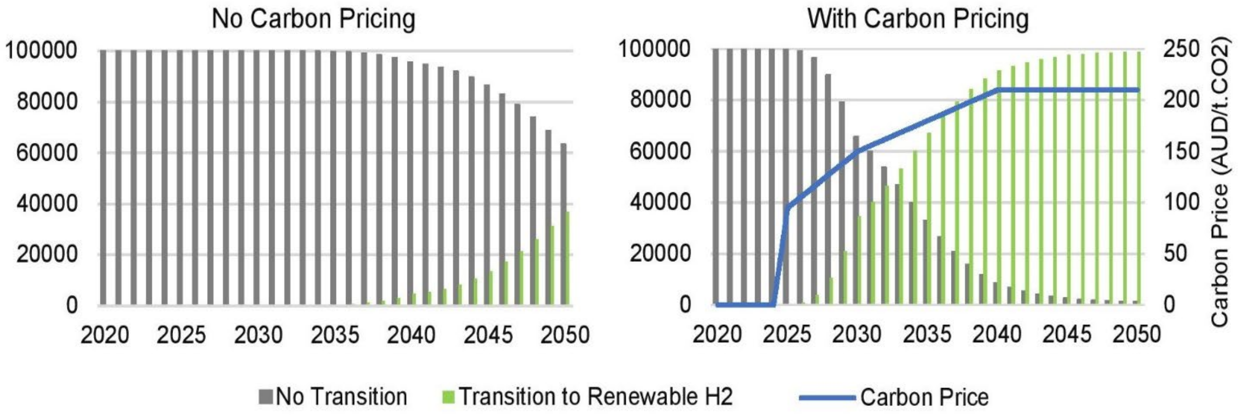

Figure 6: Accumulated number of scenarios without/with transition to renewable H_2

Figure 7 displays the combinations of factors that result in the transition to renewable hydrogen (AEL-based production) occurring in a specific year (2030 and 2040) without and with a carbon price. Each figure is normalized based on the values in the reference case in that year, while the dashed line shows the relative value of parameters most supportive of a fast transition to renewable hydrogen.

Figure 7a shows the combinations of inputs in the 68 scenarios (out of 100000 scenarios) that resulted in a transition to renewable H_2 in the year 2030. It is clear that the capacity factor, system cost of electrolyser, and the gas price all need to be significantly different from the reference values in 2030 to achieve these pathways, while the remaining 4 factors are less critical. The capacity factor should be at least 30% (8% higher than the reference case in 2030), the system cost of AEL electrolyser should be less than 830 AUD/KW (9% cheaper than the reference case in 2030), while the gas price should be higher than 11 AUD/GJ (39% more expensive than the reference value in 2030). Figure S2 in the supplementary section shows the cumulative probability distribution of the LCOH for the three technologies in 2030 when the transition to renewable hydrogen happens without the carbon price. Figure S3 also illustrates the correlation between the capital cost of AEL electrolyser and the discount rate in scenarios which allow a transition in 2030. Within the uncertainty ranges considered, there was no simulation run showing the transition to renewable hydrogen (PEM based) before 2030.

Figure 7b shows the combinations of over 250 scenarios that induce the transition in the year 2040[2]. In this case, there are numerous pathways to enable the transition, allowing most of the factors to take a wide range of values, with only the gas price above a certain threshold of 7 AUD/GJ. In order to achieve these transition pathways, the median values for the capital cost of solar PV, the capacity factor, and the system cost of AEL electrolyser are 720 AUD/KW, 30% and 520 AUD/KW. The spread of values for the efficiency, the stack lifetime, and the discount rate is uniform and covers the low-high range.

Figures 7c and 7d show the combinations of over 250 scenarios that lead to a transition only in the years 2030 and 2040 with carbon pricing. Compared to Figure 7a and 7b, implementing the carbon price will facilitate the transition to renewable hydrogen with many more combinations. In particular, without a carbon price, the high gas price has been identified as a key factor that enables the transition (Figures 7a and 7b), however when considering the price on carbon, the high gas price is no longer a critical factor (Figures 7c and 7d) because a high gas price has often enabled an earlier transition. Besides, a wide range of capacity factors, and system cost of electrolysers can allow the transition to renewable hydrogen in 2030 (Figure 7c), in contrast to the stringent requirements for transition in Figure 7a. As expected for the transition in 2040, unfavorable cases, such as more expensive electrolyser, lower capacity factor and cheaper gas price can still catalyze the transition provided other inputs are favorable.

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[2] We only include the transitions runs happen in 2040, thus the transitions that occurred before 2040 e.g., 2039 are excluded.

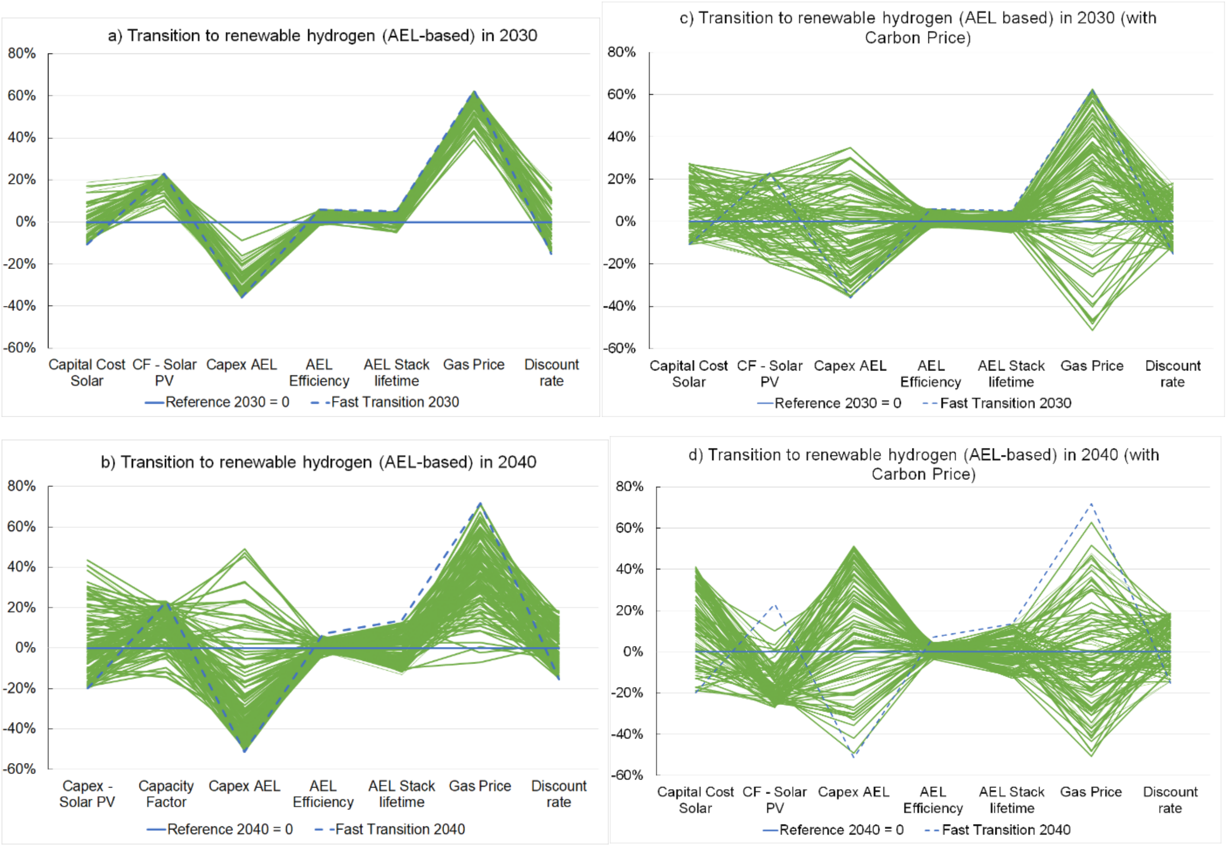

Figure 7: Combinations of seven factors that results in transition to AEL-based hydrogen production in a) 2030, b) 2040, and c) in 2030 with carbon price and d) in 2040 with carbon price

The implications of uncertainty on hydrogen production and associated emissions are assessed using the dynamic simulation model, without and with carbon price in Figures 8 and 9, respectively. Figure 8 demonstrates the growth in the hydrogen production by each technology assessed, from 2020 to 2050, with confidence bounds showing the spread at each period in time. In the absence of a carbon price hydrogen production will continue to be dominated by SMR in 2050 in 75% of scenarios, while in only 25% of scenarios renewable hydrogen production will exceed 1Mt. Critically, only around 5% of scenarios predict that hydrogen production will provide any of the hydrogen demand before 2040, which can still significantly reduce the hydrogen production from natural gas based SMR to below 4 Mt in 2050.

In the situation that carbon price is implemented, the volume of renewable H_2 is significantly increased. In the median case, renewable hydrogen will dominate production by 2040, exceeding 1Mt, and continues to grow rapidly to meet the increased demand, reaching a maximum of 7.9 Mt in 2050. Only in 10% of scenarios, with very low gas prices, does SMR contribute more than 1 Mt to hydrogen production in 2050 (Figure 8).

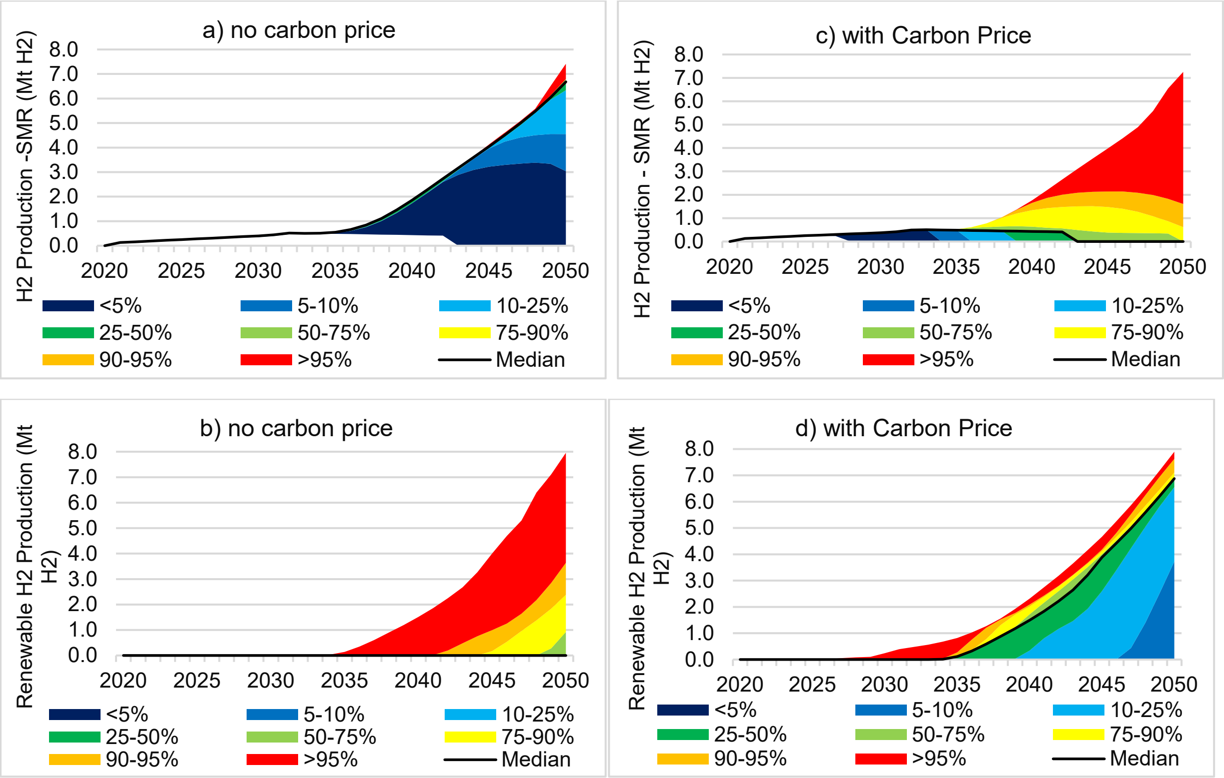

Figure 8: The confidence bounds for the hydrogen production from different technologies without and with carbon pricing

Figure 9 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 [48].

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 S4 illustrates the improvement in the average emissions intensity of Australian hydrogen production without and with carbon pricing until 2050. Without a carbon price, the median emission intensity of Australian hydrogen will be 12.9 CO_2/kg H_2 from 2020 to 2050, with only in 5% chance of it reducing below 5.7 kg CO_2/kg H_2 by 2050. In contrast, the median emissions intensity of Australian hydrogen rapidly declines from 12.9 CO_2/kg H_2 in 2033 to zero by 2043.

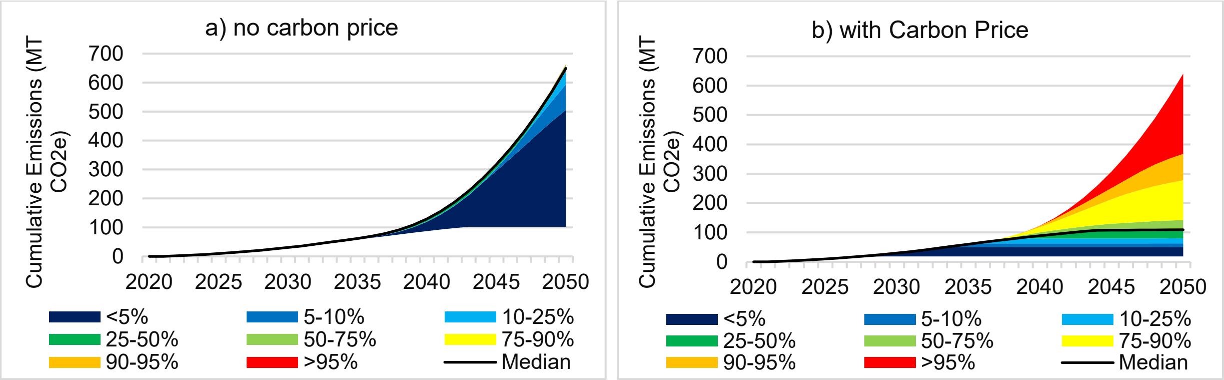

Figure 9: The confidence bounds for cumulative emissions from hydrogen production and feedstock supply without and with carbon price

Discussion

The analysis above highlights the importance of uncertainty analysis when exploring technology development pathways, and how the transition can be affected considerably by the uncertainties associated with the projections for techno-economic factors.

The results of the reference LCOH calculation in Figure 5 (black line) are consistent with recent reporting by the IEA [6]. They estimated a global average LCOH for SMR based hydrogen production in 2019 (USD$ 0.7-1.6 (AUS$ 1.0-2.3) per kg H_2), and a significant reduction in the production cost of renewable hydrogen from USD$ 3.2-7.7 USD (AUS$ 4.6-11.2) per kg H_2 in 2019 to USD$ 1.3-3.3 (AUS$ 1.9-4.8) per kg H_2 in 2050. Our LCOH for the reference case falls within the IEA range, while the uncertainty analysis presented in fig 5 shows that the LCOH can become considerably cheaper, than the global average (more than 40%), due to the potential for lower cost of solar PV in Australia.

The results of the uncertainty analysis also show that the LCOH of renewable hydrogen can reduce to less than $3/kg H_2 before 2030, which is consistent with the findings of Longden, et al., 2020. Moreover, in 5% of scenarios the LCOH of renewable hydrogen can reach AUD$2/kg before 2040, which was the target price designated as a stretch goal for Australian hydrogen in the recently announced Technology Investment Roadmap (2020) [49].

The thresholds needed to achieve the $2/kg H_2 target, are as follows: the CAPEX of solar PV should be below 800 AUD/kW (7% lower than the reference in 2030), the capacity factor should be at least 30% (17% higher than the reference case in 2030), the system cost of AEL electrolyser should be less than 570 AUD/KW (37% cheaper than the reference case in 2030), while the electrical efficiency and stack lifetime should be higher than the reference case in 2030. It is clear that the most critical factor is the system cost of AEL electrolysers which should become cheaper than the most optimistic projections of IEA for 2030.

We also found that the capacity factor, system cost of electrolyser and the prices of energy (the electricity and natural gas) are the most important factors, which is consistent with the conclusion of a recent work by Overbeek [14].

A key finding of this analysis is that hydrogen production in Australia is likely to be dominated by fossil fuel based SMR production in the absence of a carbon price. We calculate that meeting the demand for hydrogen projected by Deloitte in the ‘targeted deployment’ scenario will result in significant cumulative emissions (>650 MT CO2e) over the next 30 years, exceeding the total annual emissions reported by Australia in 2018 (Figure 9). Thus, a rapid transition to renewable hydrogen is critical to meet emissions reductions goals.

The analysis identifies the key factors that can advance the transition to renewable hydrogen to 2030: the improvement of the capacity factor to 30%, the reduction in the system cost of AEL electrolysers to below 830 AUD/kW, and a high gas price over 11 AUD/GJ. While optimistic, these thresholds are feasible and achievable. Optimal site selection for a Solar PV plant will enable high capacity factors for solar PV and electrolyser systems and the identified threshold for the system cost of AEL electrolysers is well within the uncertainty range projected by IEA (580-1250 AUD/kW) [2].

The reduction in the system cost of AEL electrolysers can be accomplished through many measures such as increasing the scale of the electrolyser manufacturing plants, as well as aggressive investment in R&D. Coordinated R&D activities can also enable improvement in the electrical efficiency and stack lifetime of electrolysers. The recent trend of rapid reduction in the LCOE of solar PV and onshore wind suggests that similar pattern can be envisioned for the system cost of electrolysers.

While several previous studies have also recognized the importance of the capacity factor and the system cost of electrolyser, few have explored the role of the gas price on the cost competitiveness of renewable hydrogen with fossil-based hydrogen production. The results of uncertainty analysis confirm that the impact of the other four techno-economic factors examined is less critical, mainly because the range of the uncertainty is rather small, particularly in the case of the capital cost of solar PV, and the efficiency of electrolysers.

We show that without additional policy intervention, there are few scenarios that show the increased demand for hydrogen will be met with renewable technologies within the next 30 years, resulting in an addition 650 MT CO_2-e of cumulative emissions by 2050, which larger than Australia's typical annual emissions (537 Mt CO_2-e in 2018 [48]). However, the application of a price on carbon emissions at a level in line with IEA projections [47] can significantly increase the probability of an early transition, and reduce cumulative emissions in 2050 to 110 MT CO_2-e. In order to achieve climate targets, policy makers can also design supportive policies towards renewable hydrogen production (e.g., financing green investment). We will explore the impact of other policies (such as investment in R&D and fiscal incentives) on reducing the emissions in subsequent work.

In this work, we have not considered CCS technologies for reducing emissions associated with SMR hydrogen production due to the complexity in defining realistic and costs and emissions reduction potential. Capture rates depend on the technology used and costs can vary with technology, and depend on the plant location for transport and storage costs [3][50]. A complementary analysis will be conducted in the future to assess the significance of the uncertainties in cost and emissions intensity and how they could affect the transition to renewable hydrogen.

4. 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.

From the seven techno-economic factors that are considered to be important for the transition to renewable hydrogen, this study identifies the most critical: the capacity factor, the system cost of electrolyser and the prices of feedstocks (the electricity and natural gas). In addition, we identify the thresholds needed for the transition to renewable hydrogen in 2030, in the absence of a carbon price.

While these thresholds are aligned with the most optimistic predictions for electrolyser and solar energy costs and capacity factors, they could be reached with economies of scale requiring aggressive expansion of the capacity of installed electrolysers around the world, and by targeting locations in Australia with the potential to support very low-cost, high-capacity factor solar power. However, our analysis demonstrates that adoption of the carbon price would remove these stringent requirements and vastly increase the pathways for a transition to renewable hydrogen.

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Supplementary materials

Figure S1 shows the percentage of simulation runs that results in transition to renewable hydrogen with different simulation runs. It can be observed that with increasing the number of simulations runs to 100k, the variation in the percentage of simulation runs that result in the transition to renewable H_2 decreases significantly. Besides, there is no significant change with an increase to 200k simulation runs, thus in this analysis results for a case with 100k simulation runs are presented.

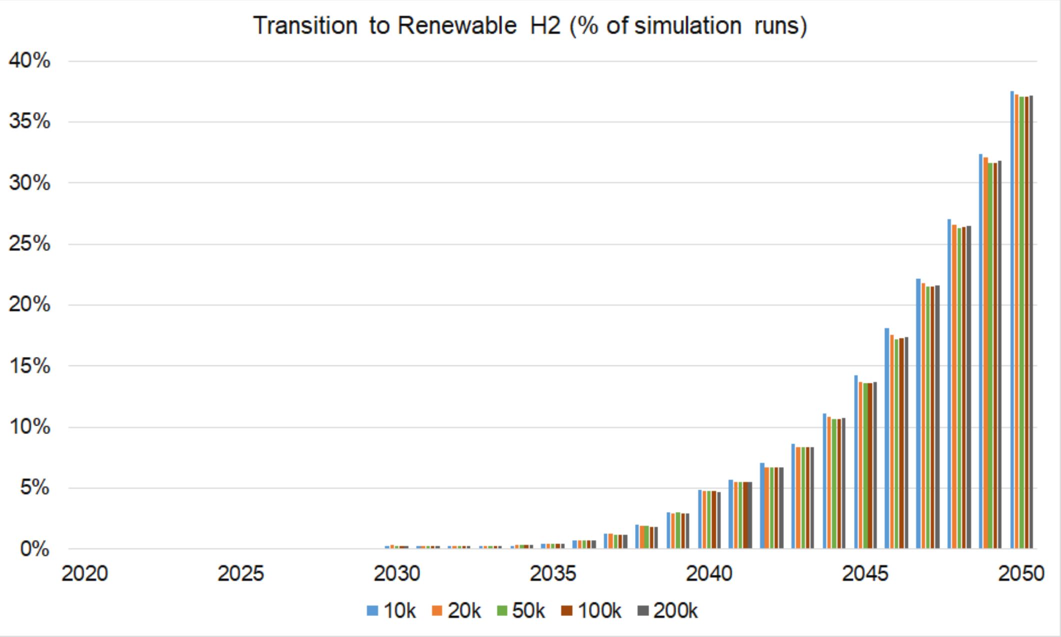

Figure S1: Percentage of simulation runs with transition to renewable H_2

Figure S2 shows the cumulative probability distribution of LCOH of three technologies in 2030 when the transition to renewable hydrogen could happen without the carbon price.

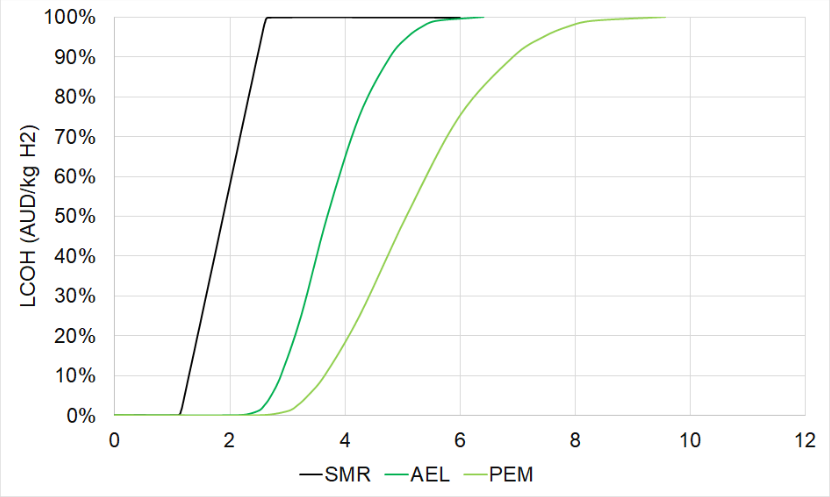

Figure S2: The cumulative probability distribution of LCOH of three technologies in 2030

Figure S3 shows the correlation of the system cost of electrolyser with discount rate in transition runs in 2030. As expected, the majority of transition happens when the discount rate is lower (< 6%). In the few cases with higher discount rate, the system cost of electrolyser should be less than 645 AUD/KW, with the exception of two points A1 and A2, identified in the Figure S2. While both points, corresponds with relatively high capital cost (660 AUD/KW and 710 AUD/KW) and high discount rate (6.4-6.5%), all the other factors need to be much better than the reference value. For example, the efficiency should be higher than 70% (4% better than the reference), the stack lifetime should be higher than 98200 hours (3% better than the reference) and the gas price should be higher than 12.4 AUD/GJ (55% better than the reference), while the capital cost of solar PV should be at least similar to the reference value in 2030.

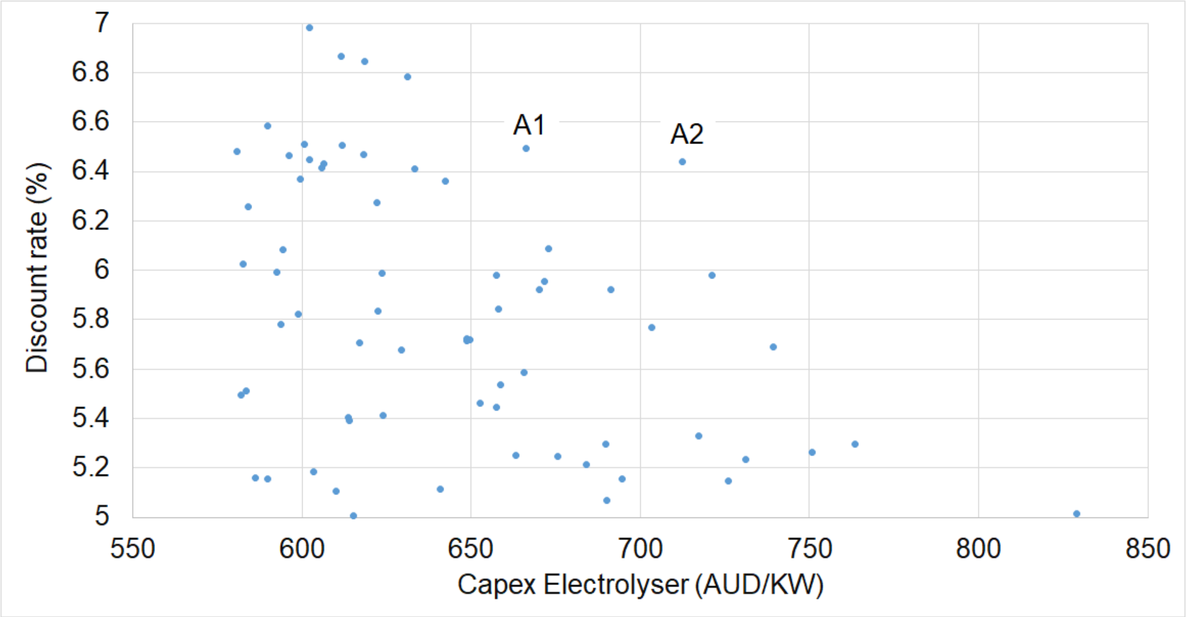

Figure S3: Combinations of capital cost of electrolyser and discount rate that results in transition to renewable H_2

Figure S4 illustrates the improvement in the average emissions intensity of hydrogen production without and with carbon pricing until 2050. It is clear that without a carbon price, the median emission intensity of Australian hydrogen will be 12.9 CO_2/kg H_2 from 2020 to 2050, with only in 5% of simulation runs, below 5.7 kg CO_2/kg H_2 by 2050. In contrast, the median emissions intensity of Australian hydrogen rapidly declines from 12.9 CO_2/kg H_2 in 2033 to zero by 2043.

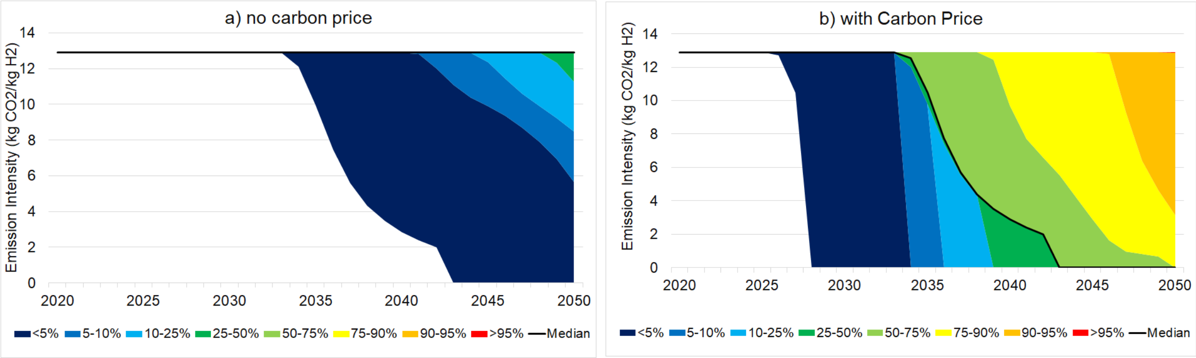

Figure S4: The confidence bounds for emission intensity of produced hydrogen without and with carbon price