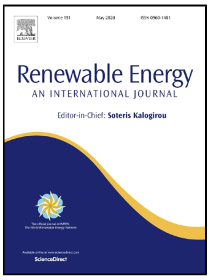

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Quantification of fresh water Consumption and Scarcity Footprint of Hydrogen from Water Electrolysis: A Methodology Framework

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Abstract:
Towards decarbonizing the global economy, hydrogen production through water electrolysis is expected to be one of the key solutions for variable renewable energy storage and sector coupling, in particular, via the transport sector in the next few decades. Even though water is an important aspect of the environmental impact, assessment of hydrogen production on water is lacking. This paper proposes a comprehensive methodology for assessing the water footprint of hydrogen production from electrolysis. A major innovative aspect is to demonstrate the geographical distribution of the footprint along the supply chain. The water footprint for hydrogen produced from grid electricity, wind and solar power in Australia was analysed as a case study. Sensitivity analysis was used to evaluate the influence of different parameters including Solar Radiation Level, Silicon Efficiency, and Lifetime of PV Modules. The study find that the water footprint is much less than that reported in the literature and many part of the water could be consumed outside of hydrogen producing countries. The quantity of water footprint varies significantly among different assumption of parameters. The findings provide insights into both domestic and cross-boundary impacts of hydrogen electrolysis and can thus inform policy debates in each nation and beyond.

Keywords: Power to hydrogen; water electrolysis; water footprint; life cycle assessment; Australia;

Nomenclature

SOEC	Solid oxide electrolyser cell
Solar2H_2	Solar to hydrogen
PV	Photovoltaic
PEM	Proton exchange membrane
AEL	Alkaline electrolysis
P2H	Power to hydrogen
LCA	Life cycle assessment

1 Introduction

Hydrogen gas ('hydrogen, H2') has the potential to decarbonize sectors where reducing emissions has proved hardest, like heavy industry and long-haul transport and become a fundamental solution to our dependence on fossil fuels as well as greenhouse gas emissions sourced from energy consumption (IEA, 2019). Clean hydrogen, derived from low or zero emissions sources, can enable decarbonisation across the energy and industrial sectors (Bruce et al., 2018). Hydrogen, together with battery, are considered the two technologies with the most potential to decarbonise the transport sector (Anandarajah, McDowall, and Ekins, 2013). While electricity vehicles will play a big role around the world, hydrogen fuel-cell vehicles have a strong ability to provide long-distance travel and long-haul freight transport (IEA, 2019). However, hydrogen is a secondary energy and is not necessarily low-carbon, as it can be produced from fossil fuels – either directly or indirectly – through electricity. Understanding the cleanness of hydrogen is important for the sustainable development of hydrogen potential, as countries' long-term aim is to accept low or zero emissions hydrogen (ACIL Allen Consulting, 2018). The life cycle environmental impact of hydrogen production needs to compare H2 with its alternatives and to achieve policy changes and industrial acceptance (Cetinkaya, Dincer, and Naterer, 2012).

Since hydrogen is made from water, and energy and equipment that are needed to produce hydrogen consume water, the water footprint of hydrogen also needs to be understood. Water consumption is emerging as one of the key subjects in the life cycle analysis of alternative fuels, as the water consumption rate may have a fundamental role in terms of human health and natural environmental impacts (Mehmeti et al., 2018). Theoretically, 1 Normal cubic meter (Nm3) of hydrogen consumes 0.81 litres of water, but the water consumption is usually 25% higher in reality (Barbir, 2005) – i.e. 1 Nm^3 (0.09 kilogram (kg)) of hydrogen requires 1 litre (1 kg) of water. While the direct water consumption may not be impressive, the indirect water consumption from the generation of energy and equipment that are used to produce hydrogen can be 20 times more than the direct water consumption, depending on the electricity supply chain (Mehmeti et al., 2018). Sternberg and Bardow (2015) highlighted that the water footprint is an important potential environmental impact which should be considered once the assessment methods are well established and sufficient data become available. However, while the environmental impact is critical to assess the sustainability of hydrogen, studies in the literature is limited.

Gaps remain in environmental impact assessments of hydrogen. First, the impacts of climate change have been frequently assessed (e.g. Acar and Dincer, 2014; Cetinkaya, Dincer, and Naterer, 2012; Dufour et al., 2009; and Smitkova, Janíček, and Riccardi, 2011), followed by acidification potential. However, other impacts such as water are often not addressed (Bhandari et al., 2014). Mehmeti et al. (2018), the only study on water footprint in the literature, assessed the impact of 17 production technologies on environmental indicators including water consumption potential and water scarcity footprint. The study showed that the production of 1 kg of hydrogen requires 8.82-223.39 m^3 of water consumption and 379-9,604.3 m^3-eq in a water scarcity footprint. However, it did not provide transparency and details on how these numbers were derived, so their accuracy is unknown. Second, no study has assessed the geographical distribution of these footprints along the supply chains, which extend broadly in the case of renewable hydrogen. Since water is consumed along the entire production supply chain and various production processes are heavily interdependent, a life cycle assessment (LCA) perspective is required to estimate the water-related impact of hydrogen production. Third, many people have worked on sensitivity analysis without considering how technologies change and could thus lead to misleading results.

This study aims to quantify the freshwater withdrawal, consumption, and scarcity weighted footprint as well as the social impact of hydrogen production and their cross-country distribution, including consideration of electrolysis equipment and operations. We will employ scenario analysis and an LCA approach. Although many technologies can produce hydrogen (Mehmeti et al., 2018), we focus on water electrolysis from electricity, which is expected to develop rapidly. Electrolysis powered by renewable electricity, solar photo-electrochemical (PEC), high-temperature electrolysis (powered by nuclear or solar), thermal water splitting (TWS) (powered by nuclear or solar), and biological pathways have the potential to achieve near-zero carbon emissions (Tong et al., 2017).

This study makes contributions to the literature by being a pioneer on three fronts. First, it provides a methodological framework for further study of the water footprint of hydrogen from water electrolysis. The methodology not only considers direct water consumption and emissions from electrolysis and energy production, but also quantifies indirect water consumption produced during the manufacturing of the equipment as well as the operational phase. Second, we consider the distribution of the water consumption across different countries along the supply chains. We quantify the embedded water consumption of equipment, whose supply chain is often traverses several countries. Third, we are the first study to quantify the water footprint of hydrogen produced in Australia, which is expected to be a major exporter of hydrogen. The results and methodologies are expected to play an active role in future policy debates on the environmental impact of hydrogen production.

The paper is structured as blow. The next section introduces the background and review the literature. Section 3 presents the methodology of quantifying water footprint. Section 4 applies the methodology to the Australian case study with sensitivity analysis. The last section concludes the paper.

2 Background and Literature Review

2.1 Current Status and Prospect of Hydrogen

Hydrogen, which is produced primarily by splitting water (electrochemical) or reacting fossil fuels with steam or oxygen (thermochemical), is being used as feedstock for a range of industrial processes. Many technologies can produce hydrogen from both fossil fuels and electricity, such as steam reforming of natural gas, coal and biomass gasification and reforming, water electrolysis via proton exchange membrane (PEM) fuel cells, solid oxide electrolyser cells (SOECs), and dark fermentation of lignocellulose biomass (Mehmeti et al., 2018). According to the Hydrogen Council (2017), global annual hydrogen production is relatively stable at about 55 million tons and is mainly produced from non-renewable sources. The major applications for hydrogen are non-energy uses such as petroleum refining, fertiliser production, methanol production, metallurgy, and food production, while energy uses only account for about 1% and 2% of total hydrogen consumption. For example, half of the hydrogen produced is used to produce ammonia (ACIL Allen Consulting, 2018).

Although hydrogen is mainly for non-energy use, it has emerged as a key energy carrier for the future in a world that is increasingly making efforts to decarbonise the economy. Hydrogen is highly expected in supplement renewable power generation and help replace fossil fuels in transportation. In its 2°C Scenario (2DS), the International Energy Agency (IEA, 2015) projected that 30,000 fuel cell electric vehicles (FCEVs) would be sold in the United States, the European Union, and Japan by 2020. Due to the maturing of technologies and new breakthroughs, as well as achieving economies of scale and benefiting from the learning curve, a self-sustaining market could be achieved 15–20 years after the introduction of the first 10,000 FCEVs. The share of FCEVs in the passenger car fleet in these markets will reach 30% by 2050. The unanimous recognition of hydrogen's application in the transport sector across countries has led to plans to build about 2,800 hydrogen refuelling stations worldwide by 2025 (Hydrogen Council, 2017). Table 1 summarises the development plans of several leading countries in hydrogen energy.

Table 1: Announced Plan/Estimation for Hydrogen Stations and Fuel Cell Vehicles

Country	2020		2025		2030	
	FGEV	Stations	FGEV	Stations	FGEV	Stations
China	10,000	100			2 million	1,000
France		22		355		600
Germany	150,000	100		400	1.8 million	900
Japan	40,000	160	200,000	320	800,000	900
Republic of Korea	10,000	80	150,000	210	630,000	520
United Kingdom		65		300		1100
United States	20,000	115	90,000–200,000	320–570	1.8 million–4.5 million*	1,500–3,300*

FGEV = fuel cell electric vehicle.
* 2035 figures.
Sources: van der Laak et al. (2015); Melaina et al. (2017); IEA (2015).

More importantly, hydrogen could store renewable energy from intermittent sources through power-to-gas (P2G) technology as an alternative to large-scale batteries or other storage systems. Such variable renewable energies (VREs), which would otherwise be curtailed, could be used to generate hydrogen at lower price. The hydrogen produced from the P2G technology can be either generated electricity in need or as a heating fuel in our homes and buildings. In terms of emissions, as the typical exhaust substance generated by the consumption of hydrogen as an energy carrier is pure water (H_2O), it is considered clean energy.

The development of hydrogen for energy use also creates an international market for renewable energy. The production of hydrogen from VREs could make some countries which are rich in VREs (e.g. Denmark) or hydropower (e.g. Norway) become interested in exports hydrogen made from clean energy and sell to other countries. The IEA projects that the global market for hydrogen will reach $155 billion by 2022 (IEA, 2017). The first demonstrations of the use of hydrogen for energy could be deployed as early as 2030. The Shell Sky scenario projects that hydrogen may cover 10% of the final global energy demand and up to 25% of the transport demand in 2100 (Hydrogen Council, 2017). In a more ambitious projection, the Hydrogen Council projected that hydrogen will account for at least 18% of the world's total final energy demand in 2050 (Hulst, 2018).

Table 2 lists ARENA's projection of demand for hydrogen in three difference scenarios, based on the IEA's projection of energy consumption by industry and by country in its Sustainable Development Scenario and the projected prices of the Commonwealth Scientific and Industrial Research for hydrogen supplied from Australia (production, storage, and transport) (ACIL Allen Consulting, 2018).

Table 2: Projected Global Demand for Hydrogen

('000 tons)

Country Scenarios	2025 Low	 Medium	 High	2030 Low	 Medium	 High	2040 Low	 Medium	 High
Japan	88	516	1,338	875	1,761	3,858	1,896	4,131	9,573
Republic of Korea	74	223	493	373	728	1,562	1,001	2,175	5,304
Singapore	3	15	31	27	51	103	96	168	481
China	48	226	698	1,028	3,318	7,009	7,853	17,430	40,989
Rest of the World	98	448	1,170	1,053	2,678	5,729	4,958	10,927	25,758
Total	**311**	**1,429**	**3,731**	**3,357**	**8,536**	**18,260**	**15,804**	**34,831**	**82,105**

Note: The projected demand in the high scenario is similar to the Hydrogen Council (2017) projection. The numbers may not be completely precise because of rounding.

Source: ACIL Allen Consulting (2018).

2.2 Sustainability and Water Footprint of Hydrogen

The sustainability of hydrogen depends on its environmental impact. While it is emission-free in the process of fuel cell utilisation, hydrogen could generate significant emissions in some production technologies such as steam reforming of natural gas and coal gasification. Parra et al. (2017) reviewed the studies on the economic feasibility of hydrogen production. Even in the case of electrolysis, where no emissions are generated during the process, the life cycle emissions could still be significant if the electricity is not produced from renewable energy. While hydrogen made from 100% renewable electricity and electrolysis will not have emissions in its production stage, there could be significant indirect emissions from the manufacturing of the equipment to produce it.

The production of hydrogen from fossil fuels is attractive in cost terms and would become popular if no emissions constraints were in place. For example, with the adoption of Carbon capture and storage (CCS) technologies which can reduce the emissions from fossil-based pathways by 80%–90% or more, the cost of hydrogen production remains below $4 per kg (Tong et al., 2017). Australia is considering producing hydrogen from brown coal resources in Victoria (Bruce et al., 2018).

Although the key parameters used in studies of the climate change impacts of hydrogen production are varied, sensitivity analysis is lacking. In Dufour et al. (2009), the total environmental impact and carbon dioxide emissions from thermal and autocatalytic decomposition of methane were studied using LCA tools. Smitkova, Janíček, and Riccardi (2011) compared the LCA results of different hydrogen production technologies in terms of three damage categories – human health, ecosystem quality, and resources – but did not report the carbon footprint. Cetinkaya, Dincer, and Naterer (2012) compared the life cycle impact of five methods of hydrogen production, and found thermochemical water splitting with the copper–chlorine cycle (Cu–Cl cycle) the most favourable in terms of carbon dioxide equivalent emissions, followed by wind and solar electrolysis. Acar and Dincer (2014) conducted a comparative economic, social, and environmental (global warming potential, GWP and acidification potential, AP) impact assessment of eight hydrogen production methods from renewable and non-renewable sources,[1] using Turkey as a case study. Unusually, it found that thermochemical water splitting with the Cu–Cl and sulphur–iodine (S–I) cycles was more environmentally friendly than traditional methods, including wind, solar, and high-temperature electrolysis.

There are only a few studies that assess the life cycle environmental impact of hydrogen production and they mainly focuses on climate change. In a review 21 LCA studies of hydrogen production technologies with a focus on electrolysis, Bhandari et al. (2014) found that the impact on climate change is most frequently quantified, followed by acidification potential, but the other impacts are often not addressed. Ghandehariun and Kumar (2016) estimated the carbon footprint of hydrogen production through water electrolysis using wind power. Holger et al. (2017) studied the social footprint, considering five major social impact categories (labour rights, human rights, governance, health and safety, and community infrastructure), but the methodology, social LCA, is not popular in the literature.

Only a few studies have assessed the life cycle environmental impact of hydrogen production, but mainly focusing on climate change. Most studies on the environmental impact of hydrogen in the literature are in the context of P2G for storage purposes, such as Parra et al. (2017) and Vo et al. (2017). For example, Sternberg and Bardow (2015) compared the environmental impact of energy storage systems providing different products including hydrogen, but it is not a life cycle analysis. Burmistrz et al. (2016) estimated the carbon footprint of two mainstream gasification technologies for hydrogen production from sub-bituminous coal, but made no efforts to estimate the footprint of other feedstock.

There is no rigorous analysis of the nexus of hydrogen and its associated water use and impact. Mehmeti et al. (2018) is the only estimation of water consumption potential and water scarcity footprint in about 17 hydrogen production pathways using the LCA impact assessment method ReCiPe 2016. They found a significant range of water consumption from electrolysis: from 8.8 m^3 when wind power is used to 223 m^3 when grid electricity is used. This analysis also suggested that a trade-off might exist between water impact and emissions since it found that that water-related impacts tend to be higher in technologies which have relatively low scores of global warm and fine particulate matter (Mehmeti et al., 2018). However, this paper did not present method, included parameters. Estimation of water consumption along the supply chains was also lacking.

3 Methodology

In this research, we propose a methodology of measuring the freshwater consumption (FWC) and (fresh) water scarcity footprint (WSF) of hydrogen production from water electrolysis. This includes defining the functional unit, system boundary, life cycle water inventory collection, and allocation approaches, as well as calculating both FWC and WSF. In this study, we clarified different terms and definitions related to water concepts. The proposed approach focuses on freshwater, but it's also applicable to seawater and brackish water.

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[1] The assessed methods include natural gas steam reforming, coal gasification, water electrolysis via wind and solar energies, biomass gasification, thermochemical water splitting with Cu–Cl and S–I cycles, and high-temperature electrolysis.

3.1 Function unit, System Boundary, and Allocation

The function unit of this study is set at 1 kg of hydrogen (purity >99.9%, at 30 bar). Power to hydrogen technologies will simultaneously produce hydrogen, oxygen, and excess heat (equation 1).

$$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g);\ E_0 = +1.229\ V \quad (1)$$

As oxygen and excess heat are often not valorised, they are treated as waste using cut-off allocation. In this standard hydrogen production system (Figure 1), the default system boundary includes electricity generation from either grid mix, solar or wind sources, supply and purification of water, the installation of electrolysis equipment, and the power plant. The storage, liquefaction, transport, and use of hydrogen are optional, excluded from the system boundary.

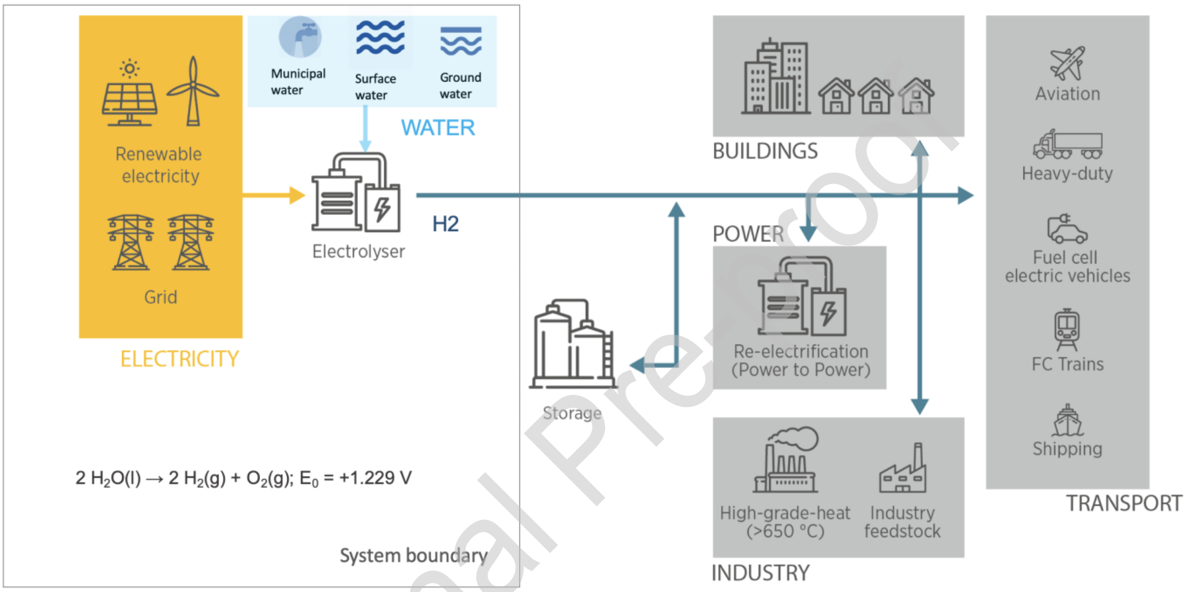

Figure 1: Concept of Power to Hydrogen

Source: Adapted from IRENA (2019)

3.2 Water Footprint Framework and Measurement

The water footprint assessment in this study follows the International Organization for Standardization (ISO) norm 14046 for water footprint in LCA, its practitioners' guide (ISO and ITC, 2017), and the Water Use in Life Cycle Assessment (WULCA) consensus characterisation model for water scarcity footprints (Boulay et al., 2017). The detailed terms and definitions related to various water concepts used in this study are given below:

- Water footprint: metric(s) that quantifies the potential environmental impacts related to water (*ISO 14046 clause* 3.3.1).
- Water footprint assessment: compilation and evaluation of the inputs, outputs and the potential environmental impacts related to water used or affected by a product, process or organization (*ISO 14046 clause* 3.3.2).
- Water use: use of water by human activity. Use includes, but is not limited to, any water withdrawal, water release or other human activities within the drainage basin impacting

water flows and/or quality, including in-stream uses such as fishing, recreation, transportation. (*ISO 14046 clause* 3.2.1).

- Water withdrawal: anthropogenic removal of water from any water body or from any drainage basin, either permanently or temporarily (*ISO 14046 clause* 3.2.2)
- Water consumption: water removed from, but not returned to, the same drainage basin. Water consumption can be because of evaporation, transpiration, integration into a product, or release into a different drainage basin or the sea. Change in evaporation caused by land-use change is considered water consumption (e.g. reservoir). (*ISO 14046 clause* 3.2.1).
- Water scarcity: extent to which demand for water compares to the replenishment of water in an area, e.g. a drainage basin, without taking into account the water quality (*ISO 14046 clause* 3.3.17).
- Water scarcitiy footprint: potential impacts associated with the quantity aspect of water use (i.e., water consumption) without considering the additional quality component of availability (Boulay et al., 2017).
- Water footprint inventory analysis: phase of water footprint assessment involving compilation and quantification of inputs and outputs related to water for products, processes or organizations as stated in the goal and scope definition phase (*ISO 14046 clause* 3.3.7).
- Freshwater: water having a low concentration of dissolved solids (*ISO 14046 clause* 3.1.1).

The overall conceptual framework of water footprint in LCA is illustrated in Figure 2. Water footprint measures reduced water availability from consumption and degradation (water availability footprint), and impacts from pollution (water degradation footprint). In this study, we will quantify both the water consumption and water scarcity footprint of deploying power to hydrogen technologies that can be applied to any location.

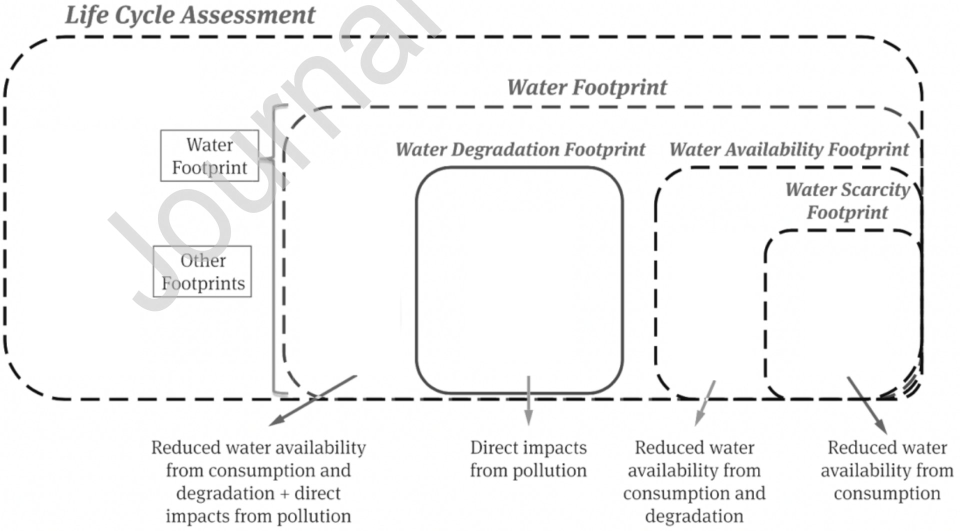

Figure 2: The Concept of Water Footprint in the Framework of LCA.
Source: Adapted from ISO (2017).

The water use (water consumption or water withdrawal) can be evaluated based on equation (2).

$$Freshwater\ consumption = (FWC_{mol} + FWC_{coo}) + (FWC_{ele} + FWC_{mat} + FWC_{dis}) \quad (2)$$

where, FWC_{mol} refers to direct molecular FWC to split water into hydrogen and oxygen; FWC_{coo} refers to direct cooling water consumption; FWC_{ele} refers to indirect water consumption embodied in electric energy consumption; FWC_{mat} refers to indirect water consumption embodied in material and equipment in electrolysers; and FWC_{dis} refers to indirect water consumption embodied in waste disposals.

Considering the high spatial variability of water scarcity, the water scarcity footprint can be further computed based on water consumption, as shown in equation (3).

$$freshwater\ scarcity\ footprint = freshwater\ consumption * \ WSI \quad (3)$$

According to ISO 14046, water scarcity measures the extent to which demand for water compares to the replenishment of water in an area, e.g. a drainage basin, without taking into account the water quality. Various approach are available to estimate water scarcity indices (WSI) for a given region at certain time period. Broadly speaking, it includes methods based on ratio of water withdrawal-to-availability (WTA) (Frischknecht et al. 2008; Pfister et al. 2009) or water consumption-to-availability (CTA) ratio (Boulay et al. 2011; Hoekstra et al. 2012; Berger et al. 2014). However, all of these methods only considered water use from human activities but failed to include the demand from ecosystems (Boulay et al. 2015). As a result, the consensus approach AWARE (water consumption based on available water remaining), based on the concept of the inverse of availability minus demand (1/AMD), is built through a consensus building process under the UNEP-SETAC Water Use in Life Cycle Assessment (WULCA) working group. The characterisation model for this water scarcity midpoint method has a native spatial scale at 0.5° × 0.5°grid cell level and also at aggregated watershed or country levels. Further discussions and detailed are available in the methodology paper published by (Boulay et al., 2017). In the following analysis, this water scarcity midpoint method is used, as it’s considered to be the state of the art in the LCA community and also widely accepted by LCA experts from academia, consultant, industry, and governmental institutions.

3.3 Life Cycle Inventory Data Collection

Table 3 shows the life cycle data used to build the water inventory and impact assessment of power to hydrogen concepts. It starts from defining the goal and scope, where the functional unit is 1 kg of hydrogen produced through water electrolysis. The electricity input for producing 1 kg of hydrogen varies depending on the electrolyser technology (alkaline electrolysis or PEM), producer brand, and scale of installation ; and varies from 50 kilowatt-hours (kWh) to 65 kWh on average (Götz et al., 2016; United States Department of Energy, 2019). In this study, we use 55 kWh as the default value. The electrolysis equipment data is modelled on the foreground data obtained from the NEEDs project[2] using ecoinvent v3.4 (ecoinvent, 2017) as background data. The water inventory per kWh of different electricity generation profiles (grid mix, solar photovoltaic (PV), or wind power) is modelled on the ecoinvent v3.4 database in SimaPro v8.5.3, with modifications to ensure water balance by region. The silicon consumption per watt and the supply chain information of PV data sets

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[2] http://www.needs-project.org/

are updated based on the IEA Photovoltaic Power Systems Programme (PVPS) report (Masson and Kaizuka, 2017) and China PV industry development road map (CPIA and CCID Consulting, 2017) to reflect the latest developments.

Table 3: Life Cycle Data Collection and Reference Sources

Life cycle stage	Category	Sub-category	Value	Unit/ Functional unit	Comment	Reference
1.Define goal and scope	Functional unit		1	kg	1 kg of hydrogen	Stoichiometry
	Temporal horizon		2010–2020	-	2015–2020	
	By product	Oxygen	8	kg		
		Surplus heat	-	MJ		
2. Life cycle water inventory analysis and results (modelling water inputs and outputs with indication of region and water body)	Energy input of electrolysis	Grid mix	55	kWh	Range: 50–65 kWh/kg of hydrogen	(Götz et al., 2016) (United States Department of Energy, 2019)
		PV				
		Wind				
	Electrolysis equipment and Plant input	AEL	0.6	litre	Scale: 60 Nm^3 H2 (AEL)	NEEDs project http://www.needs-project.org/
	PV installation	-	1.66	litre	8 gallons per MWh	(Frisvold and Marquez, 2013)
	Operation water input	-	9	litre	Process water input during electrolysis	Stoichiometry
3.Impact Assessment	Impact category choice	Water scarcity footprint	-	m^3-eq		n.r.
	Characterisation model choice	AWARE	0–100	m^3-eq		(Boulay et al., 2017)
	Normalisation and weighting	Not included	-			n.r.

Notes: AEL = alkaline electrolysis, H2 = Hydrogen, kg = kilogram, kWh = kilowatt-hour, m^3-eq = cubic meter equivalent, MJ = megajoule, MWh = megawatt-hour, n.r. = , PV = photovoltaic.
Source: Authors' own compilation from various sources.

4 Case Study of Australia's Hydrogen for Export

To understand the impact of hydrogen production on water, this study uses Australia as a case study. Australia has a number of natural advantages for the production of renewable hydrogen for export, including the quality of renewable resources, small demand relative to potential supply, a stable political and financial environment, and existing trading relationships. For the East Asian hydrogen market, Australia's hydrogen has a number of advantages, such as the relatively low landed cost of hydrogen, proximity to the market, well-established energy trading relationships, and experience in large-scale energy infrastructure construction (ACIL Allen Consulting, 2018).

It has been projected that Australia could export 0.6 to 3.2 million tonnes of hydrogen by 2040, about 4% of the global total demand of hydrogen from 15.8 to 82.1 million tonnes (Figure 3).

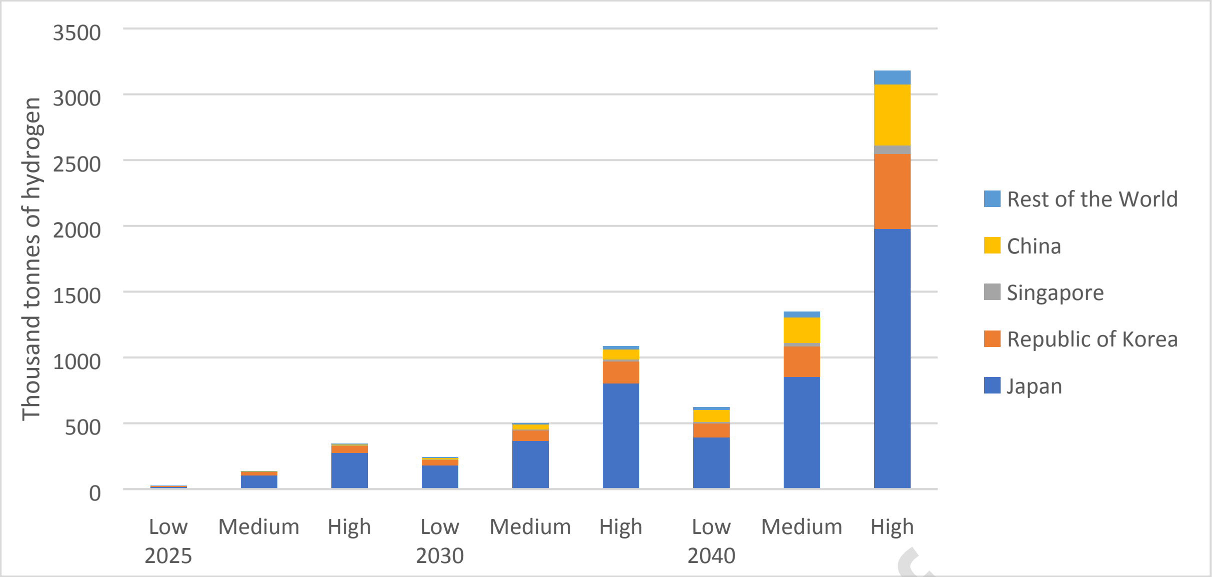
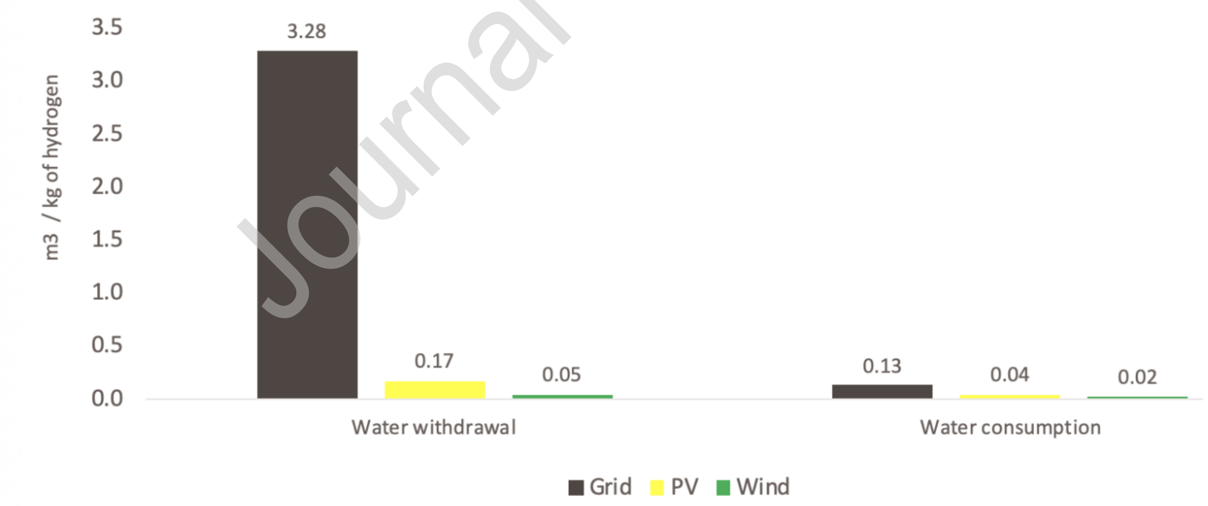


Figure 3: Australia’s potential export of hydrogen

Source: (ACIL Allen Consulting, 2018)

4.1 Freshwater withdrawal and consumption

Figure 4 shows the life cycle water inventory of producing hydrogen in Australia from grid electricity, PV, and wind. The production of 1 kg of hydrogen in Australia consumes 0.13 m^3 of water when grid electricity is used, 0.04 m^3 of water when PV is used, and 0.02 m^3 of water when wind electricity is used.



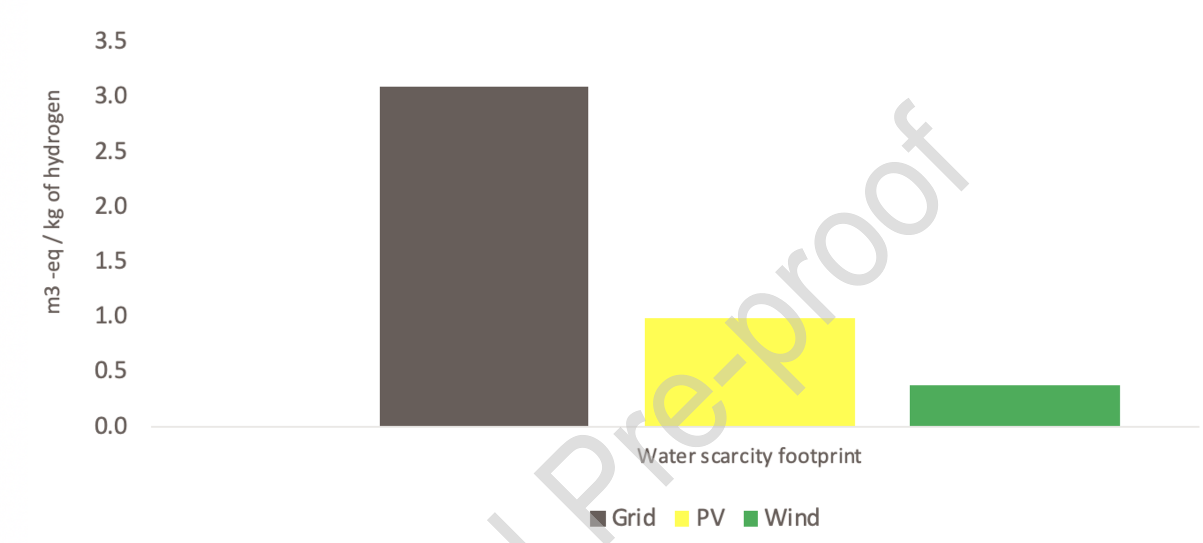
Note: kg = kilogram, m^3 = cubic meter, PV = photovoltaic.

Figure 4: **Water Withdrawal and Consumption for Producing 1 kg of Hydrogen with Grid Electricity, PV, and Wind Power in Australia**

Source: Authors’ calculation.

However, the water withdrawal is much higher than the water consumption. The ratios of the three technologies are also quite different. Water withdrawal from grid electricity is 19 times that of PV, while water consumption from grid electricity is three times that of PV. The increasing gap between grid hydrogen and PV and wind is due to the significant amount of water used in the operational stage, mainly for cooling. Although a large portion of water in the operational stage will not be consumed, it has to be withdrawn first from the ecological system.

The scarcity footprint has a similar pattern to the water consumption – that is, grid electricity has the highest water scarcity impact while the wind hydrogen has the least (Figure 5). The similar pattern is due to the same water scarcity index that scale up the water consumption footprint.



Notes: kg = kilogram, m^3-eq = cubic meter equivalent, PV = photovoltaic.

Figure 5: Water Scarcity Footprint of Producing 1 kg of Hydrogen with Grid Electricity, PV and Wind Power in Australia

Source: Model estimations

Figure 6 below shows the distribution of water consumption and scarcity across regions is quite different. We group the geographical areas into three regions: Australia, China, and the rest of the world and find that only some parts of water consumption occur in Australia. The share of Australian domestic water in the total consumption is lowest in the case of PV hydrogen (25%) and highest in the case of grid hydrogen (73%). China accounts for a higher share of water consumption than Australia in the case of PV hydrogen (34%). This is because the PV modules, which are water-intensive, are produced overseas, mainly in China. The slight difference in composition between water consumption and water scarcity is due to differences in the water scarcity index, which is highest in China, followed by Australia and then the rest of the world.

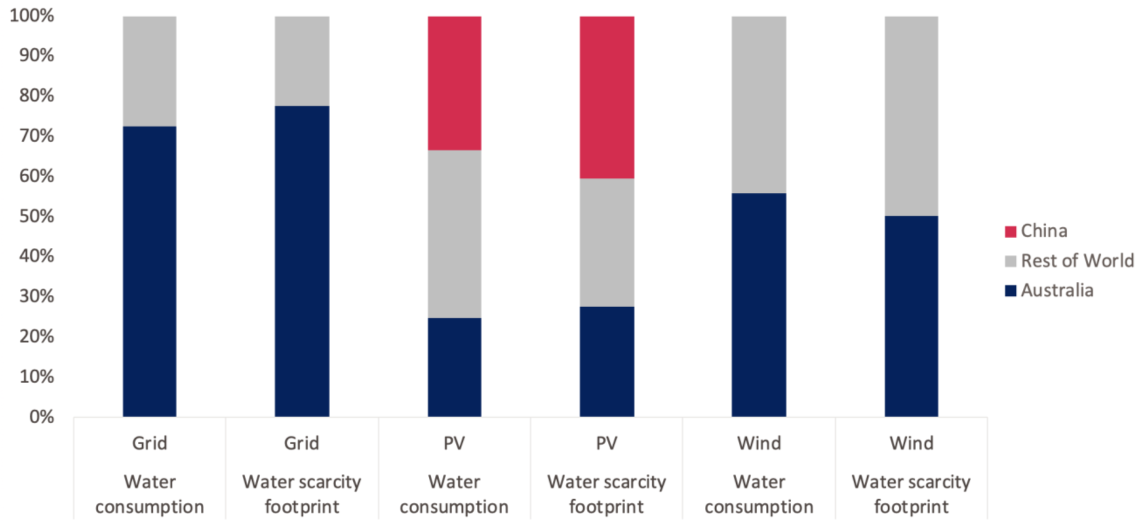


Figure 6: **Distribution of Water Consumption and Water Scarcity Footprint Across Regions**

Source: Model estimations

4.2 Aggregate Water Footprint of Australia's Hydrogen Exports

We also estimate the total water consumption to produce Australia's export hydrogen. ACIL Allen Consulting (2018) projected that Australia could export 0.6 million–3.2 million tons of hydrogen in 2040 – about 4% of the global total demand for hydrogen (15.8 million–82.1 million tons).

Table 4 shows the estimated aggregate water withdrawal, consumption and scarcity footprint of producing Australia's hydrogen for export from water electrolysis through grid, PV, and wind power, respectively, considering the high demand scenario in 2040 presented in ACIL Allen Consulting (2018). It shows the annual water consumption from producing hydrogen for export is 55-411 gigalitres. The highest water consumption case is 411 gigalitres, assuming the current grid electricity water consumption intensity. Based on the prior estimation in Figure 6 that 73% of water consumption is sourcing from Australia domestically, the worst scenario for domestic water consumption in Australia by 2040 is estimated to be 300 gigalitres, for producing 3.2 million metric ton of hydrogen used for foreign export. It represents 2% of Australia's total consumption use of water (16,558 gigalitres) (Australian Bureau of Statistics, n.d.).

Table 4: **Total Water Footprint for the Production of 3.2 million metric tons of Hydrogen for Export – High Demand Scenario in 2040**

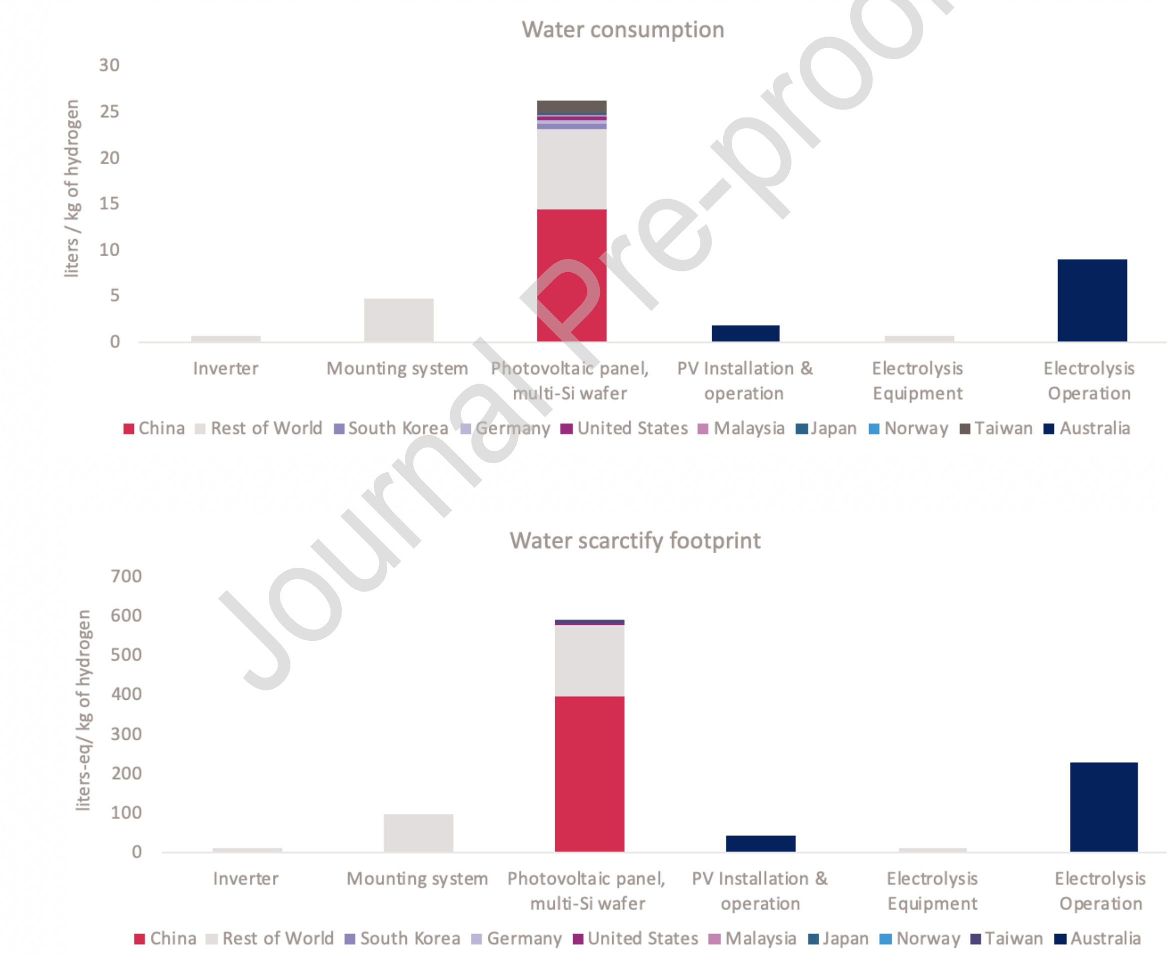
Indicator	Unit	Grid	PV	Wind
Water withdrawal	Gigalitres	10,441	549	145
Water consumption	Gigalitres	411	136	55
Water scarcity footprint	Gigalitres-eq	9,829	3,126	1,216

PV = photovoltaic.
Source Authors' own calculation.

4.3 Further Analysis of Water Electrolysis from Solar Power (Solar2H_2)

4.3.1 Distribution of water footprint of Solar2H_2 along value chain across different regions

To understand the impact of the water footprint across the life cycle stage and across regions, we use solar to hydrogen (Solar2H_2) as an example. We break the supply chain into six steps, as shown in Figure 7. In the Solar2H_2 case, water consumption in Australia only occurs in two stages: (i) PV installation and operation and (ii) electrolysis operation. Both stages see only water from Australia consumed. However, in the case of PV panels and wafers, China produced 86% of global wafers, 66% of PV cells, and 69% of PV modules in 2016 (Masson and Kaizuka, 2017). In the mounting system and electrolysis stages, water consumption mainly occurs in unspecified regions (rest of the world). Water scarcity has a similar pattern to that of water consumption, but the impact falls more on China than other countries, reflecting the higher water scarcity index in China than in the rest of the world.



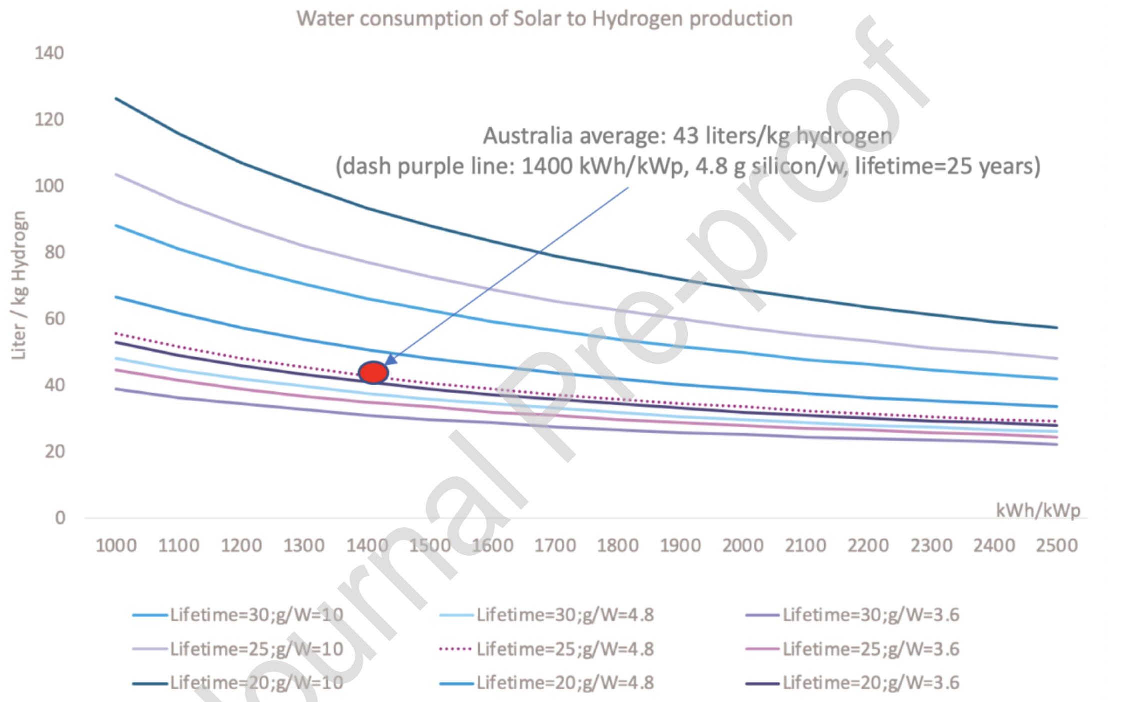
Notes: eq = equivalent, kg = kilogram, PV = photovoltaic, Si = silicon.

Figure 7: Distribution of Water Consumption and Water Scarcity Footprint of Solar2h2 along Value Chain

Source: model estimation.

4.3.2 *Sensitivity of solar radiation efficiency, silicon efficiency, and PV module lifetime*

The above analysis of Solar2H_2 is based on fixed parameters collected from the literature, which is common practice. However, the analysis does not consider the heterogeneity of the technical and resource parameters. In this analysis, we consider heterogeneity through three different aspects: the lifetime of the project, silicon efficiency, and different solar radiation levels. While PV is often assumed to have a lifespan of 25 years, 20- and 30-year lifespans are also considered for the sensitivity analysis. We vary the silicon efficiency from 3.6 to 10, based on the *Polysilicon Market Outlook 2020* (Bernreuter, 2016). We also vary the solar radiation level from 1,000 to 2,500 kWh per kilowatt-peak (kWp) based on the global horizontal irradiation from the global solar atlas (World Bank, n.d.). **Figure 8** shows that the water consumption can vary from 22 to 126 litres/kg of hydrogen, depending on the silicon consumption per watt, the lifetime of the PV modules, and the solar irradiation level.



Notes: g/W = gram/Watt-peak, kWh = kilowatt-hour, kWp = kilowatt-peak, PV = photovoltaic, Solar2h_2 = Solar PV to Hydrogen.

Figure 8: Scenario Analysis of Water Consumption of Solar2h_2 in Australia with Different Solar Radiation Level, Silicon Efficiency, and Lifetime of PV Modules

Source: Model estimation.

4.4 Comparison with Previous Studies

Table 5 shows the comparison of the previous estimates and our estimate of water consumption and the water scarcity footprint of producing hydrogen through water electrolysis. Mehmeti et al. (2018) estimated that the water consumption of producing 1 kg of hydrogen from water electrolysis was 8.8–223 m^3, whereas ACIL Allen Consulting (2018) only calculated the operating water input during electrolysis (9 litres/kg of hydrogen). These studies either overestimated or understated the water consumption of producing hydrogen.

Our estimate indicates that the water consumption required for the highest demand scenario (3.2 million kg) of hydrogen for export in Australia in 2040 will contribute to a maximum of 2% of the total national water consumption, as discussed in Section 2.2.

Table 5: Comparison of the Water Consumption Intensity and Water Scarcity Footprint of Hydrogen Production

Studies	**System boundary**	**Water consumption intensity** (litre/kg)	**Water consumption in high export scenario** (gigalitre)	**Water scarcity footprint** (litre/kg)
Mehmeti et al. (2018)	Cradle to gate	8,800–223,000	28,000–709,140	379,300 (SOEC wind)–960,4300 (PEM grid mix)
ACIL Allen Consulting (2018)	Operating water use during electrolysis phase	9	28.6	No data
Our estimate in this study	Cradle to gate	17 (wind), 43 (PV), 129 (grid mix)	55 (wind), 136 (PV), 411 (grid mix)	380 (wind), 980 (PV), 3090 (grid mix)

Notes: kg = kilogram, PEM = proton exchange membrane, PV = photovoltaic, SOEC = solid oxide electrolyser cell.
Source: Authors’ compilation from various sources.

5 Conclusion

Hydrogen is a secondary energy and not necessarily low-carbon, as it can be produced from fossil fuels – either directly or indirectly through electricity. While low-carbon hydrogen is of high interest for future energy development, and has been actively promoted in many countries, its impact on water consumption and scarcity has not been well studied.

This paper proposed a methodological framework to quantify the water footprint of hydrogen produced from water electrolysis. Applying a life cycle analysis concept, it not only quantified the direct water consumption but also the indirect water consumption embodied in the equipment and occurring during the operational stage. The methodology is innovative to the literature. This methodology was then applied to the case of Australia for three electricity sources: grid, solar PV, and wind power.

The water footprint depends on the source of electricity. Grid electricity (in the case of Australia) has the highest impact, while wind has the least. In the case of Solar2H_2, the largest proportion of water was consumed during the PV panel production stage, followed by liquefaction. The distribution of water consumption differs according to the source of electricity. While grid electricity primarily consumes water locally, Solar2H_2 consumes most of the water from China while Wind2H_2 has a diversified water footprint.

The Australian case study suggests that producing hydrogen from grid electricity is not desirable if the grid electricity is dominated by fossil fuels, as it has the highest water footprint and impact on water scarcity. However, if the grid electricity is mainly produced from renewable energy sources, it may offer a better source for hydrogen production as it can transfer VREs to different geographical areas and allow larger scale and cheaper production. Sensitivity studies demonstrate that technology change is the dominant driver in reducing the water scarcity footprint.

This study has the following policy suggestions. First, production from grid electricity that is depending on fossil fuels, as in the case of Australia, is undesirable due to its highest water footprint and impact on water scarcity. Second, in the promotion of hydrogen produced from renewable energy, the global community needs to be aware of the transboundary impact on water. Countries that is considering import hydrogen needs to take water scarcity in the exporting countries into consideration.The impact of water stressed countries, such as China in Solar2H_2, needs to be taken into consideration. Third, countries engaging in large-scale hydrogen production need to prepare measures to offset the potential negative ecologic impact. Development of hydrogen projects in resource scare regions, such as Africa, needs to be cautious as resource scarcity impact would be too high to proceed. This study may be particularly useful for countries that are suffering from water shortages but have abundant hydrogen production potential. Otherwise, hydrogen exports may be vulnerable to the criticism of biofuels – that rich people fuel their tanks with poor people's food.

The current study could be extended to study the impact of water consumption on food and agricultural production and health, to estimate the social and private costs of hydrogen supply, including the supply, use, and treatment of water.

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Author contributions

Xunpeng Shi contributed to the conceptualization, writing - Original Draft， resources， project administration and funding acquisition. Xun Liao developed the methodology, data collection, modelling and analysis, visualisation, interpretation, and writing - review & editing. Yanfei Li provided information on the hydrogen market.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights:

- Water consumption and scarcity footprint of hydrogen production through water electrolysis is quantified.
- The water scarcity footprint of hydrogen is 3,000 times less than the quantity reported in the literature.
- Water consumption for Australia’s highest hydrogen export in 2040 will only be 2% of the national total.
- Water consumption from solar PV to hydrogen can vary from 22 to 126 litres per kg of hydrogen.
- Australia’s hydrogen production from solar PV consumes more water in China than in Australia.