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The hydrogen economy - Where is the water?

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ABSTRACT

“Green hydrogen”, i.e. hydrogen produced by splitting water with a carbon “free” source of electricity via electrolysis, is set to become the energy vector enabling a deep decarbonisation of society and a virtuous water based energy cycle. If to date, water electrolysis is considered to be a scalable technology, the source of water to enable a “green hydrogen” economy at scale is questionable. Countries with the highest renewable energy potential like Australia, are also among the driest places on earth. Globally 380,000 GL/year of wastewater is available, and this is much more than the 34,500 GL/year of water required to produce the projected 2.3 Gt of hydrogen of a mature hydrogen economy. Hence the need to assess both technically and economically whether some wastewater treatment effluent, are a better source for green hydrogen. Analysis of Sydney Water’s wastewater treatment plants alone shows that these plants have 37.6 ML/day of unused tertiary effluents, which if electrolysed would generate 420,000 t H_2/day or 0.88 Mt H_2/year, and cover ~100% of Australia’s estimated production by 2030. Furthermore, the production of oxygen as a by-product of the electrolysis process could lead to significant benefits to the water industry, not only in reducing the cost of the hydrogen produced for $3/kg (assuming a price of oxygen of $3–4 per kg), but also in improving the environmental footprint of wastewater treatment plants by enabling the onsite re-use of oxygen for the treatment of the wastewater. Compared to desalinated water that requires large investments, or stormwater that is unpredictable, it is apparent that the water utilities have a critical role to play in managing water assets that are “climate independent” as the next “golden oil” opportunity and in enabling a “responsible” hydrogen industry, that sensibly manages its water demands and does not compete with existing water potable water demand.

1. Introduction

Hydrogen as a clean energy carrier is a critical component of the global decarbonisation trend. Hydrogen has the highest energy density of any fuels, 3 times that of gasoline. Hydrogen is easier to store and transport than electricity, and can facilitate the decarbonisation of sectors that are difficult to electrify [1]. Hydrogen can be produced from many different sources, including coal, natural gas, biomass and through the electrolysis of water. At present natural gas steam reforming remains the most economically viable approach to produce hydrogen at scale at ~$2/kg [2]. However, this process leads to CO_2 emissions that may be difficult to mitigateeven through carbon capture and storage. If the transition would need some level of adaptations, the future global hydrogen market has to be fully decarbonised, and most hydrogen (“green hydrogen”) sourced from water, using a decarbonised energy source to enable a virtuous energy cycle. It is predicted that green hydrogen could provide 24% of global energy needs by 2050 (i.e. ~ 38,000 TWh), helping to cut emissions by around a third. In doing so, the transition to green hydrogen could enable $11 trillion of infrastructure investment opportunities over the next 30 years and direct annual revenues of $2.5 trillion [3–5].

Today, green hydrogen is mostly produced by using a decarbonised source of electricity to split water into hydrogen and oxygen in an electrolyser [6,7]. Other technologies for direct splitting of water, such as concentrated solar, direct solar desalination, or photocatalytic are less mature [8–11]. Expanding the use of solar and wind can exponentially increase green hydrogen production [12,13].

Global hydrogen production is predicted to reach 530 Mt/year by 2050 [14]. Assuming the theoretical minimum consumption of 9 kg water for every kg of hydrogen produced, this would be equivalent to 4770 GL of water. Some have stressed that the water needs are higher and around 60 to 95 kg of water per kg of hydrogen [15], when considering the entire demineralization process to purify water before electrolysis and the requirements for cooling water to run the electrolysers. However, most of this additional water is returned to the environment. In practice, the amount of water effectively consumed is ~15 kg per kg of hydrogen and this would correspond to 7950 GL of water [16,17]. When considering a full life cycle analysis on average the solar to hy-

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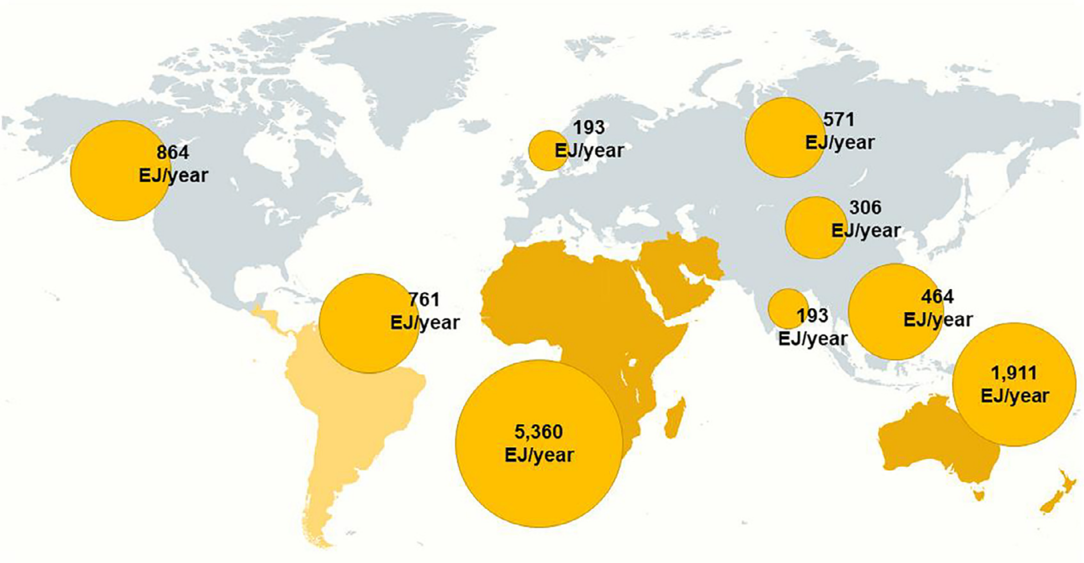

Fig. 1. Technical renewable energy potential for 2050 in EJ/year adapted from reference [26]. This corresponds to the potential renewable energy generation given system performance, topographic, environmental, and land-use constraints.

drogen water foot print is ~ 43 L of water per kg of hydrogen [18]. For comparison, the extraction and refining of oil has an average water foot print of 133 L of water per kg of oil [19,20].

Predictions have also been made that the fully mature hydrogen economy would need about 2.3 Gt of hydrogen per year, which would need approximately 34,500 GL/year of water globally [21]. Such a larger number may challenge the validity of using water as a source for the "green hydrogen" economy. However, 34,500 GL is relatively small. It is almost 3 times the water consumption of Australia (500 kL per capita in 2019) [22]. Globally, the need for water are larger, e.g. agriculture (3,1 million GL), industry (800,000 GL) and wastewater (380,000 GL) [23].

It is important to note that the regions with the most renewable energy potential and the space to install green hydrogen plants are also areas where water stress is a growing concern (Fig. 1). The challenges are associated with the potential impacts of climate change and rainfall variability. For example, across southwest Australia, winter and spring rainfall are projected to decrease by an additional 15% by 2030 [24,25]. Understanding local water use and developing effective approaches for water management will be critical to balance economic development with ecosystems and facilitate social acceptance. The challenges associated with water management and the hydrogen economy are currently largely underestimated, and if not properly addressed could lead to significant push-back.

The role of the water industry in the hydrogen economy needs to be better framed and understood. The water industry, as a well-established actor with significant experience in water management, has a critical role to play not only to help frame this transition around water utilization but also in facilitating the mechanisms for a hydrogen industry that is "responsible", i.e. sustainable, circular, socially responsible and does not lead to increase water stress and competition. The water industry produces wastewater streams that could become a sustainable source of hydrogen, as the preferred option over potable water or desalinated water. In Australia, more than 90% of the tertiary treatment effluents are returned to the environment. These effluents could provide a reliable, affordable, "climate independent" source of water to produce green hydrogen. Herein, we discuss the importance of water management for the hydrogen economy and the potential of desalinated water in comparison to wastewater. In particular, the potential of tertiary water effluents is evaluated as well as their suitability for electrolysis in the Australian context. For this data from Sydney Water's Wastewater Treatment Plants (WWTPs), also known as water resource recovery facilities, have been analysed. The potential of oxygen as a by-product of the water electrolysis process is also reviewed.

2. Why understanding, planning and managing water use is critical for the H_2 economy?

Water ecosystems can be under significant pressure especially, if not well managed [27,28]. Fig. 2 illustrates a typical ecosystem linked to human activities including urban areas, industry and agriculture. In such a nexus, a delicate balance exists between precipitation, evaporation, the amount of extracted water for human activities and the quality of the water returned to the environment. Often to improve water resilience, desalination plants are built mainly for providing drinking water. The question is then around the additional pressure a hydrogen economy at scale could impose on water systems especially in the context of climate change and extreme variability in rainfall. Green hydrogen will interlink the energy-water-nexus in unprecedented ways, because water and energy, for the first time, will directly rely on each other. Current policies around energy and water have been developed in isolation [29], and if not better integrated to enable resilience and adaptability, it is likely that hydrogen demands will directly compete with existing water sectors. New frameworks and assessment mechanisms are needed to ensure sustainability in energy and water security. This includes (i) developing an accurate understanding of current and future energy and water security in the regions where hydrogen will be produced, (ii) addressing policies that are weakening energy and water security or exacerbate shortages, and (ii) enabling strategies to adapt and decouple hydrogen production from existing water use.

The proliferation of desalination plants and inter-basin transfer to deal with water scarcity and hydrogen production may not be the answer. A typical large scale desalination plant produces 100,000 m^3 (1000 L) of water per day at a cost of \$2 million per m^3 of water produced per day [30]. This equates to a capex of \$200 million to produce 36 GL of water per year – only 0.4% of the total amount of the 7950 GL of water required by 2050 to produce 530 Mt of green hydrogen (Fig. 3). If Australia was to produce the projected 18 Mt of "green hydrogen" by 2050 without disturbing existing water demand [14], this would require at least 280 GL of desalinated water, for example (Fig. 3). Existing de-

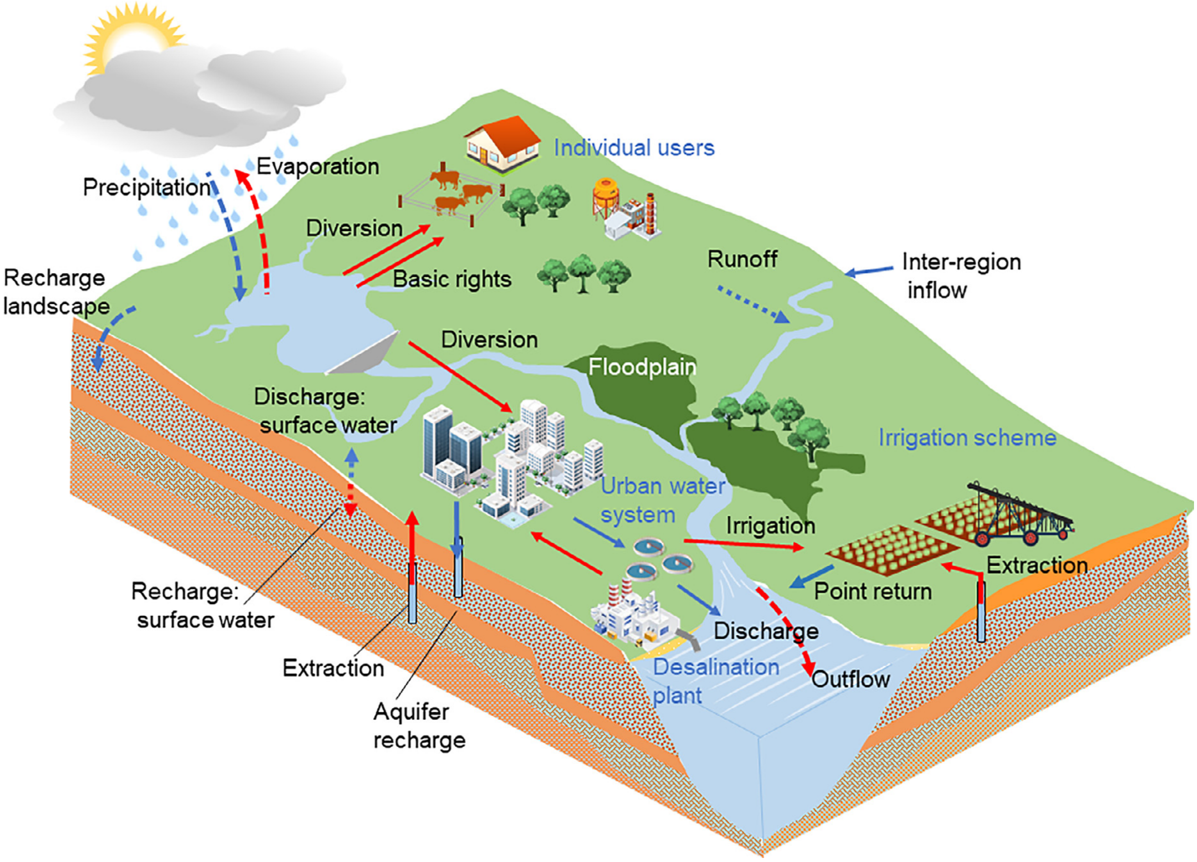

Fig. 2. Schematic of a typical water hydrological cycle embedding human activities with water inflows and outflows. Additional extraction may lead to large impacts on regional water ecosystems. This should be managed in line with the United Nation Sustainable Development Goal 6.

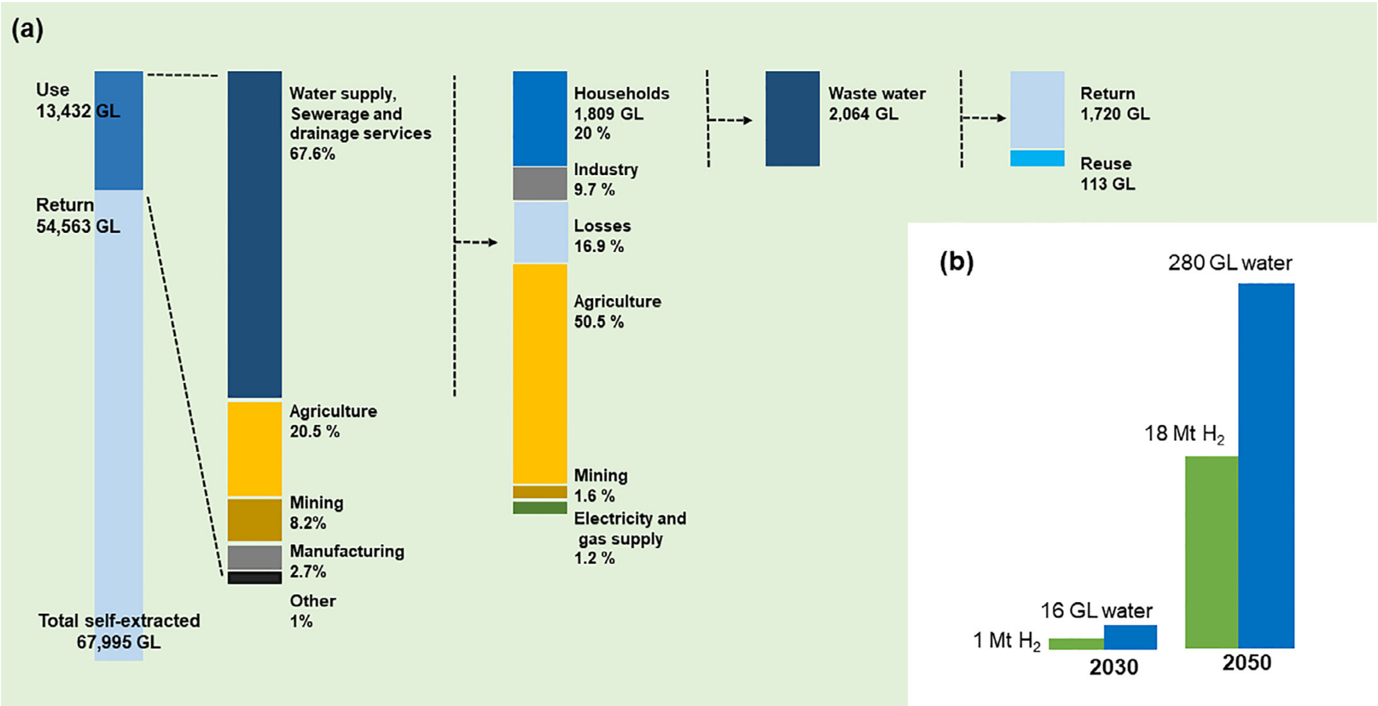

Fig. 3. (a) Summary of water extraction and use in Australia in 2019 – Source Australian Bureau of Statistics [22]. In total 67,995 GL are extracted. A large fraction, 54,563 GL, mainly used for hydropower is returned to the environment. Out of the 13,432 GL used, 1720 GL is returned to the environment after treatment in WWTPs. (b) Projected hydrogen export opportunity for Australia and equivalent amount of water assuming that all the hydrogen is “green” [14,37].

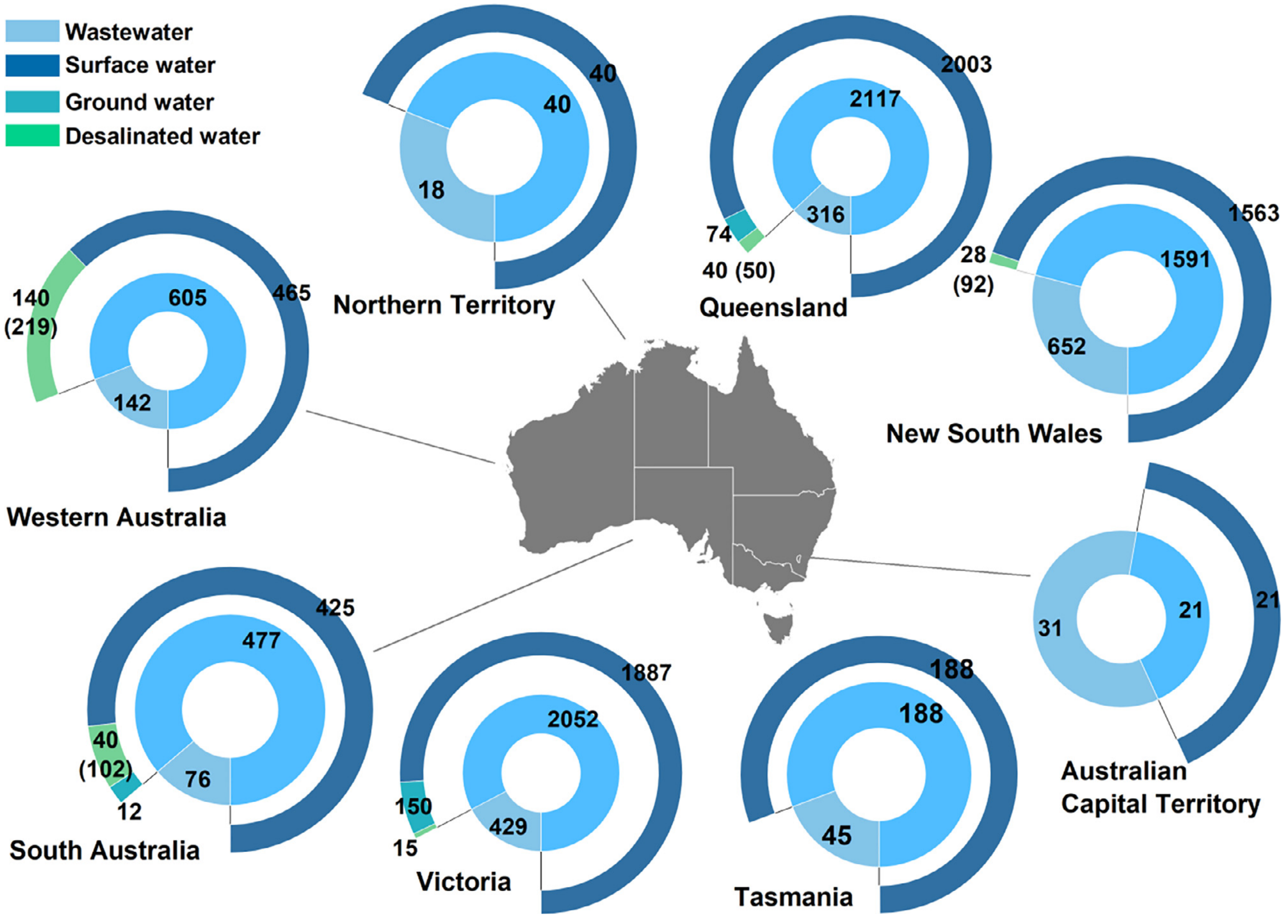

Fig. 4. Summary of water use across the Australian states. All the states have significant amount of wastewater that could be used for hydrogen production. Existing desalination would not be sufficient to support the water needs for hydrogen. Building additional desalination capacity may be less effective than enabling the re-use of wastewater and a circular economy.

salination plants across Australia do not have the capacity to produce the additional water required for hydrogen production (Fig. 4), because these have been built for improving water resilience. For example, the importance of desalination as a reliable source of water continues to grow for drinking water in Western Australia and South Australia, where constraints on conventional water sources exist. Additional large desalination plants (a $1.6 billion investment) would be needed to produce these 18 Mt of hydrogen per year. Assuming a consumption of 3 kWh per m^3 of water produced in current reverse osmosis plants [31], additional electricity generation in the range of 2400 MWh would be needed to run these plants. Given the low cost of solar ($40 per MWh) these future desalination plants could run on solar, for example. Initial predictions have shown that desalination would lead to treated water at $2–3 per m^3 and add a cost of $0.05 per Kg of H_2 [32,33]. Further treatment to reduce the environmental impact of the brine resulting from the desalination process would increase the cost of the treated water by another $0.6–2.4 per m^3 [34]. Considering the target of producing green hydrogen at $2 per Kg of H_2, the water cost through desalination may be 5% of the total hydrogen cost, but using seawater would increase water extraction up to 5 times, impact local ocean diversity through extensive extraction of microbial organisms within the sea water, and continue to lead to brine management and disposal issues [35].

3. Effluents from wastewater treatment as the alternative source for “green hydrogen”

An alternative is to appropriately manage and use tertiary effluents from wastewater, i.e. enable a “second life” to water that has already been extracted and used. Globally 380,000 GL of wastewater is available [23], and this amount is much larger than the 34,500 GL of water required to produce the projected 2.3 Gt of hydrogen when the economy has reached maturity. In Australia, 1720 GL of tertiary effluents from wastewater are returned to the environment every year (Fig. 3**a**). If that water could be converted to hydrogen this would correspond to a yearly production of green hydrogen of 0.1 Gt, i.e. the projected global hydrogen demand by 2050 and 5% of 2.3 Gt of the future hydrogen economy, and this with no major additional investment as compared to desalination. In addition, re-use of tertiary effluents from WWTPs will help improve their environmental impact [36].

However, tertiary water effluent resources are not evenly distributed across Australia and in the majority of the states these resources are located near major urban areas. Co-location of hydrogen production hubs and tertiary water effluents is thus an important aspect that should be addressed by more informed policies. Current strategies implemented across many countries around the deployment of “hydrogen hubs - where the hydrogen industry is co-located with hydrogen export capabilities” have to date not considered the need to access water and the importance of co-location of water resources and hydrogen production. From Fig. 4, it can be seen that the state of New South Wales (NSW) has the highest potential of green hydrogen from wastewater. Out of the 652 GL, only 75 GL are currently reused, mainly for agriculture, with the 577 GL remaining that could be converted into 38 Mt of hydrogen.

To further refine this potential, data from Sydney Water, one of the largest water utility in Australia’s and NSW based, were assessed (**Table S1**). The average effluent production of Sydney Water’s 16 tertiary

WWTPs is of 66.2 GL of tertiary effluents per year, with 13.7 GL per year that is currently unused and thus a potential source for hydrogen production. Running these unused effluents through conventional electrolysers could generate 0.88 MtH_2/year, which is almost 100% of the total amount of H_2 Australia could export in 2030 (Fig. 3**b**). As the market grows toward a projected Australian H_2 opportunity of 18 MtH_2/year by 2050, these unused effluents could represent 15% of Australian hydrogen export. If all Australia's hydrogen was green in 2050, the additional~ 700 ML/day of unused effluents, in addition to NSW, could be sources from tertiary water effluents across the various Australian states (Fig. 4). Sourcing hydrogen from recycled effluents would support a circular economy approach by keeping resources in use and avoiding waste [38,39].

In the scenario above, considering the cost of alkaline or polymer electrolyte membrane electrolysis and their performance specifications (**Table S2)**, generating 0.88 MtH_2/year would require $5 to 8 billion in CAPEX (equipment excluding other costs) to install 5 to 6 GW of electrolysis capacity (**Table S3)**. This may be seen as a significant investment, but a rough initial estimate only considering the CAPEX investment and a price of hydrogen at $2/kg, leads to a payback time of 3.3 to 4.4 years. To date, most models lead to a levelised cost of renewable hydrogen, i.e. produced from wind/solar with electrolysis, of $4 to $6/kg of H_2, [40] and using desalinated water instead of tertiary water effluents from WWTPs would add an additional cost as previously discussed. In these predicted levelised cost of hydrogen, the main barriers remain the cost of "renewable electricity" and current electrolysers. These are expected to considerably decrease over the coming years, in particular as the manufacturing capacity of electrolysers significantly increases [41]. However, it is likely that the target of hydrogen at $2/kg will only become commercially viable, when advanced water electrolysis technology enabling an intensification of green hydrogen production, e.g. by high efficiency direct solar to hydrogen, will emerge.

4. Suitability of wastewater effluents for water electrolysis

It should be noted that current electrolysers need water input of "guarantee" quality, regardless the source of water, to effectively operate (**Table S4**). Water for electrolysis should typically be of ionic conductivity maintained at $< 5\mu S\ cm^{-1}$ (ISO 2696 level 2), and monitored to avoid any premature failure of the electrodes splitting the water into hydrogen and oxygen in electrolysers. Water impurities that could lead to irreversible damage includes:

- Cations such as Fe^{3+}, Ca^{2+}, Al^{3+} and $Na^{+\cdot}$ that can lower the proton conductivity of the membranes in polymer electrolyte membrane electrolysers, or deposit on diaphragms due to concentration gradients in alkaline electrolysers;
- Sulphates that poison the electrodes splitting the water;
- Chlorides concentrations > 0.1 ppm that lead to extensive production of oxychloride (OCl) in alkaline electrolysers, chlorine gas (Cl_2) in polymer electrolyte membrane electrolysers and these also poison the electrodes;
- Biofilms that can lead to the formation of organics and other organic compounds. These will foam and cause faradaic issues significantly reducing the efficiency of water electrolysis.

Asserting the suitability of tertiary wastewater effluents for water electrolysis is thus critical.

Based on the analysis of the data provided by Sydney Water, it was found that tertiary water effluents are mostly of adequate quality to be electrolysed (Fig. 5), but additional purification by using appropriate deionisation techniques will be required to maintain the levels of the various elements within specifications. In particular, on the data analysed, the high level of chlorine is a concern. Langelier saturation and Silt density are also consistently not reported across existing WWTPs and this means that current data recording across WWTPs will have to be upgraded including in the frequency of data recording before tertiary effluents can be used for electrolysis.

From this analysis, it can thus be concluded that with adequate additional water treatment, e.g. through reverse osmosis or alternative technology, and suitable water quality monitoring frameworks, tertiary water effluents could very easily become a reliable source for green hydrogen production.

5. The opportunity of electrolytic oxygen in WWTPs

Oxygen (O_2) as a by-product of the electrolysis process if often vented to the atmosphere because to date it has no commercial value. However, in the context of wastewater treatment, a source of high purity O_2 would have a significant value because it would lead to a 10 fold increase in the amount of solubilised O_2 in the digesters [42], and could potentially be converted to ozone for further disinfection of the treated water. During water electrolysis, for every 1 kg of hydrogen 8 kg of O_2 would also be theoretically be co-generated [43], and valorisation of this O_2 could enable some paths in the reduction of the hydrogen production cost. In this respect, it has been proposed that if the market price of this electrolytic O_2 was of $3–4 per kg, then the hydrogen price would reduce to around $3 per kg, instead of the current $6 per kg [44].

Assuming 0.88 Mt H_2 is produced per year, at total 5.22 Mt O_2/year would be produced per year from Sydney Water's WWTPs. Considering that a total of 0.73 Mt air/year is currently used to drive the aeration processes across Sydney Water's WWTPs (**Table S5**), the substitution of exiting air blowers is equivalent to 0.82 Mt O_2/year. This is far less than the projected ~5.22 Mt O_2 that would be produced per year from water electrolysis across the WWTPs., and will lead to an additional opportunity to commercialize the remaining O_2 if suitable markets exist. One possible market is associated with fuel cells. To date, these are mainly run under air, but feeding the fuel cell with pure oxygen instead of air can lead to >17% increase in overall efficiency [45]. The direct use of O_2 in WWTPS digesters has also significant advantages because it would substitute the existing air blowers in aerobic digestion systems.. Additional retrofitting cost would be required to address the impact of pure oxygen on blowers. O_2 is produced from the electrolysers at native pressures of > 500 kPa, which is significantly higher than the 80 kPa delivered by existing air blowers. As such, the total electrical energy spent in running the aerobic digestion processes could also be saved. Assuming a wholesale cost of electricity of 0.07 $/kWh, this would represent an OPEX cost savings (mostly from power consumption) in the order of ~ $1.5 Million (Fig. S1).

WWTPs have long been regarded as attractive candidates for sector coupling and hydrogen production [46–48]. However, at this early stage of the hydrogen landscape some level of uncertainty on the right time to transition may persist among the industry despite the significant role the water industry has to play; not only in framing the opportunity but also in acting as an enabler of the hydrogen industry. Early markets already exist. One of these is in the injection of hydrogen into the natural gas network. The size of the whole domestic opportunity for hydrogen injection into the Australian natural gas grid at 10% H_2 injected is estimated to be of ~ 9.1 GNm^3/year or ~ 75 kt H_2/year by 2030. This may seem small as compared to the potential capacity from existing tertiary water effluents. However, this could provide a path to enable an early position of the water industry in the hydrogen market.

6. Australia and the water/hydrogen economy

The long established spatial and temporal patterns of the water hydrological cycle (Fig. 2) have influenced the distribution of populations across Australia. Major cities are along the coast where precipitations are more likely to occur because of the higher levels of atmospheric marine moisture [49]. To date, the impact of climate change on water distribution and availability is uncertain, because exiting models are not sufficiently robust to accurately predict the evolution of the global

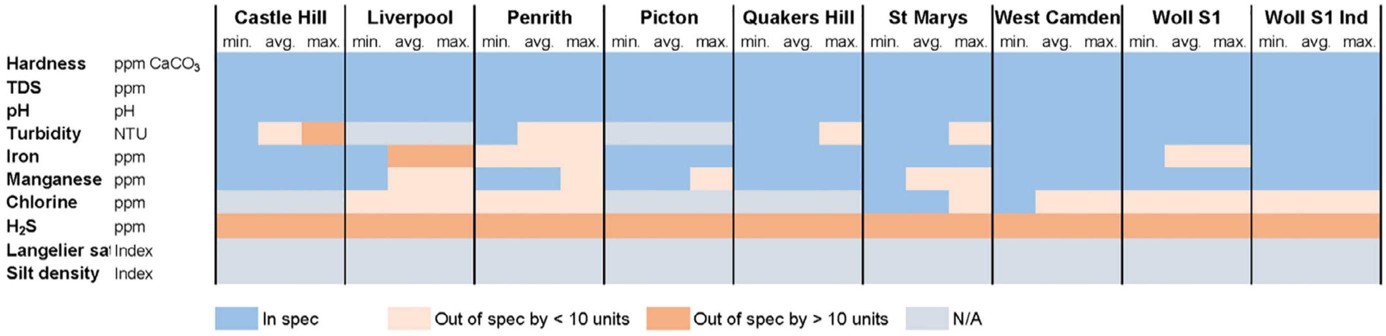

Fig. 5. Tertiary Effluent water suitability for electrolysis. Spec: Specifications, and N/A: Not Available. In spec means that the amount is below the concentration for water electrolysis and vice versa Out of spec means that the concentration is higher than the minimum acceptable amounts for electrolysis as per Table S4.

water fluxes [50]. Australia has been known as the land of droughts and flooding rains, and Australia's populations have long had to cope with this variability. A simplified view of climate change models predicts that dry regions are to become drier and wet regions wetter, with an intensification of dry and wet seasons or weather events [51]. In this context, the idea that exporting green hydrogen or indeed water to the world will lead to a depletion of water resources across Australia and intensify water stress is not true. Global water systems on earth are balanced between various water "reservoirs" including oceans, water vapor in the atmosphere, surface and ground water, and water in the cryosphere reservoirs, i.e. the glaciers, Antarctica and Greenland. These various reservoirs exchange water through evaporation and precipitations in the order of 4×10^8 GL per year [50]. In comparison, the expected 280 GL of water to be exported by Australia in 2050 (Fig. 3) is insignificant on Australia's overall water hydrological cycle. However, understanding and well managing the availability of regional water resources is critical especially when considering the intensification in the water hydrological cycle, i.e. an increase in the frequency of floods and droughts, currently observed [52]. In this context, it has been suggested that stormwater may be an additional source of water to produce hydrogen. However, stormwater are an unpredictable water source, not only in its intensity, i.e. the amount of water to be available, but also its location and temporal patterns. In addition, in comparison to tertiary water effluents, any stormwater will need to go through extensive purification before electrolysis. Although an interesting idea, the use of stormwater seems inadequate for a hydrogen industry at scale that will require a secure and constant supply of water. Innovation is however needed to facilitate a better use of water through electrolysis, not only in the amount of water that can be converted to hydrogen, but also the type of water that could be directly electrolyzed, so less pure water resources can be converted to hydrogen).

7. Conclusions

Unused tertiary water effluents have a significant potential in leading to the production of green hydrogen at scale with lower investments compared to desalinated water and a security in water supply as compared to stormwater In an efficient circular economy, use of recycled effluent for green hydrogen seems more sensible than building additional desalination plants purely for hydrogen production. Tertiary water effluents with little additional purification, mainly to ensure that chlorine levels are below 0.1 ppm at all time, are highly suited for electrolysis. In this context, the water industry has a significant opportunity to venture into the new green energy markets to enable a decarbonisation of society. For example, Sydney Water alone, as a major water utility in Australia, could produce from the tertiary water effluents across its WWTPs 420,000 t of hydrogen per day or 0.88Mt of hydrogen per year and this would cover ~100% of the estimated Australian hydrogen production by 2030. However, given the expertise of the water industry, it is apparent that water utilities have a broader and important role to play in the green hydrogen economy, not only to help shape appropriate management schemes of the regional water resources but also in enabling a "responsible" hydrogen industry, where water for hydrogen use is not directly competing with existing needs and does not lead to additional water stress. To date, water and energy policies are not integrated and green hydrogen creates unparalleled links in the energy-water nexus. Australia by tradition has always exported its resources as raw materials and let others overseas with the value added. Whatever the strategy, it is apparent that the water industry will be in the near future more intimately liked to global energy markets and thus subjected to intense market competition and challenges including in retaining national sovereignty. In this respect, the role of energy and access to energy to maintain developed societies and competitive economies should not be underestimated. The hydrogen opportunity goes beyond export. Given their central location, i.e. often in urban hubs, WWTP$_S$ facilities incorporating hydrogen production could enable new transport hubs, energy self-sufficient communities, and means to co-locate hydrogen generation with "green" farming and bio-resource hubs, leading to renewed economic models along a circular economy.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2022.100123.

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