Green hydrogen: water use implications and opportunities

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Substituting green hydrogen for conventional fuels will serve to decarbonise the energy system and reduce its water consumption. Benefits will also accrue for the water sector, including improving the efficiency of wastewater treatment, oxygenating hypoxic water bodies, improving the provision of drinking water supplies in arid regions, and making better use of the seawater resource. Accordingly it is recommended that national 'net zero' strategies address renewable electricity, green hydrogen and water use in a more integrated manner.

Water savings from green hydrogen

Water consumption has been increasing at over twice the rate of population growth over the past 100 years, with about 70% now being used by agriculture, 19% by industry and 11% in buildings.[1] Although there is no water shortage globally, fresh water scarcity threatens food security and nutrition for about 25% of the world population and, on average, only two in three people have access to safe drinking water.[2,3]

Rather than being directly consumed by end users, the majority of water use today occurs within the supply chains that serve each sector of the economy. Most existing industrial and transport activities have large water footprints, because of their dependency on hydrocarbon fuels and/or electricity generated by thermal power plants. It is therefore important to consider the impact on water use of switching to renewable electricity and green hydrogen.

The water consumption rate for electrolysis is $9kgH_2O/kgH_2$, which may be expressed as 0.27t/MWh (LHV). However, irrespective of the source, the input water to an electrolyser stack must first be cleaned and deionised. The reverse osmosis purification process is commonly used prior to deionisation to ensure the electrolyser receives water of a sufficiently low electrical conductivity. A proportion of the water withdrawn from the supply is therefore rejected. For fresh water, the required withdrawal rate ranges from about 0.3t/MWh for very clean input water to approximately 1.5t/MWh for river water. At present, a typical value for a commercially available PEM electrolyser connected to the mains water supply is 0.51t/MWh ($17kg/kgH_2$).

Thermodynamic cycles for converting fuel to electricity tend to use substantial amounts of water for producing superheated high-pressure steam and for cooling the low-pressure exhaust from the steam turbine to maximise cycle efficiency. For example, thermal power plant account for 41% of all freshwater withdrawals in the USA.[4] By comparison, wind and solar power generation have zero or minimal water footprints, so their increased adoption will yield large water savings. In the chemical and food-and-beverage-processing sectors, it has recently been estimated that water savings of nearly 60% can be achieved if the purchase of renewables is increased by 50%.[5]

Water withdrawal rates by power stations vary widely and are a strong function of the cooling technique employed, but the rates of water consumption relate mainly to the efficiency of generation, including CO_2 capture and sequestration CCS) where applicable. Consumption values have been estimated as 1.9t/MWh_e for combined-cycle gas turbines with cooling towers and CCS, 2.0t/MWh_e for integrated gasification combined cycle coal power stations with cooling towers and CCS, and 2.5t/MWh_e for nuclear power stations with cooling towers.[6] Hence the water footprint of electrolytic hydrogen is heavily influenced by the power source. For example, an electrolyser of 70% efficiency will produce hydrogen with a water footprint of about 4.1t/MWh if powered by nuclear electricity (assuming 2.5t/MWh_e) versus 0.51t/MWh if powered by wind electricity (assuming 0t/MWh_e).

The water savings achieved by adopting green hydrogen depend on the fuel that is being displaced and whether a combustion device, engine or fuel cell is being used. The volume of water used in the extraction of crude oil usually amounts to 6-8 times that of the oil produced, or up to 12 times if enhanced oil recovery techniques are applied (such as injecting water, steam or CO_2 into the well).[8] Because of this and the need to use water (steam) for refining crude oil, the overall water footprint of petrol is estimated to lie in the range 0.3-1.3t/MWh.[8,9]

For biofuels the water footprint is a strong function of whether the crop is rain-fed or irrigated. For example, values of >200t/MWh apply in some regions for ethanol produced from irrigated sugar beet and >1400t/MWh for biodiesel produced from irrigated soybean.[10] Accordingly, depending on the biomass source, the water footprints of commonly available transport fuels (e.g. blended petrol containing 10% ethanol, or diesel containing 5% biodiesel) can be much higher than those based solely on petroleum. In the transport sector, the water savings realised by preferring green hydrogen to hydrocarbon fuels are further enhanced by using fuel cell electric vehicles, because these typically consume <50% of the energy to travel the same distance as equivalent vehicles with engine-driven powertrains.

Effect of green hydrogen on the global water resource

An important question is: do we have enough water to satisfy our future demand for green hydrogen? This is analogous to the long established, but no longer relevant, question as to whether we have enough oil and gas reserves to satisfy our future energy demand.

The total mass of water on Earth is about $1.4x10^{21}$kg. Approximately 2.5% of this is fresh water, of which only $9.3x10^{16}$kg is classified as accessible surface water in lakes and rivers – glaciers and groundwater account for >99.7% of the fresh water resource. We currently use about $4.6x10^{15}$kg of water p.a.[11,12] and estimates suggest that we produce about $3.6x10^{14}$kg of wastewater p.a., which needs to be treated before being returned to rivers or used for human consumption.[13] Interestingly the current annual loss of glacier ice due to global warming is of a similar magnitude to this, about $3.4x10^{14}$kg.[14] Accessible fresh water and wastewater can enable green hydrogen production, but electrolysers will need to use desalinated seawater in arid regions and at offshore wind/solar farms. Fortunately the seawater resource on Earth is approximately 39 times greater than the fresh water resource. Together these respective amounts frame the water resources available for satisfying both established uses and the new demand associated with green hydrogen production (Figure 1).

At present, global consumption of molecular energy in the form of oil, natural gas and coal amounts to approximately 162,000TWh p.a.[15] Predictions of future requirements for green hydrogen vary but, put simply, if all this fossil fuel consumption were replaced with green hydrogen, the annual water use for electrolysis (assuming 0.51t/MWh) would be 8.3×10^{13}kg, or approximately 28kg per person per day. This is equivalent to using 0.000006% of the seawater resource, or 0.09% of the accessible fresh water resource. It amounts to 1.8% of current global water consumption. Alternatively it may be expressed as approximately one quarter of our current annual rate of wastewater production, or of the fresh water added to the ocean due to glacier ice melt. This outlines the potential scale of water consumption in a future 'net zero' scenario involving a multi-terawatt deployment of electrolysers. Clearly the new load placed on Earth's water resource would be very small compared with our current consumption and it would be counteracted by water savings achieved by reducing the use of hydrocarbon fuels and electricity generated by thermal power plant.

Water use due to electrolysis should, however, not be viewed as gradually using up the water resource, because when green hydrogen is oxidised (by combustion or via a fuel cell) it yields the same amount of water as was originally electrolysed. This may enter the atmosphere as water vapour, or be condensed at the point of use and recovered as liquid water. Moreover the production of green hydrogen simultaneously produces oxygen in the exact amount required to oxidise the hydrogen: this is an important characteristic, because atmospheric oxygen depletion is contributing to global warming.[16] Consequently the widespread production and use of green hydrogen is expected to have a comparatively neutral effect upon Earth's water and oxygen resources, and the increased adoption of renewable energy (as electricity and hydrogen) will serve to reduce global water consumption.

Green hydrogen is therefore widely viewed as the 'net zero' fuel for our future energy system, with green oxygen replenishing the associated consumption of atmospheric oxygen. However, it should be noted that some of the hydrogen will be required as a feedstock (e.g. for ammonia and methanol production) rather than as a fuel, and some of the green oxygen will be applied to industrial processes and water oxygenation as opposed to being vented to the atmosphere.[14] For instance, hydrogen and nitrogen will be carried into plants in the form of ammonium, and oxygen will be used by the steel industry.[17] It is therefore important to identify synergies between the electrolyser's need for water and the use of both green hydrogen and oxygen, because these could accelerate the deployment of electrolysis in the limited period we have left to combat climate change.

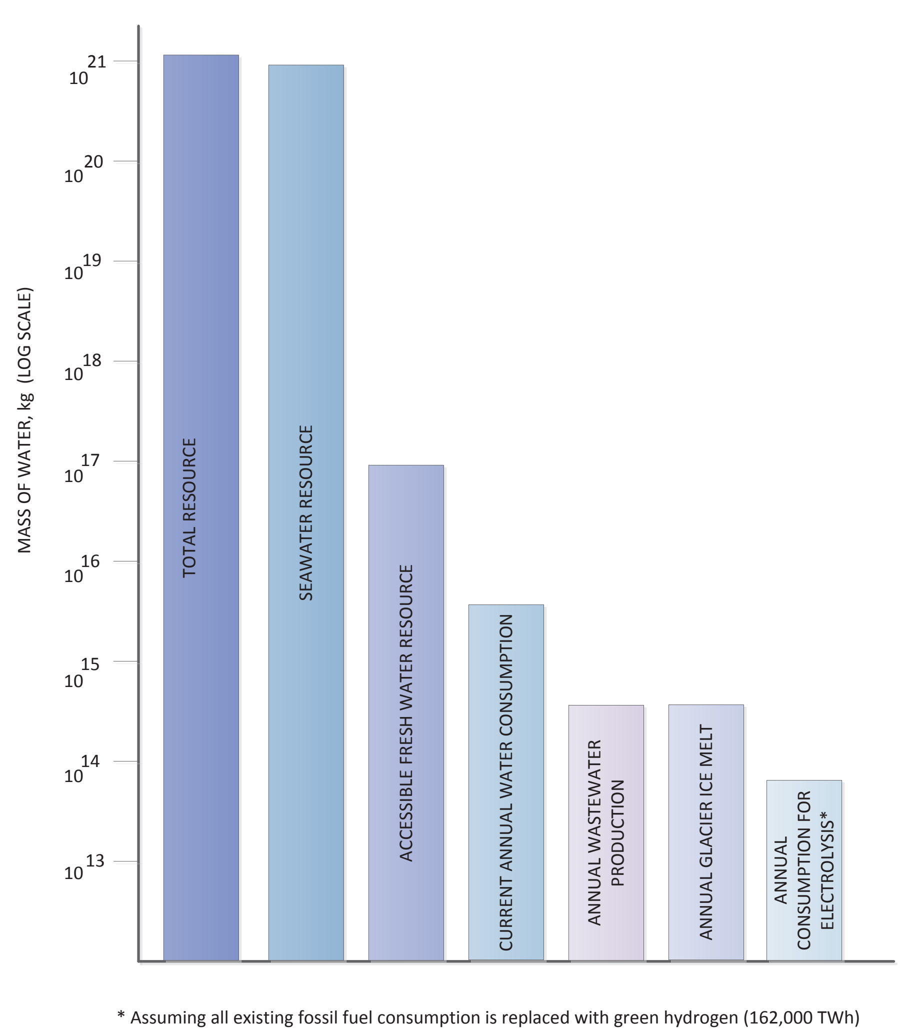

Figure 1: Annual water requirement of green hydrogen production relative to Earth's water resources

Wastewater as a hydrogen feedstock

The use of oxygen as well as hydrogen improves the commercial viability of electrolysis. When a guaranteed demand for oxygen exists, some of the costs of hydrogen production can be offset. The water industry is particularly well placed to exploit this, because it has scope to:
- Provide the necessary water for electrolysis; Process the water stream rejected by the electrolyser system;
- Utilise green oxygen for wastewater treatment to improve process efficiency;
- Recover heat from the electrolyser to improve process efficiency;
- Use waste-to-energy or renewable power sources on site to provide electricity;
- Export green hydrogen.

Wastewater treatment results in the emission of three global warming gases (nitrous oxide (N_2O), methane (CH_4) and CO_2).[18] Cleaning wastewater is essential for ensuring water of sufficient quality is produced for returning to rivers and the ocean, or for use as drinking water. Aeration of active sludge is the most critical part of the energy-intensive wastewater treatment process, where microorganisms and oxygen work together to break down the organic matter. Achieving adequate dissolved oxygen levels is key to this biological process, otherwise degradation of the sludge can occur only under septic conditions, which is very slow, malodorous and yields hydrogen sulphide, methane and organic acids. Air is conventionally used, but supplementing it with oxygen improves the efficiency of waste water treatment, and this manifests as savings in capital equipment and energy costs.

The water industry has the potential to use electrolysers to meet its own oxygen requirements, while simultaneously producing green hydrogen for other applications including vehicle refuelling and/or injection into nearby gas distribution networks or industrial processes. Because wastewater treatment plants tend to be located relatively close to towns, they offer numerous possibilities for creating decentralised hydrogen hubs and driving the deployment of electrolysers. There are approximately 34,000 wastewater treatment plants in the US and Europe.[19] Also there are now over 400 hypoxic zones in the world (including 165,000km^2 in the Gulf of Oman and 20,000km^2 in the Gulf of Mexico,[20]) where large scale electrolyser facilities could be used to help raise dissolved oxygen levels as well as produce green hydrogen.

Table 1: Water requirements for households using green hydrogen for home heating and fuelling cars

	One-person household (modern apartment) using one car	Average UK household using one car	Four-person household (old detached house) using two cars
Current average water consumption, kg/day[29]	154	349	534
Approximate energy demand for space heating and hot water,* kWh/day[30]	26	34	64
Water requirement for making hydrogen for a fuel cell car travelling 50km/day, kg/day	8.5	8.5	17
Water requirement for making hydrogen for heating the home (assuming a hydrogen boiler efficiency of 95%), kg/day	14.0	18.3	34.4
Total water footprint, kg/day	176.5	375.8	577.9
Increase in household's water footprint due to use of green hydrogen, %	15	8	10

*Heat demand is a function of several factors, including dwelling age, size, orientation, glazing area, insulation level, local climate, preferred indoor temperature, occupancy patterns and tenure.

Seawater as a hydrogen feedstock

Seawater consists of numerous minerals and metals, ranging from sodium to gold, which have an estimated total mass of 5x10^{19}kg.[21] Seawater may be mined for elements such as magnesium (1272ppm), calcium (400ppm), bromine (65ppm), lithium (0.1ppm) and iodine (0.05ppm). For example, 63% of magnesium production in the USA is sourced from seawater and brine.[22]

It has been estimated that approximately 2.4x10^{13}kg of desalinated water is produced annually and that demand is increasing at >9% p.a.[23] There are now >21,000 desalination plants in at least 174 countries, which are used mainly for supplying drinking water, irrigating crops and oil and gas extraction.[24] They operate thermally by distillation or mechanically via reverse osmosis, with the latter being more common. Reverse osmosis has a relatively low electricity requirement for desalination of approximately 0.003kWh/kgH_2O[25], so an electrolyser system consuming 17kgH_2O/kgH_2 will incur an additional electricity consumption of about 0.05kWh/kgH_2. This equates to an energy overhead upon the electrolyser of only 0.1% relative to producing green hydrogen from fresh water.

The brine effluents produced by desalination plant are ion rich and of relatively high density, so their disposal effects the local marine environment by altering light levels and causing hypoxic and anoxic conditions on the sea bed.[26] To reduce this, before the brine is discharged back into the ocean it may be diluted with seawater, oxygenated with green oxygen and mined to recover minerals.

In general the implementation of green hydrogen production from seawater affords an interesting set of secondary opportunities, including:
• The integration of an electrolyser and its desalination plant with a renewable power source as an engineering product[27,28];
• The provision of a rainfall-independent drinking water supply by oversizing the desalination plant relative to the water requirement of the electrolyser;
• Use of green oxygen for oxygenating desalination effluents and hypoxic zones in estuaries and coastal areas;
• Extraction of minerals from the desalination effluent;
• Off-grid production of hydrogen, oxygen and drinking water in regions where the electricity grid is weak or non-existent.

Water use and recovery

In developing countries, the high demand placed on traditional water sources is causing communities to increasingly use rainwater, stormwater, brackish water and seawater. By implementing green hydrogen production, a new impetus could be established for resolving water supply problems. By oversizing the water purification plant required by an electrolyser facility, a contribution can be made to supplying clean drinking water. In general, an integrated approach to providing green hydrogen and water could assist public health, as well as decarbonisation, objectives in many regions of the world.

In developed countries, the existing water consumption per household far exceeds that needed to produce green hydrogen for fuelling a fuel cell car or heating a house. For example, for an average UK household with a water consumption of 349kg/day,[29] a water overhead of 27kg/day would be sufficient to produce enough green hydrogen for space heating, hot water and travelling 50km/day in a fuel cell car. Household water use and heat demand vary across the building stock, but in general the amount of water required for switching heat and mobility to green hydrogen equates to only a small percentage of existing use (Table 1). Furthermore it should be remembered that water savings will be achieved by households switching away from purchasing conventional fuels to buying renewable electricity and green hydrogen.

Where feasible, it is desirable to recover liquid water from hydrogen use (for example, from hydrogen boilers, combined heat-and-power systems and fuel cells). This will reduce the amount of water vapour that would otherwise be ejected to the atmosphere due to fuel use, which will help reduce global warming and enable the latent heat of vaporisation to be recovered in thermal applications (and hence the higher heating value of hydrogen to be utilised – 39.4kWh/kgH_2 HHV versus 33.3kWh/kgH_2 LHV).

Conclusions

Energy is used in two forms (electrons and molecules) and it is now critical that both electricity and fuel are produced in an environmentally sustainable manner. If all existing fossil fuel use were switched to green hydrogen, the water requirement for electrolysis would amount to 1.8% of current global water consumption. This new demand would be counterbalanced by water savings achieved by not having to produce fuels from petroleum or biomass and by reducing the use of conventional thermal power plant. Furthermore, when green hydrogen is oxidised by combustion equipment and fuel cells, the same amount of water that was originally consumed by electrolysis is released back into the environment. Therefore, in general, a massive deployment of electrolysis will have a relatively neutral impact on the global water resource.

The water required by electrolysers can be sourced from accessible fresh water, seawater and wastewater. In each case it must be purified and deionised prior to electrolysis. In dry regions, islands and offshore locations, electrolysers will rely mainly on the seawater resource and this must first be desalinated (either at scale or by integration within the electrolyser system). Accordingly there are distinct opportunities for deploying electrolysers, ranging from decentralised hydrogen hubs at wastewater treatment plants to gigawatt-scale hydrogen production at offshore wind/solar farms.

Several additional benefits are obtainable for the water industry, including improving the provision of drinking water in developing countries and oxygenating hypoxic zones in lakes, rivers and coastal regions. Therefore it is recommended that electrolysis should play a more central role in future policies concerning energy and water: achieving a multi-terawatt electrolyser capacity by mid-century would yield massive positive benefits.

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