HYDROGEN REPORT JAN 2024

WATER REQUIREMENTS FOR VARIOUS APPROACHES TO HYDROGEN PRODUCTION:

Quantitative, Siting, and Resilience Considerations

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REPORT PREFACE

This report on hydrogen production is based on a larger technical work, What Good Is Hydrogen? A Technical Exploration of the Potential of Hydrogen to Contribute to a Decarbonized Energy System,[1] also produced by IEER for Just Solutions Collective. The high water intensity of hydrogen production raises important issues for siting hydrogen production facilities, competition among water uses in water-stressed areas, and water rights, including in areas where water-intensive thermo-electric generation is being replaced by wind and solar electricity, which need almost no water.

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Preface

This report on hydrogen production is based on a larger technical work, *What Good Is Hydrogen? A Technical Exploration of the Potential of Hydrogen to Contribute to a Decarbonized Energy System,*[1] also produced by IEER for Just Solutions Collective. The high water intensity of hydrogen production raises important issues for siting hydrogen production facilities, competition among water uses in waterstressed areas, and water rights, including in areas where water-intensive thermo-electric generation is being replaced by wind and solar electricity, which need almost no water.

Another reason to discuss water in a separate report is that water use has so far played a relatively minor role in the policy discussions and formulations of hydrogen policy. Yet, if hydrogen is to play a major role in a decarbonized energy system, the reliability of its supply in the face of intensifying weather extremes and prolonged droughts should be an essential consideration. The electricity system needs significant restructuring to increase its resilience even as it is being decarbonized. Some or much of that increased resilience could be compromised unless resilience considerations are also built into hydrogen production decisions, including water supply for its production.

There is also reduction in water use when hydrogen replaces fossil fuels; the specifics depend on which fossil fuels are displaced, the relative efficiency of hydrogen use compared to the fossil fuels displaced, and the specific methods of fossil fuel and hydrogen production. This displacement of water use would generally occur in locations different from those where hydrogen is produced. Thus, global balance is important for considering the overall impact. However, site-specific issues will remain critical, notably with large-scale hydrogen production. Given the magnitude of the on-site water use involved, we focus on the site-specific issues in this report, while illustrating global issues in some places.

This report is designed to provide estimates of water use for hydrogen in the context of emerging national hydrogen policy. We use national data and typical values to arrive at these estimates. For instance, we use the national average water consumption for electricity generation when estimating grid-electricity-related water requirements for electrolysis. The value at a specific site will depend on the local mix of grid electricity. There is also a wide range of estimates for water purification requirements. These considerations point to the need for a site-specific assessment when evaluating hydrogen hub proposals especially since the availability of water and the emerging stresses on water supply vary significantly across the country. While the general approach applies to other countries as well, the water considerations in this report are specific to the United States.

It is critical to note is that a true “apples-to-apples” comparison of water requirements when green hydrogen displaces grey hydrogen or fossil fuels – as in steel production and truck fuel examples in this report – is extremely difficult and, to some extent, impossible. That is because the water pollution caused by fossil fuel production is widespread and vast. For example, mountain top removal for coal mining has polluted thousands of miles of streams. Likewise, much oil and most natural gas in the United States is produced by hydraulic fracturing, which injects chemical-laden water into the ground. We have discussed this issue in this report, providing some qualitative notions and some data points of the extent of pollution reduction on a national and global basis that could result if green hydrogen displaces fossil fuels. But the quantitative analysis in Sections II to IV does not reflect the positive water implications of that.

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[1] Makhijani and Hersbach, forthcoming 2023

The full hydrogen report, *What Good is Hydrogen?*, is scheduled to be issued in early 2024. IEER is also producing a companion report on long-duration energy storage, including a discussion of the role that hydrogen might play in a decarbonized, resilient electricity system.

One of us, Arjun Makhijani, owes special thanks to Aiko Schaefer, Executive Director of Just Solutions Collective, for the trust and confidence she has reposed in him and in the Institute for Energy and Environmental Research (IEER) to lead the critical work on hydrogen and long-duration storage. Matteo Bertagni (Princeton University) and Elena Kreiger (PSE Healthy Energy) sent very useful comments on *What Good Is Hydrogen?*, including on water use questions. We have benefited from many useful comments and suggestions from members of the Research Collaborative that have materially improved the scope and content of the report. The Research Collaborative was appointed by Just Solutions to develop an environmental justice framework for energy transition technologies and to review the reports being prepared by IEER for Just Solutions as part of the Breakthrough Foundation grant. We are also very thankful to Breakthrough Energy Foundation for funding this work, via Just Solutions Collective, and to Ani Kame'enui, the Program Officer at Breakthrough Energy for the reviews and comments on the hydrogen report in the course or its preparation. As the authors of the report, we alone are responsible for any errors that might remain and for its contents, findings, and recommendations.

November 2023

Arjun Makhijani President, IEER	**Thom Hersbach** Project Scientist, SLAC National Accelerator Laboratory Policy Fellow, Stanford Woods Institute for the Environment

Findings regarding water use for hydrogen production

There following are the main findings from the above analysis of water use for hydrogen in this report:

- **Overall water consumption for using hydrogen as an energy source will be very large:** Commodity hydrogen production would grow by about five times between 2020 and 2050 under DOE's optimistic estimate of hydrogen demand in its 2050 draft hydrogen strategy. However, water consumption for hydrogen production would increase roughly ten times, from 33 billion gallons a year in 2021 to roughly 200 to 400 billion gallons a year by 2050. The disproportionate increase is largely due to the higher water intensity of green, blue, and especially pink hydrogen compared to present-day steam methane reforming without CCS. If green hydrogen is the main production mode and hydrogen use is close to the low end of DOE estimates, water requirements would be in the neighborhood of 140 billion gallons per year.
- **Some of the water used for hydrogen production can be recovered and reused:** Hydrogen and oxygen react in fuel cells to produce water that can be recovered and reused for stationary applications such as combined heat and power and peaking generation. This is an important advantage of fuel cells relative to burning hydrogen.
- **Low-carbon hydrogen is more water-intensive than grey hydrogen, especially if produced with nuclear energy cooled by freshwater sources:** Green and blue hydrogen are roughly similar in terms of water consumption and larger than grey hydrogen. In contrast, if thermoelectric sources like nuclear are used for electrolytic hydrogen production, freshwater consumption for electrolytic hydrogen would increase more rapidly.
- **Hydrogen production could stress freshwater supplies in certain areas:** For example, states supplied by water from the Colorado River already experience severe water stresses between residential, commercial, and agricultural uses.[2] Water use for hydrogen has the potential to increase such stresses significantly, with concomitant economic, legal, and political implications.
- **Both gross and net water use should be considered:** Water requirements for fossil fuel production are reduced when hydrogen displaces fossil fuel use. The amount displaced will depend on the specific end use, the specific fossil fuel displaced, and the place and method of its production. In the two examples in this report – steel production from iron ore and Class 8 trucks – about half the water use is offset when green hydrogen replaces fossil fuels.
- **It is critical to consider gross water use at the hydrogen production site:** Siting hydrogen production should take local water availability into account, since the water use reduction for fossil fuel production will generally occur at sites different from the site of hydrogen production.
- **All hydrogen production infrastructure will have some water-related pollution impacts** but the net impact will depend on which fossil fuels are displaced, the hydrogen production method, and the efficiency of hydrogen use.
- **Green hydrogen used to displace fossil fuels has large water-related environmental benefits through avoided fossil fuel production, transportation, and use.** Fracking-related water pollution, pollution related to coal ash ponds and mountaintop removal, pollution related to oil spills, and routine oil pollution of the ocean would all be avoided. Acid rain due to burning sulfur-containing fossil fuels and, if hydrogen is not burned, due to nitrogen oxide emissions, would also be avoided.

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[2] James 2022. While the immediate crisis in the Colorado River Basin has eased somewhat due to heavy precipitation during the 2022-2023 winter, the shortage is structural and expected to continue.

I. Introduction

Hydrogen (H_2) is not at present a major energy source at present in large measure because it is a secondary fuel – that is, it must be produced from other primary energy sources. Yet, like electricity, it is an energy carrier that could serve useful purposes. Currently, the most common primary energy source used to produce hydrogen is natural gas. Methane, the main constituent of natural gas, is rich in hydrogen atoms: its chemical formula is CH_4. Methane-derived hydrogen is generally not used for energy purposes, because it is often cheaper to directly use the natural gas a fuel. Instead, hydrogen is currently produced from methane as a chemical commodity for use in many industries, mostly in petroleum refining and for ammonia and methanol production.

The necessity of a decarbonized energy system has created a widespread interest in hydrogen as an energy source, since it emits no carbon dioxide (CO_2) when so used.[3] If hydrogen can be made economically enough with low- or zero-CO_2 emissions, it could theoretically play a significant role in the energy system. The two low-carbon production methods most widely considered are (i) hydrogen produced from natural gas with the CO_2 being sequestered and (ii) hydrogen produced by electrolysis of water using a low- or zero-carbon electricity source. The larger report that we are writing will address the range of technical issues involved with producing, transporting, storing, and using hydrogen in detail. In this report, we consider water issues associated with the following production processes:

1. Hydrogen made from natural gas without carbon capture – called "grey" (or "gray") hydrogen;
2. Hydrogen made from natural gas with carbon capture and sequestration (CCS) – called "blue" hydrogen;
3. Hydrogen made by electrolysis (splitting water (H_2O) into hydrogen and oxygen gases using electricity)
    a. using renewable electricity (solar or wind) – called "green" hydrogen;
    b. using nuclear electricity – called "pink" hydrogen;
    c. using grid electricity – called "yellow" hydrogen.

Using electricity to recover hydrogen by splitting water into its component elements necessitates consideration of the water requirements for electricity generation; as discussed below, these can vary from essentially zero (wind-generated electricity) to very large (nuclear and other thermo-electric generation).

II. Water consumption and withdrawals

Water (H_2O) is an essential input for both electrolysis and fossil-fuel-based hydrogen production since the hydrogen atoms in H_2O provides part (fossil fuel cases) or all (electrolysis) of the hydrogen atoms in the final product.

For each of these processes, the minimum feed water requirements arise from considerations of basic chemistry. This minimum water demand is called the 'stoichiometric requirement'. In the case of methane (CH_4), half the hydrogen comes from methane and half from steam (H_2O); the production method is called "steam methane reforming" (SMR):

$CH_4 + H_2O \rightarrow CO + 3\ H_2$

$CO + H_2O \rightarrow CO_2 + H_2$

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[3] It combines with oxygen in air: $2\ H_2 + O_2 \rightarrow 2\ H_2O$. This is the only product when fuel cells are used. When hydrogen is burned using air (as for instance in a gas turbine), it also results in nitrogen oxide pollution.

Combined, these reactions yield the following overall result (shown with molar masses for each input and output):
CH_4 (1 mole = 16 grams) + 2 H_2O (2 moles = 36 grams) → CO_2 (1 mole = 44 grams) + 4 H_2 (4 moles = 8 grams).
This translates into 4.5 kilograms of water per kilogram of hydrogen, which is equivalent to 1.19 gallons (4.5 liters).[4]

For electrolysis, the net reaction is simpler; but as with SMR it also involves catalysts:

2 H_2O (2 moles = 36 grams) → 2 H_2 (2 moles = 4 grams) + O_2 (1 mole = 32 grams).
This equates to 9 liters of water per kilogram of hydrogen, which is 2.38 gallons (9 liters).

Thus, the stoichiometric water requirement for electrolytic hydrogen per unit mass of hydrogen is double that for steam methane reforming. However, it should be noted that the actual raw water requirements for both steam methane reforming and electrolysis are higher than the aforementioned theoretical minimums, in large measure due to water purity requirements. Because input water streams require low concentrations of dissolved solids, any 'raw' water is processed to the required purity. Such purification results in some water being rejected.[5] The amount of rejected water depends on the purity of the input water. Consequently, a significant part of the variation in water withdrawal for steam methane reforming and electrolysis is due to the varying purity of the input water. The addition of carbon capture and sequestration – essential for "blue" hydrogen – increases water use significantly. Thus, converting a grey hydrogen site to a blue hydrogen site will, among other things, generally increase water requirements. This makes water requirements for green and blue hydrogen generally comparable.

An additional source of water consumption is the water that is required for producing the electricity needed for hydrogen production, because all methods of hydrogen production require electricity to power their equipment. Electricity is a small fraction of the energy for grey hydrogen and does not impact water use much, but the impact is increased when an energy-intensive CCS process is added for blue hydrogen.

In electrolysis, electricity is the energy source used to break apart the hydrogen-oxygen bond in H_2O. As a result, the water requirements for electricity production also become a factor in the water intensity of electrolytic hydrogen. Water demands will be high when using grid electricity to do so, because most generation in the United States is "thermo-electric" (also called "thermal") electricity generation: a fuel is used to boil water into high pressure steam, which drives a steam turbine, which in turn drives the electricity generator. A schematic of thermo-electric generation, as exemplified by a pressurized water nuclear reactor, is shown in Figure 1. It shows how the steam that drives the turbine-generator set is produced and condensed so that the steam water can be used in a closed loop. A separate stream of water used in the condenser (bottom right half of Figure 1); the condenser water carries away the latent heat in steam and condenses the steam back into water. The process is the same for nuclear, coal-fired, and natural gas boiler power plants, though the boiling is differently arranged. Typically, about two-thirds of the energy in the fuel is transferred into the condenser water; this explains the large water requirements of thermo-electric generation.[6]

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[4] A kilogram of hydrogen is roughly equivalent in energy terms to a gallon of gasoline.

[5] The rejected water is often 2 to 4 times more concentrated in dissolved solids than the feed water, and can therefore generally be used for other purposes. It is therefore considered to be withdrawn, and not consumed. (See Section II.a and II.b.)

[6] Natural gas combined cycle plants use both a gas turbine and a steam turbine. They are much more efficient than coal or nuclear plants and, as a result, use much less water.

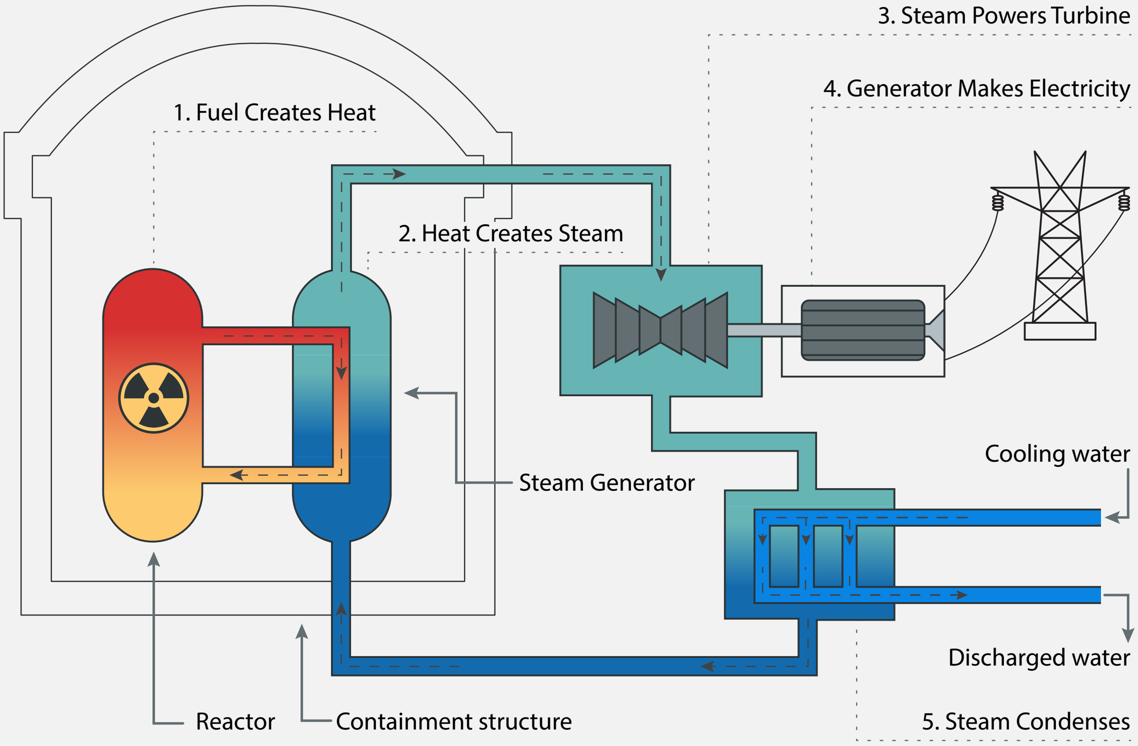

Figure 1: Schematic of a nuclear power plant, showing the condenser. Based on a Nuclear Regulatory Commission schematic at https://www.nrc.gov/images/reading-rm/basic-ref/students/student-pwr.gif

The condenser water consumption in thermo-electric generation is very large: millions of gallons a day are heated up and evaporated – thus being lost to use – in a typical 1,000-megawatt nuclear power plant. In contrast, wind generation uses essentially no water, and solar utility-scale photovoltaic generation only requires a small amount of water for periodically cleaning the panels. As a result, the water requirements for electrolytic hydrogen are driven in large measure by the electricity generation method. The different water requirements for grid-, nuclear-, and renewable-driven electrolysis are explored in the following sections, and presented quantitatively in Figure 2.

We distinguish between water *consumption* and water *withdrawals*. Water withdrawal refers to all input water for hydrogen production. The amount of water withdrawn is the sum of water that is consumed and water that is eventually returned to the source from where it was withdrawn. Water consumption means the water is used up in the process of hydrogen production in the following ways:

- The hydrogen in the water becomes part of the hydrogen product (see the equations above).
- The portion of the water needed for electricity generation that is lost to use (by evaporation in the case of thermo-electric generation or in other ways as, for instance, when solar panels are washed down).

Other streams of water are withdrawn, but not consumed. Examples include:

- The water rejected during reverse osmosis water purification. Such purification yields a pure water stream, and a discharge stream that contains all dissolved solids that were removed from the pure water stream. Although more concentrated, the discharge stream is often clean enough to be discharged and is therefore not consumed.[7]
- The portion of the water needed for electricity generation that is not used. For example, 'once-through cooling' of power plants (see below) returns most of its withdrawn water back into the water body from where it was taken initially.

Water is also needed to produce excess steam (i.e. above the stoichiometric requirement) to drive methane reformation; it is usually subsequently recovered and reused and therefore not included in our water consumption calculations.

Water withdrawals for thermo-electric generation are larger, sometimes much larger, than water consumption, since some of the water withdrawn is not evaporated and can be re-used. Water withdrawal can be a major issue in the case of thermo-electric generation, as explained below. Even though much or most of the water withdrawn for thermo-electric generation can be re-used downstream, large withdrawals can pose constraints on production during extreme weather events, notably when the intake water temperature is high and/or when drought reduces the water available for electricity production. These factors already occasionally affect nuclear electricity generation.

We will consider three methods of water use in thermo-electric generation:

1. **Once-through cooling:** Water is taken in from a source like a river, lake, or ocean then used in the condenser, where it is heated up, followed by discharge into the same water body from which it was withdrawn. Some of the warmed water evaporates. Typically, the amount withdrawn is well over an order of magnitude larger than the amount evaporated.
2. **Cooling lake:** A large artificial lake is established and filled as the source of intake water. The water is discharged back into the lake at a different point; it circulates back around the lake to the intake, cooling down in the process – and resulting in evaporation of some of the water.
3. **Cooling tower:** The heated water from the condenser is fed by nozzles into the top of a cooling tower, cooling down as some of the water evaporates. The cooler water, collected at the bottom, can be reused a number of times before it gathers too many impurities for reuse and must be discarded. Cooling towers have the highest water consumption and the lowest water withdrawal requirements.

We consider annual averages for each of these three cooling methods when there is fresh-water intake – the topic of this report.[8] Many thermal plants, including some nuclear plants, are located on coastal sites and use seawater for cooling. They have their own environmental impacts that are beyond the scope of this report; we only note here that those impacts led the California State Water Resources Control Board to adopt a policy in 2010 of ordering a stop to once-through cooling for all thermo-electric plants, including nuclear plants, by adoption of recirculating methods or by reducing impacts by alternative specified methods.[9]

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[7] Han and Elgowainy 2017

[8] Withdrawals and consumption are seasonal for any given plant due to seasonal water temperature variations.

[9] California Water Resources Board 2021

a. Estimates of water consumption

Figure 2 shows the freshwater consumption for grey, blue, green, and the three methods of cooling nuclear power plants in case of pink hydrogen.[10] In this Figure, the bottom (blue) segment of each column expresses the amount of water that is used directly for hydrogen production. This type of water consumption entails stoichiometric water requirements, as well as process cooling water needs. An additional water use relates to the electricity that drives hydrogen production; most electricity sources require some amount of water, which is reflected by the top (red) segments of each column in Figure 2.

These electricity needs are most important for electrolysis, which uses more electricity than other hydrogen production methods. Finally, natural gas-based hydrogen has some water requirements for obtaining natural gas.[11] These are reflected by the middle (yellow) segments for grey and blue hydrogen in Figure 2.

Between these options, driving electrolysis with nuclear electricity consumes the most water, because nuclear power plants are thermo-electric generation methods. A different estimate for each nuclear plant cooling method is shown. Reactors in coastal areas use seawater for cooling, but the water consumption estimates in Figure 2 apply only to reactors that use fresh-water for cooling.

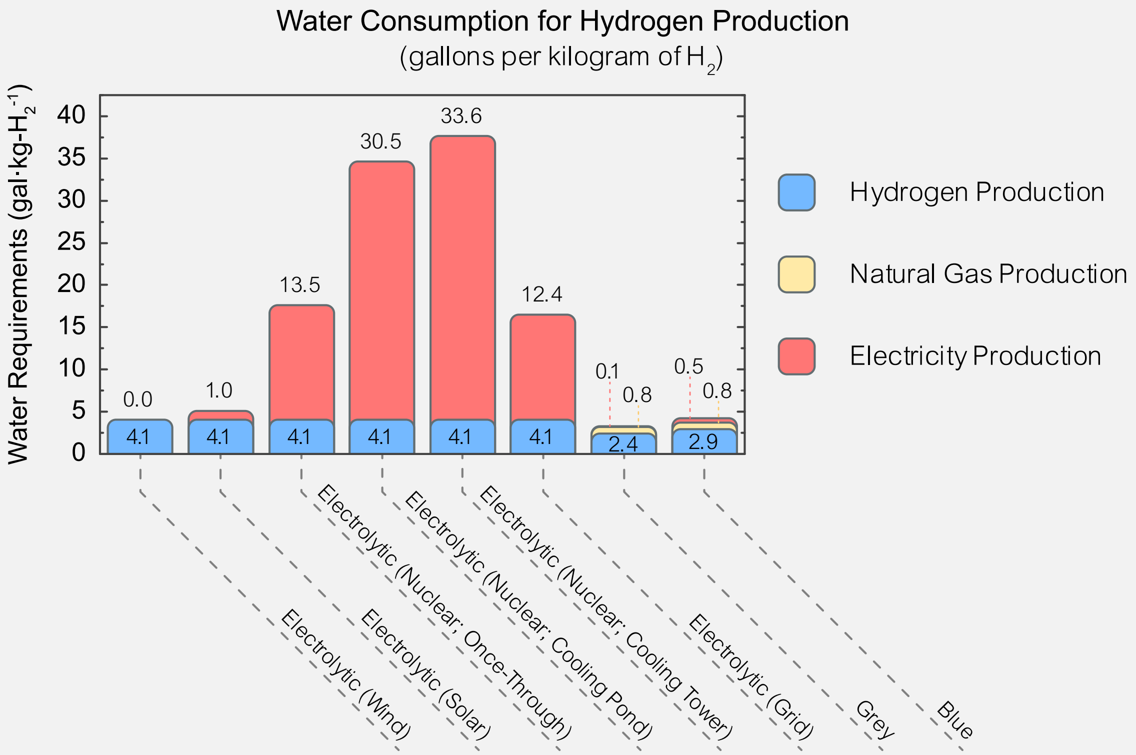

Figure 2: Water consumption for various methods of hydrogen production. Steam methane reforming without CCS ("grey" hydrogen) is the current dominant technology. Values rounded to the nearest tenth of a gallon. The numbers at the tops of the bars represent the water consumption for the electricity portion alone. The total water use should be read off from the axis at the right of the chart.

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[10] Argonne 2022. "Auto-thermal reforming" is a variation of steam methane reforming of natural gas with similar water requirements; it is therefore not shown separately. Several other hydrogen production methods are also analyzed in the Argonne report. We have focused here on the ones that are proposed for the widest use.

[11] Lampert 2015, Table 7.

Note 1: Electricity-related water requirements for non-electrolytic hydrogen production methods taken as 250 gallons/MWh; this is the 2015 national average consumption over all sources of electricity production.
Note 2: Typical values for raw water required for the process have been used. Variations due to differences in raw water purity are not shown.
Note 3: Steam methane reforming requires excess steam to drive its process. The water required for this steam is assumed to be recycled and therefore not included in this figure.
Note 4: We have not considered energy requirements for liquefying natural gas since natural gas distribution in the United States is by pipeline.
Sources: Han and Elgowainy 2017, Table 9 for hydrogen production values (blue bars), Lampert et al. 2015 and EIA 2023A for natural gas water consumption, and UCS 2011 for electricity water requirements. We used 0.25 gallons per kWh for grid-supplied electricity; this is the overall national average water consumption for 2015; calculated from USGS 2019, Table 5. Only fresh-water consumption is included.[12]

Likewise, grid-powered electrolysis requires large amounts of water, because most electricity is still produced using thermo-electric generation. The electricity generation part for grid-powered electrolysis can be expected to decline over time as the fraction of low-water generation methods, like solar and wind, increases. Analogously, there is considerable variation in average grid electricity water use due to the variation in thermo-electric generation across U.S. regions; the national average was used in Figure 2 for purposes of illustration only. Site-specific calculations should be done when evaluating hydrogen hub proposals.

In sum, Figure 2 indicates that water requirements for the electricity needed for electrolysis depend greatly on the method of generation, ranging from essentially zero for wind, to small for solar (for panel cleaning), to very large for nuclear and other thermo-electric generation: water consumption for electricity generation dominates the total in the nuclear electrolysis case. This makes “pink” hydrogen the most freshwater-intensive method among those shown in Figure 2.

It is also important to note that the numbers in Figure 2 are general estimates, which are useful for comparing different hydrogen production technologies, but unsuitable for calculating the water usage of a specific hydrogen production site. Like any analysis, the one in Figure 2 is sensitive to the assumptions that underlie it: this point is highlighted in Section IV-b, but is also apparent from a separate analysis by the National Energy Technology Laboratory (NETL).[13] This analysis estimates the values of the blue bars in Figure 2 for grey and blue hydrogen to be 4.2 and 6.4 gallons per kilogram of hydrogen, respectively. This difference illustrates that the exact water requirements of hydrogen production will vary from site to site and for proposed projects must be calculated on a site specific basis.

A final caveat is that the water input for electrolysis is somewhat affected by the efficiency of the electrolyzer, which determines how much electricity is required to make hydrogen. Figure 2 assumes an electrolyzer system efficiency of 65%, which means that 65% of input electricity is stored as chemical energy in hydrogen.[14] If system efficiency increases to the DOE ultimate target of 77%, the electricity required for electrolysis will drop by 15.6%. The corresponding electricity-related water requirements would drop accordingly. However, hydrogen produced using nuclear or grid-electricity would still be the most water intensive options.

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[12] Water requirements for the capital investments required for hydrogen production are not taken into account in Figure 2. While this omission means the total shown is not a complete life-cycle water consumption estimate, it is still reasonable since hydrogen would displace fossil fuel use and fossil fuel production also has water use associated with its capital investment.
[13] NETL 2022, Exhibit 5-6 1
[14] DOE 2023

b. Water withdrawals

The issue of withdrawal amount is important because water supply can and does become more constrained in times of very hot weather and/or drought. Thermo-electric power plants in the United States have been forced to curtail generation on occasion in such circumstances. This issue is also important because periods of very hot weather are also times of high electricity demand for airconditioning. Electrolytic hydrogen production using thermo-electric generation such as nuclear or geothermal electricity could therefore be adversely impacted as hot weather events become more intense and frequent. This could reduce hydrogen supply reliability and increase costs. Climate change impacts on hydrogen production due to water availability are likely to vary greatly across the United States. As a result, it will be essential to factor in climate change into possible deterioration of the reliability of hydrogen supply due to water availability on a site-specific basis when siting hydrogen production facilities.

Water withdrawal requirements per kilogram of hydrogen using nuclear generation are approximately as follows:

- About 2,000 gallons for *once-through cooling;*
- About 350 gallons for *cooling ponds;*
- About 55 gallons for *cooling towers.*

Figure 3 compares the water consumption and water withdrawal requirements for the electricity generation portion of pink hydrogen production corresponding to the three methods of nuclear plant cooling.

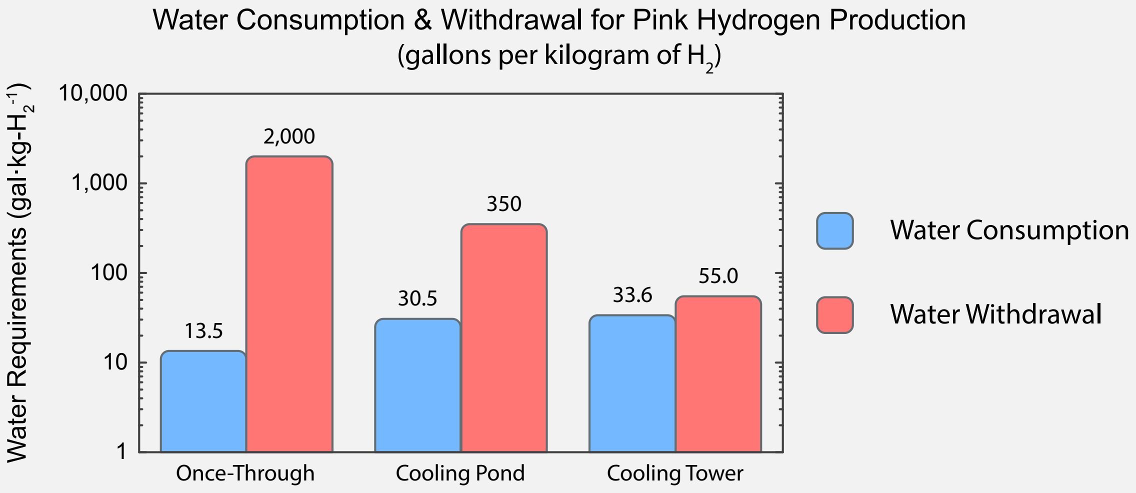

Figure 3: Comparison of water consumption and withdrawal requirements for nuclear electricity required for pink hydrogen production by cooling method; note the logarithmic scale on the vertical axis. Process water requirements of about 8 gallons per kilogram of hydrogen not shown.
Source: Calculated using USGS 2019, Table 5

The water withdrawal requirements for grid-based electrolysis (yellow hydrogen) are similarly high: about 360 gallons per kilogram of hydrogen – similar to the cooling pond case for pink hydrogen shown above in Figure 3.

Figure 3 shows that water withdrawal outpaces water consumption but the ratio depends on the method of power plant cooling. The ratio varies from less than 2 for cooling tower cooling to about 12 for cooling ponds to about 150 for once-through cooling. This difference is not an issue when using low-water electricity generation methods, like wind and solar generation, for which water withdrawal and consumption are very low and also comparable to each other.

Figure 3 also highlights the differing trends for water consumption and withdrawal between cooling techniques. Notably, once-through cooling has the lowest water consumption, but requires about 6 times the water withdrawal of cooling ponds and 36 times the water withdrawal of cooling towers. But cooling towers and cooling ponds *consume* much more water mainly by evaporation: 2.5 and 2.3 times respectively relative to once-through cooling.

c. Additional water requirements

There are also water requirements for the production of the equipment used to make hydrogen. The catalysts required for hydrogen production are important in this regard. For example, some types of electrolyzers contain rare metals like platinum and iridium. For example, a 1-MW proton electron membrane electrolysis plant requires 0.75 kilograms of iridium and 0.075 kilograms of platinum.[15] Both of these metals are predominantly mined in South Africa, where mining this quantity of metal requires 59,000 gallons of water (approximately a tenth of an Olympic swimming pool).[16] These are one-time water requirements that occur while acquiring the materials that will last years in an electrolyzer; as a result the requirements per kilogram of hydrogen are low. But the impacts in the metal-producing areas can be high (see Section V).

The issue of water use also applies to steam methane reforming, which uses nickel-based catalysts. The use of rarer metals, like rhodium and platinum, is also being investigated.[17] It takes about 80 gallons of water to produce one kilogram of nickel.[18] However it should be noted that the total amount of water needed for catalysts per unit of hydrogen production is smaller than the rounding error of 0.1 gallon per kilogram of hydrogen. It is the pollution impacts that are more critical (see Section V below).

III. Total water consumption for hydrogen scenarios

We can put water use per unit of hydrogen production in perspective by estimating the total water consumption requirements hydrogen production. We use the draft Clean Hydrogen Strategy and Roadmap of the Department of Energy to illustrate the order of magnitude of water consumption involved. In its “optimistic” scenario, the DOE envisions about the same level of hydrogen production in 2030 as at present (commodity hydrogen is about 10 million metric tons), but produced as green hydrogen or blue hydrogen. Hydrogen production would further increase to 20 million metric tons by 2040 and 50 million by 2050.[19] If the DOE target of $1 per kilogram for green hydrogen is achieved by 2030, production of this type of hydrogen component would be expected to rise rapidly after 2030, having the lowest warming impact and possibly also the lowest cost.

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[15] Bareiß, K. 2019
[16] Buchspies et al. 2017
[17] Ruban et al. 2023
[18] Elshkaki e al. 2017
[19] DOE Strategy 2023

The following mix of hydrogen production methods was used to estimate the water consumption that is implied by the levels of production in the optimistic scenario in the draft DOE hydrogen strategy:

- 2020 – grey hydrogen – 10 million metric tons of H_2;
- 2030 – 90% blue hydrogen and 10% green hydrogen – 10 million metric tons of H_2;
- 2040 – 60% blue hydrogen and 40% green hydrogen – 20 million metric tons of H_2;
- 2050 Option 1: 40% blue hydrogen and 60% green hydrogen – 50 million metric tons of H_2;
- 2050 Option 2: 30% blue hydrogen, 60% green hydrogen and 10% "pink" hydrogen using freshwater-cooled nuclear-generated electricity for electrolytic production – 50 million metric tons of H_2.

The above assumptions are not an estimate or endorsement of any particular hydrogen mix; they are used here to provide an order of magnitude estimate of the water requirements in the DOE draft hydrogen strategy shown in Figure 4. They are illustrative calculations since neither the scale nor mix of hydrogen production methods can be forecast with any certainty. Water use for hydrogen production would rise rapidly in the DOE optimistic scenario with any mix of low-carbon production methods, mainly due to production increases but also because all three low-carbon hydrogen production methods – green, blue, pink – are more water-intensive than the present dominant method – steam methane reforming without CCS. The estimates shown in Figure 4 are relatively insensitive to the partition between green and blue hydrogen, since water consumption for both methods per metric ton of hydrogen is similar.

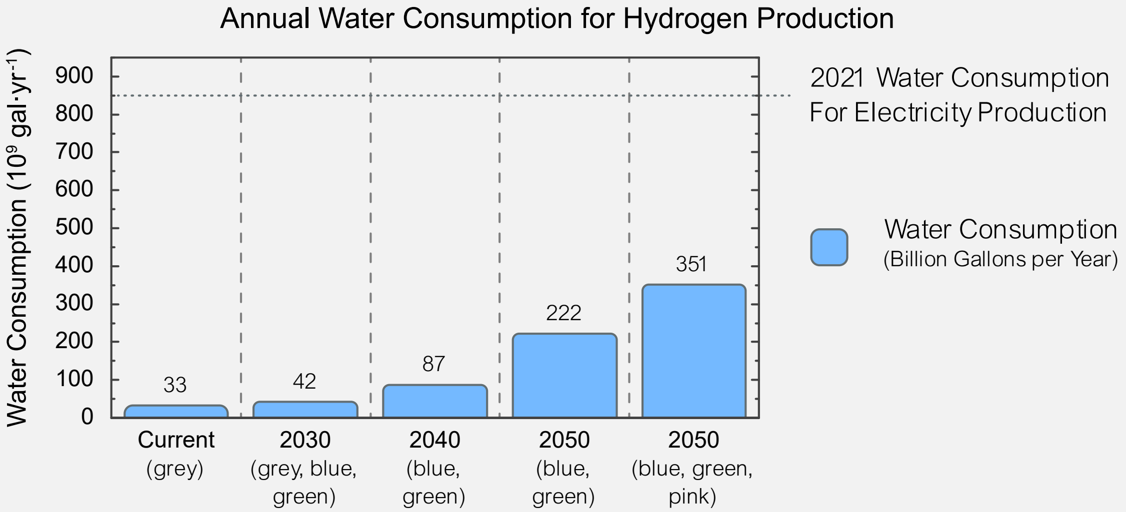

Figure 4: Estimates of water consumption for hydrogen production corresponding to optimistic production levels in DOE's Draft Hydrogen Strategy (DOE Strategy 2023). Based on Figure 2 estimates of water use per metric ton of hydrogen and USGS 2019 Table 5. Nuclear power water intensity is estimated using an unweighted average of all three nuclear cooling methods in Figure 2.

As Figure 4 indicates, water use in 2050 would be significantly larger if a substantial proportion of hydrogen were produced by nuclear-powered electrolysis: the rightmost column in Figure 3 shows that if only 10% of the hydrogen production is shifted from "blue" (steam methane reforming with CCS) to "pink" (electrolysis with nuclear energy), water consumption would rise by about 30%.

Recent literature confirms the importance of taking water requirements into account. Grubert (2023) has also noted the dependance of the water-intensity of electrolytic hydrogen on the specific source of electricity used. Given that the present electricity grid is dominated by thermo-electric generation "if the water intensity of the grid remained the same as its historical [2014] value, electrolytic hydrogen production of 15 EJ or more would require as much freshwater consumption as the entire 2014 US energy system." [20] 15 EJ (exajoules) is about 15% of U.S. energy use; that amount of hydrogen may displace roughly 25% of U.S. fossil fuel use, with the precise amount depending on the specific fossil fuel uses displaced and the efficiency of hydrogen use in those specific applications. Overall, the numbers presented in Figure 4 agree roughly with those estimated by Grubert (2023): approximately 400 to 500 billion gallons per year for two scenarios producing approximately 50 million metric tons of hydrogen per year.[21]

Considerations relating to net water consumption, taking into account the reduction in water use due to lower fossil fuel use, are more complex; we discuss them briefly here. Figure 4 compares water consumption corresponding to the DOE draft hydrogen strategy with the water consumption by the United States electricity sector in 2021. Electricity generation consumes more water than any other industry in the United States, other than agriculture.[22,23] The comparison with electricity-based water demand explicitly shown as a percentage number in Figure 5. As Figures I-4 and I-5 show, fifty million metric tons of hydrogen production would require roughly eight to ten times water the consumption for present-day hydrogen production. It would raise freshwater use to roughly 200 billion to 400 billion gallons a year (rounded) – which would be between about 25% and 40% (rounded) of the 2021 water consumption in the electricity sector.

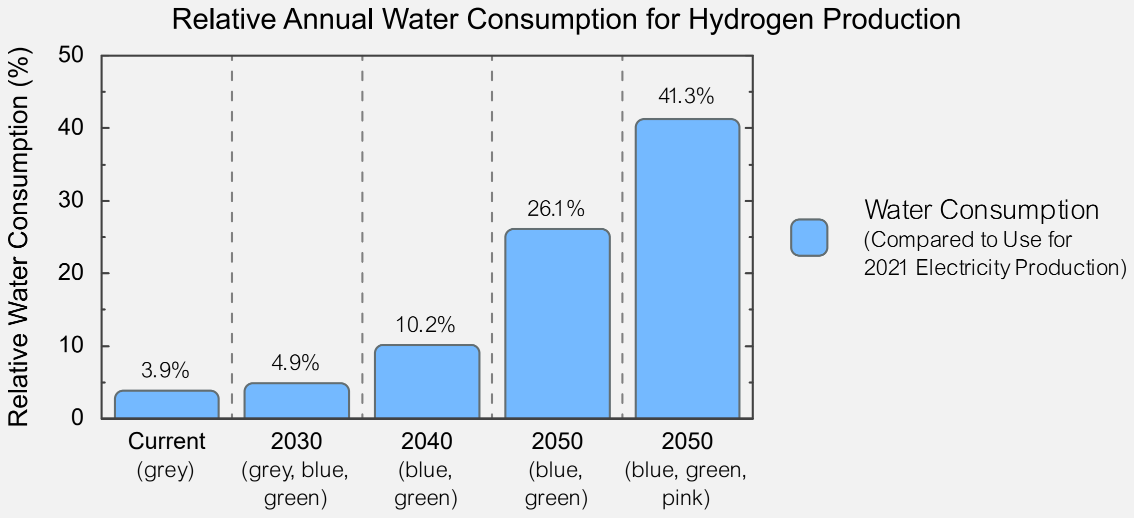

Figure 5: Hydrogen production water consumption as a percentage of 2021 electricity sector water consumption. Source: Data in Figure 4.

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[20] Grubert 2023

[21] The paper assumes an electrolyzer efficiency of 75%. Its 'Williams Low Demand' scenario estimates 450 billion gallons per year to produce 44 million metric tons of hydrogen per year, while its 'Williams Central' scenario estimates 530 billion gallons per year for 57 million metric tons of hydrogen per year. The water intensity of the electricity grid differs slightly for each scenario.

[22] Dieter et al. 2018

[23] Water consumption in the electricity sector in 2021 was about 850 billion gallons. USGS 2019, op. cit., Table 5.
This publication provides the 2015 water consumption estimates. We calculated the approximate 2021 water consumption requirements by factoring in the changes in electricity generation between 2015 and 2021. Electricity generation data are from the Energy Information Administration at https://www.eia.gov/energyexplained/electricity/charts/generation-major-source.csv Electricity sector fresh water withdrawals in 2015 were 80 billion gallons a day (USGS 2019, Table 5), compared to 118 billion gallons a day for irrigation (USGS 2018 p. 1). However, only about 3.4% of thermoelectric generation freshwater withdrawal is actually consumed by evaporation. (Note: USGS 2018 has a somewhat higher freshwater withdrawal for electricity generation (96 billion gallons a day) than USGS 2019, which we have used in this report.

The DOE also has a base case in which hydrogen demand by 2050 would be roughly half of the optimistic 2050 level. As a result, the range of potential water consumption for hydrogen production would be 110 to 350 billion gallons per year in 2050, depending mainly on total hydrogen demand but also on how much of the hydrogen is produced using nuclear electricity.[24]

Our own estimate of hydrogen use in What Good Is Hydrogen? that would provide a clear climate benefit by 2050 – roughly 30 million metric tons (rounded) – is towards the lower end of the DOE range. This would entail using about 140 billion gallons a year of water for making green hydrogen from renewable energy that would otherwise be curtailed. These are indicative numbers from a climate perspective and do not take siting and water justice issues into account. They should not be seen as a recommendation, but rather as an illustration for comparison with the draft DOE hydrogen strategy. Moreover, the portion of hydrogen production process water used in stationary applications could be recovered. This would be the case, for example, in fuel cell peaking generation and combined heat and power in industry – but not if the hydrogen is burned (which we do not recommend). Thus, the net water requirements for green hydrogen in the mix of applications we recommend could be lower than 140 billion gallons per year – especially since we do not recommend use in buildings and only minor use, if necessary, for long-distance trucking transport relative to DOE's optimistic case.

Figure 5 also shows the evolution of water consumption for DOE's optimistic hydrogen production scenario as a percentage of the 2021 water consumption in the electricity sector. Forty percent of 2021 electricity generation water consumption may well make hydrogen production the dominant water user sometime between 2030 and 2050, except for agriculture. This is because water consumption in the electricity sector, which has already been declining, will decline rapidly as the fraction of solar and wind generation increases: utility-scale solar generation consumes only about 5% of the water consumed by coal-fired generation per unit of power production, while wind-generated electricity requires essentially none.

Freshwater consumption for hydrogen could be reduced in a variety of ways. For instance, purified sanitary wastewater that may be unacceptable for residential uses for social reasons could, if it met the purity criteria, be used for hydrogen production.[25,26] However, unless non-potable water of adequate quality is already available, water purification would add to the expense of hydrogen production. The type of input water would also determine electricity usage and pollution issues associated with hydrogen production, which in turn affects environmental justice burdens and public health impacts.[27] Alternatively, the direct use of seawater – that is, without desalination – for electrolysis would reduce freshwater requirements to a small amount. However, this is a nascent technology that is currently far from commercially feasible.

Mining geologic aquifers of brackish water or using oil and gas-related produced water and purifying it for hydrogen production has also been proposed where fresh water is scarce. Specifically, it has been proposed to examine this possibility for New Mexico.[28] There are a large number of technical, ecological, and environmental justice considerations associated with such an approach including the priorities for water use where it is already scarce. The issue is briefly discussed Chapter V on environmental justice considerations.

Finally, distributed hydrogen production facilities may be appropriate for instance to support community microgrids to strengthen resilience of electricity supply and ensure continuity of supply to essential loads during multi-day grid outages.[29]

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[24] We should note that only hydrogen from new nuclear reactors with capacity dedicated to that end would result in net greenhouse gas emission reductions. Diverting existing nuclear electricity for hydrogen production – as is being done with DOE support at the Nine Mile Point nuclear plant in New York State – would generally have significantly increased net emissions even though the onsite emissions would be zero. The nuclear electricity for hydrogen would be diverted from existing loads – which then would have to be supplied from the electricity grid resulting in associated carbon emissions. We estimate that in the case of the Nine Mile Point pilot plant, the global emissions per kilogram of hydrogen would be greater than those associated with grey hydrogen. Makhijani and Hersbach 2024 forthcoming.

[25] LA City Council 2022

[26] Water purity standards for electrolysis are higher than those for residential water supply.

[27] These potential impacts would likely be much lower than the impacts of fossil-based technologies that would be replaced by hydrogen. This consideration is further explored in section V.

[28] New Mexico Consortium, no date.

[29] IEER is exploring community microgrids and long-duration energy storage and preparing a report on that topic for Just Solutions Collective.

IV Net water requirements with examples for two specific end uses

When hydrogen displaces fossil fuels, the water requirements for producing the latter are eliminated. The net water use in the country (or the world, in the case of imported fossil fuels) are therefore lower than the water requirements discussed above which do not take the reduction into account. In this brief discussion, we assume that the displaced fossil fuels are produced in the United States, a realistic assumption (despite the fact that there are some petroleum imports and exports). We also assume that, for an initial order of magnitude estimate, the water requirements for the production infrastructure required for hydrogen – the steel, the cement and other materials — and that needed for fossil fuels it displaces are about the same. We focus here on two considerations important for estimating net changes in water use:

- The water use that is eliminated because the displaced fossil fuels (including any water requirements for processing them) are no longer being produced;
- The reduction in water use for those cases where hydrogen is used much more efficiently than the fossil fuels that are displaced so that fewer British thermal units (Btus) of hydrogen are needed to do the same job.

We provide two examples – one where hydrogen is far more efficient than fossil fuels (steel production) and the other where efficiency is comparable:

- Steel production from iron ore using coking coal compared to green hydrogen;
- Fuel cell Class 8 truck compared to a new diesel truck.

a. Steel

Making steel from iron ore requires coke, which is made from coal. Surface as well as underground coal mining operations require significant amounts of water. So does processing metallurgical coal into coke suitable for reducing iron ore to pig iron in a blast furnace. As discussed in the Makhijani and Hersbach report (2024 – forthcoming), it takes over 600 kilograms of coke to make a metric ton of steel; this is replaced by about 60 kilograms of hydrogen. Using EPA estimates for quenching coke (so that it does not burn once made) of 1,130 liters per ton[30] and Meldrum *et al.* for surface and underground mining water requirements,[31] we estimate that roughly 1 cubic meter (264 gallons) of water is needed for coke production to create one metric ton of steel and 2 cubic meters (528 gallons) of water would be needed To make green hydrogen, roughly half the water requirement for reducing iron ore is offset by avoiding coke production. However, this calculation doesn't fully account for all the water involved in coal production. Metallurgical coal comes from mines east of the Mississippi, where mountaintop removal is a common method of surface mining. This type of mining results in pollution of streams, making water unusable without purification – which involves its own losses. According to the NGO Appalachian Voices, over 2,000 miles of streams have been buried by mountaintop removal. By the year 2012, 1.4 million acres of forest had been destroyed;[32] that, of course, has its own impact on water resources. It is therefore difficult to do an apples-to-apples comparison since significant water resources are indirectly used up in coal production. Overall, the water impact in going from coke to green hydrogen could range from somewhat increasing water use to decreasing it. There would also be significant reductions in water and air pollution. The latter benefits will be highlighted in our full report on hydrogen.

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[29] IEER is exploring community microgrids and long-duration energy storage and preparing a report on that topic for Just Solutions Collective.

[30] EPA 1995

[31] Meldrum 2013

[32] Appalachian Voices, no date

b. Class 8 Trucks

Figure 6 shows the water requirements per mile for producing, transporting and using “blue” or “green” hydrogen to power a new Class 8 fuel cell truck compared to a new diesel truck. It also shows the CO2 equivalent (CO2-eq) emissions in each case.

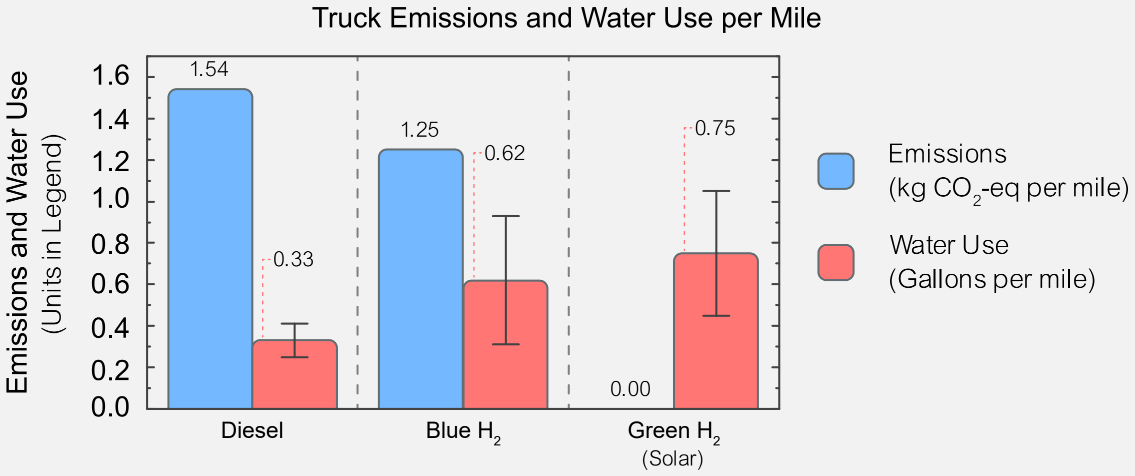

Figure 6: Water requirements and CO_2-eq emissions per mile for diesel and hydrogen fuel cell Class 8 trucks. Values from the Argonne National Laboratory GREET model (Argonne 2022) adjusted to account for methane leaks at 2.7% and 20-year methane global warming potential of 82.5.[33] Truck efficiencies used: new diesel: 6.65 miles per gallon diesel; fuel cell: 6.81 miles per kilogram hydrogen (Argonne 2021, Table 3.5, Tractor, day-cab truck, low values for 2025 models). Relative values are unchanged if the higher mileage values are used since both diesel and fuel truck efficiency increase by about the same amount.

Sources: For water: Han and Elgowainy 2017 (diesel water intensity and all 10-90 interval ranges), Figure 2 (hydrogen water intensity), and Argonne 2021 (truck mileage); for CO_2-eq: IEER analysis of transportation emissions. As Figure 6 indicates that green hydrogen can drastically cut per-mile CO_2-eq emissions in comparison to diesel trucks. The CO_2-eq value for blue hydrogen is close to but slightly lower than a new diesel truck; however it has not been adjusted for the fraction of CO_2 captured and sequestered, which Argonne 2022 assumes is 96% (p. 6). Actual experience indicates the amount sequestered could be far lower. A reduction of CCS performance to 70% would add about 0.33 kg CO_2 per mile, making blue hydrogen CO_2-eq emissions 1.58 kg CO_2-eq per mile or about the same as diesel.[34] In addition, blue and green hydrogen fuel cell trucks use approximately twice as much water per mile as diesel trucks do. Overall, green hydrogen has climate value in terms of reducing greenhouse gas emissions at the cost of higher water use. Blue hydrogen has essentially no climate value but higher water use than diesel.

However, this analysis only considers direct water consumption. This caveat is notable, because a full water assessment also necessitates evaluating the water pollution associated with petroleum production and refining; that is not accounted for in Figure 6, because it is challenging to quantify comprehensively. Such pollution indirectly affects global water availability because polluted resources are either unusable or require water treatment – which is energy-intensive. Pollution-related issues are briefly discussed in Section V of this report.

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[34] Schlissel and Juhn 2023 (in Figure 5) provide data indicating a range of capture and sequestration values for commercial scale projects not involving secondary oil production from 38% to 83%.

Furthermore, even in situations where the net global water consumption changes little, it will still be necessary to consider water resource availability at the place(s) where hydrogen production is sited since, typically, the corresponding reduction in water use would occur at a different location. There will be exceptions to this. For instance, the production of hydrogen feedstock and ammonia production can be co-located or located in close proximity. If green hydrogen using wind energy were to replace steam methane reforming in such cases, the area-specific water requirements would increase much less. Increases in water use patterns would be similarly modest if conversion of grey to blue hydrogen is being considered to reduce CO_2 emissions.

To further illustrate the importance of site-specific analyses, Figure 6 indicates the uncertainty in water consumption estimates. These uncertainties correspond to the lowest (10th percentile) and highest (90th percentile) results from an analysis in Han and Elgowainy 2017; this study sought to determine the effect of variabilities in the assumptions that underlie water consumption estimates. The resulting uncertainty ranges, shown in Figure 6, indicate that actual water consumption can vary anywhere between half and double the calculated value. Therefore, the results in the present report are general estimates and do not necessarily translate to specific hydrogen production sites. This point is further underscored by a modeling study by the NETL, which estimates twice approximately twice as much water consumption than the 2.4 and 2.9 gallons presented in Figure 2.[35] Consequently, any site-specific water consumption assessment will require more detailed analysis for that particular site and hydrogen production proposal.

V. Some environmental impact and environmental justice considerations

While this report primarily considers the quantitative aspects of water requirements for hydrogen production (and to a lesser extent, use) there are some evident qualitative water-related ecological, environmental justice, and economic justice considerations that we set for briefly here for possible future detailed study.

The large water requirements of hydrogen production at scale could have adverse economic and environmental justice impacts notably where water is scarce. Among the most important examples are six states (as well as Mexico) that draw water from the Colorado River basin. In this region, severe water shortages have already created significant economic, political, and social stresses. Large-scale hydrogen production could well aggravate these. In light of regional water stresses, the New Mexico Produced Water Research Consortium has proposed to use produced water – the water that comes up with oil and gas in especially copious quantities when production is by fracking. In the same vein, geologic brackish ground water is also being examined as a source of water to meet the state's needs. Besides the added cost of the water, there are a number of issues to be resolved before such water can be produced in quantity with the requisite quality, including the following:[36]

- It is not a renewable resource – it would be mining water.
- Land surface subsidence due to groundwater extraction;
- The risk of brackish and saline water contaminating freshwater aquifers.
- Environmental problems associated with disposal of the rejected saline water.
- Spills of saltwater from pipelines that could contaminate soil.

In the case of use of produced water from the oil and gas industry for hydrogen production, a major issue is tying hydrogen production – meant to be a low- or zero-emissions energy source of the future with a polluting industry that is at the center of greenhouse gas emissions. Produced water availability is after all contingent on continued oil and gas production – including by fracking.

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[35] NETL 2022, Exhibit 5-6

[36] New Mexico Earth Maters 2015

Possibly the most important justice issues relate to water use priorities. If geologic water deposits from an ancient sea are going to be mined and purified at some expense and risk in a region where water is scarce and supply increasingly conflicted an uncertain, what should it be used for? The question becomes much more acute when one considers the lack of reliable domestic clean water supply for many communities, notably Indigenous nations, in the Southwest and the immense water allocation issues that have already emerged in the Southwest.

From a qualitative life-cycle assessment point of view, we also note that both hydrogen and the fossil fuel it would replace are capital- and energy-intensive industries where the production (and refining) require large amounts of basic industrial materials like steel and cement. Thus, we assume that these infrastructural components cancel out when replacing fossil-based technologies for hydrogen-based ones. Analogously, catalysts containing platinum-group and other metals are used in hydrogen production (as noted above), but they are also used in petroleum refining.[37] These catalysts will have water impacts in both fossil- and hydrogen-based industries.

For instance, platinum-group metals are mined predominantly in South Africa. Water usage for producing these metals creates conflicts between frontline platinum communities and mining companies, to the extent that "platinum belt communities are at risk of becoming green sacrifice zones to satisfy the climate ambitions of Global North countries."[38] This water use for platinum and iridium mining are associated with high environmental and social risks.[39] While water use per kilogram of hydrogen is not high, production is concentrated, such that water scarcity and water quality degradation are a real threat at mining locations.

But platinum is also used in petroleum refining, and this use of platinum can be reduced when hydrogen displaces fossil resources. Thus, when the same metals are used for the displacing and the displaced technology, the question of net change is important: other things (such as import and export policies) being equal, hydrogen production may increase or decrease water quantity and quality impacts in the same areas.

In situations where hydrogen production does cause a net increase in metal catalyst production, such as with nickel in steam methane reforming or next-generation electrolyzers, the impacts could be severe. Specifically, Indonesia holds the world's largest nickel reserves;[40] it currently meets 30% of global nickel demand, and is projected to account for the majority of global nickel production growth between 2021 and 2025.[41] Nickel is also used in electric vehicle batteries. Where nickel is mined, local water quality degradation can be and has been severe. For example, 'red soil' waste from mine excavation and coal plant wastewater has entered waters near the village of Kurisa (Indonesia), reducing local fish populations and forcing fish communities to go farther out to sea.[42] These reduced fishing yields and expensive trips to unpolluted sea areas have reduced fishermen's incomes. Likewise, local nickel mine workers are left exploited by their employer,[43] and according to local workers: "deaths and injuries are common".[44]

These mining-related impacts for electrolytic hydrogen are exacerbated for pink hydrogen, which uses nuclear energy to drive electrolysis. This nuclear energy is produced using uranium as a fuel, which has significant environmental impacts when mined. Such impacts depend on where and how uranium is mined; currently, 95% of uranium is imported mainly from Canada (27%), Kazakhstan (25%), Uzbekistan (11%), Australia (9%) with the rest being from smaller-producing countries.[45] The remaining 5% is produced domestically, predominantly through a process called 'in-situ leaching'. This process targets low-grade uranium ores that are located in an aquifer, by injecting an acidic or basic liquid into the aquifer to dissolve any solid uranium that is present. In most American in-situ leaching mines, this liquid is an oxygenated sodium bicarbonate (baking soda) solution.[46] Once this uranium-rich liquid is pumped back up from a uranium-containing aquifer, all dissolved uranium is removed and the uranium-free liquid is reinjected into the aquifer. In a 2012 report, the Natural Resources Defense Council identifies several key environmental impacts of in-situ leaching:[47]

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[37] Beirne 2013
[38] Matsabu 2022
[39] Lèbre et al. 2020
[40] Rushdi et al. 2021
[41] Bennet et al. 2021
[42] McCarthy 2011
[43] Rushdi 2021
[44] Yeung 2023
[45] EIA 2023B
[46] NRDC 2012
[47] NRDC 2012

- Beyond dissolving uranium, in-situ leaching also dissolves other heavy metals. When reinjected, these heavy metals degrade the quality of the mined aquifer. Unless restored, the aquifer remains contaminated.
- In-situ leaching requires large amounts of groundwater, especially during aquifer restoration attempts. For example, restoration of the Irigaray Ranch mine in Wyoming required 545 million gallons of water. This water usage is an issue, because many uranium mines are located in areas that are expected to experience medium to extreme water sustainability risks as climate change intensifies.
- In-situ leaching operations can leak both horizontally and vertically underground. These leaks can contaminate groundwater and will likely go unnoticed if monitoring wells are not installed.
- In-situ leaching creates waste, which can be toxic to wildlife.

Given these considerations, the NRDC report notes that in-situ leaching enduringly alters and degrades aquifers in which mining has taken place, especially because aquifer restoration efforts are often unsuccessful. These effects are compounded by regulatory standards that the NRDC deemed both faulty and outdated in their 2012 report. Therefore, the water impacts of uranium mining can represent a large hidden water cost for the production of pink hydrogen. Water issues also arise when making hydrogen from natural gas, because pumping natural gas can require water for hydraulic fracturing (usually shortened to “fracking”) and pollute local water sources.

These impacts are not necessarily felt at hydrogen production plants, but at natural gas drilling sites. The former hydrogen production water needs are somewhat higher for green and blue hydrogen, compared to grey hydrogen; however blue hydrogen requires even more natural gas than grey hydrogen. As a result, all the water pollution impacts associated with natural gas production, including using fracking, would increase. Seismic impacts from reinjection of produced water would also be expected to increase.

Finally, the same pollution considerations apply when comparing water use per mile for diesel trucks to fuel cell trucks. Petroleum is also increasingly produced by fracking, thus raising the same water pollution issues as fracked natural gas. Furthermore, oil spills, when they occur, create severe pollution of rivers and seas.

When the severe water pollution consequences of fossil fuel production are taken into account, it is reasonably apparent that there are large water-related positive environmental benefits when green hydrogen displaces fossil fuels. This point is illustrated in Section IV-a for the case of steel production.

Additionally, burning sulfur-bearing fuels, like heavy oil, creates acid rain, which results in water pollution. Burning fossil fuels also creates acid rain via nitrogen oxide pollution; this pollution is avoided with hydrogen, but only if it is not burned.

Still, one should ensure that hydrogen technologies do not perpetuate the environmental injustices that are caused by the fossil technologies that it replaces. For example, the American Gulf Coast is currently overburdened with oil, gas and petrochemical infrastructure. This region is also suffering from historic droughts, heat, flooding, and freezes as the climate crisis intensifies. Hydrogen production and usage would be exposed to these extreme conditions, which could pose risks to the hydrogen infrastructure and to the residents living near such infrastructure. Thus, the general water usage and pollution concerns in this document should be evaluated for specific hydrogen proposals in light of both extreme weather events and ongoing environmental justice struggles of fence line communities.

In sum, the use of hydrogen to replace fossil fuels does not mean an end to water pollution problems, even though hydrogen use in many applications only results in water or water vapor as the end product. The capital equipment-related water quantity and quality impacts will continue, and the net impact of hydrogen production and usage will depend on the method of hydrogen production and the specific fossil fuel replaced.

The biggest and clearest positive environmental benefit of hydrogen is when it is produced with solar or wind energy. Fossil fuel-related water pollution impacts are very large, from local to global. This pollution is avoided when green hydrogen displaces fossil fuels.

The largest benefit is achieved when green hydrogen is made with renewable electricity that would otherwise be curtailed. As the fraction of solar and wind energy in the electricity system increases, most hydrogen could be made in this way, as discussed in the larger study (Makhijani and Hersbach, 2024, forthcoming) on which this water-related report is based.

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