Electric Hydrogen's Approach and its Implication on The Levelized Cost of Firm Hydrogen Supply

Prepared by Electric Hydrogen

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I. Introduction

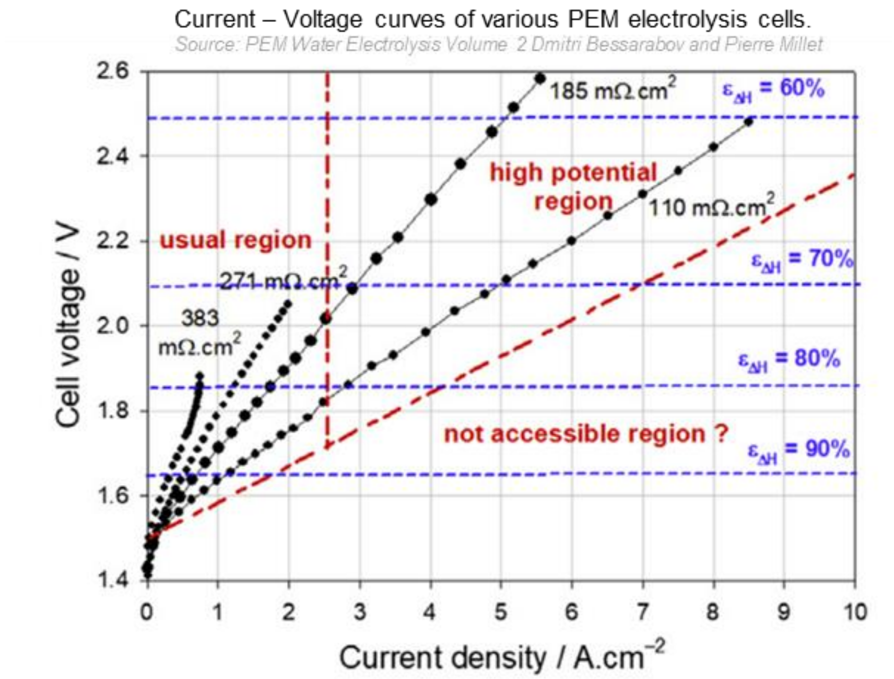
Electric Hydrogen (EH2) is bringing to market the next-generation of fully integrated and lower cost electrolysis plants to produce fossil-free hydrogen (H2) at the industrial scale. A previous publication explained EH2's product scope which is considerably greater than other solutions in the market today [1]; EH2's 100 MW-45 TPD (metric tons per day) flagship electrolysis plant includes all major system components in a single integrated package: electrolysis stacks, power converters, gas separators, thermal management, water treatment and comprehensive system controls. Enabled by breakthrough power density in the electrolyzer stacks, the overall plant is considerably smaller and lower capex per kW than competing solutions.

In this paper, we explain how the lower capex for EH2's product translates to lowest levelized cost of hydrogen (LCOH). We'll demonstrate how the analytics tools developed by EH2, primarily the EH2–LCOH+™ model (available free of charge to its customers and partners), can be used to determine the optimal configuration of a green hydrogen project.

II. Electric Hydrogen's Approach

EH2 was founded with a clear mission to help critical industries such as ammonia, steel and chemicals to decarbonize by rethinking and redesigning water electrolysis plants from the ground up. From its inception, EH2 has focused on minimizing electrolysis plant capex by: (1) pushing the cell's electrochemistry to new limits, (2) maximizing economies of scale of the stack and balance of plant (BOP) (3) streamlining and simplifying plant delivery to minimize EPC costs and related timeline overruns. An additional design constraint was to maintain high plant efficiency for low operating costs.

At the cell level, the current density (I) and voltage (V) relationship or I-V curve (also known as polarization curve) is a characteristic of an electrochemical cell and is affected by its design and operating parameters. A figure reproduced from Bessarabov and Millet's recent review book [1], a reference work on the state of PEM electrolysis technology, shows where typical PEM electrolysis operates. The I-V curves depicted in Figure 1 illustrate that the vast majority of commercial electrolyzers operate in the 1–3 A/cm^2 and 1.7–2 V region. Based on PEM technology, EH2's proprietary cell and stack designs push the power density to unprecedented levels for commercial scale. EH2's proprietary cell design enables the highest yield in the electrolysis market (in hydrogen production rate per unit area) while maintaining a high efficiency in the 75-85% range at the cell level. The higher throughput enables more compact hardware and more efficient use of stacks and BOP materials along with lower manufacturing cost per unit hydrogen produced. Higher power density in the electrolyzer stacks also reduces risks associated with market fluctuations of key materials used. This is all the more important in recent years, as the electrolysis industry has been challenged by inflationary pressures that raised the prices of metals and precious metal catalysts.


Current – Voltage curves of various PEM electrolysis cells.

Source: PEM Water Electrolysis Volume 2 Dmitri Bessarabov and Pierre Millet

Figure 1 – Typical polarization curves reproduced (without additions or modifications) from Bessarabov and Millet's review, PEM Water Electrolysis Volume 2

III. An Industry-Wide Cost Reduction Mirage (So Far)

The promises made by established electrolysis providers to reduce the system cost of electrolyzers have not yet materialized. In fact, we are seeing the opposite trend today with evidence that prices have been rising, driven by multiple factors:

- Lingering supply chain difficulties (mostly due to the COVID-19 pandemic as well as the Ukraine-Russia conflict) mean input costs of base materials are higher.
- Rising costs of metals used to manufacture stacks and balance of plant (like stainless steel and nickel for alkaline electrolyzers, and titanium, iridium, platinum, and stainless steel for PEM electrolyzers).
- Higher than anticipated EPC and engineering services costs due to novelty of projects and overall relative limited experience with electrolysis.

The International Energy Agency (IEA) began reporting on electrolysis plant prices in 2021. Based on these reports, the fully installed costs of alkaline and conventional PEM electrolysis were estimated to be 1,700 and 2,000 $/kW respectively for projects outside of China in 2023. This is a 12–21% increase compared with the agency's 2022 assessment (see Figure 2). Although the IEA clarifies that this price includes "*the equipment, gas treatment, plant balancing, and engineering, procurement, and construction cost*", a full apples-to-apples comparison is often challenging here as various suppliers and studies include different scopes and those are seldom detailed. The comparison of alkaline and PEM technology is also difficult because it is rare that the specific type of alkaline electrolyzer (atmospheric or pressurized) is mentioned, and whether the hydrogen compression capex is added (the IEA does not specify this aspect for example).

The hydrogen council and McKinsey provide a similar assessment in their latest Hydrogen Insights 2023 published in December 2023: the average fully installed system cost for a GW scale alkaline facility in the US Gulf Coast is estimated between 1,800 and 2,200 $/kW [1].

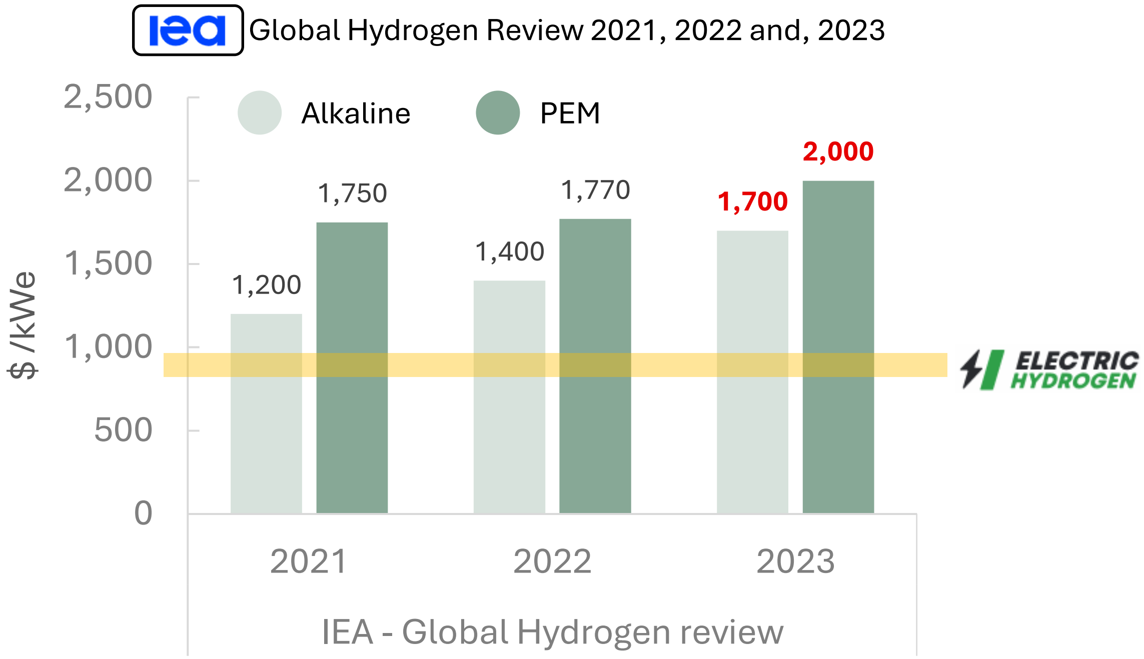


Figure 2 – Benchmark of total installed cost of electrolysis plants (outside China) published annually by the International Energy Agency (IEA). Total installed cost "including the equipment, gas treatment, plant balancing, and engineering, procurement, and construction cost."

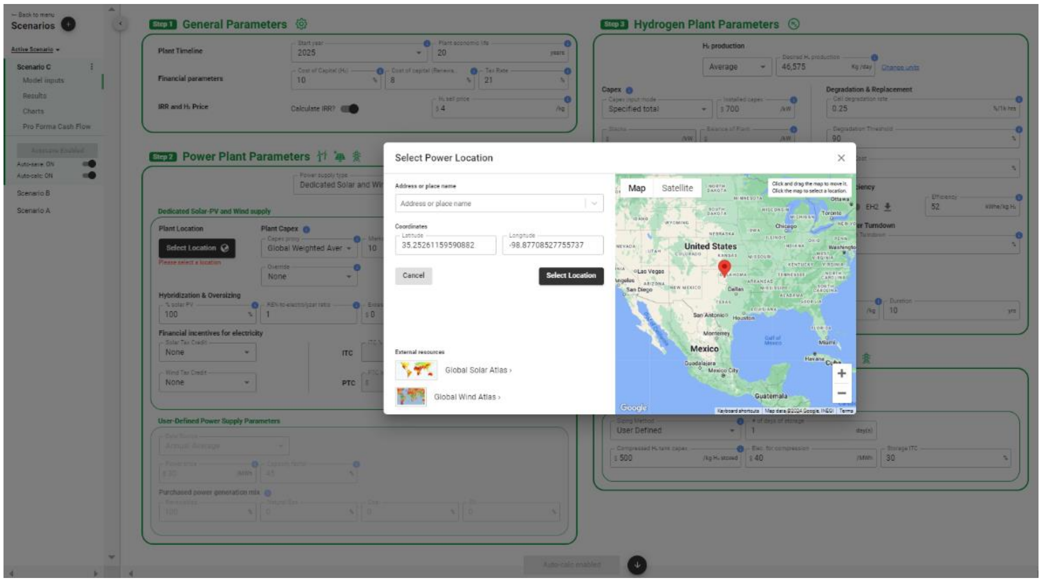
In contrast with other electrolyzer manufacturers, EH2 provides publicly indicative pricing for its fully integrated 100MW-45TPD all-inclusive electrolysis solution along with a clearly defined product and service scope (see text box below). This makes it easier for would be buyers of electrolyzers to fully understand EH2's product differentiation and compare it with other market offerings.

As of Q1-2024, EH2's indicative pricing for its all-inclusive 100 MW plant falls in the **800-900 $/kW range, fully installed**. This can be compared to the IEA's 2023 assessment for competing alkaline and conventional PEM electrolysis suppliers **at 1,700 $/kW and 2,000 $/kW, respectively.**

The **lowest possible capex** is only useful if it delivers **the lowest total levelized cost of hydrogen (LCOH)**. EH2 provides customers and partners with powerful analytics tools (accessible on EH2.com/toolkit) to estimate their likely LCOH and examine the impact of various cost levers, including the electrolyzer plant capex and the cost of the input power. In the following section, we show how EH2–LCOH+™, the detailed hourly LCOH model provided by Electric Hydrogen, can be used to clarify the full cost and feasibility of different electrolysis scenarios quickly and accurately, and ultimately help identify the optimal project configuration.

IV. The Techno-Economics of Green H2 Supply: EH2-LCOH+™ in Action

EH2 provides EH2–LCOH+™ free of charge to customers and partners. The tool is intended to help them simplify and speed up project sizing analysis as well as techno-economic assessments and feasibility studies. Very quickly, a novice user can build a scenario in a location of their choice and compare the anticipated levelized cost of producing hydrogen using EH2's technology to other suppliers and electrolysis technologies. The power supply and hydrogen plant, including an optional H2 compression and storage steps, can be sized based on a desired hydrogen output and the H2 offtaker minimum turndown, to find the optimal overall project configuration.



Select Power Location

Address or place name: Address or place name

Coordinates

Latitude: 35.25261159590882

Longitude: -98.87708527755737

Click and drag the map to move it.
Click the map to select a location.

External resources

Figure 3 – Screenshot of the EH2-LCOH+ tool showing the project setup page with location selector window.

1. Setting the Stage: A Green Ammonia Case Study

The US southern great plains, encompassing Northern Texas and Western Oklahoma, is a unique location where outstanding renewable resources and existing hydrogen consuming industries overlap. Those industries include primarily ammonia plants and petroleum refineries. The consumed hydrogen is today mostly "grey" – meaning that it is produced from natural gas using a reforming process with a relatively high carbon footprint. EH2 provides industrial scale plants (100MW+) that can supplement or act as a drop-in replacement (i.e. not requiring significant hardware or process change) to grey hydrogen used in these existing hydrogen markets.

In the map shown in Figure 4 and generated using EH2's *US Hydrogen Offtaker and Renewables Assets* tool, one can see the potential for green hydrogen demand and decarbonization in the southern great plains region. Despite not being selected as part of the 7 hubs funded by the DOE, this region has the potential of becoming one of the leading locations for green hydrogen projects in the US. Moreover, green hydrogen in this region can help improve the economics of some of the existing renewable assets suffering from a high level of curtailment (if those can be exempt from the IRA's additionality requirement). For the demonstration undertaken in this paper, we choose the location depicted by a star on the map near major existing hydrogen offtake in Western Oklahoma. For the purposes of this analysis, we will assume that the green hydrogen facility is supplying a 500,000 metric ton/year ammonia plant. With about 190 kg of H2 required for each 1 metric ton of ammonia, **this plant would require 260 tons of hydrogen per day, about 600 MWe [AC] of electrolysis (at full utilization).**

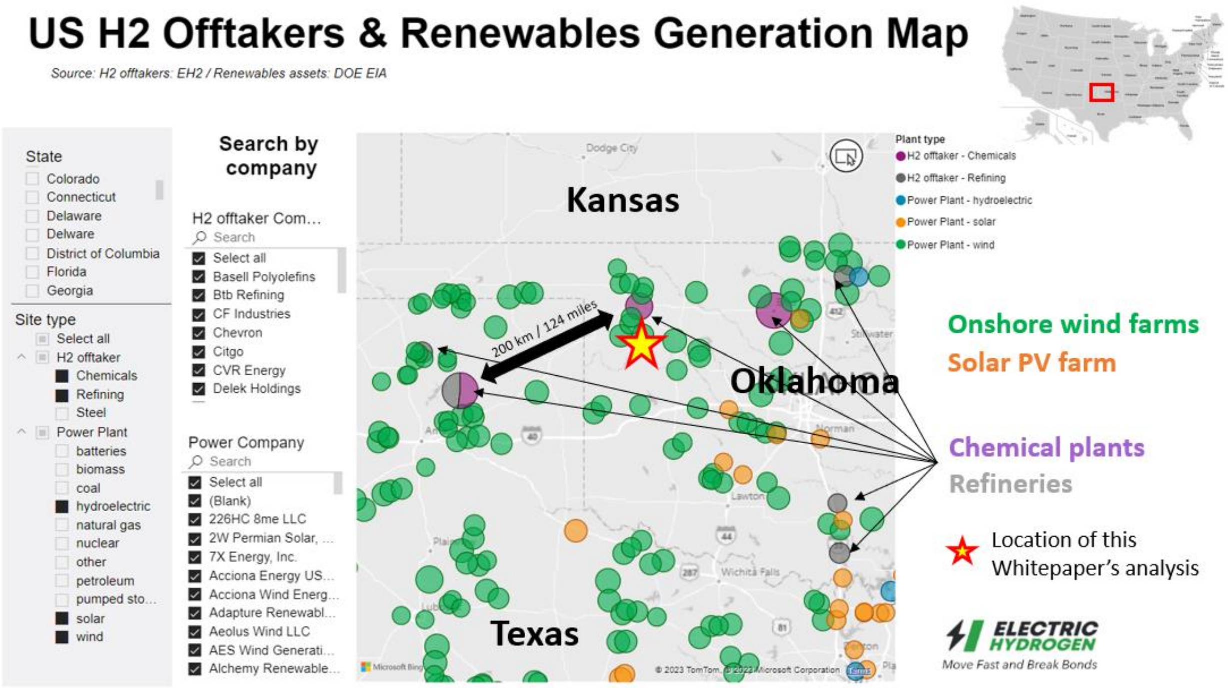


Figure 4 – A view of EH2's US Hydrogen Offtaker and Renewables Assets dashboard centered on Oklahoma and Texas

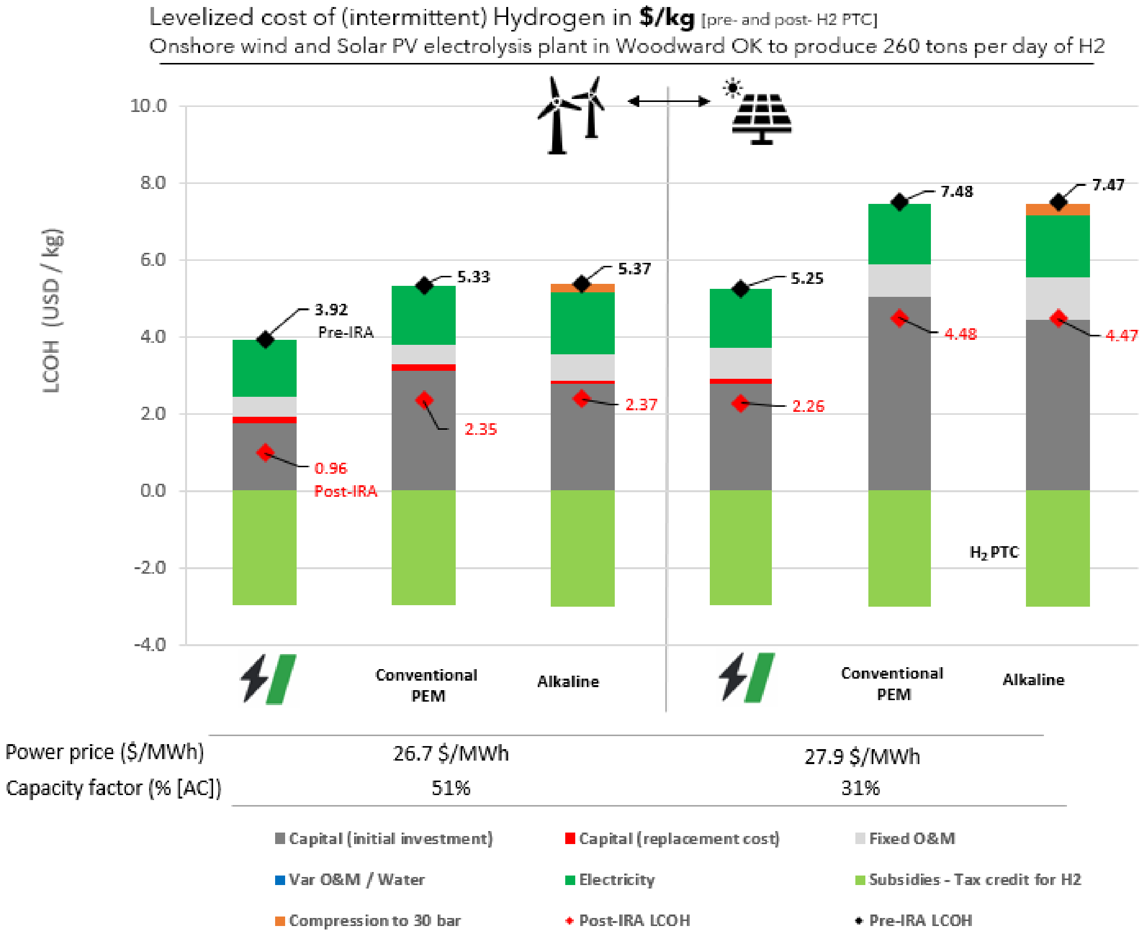
2. Intermittent LCOH: EH2 vs. Other Suppliers

How much would it cost to produce hydrogen using EH2's technology compared with competing alkaline and conventional PEM technologies in the location described above?

We have previously shown (section III) EH2's capex advantage compared to what is offered today on the market. We use here conventional PEM and alkaline capex benchmarks in line with the IEA's 2022 assessments rather than the latest 2023 one; we assume that increases in 2023 are temporary and may ease in the next few years. As discussed in our previous paper describing the importance of supplier scope [3], a cost adder for the hydrogen plant outside battery limit (OSBL) might need to be included (if additional transformers, water pre-treatment, piping outside the facility, etc., is needed). That cost adder, estimated here to be 200 $/kW would be added to all technologies evaluated. Compression is not included in the above capex cost adder but is an additional cost included in the (atmospheric) alkaline LCOH estimate for a fair comparison with PEM.

Regarding the efficiency of the plant, we assume total plant efficiencies, at full load, of 58 kWh/kg for alkaline and 56 kWh/kg for conventional PEM technologies. This is based on a list of 40+ projects surveyed by EH2. EH2's own plant total efficiency at full load is 54.5 kWh/kg. This total efficiency includes all balance of plant energy losses due to electrical efficiencies (step-down voltage transformer, AC-DC conversion, and bussing), pumping, cooling, and controlling the plant **and** hydrogen losses due to cross-over and fugitive hydrogen losses. Other assumptions and inputs to the model are detailed in Table 1 at the end of this paper.

EH2's significant capex advantage over conventional PEM and significant efficiency advantage over alkaline, allow wind-based hydrogen to be produced in Oklahoma at **3.9 $/kg without the inflation reduction act (IRA) incentives**, 26% cheaper than alkaline and conventional PEM LCOH. While having a lower initial investment compared with conventional PEM, alkaline's higher fixed O&M costs and lower efficiency make up for the capex difference. When full 3$/kg production tax credit (PTC) over 10 years is included, EH2's customers production cost is estimated at **0.96 $/kg** which is significantly lower than the 2.3-2.4 $/kg post-PTC production cost of hydrogen using alternative electrolysis technologies (see Figure 5)



Source: EH2 Analytics

Figure 5 – Levelized cost of hydrogen production using wind or solar PV in western Oklahoma and comparing EH2's plant to conventional PEM and alkaline plants.

Solar PV-to-H2 is consistently more expensive in central Oklahoma due to the relatively low utilization rate penalizing high capex solutions, especially in the relatively high cost of capital environment we are seeing in 2023-2024.

3. The Cost of Firm Hydrogen Supply

Hydrogen consuming processes often have a limited hydrogen input flow rate flexibility, with a limited turndown; operations with an intermittent input of hydrogen can have an adverse effect on the equipment or on the efficiency of the process. Hydrogen systems using EH2 technology can be modeled to build the best strategy leading to a firm supply of hydrogen. In addition to H2 consuming processes with limited flexibility, a firm supply of hydrogen might be desired anyway as it increases the utilization rate of downstream equipment and can reduce the unit cost of the hydrogen-based product downstream.

Multiple methods can be used to provide a more stable supply of green hydrogen; these are depicted in Figure 6: (1) Hydrogen storage (firming the output of an electrolyzer) , (2) oversizing of renewables compared with the installed electrolysis capacity, (3) hybridization of energy source, (4) grid supplementation or (5) battery storage. Methods (2) to (5) are all methods to firm the hydrogen output by guaranteeing a flatter input power.

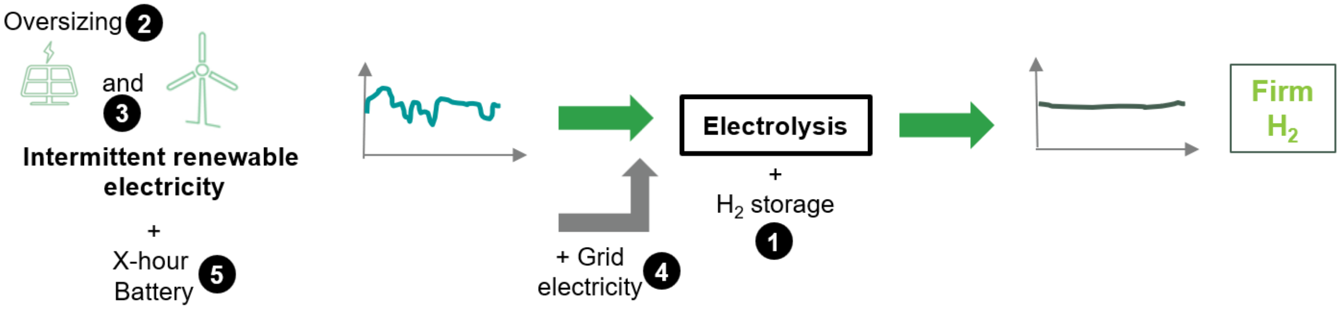


Figure 6 – Strategies to provide a more stable supply of electrolytic hydrogen.

a) Storage Requirement for Firming:

In this section, we use LCOH+ to estimate the required H2 storage to firm the H2 supply. We start with a strict storage requirement with no flexibility on the H2 offtaker side (a strict 24/7), and then introduce various methods that help reduce the size of H2 storage needed. For a strict 24/7 supply, with a capacity of renewable generation matching that of the electrolyzer, **16 days** of storage would be needed for wind generation in the western Oklahoma region, and **35 days** of H2 storage for a solar PV supply. Given the current cost of storage, this is a prohibitively expensive option.

Effect of Offtake Flexibility:

The turndown flexibility is an option that can be added in EH2-LCOH+™ to alleviate the H2 storage requirement. A simple trade-off can be made by associating offtake turndown as virtual storage.

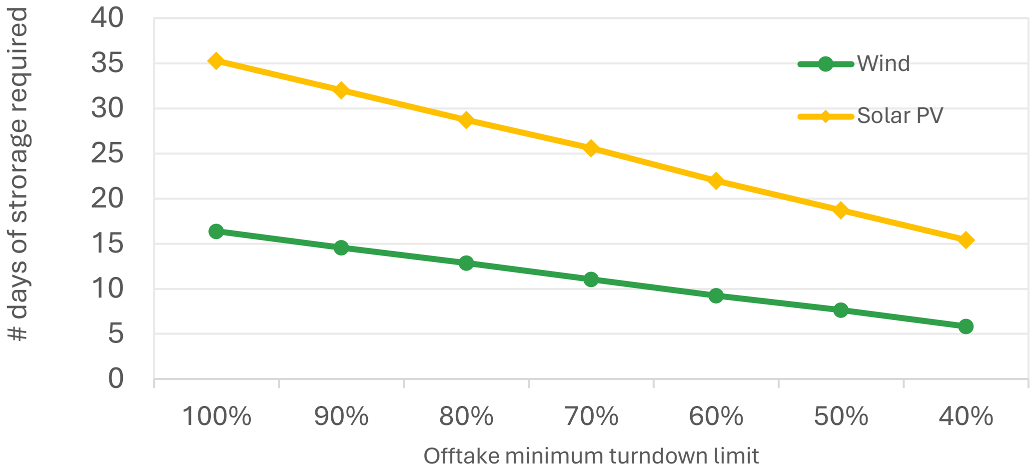


Figure 7 – Effect of offtake flexibility on the storage requirement for strict 24/7 firming of wind-to-H2

In the current example, with a 70% minimum turndown instead of a strict 24/7 supply, the storage requirement falls from 16 days to 11 days for wind-to-H2. If an offtaker can accept a frequent turndown to 60%, the storage falls below the 10-day mark, and shows a close-to-linear relationship (Figure 7).

Effect of Oversizing Renewables:

Oversizing of the renewable asset's capacity is a strategy adopted by renewables and hydrogen developers. The aim is to increase the electrolysis plant utilization rate (as can be seen in Figure 8) and either use, sell or curtail the excess electricity.

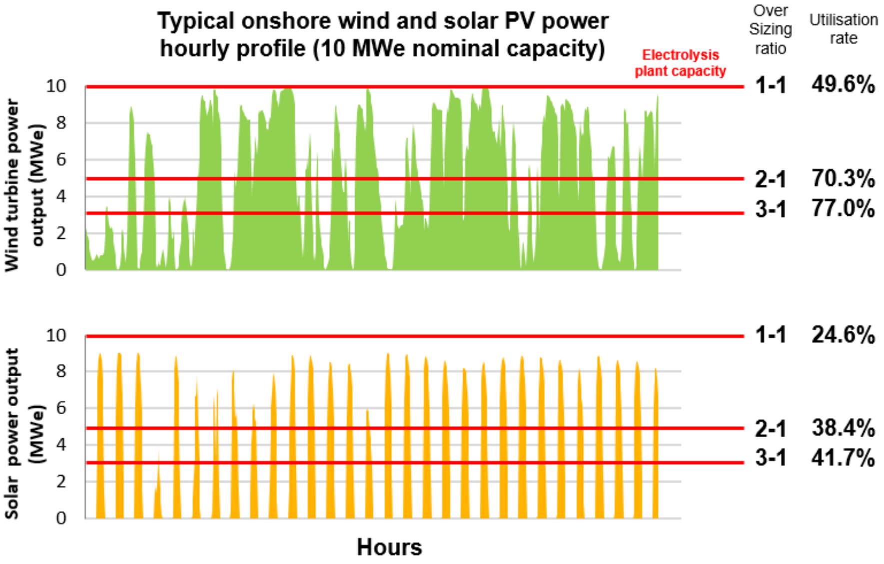


Figure 8 - Effect of over-sizing of wind and solar PV on the electrolyzer capacity factor

The electrolyzer utilization rate increases when the renewables-to-electrolyzer capacity ratio is raised as shown in Figure 9; the largest incremental utilization improvement occurs between 1:1 and 2.5:1 ratio with diminishing returns observed beyond that. At 3.5:1 ratio, a utilization rate of 77.6% for wind-H2 is reached and the associated storage requirement then falls below 10 days to meet a strict 24/7 supply.

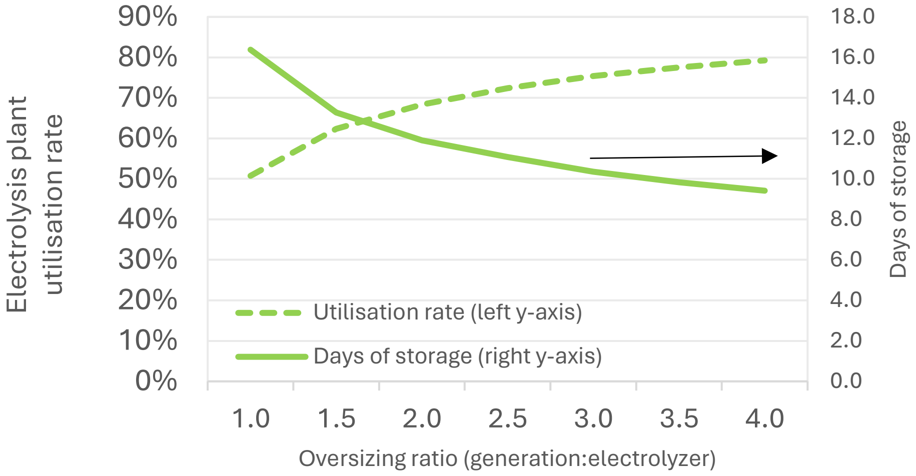


Figure 9 - Impact of oversizing ratio on the electrolyzer utilization rate and the H2 storage required to meet a strict 24/7 supply

Mixing Solar and Wind (hybridization):

Blending Solar and wind resources to power the electrolysis plant is another way to reduce the storage capacity needed for a firm supply of hydrogen. This is location dependent as solar and wind resources would need to be anti-correlated to provide this benefit (more wind when solar is down. Figure 10 shows how the H2 storage is minimized when 20% solar PV is included in the mix.

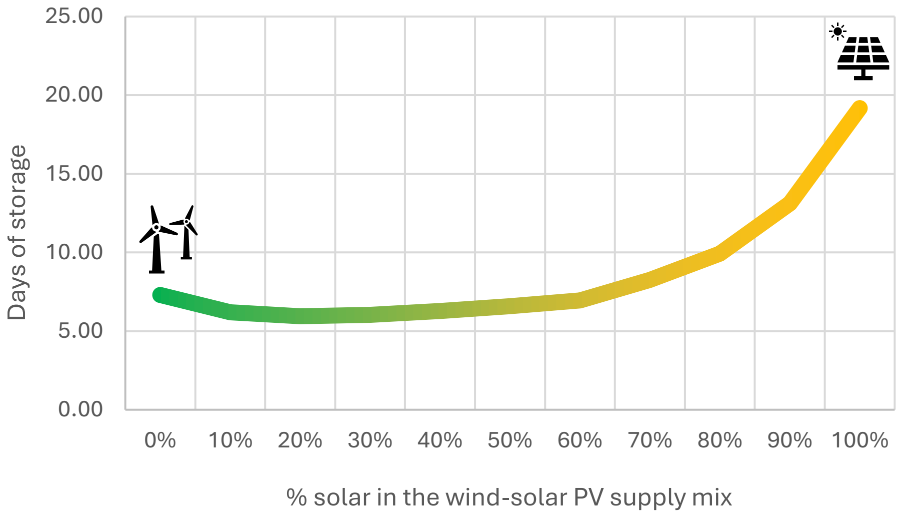


Figure 10 – impact of blending wind and solar on hydrogen storage need. Offtaker with 70% minimum turndown and a renewables-to-electrolyzer ratio of 2.5

b) Optimal Project Configuration and LCOH:

Finally, we combine the optimization methods to answer the following questions:

1. What is the best project configuration for green hydrogen in western Oklahoma and at what LCOH can a firm supply of hydrogen be supplied?

2. How does EH2's LCOH compare to competing conventional PEM and alkaline for this optimal configuration?

To do so, we consider an offtaker with 70% minimum turndown and a renewables-to-electrolyzer ratio of 2.5. These are reasonable assumptions based on how far an existing ammonia plant process can turn down without major retrofit, and the oversizing trends seen today on the market for green hydrogen being developed, respectively. Excess electricity is assumed to be sold at a realistic and relatively low price of $10/MWh. The cost of compression from 30 bar to 200 bar using reciprocating compressors along with type 1 steel tank costs are included and are used to estimate the added LCOH premium for firming. Those costs are based on direct discussions and quotes received from different H2 compression and storage vendors in the US and outside the US. The most competitive quote was received by Electric Hydrogen for H2 storage at around 300 $/kg stored but a more conservative 500 $/kg is assumed in this analysis.

The optimal cost of firm hydrogen is obtained for a renewable plant with a mix of 70% onshore wind and 30% Solar PV (Figure 11). Despite pure solar PV supply leading to a more expensive intermittent hydrogen and requiring more storage for firming, **adding solar PV in the power supply mix reduces the firm H2 cost**. This is primarily due to the reduced need for storage and secondarily due to the improved electrolyzer capacity factor. As mentioned earlier, in this specific location solar PV and wind have some degree of anti-correlation and solar would help maintain operations of the H2 plant during periods with no wind. The optimal 70%-30% configuration in this location allows for a total LCOH of firm hydrogen of 2.39 $/kg when including the PTC, a competitive LCOH with competing low-carbon H2 supply like blue hydrogen.

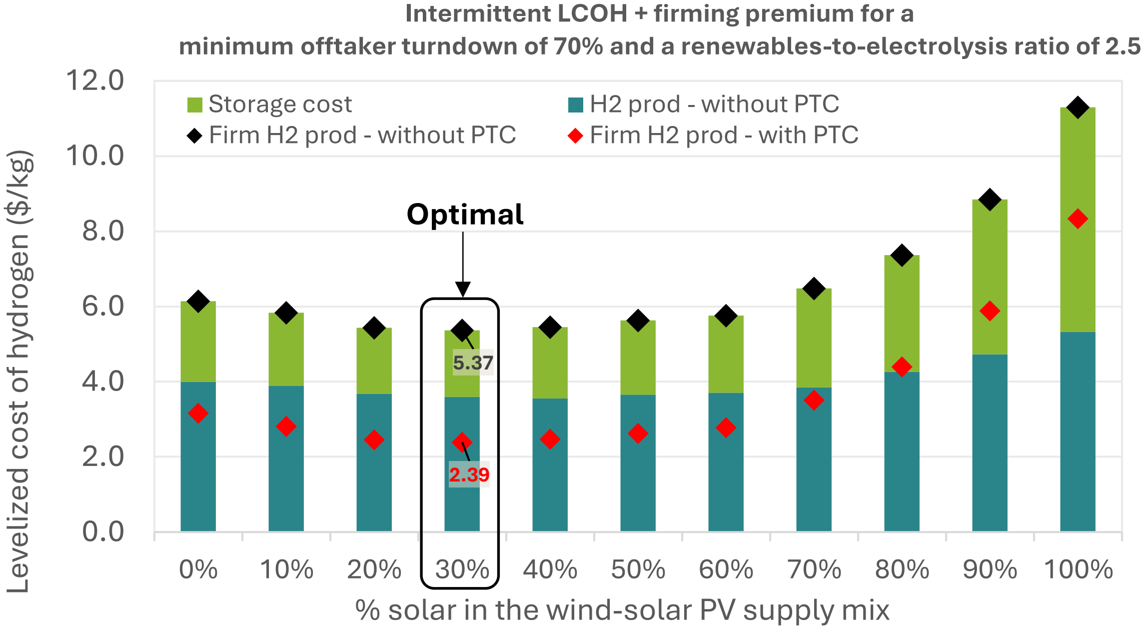


Figure 11 – Optimal configuration of wind and solar PV to achieve lowest cost of intermittent and firm hydrogen.

Comparing now the firm hydrogen production cost obtained using EH2's plant to conventional PEM and alkaline technologies, we find those configurations to have a higher firm LCOH due to the combination of a higher CapEx and energy intensity of those technologies. A +48% premium compared with alkaline and +44% compared with conventional PEM technology.

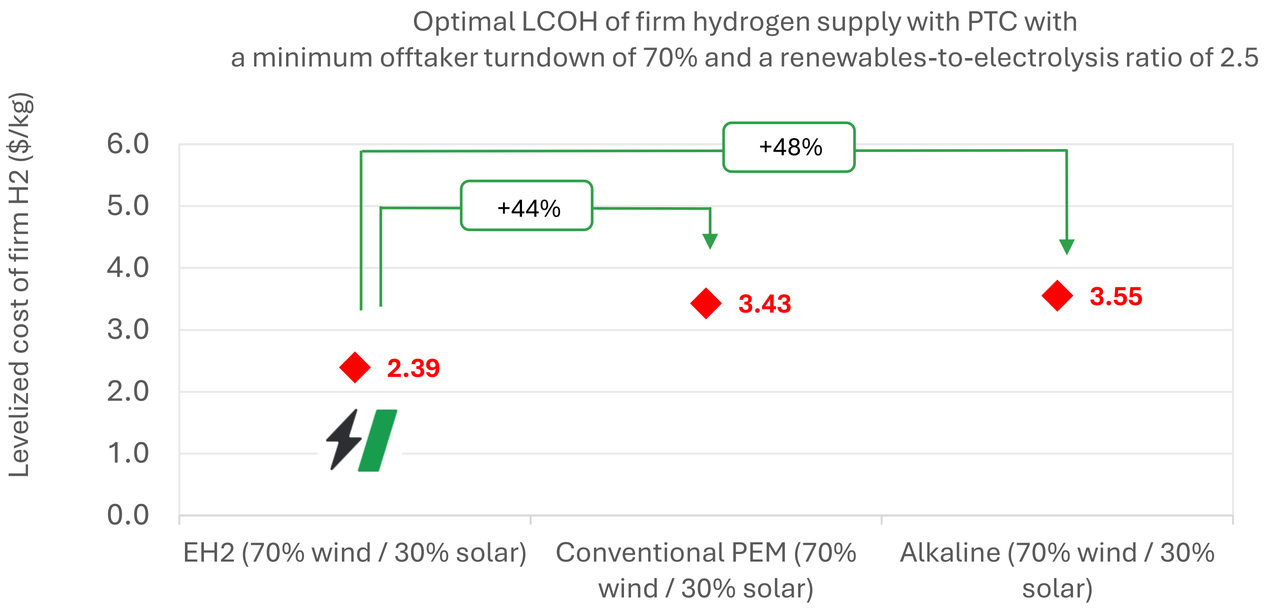


Figure 12 - Optimal LCOH of firm hydrogen supply for different H2 plant technologies

(minimum offtaker turndown of 70% and a renewables-to-electrolysis ratio of 2.5)

V. How Can EH2 help?

EH2 is taking orders today for its 100 MWe – 45 tpd fully integrated plant described in this paper. Additional support to customers is provided along their hydrogen project development journey using EH2's analytics tools. The analysis performed in this paper is an example of how customers can quickly leverage EH2-LCOH+^{TM} to find the optimal project configuration, including its techno-economics details.

If you have a large-scale project, we can help speed up your project and decarbonization plans.

Data and assumptions:

Table 1 - Assumptions and inputs to the analyzed scenario

Variable (unit)	EH2 advanced PEM	Conventional PEM	Alkaline
Plant Economic Life (years)	20 years		
Cost of capital (%)	H2 plant: 10% - Renewables: 8%		
Tax rate (%)	21% + 6%		
Installed capex ISBL* ($/kW)	850	1,700*	1,400
Additional OSBL* costs ($/kW)	200		
Plant unit size (MW [ac])	104	25	25
Stack replacement cost (%)	20%	20%	15%
Fixed O&M ($/kW-year)	40	40	50
Total plant efficiency at full load (kWh/kg)	54.5	56	58**
Electrolyzer minimum turndown (%)	10%	10%	20%
Water cost ($/m3)	1		
Onshore wind LCOE / capacity factor	26.7 $/MWh – 51% [AC]		
Solar PV LCOE / capacity factor	27.9 $/MWh – 31% [AC]		
Renewable power PTC	26 $/MWh for 10 years (for both wind and solar PV)		
Hydrogen PTC	3 $/MWh for 10 years		
Storage capex	500 $/kg H2 stored		
Excess electricity sale price	10 $/MWh		

*IEA’s 2022 assessment. ISBL/OSBL: inside/outside battery limit. **2 kWh/kg added to Alk for compression from 1 to 30 bar

References

[1] Hydrogen Insights 2023 – December 2023 (link)

[2] PEM Water Electrolysis. Bessarabov et al. Vol 1 and 2. 2018 (link)

[3] Green H_2 Plants Are Not All Created Equal: EH2's wide-scope approach to reducing cost. Electric Hydrogen Oct 2023 (https://eh2.app/whitepapers)

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