DOE Hydrogen Program, Office of Clean Energy Demonstrations Program Record	
Record: 24002	**Date:** February 22, 2024
Title: Summary of Electrolyzer Cost Data Synthesized from Applications to the DOE Clean Hydrogen Hubs Program	
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Item

DOE Regional Clean Hydrogen Hub applications provide insight on the current electrolyzer market. While real-world prices can vary, analysis on cost estimates reported by applicants in April 2023 reveal an average estimated total installed electrolyzer cost of ~$1,900/kW for projects that currently plan to use polymer electrolyte membrane (PEM) electrolyzers. The weighted average estimated cost is ~$2,100/kW across applicant projects (average size 350 MW).[1] Applicant data reveal a wide range of estimated costs, with estimates decreasing with project scale (e.g., over $3,000/kW for projects under 100 MW, and under $2,000/kW for projects over 600 MW). This record represents a snapshot in time of electrolyzer cost estimates from the first quarter of 2023, when Regional Clean Hydrogen Hub applications were written, and is not forward looking.

Key takeaways:

- Total installed electrolyzer cost estimates in Hub applications were higher than previously estimated when DOE's Clean Hydrogen Pathways to Commercial Liftoff Report was published in March 2023. Cost increases are predominantly driven by inflation, supply chain cost increases, and higher estimated installation costs from hub applicant data.
- Total installed costs feature strong economies of scale, i.e., larger projects tend to be less expensive on a per kW basis.
- Cost estimates can vary widely for any given sized project.
- Hub applicants proposed project size ranges from tens of MW to multiple GW scale. The average proposed project size was ~350 MW and the median project size was ~215 MW across all electrolyzer types. PEM average size was ~400 MW and the median size was 150 MW.
- PEM made up ~75% of proposed electrolyzer projects in hubs by capacity, with alkaline systems representing ~15%. The remaining ~10% included solid oxide electrolyzer cell (SOEC), to-be-determined, and others.

[1] All averages provided are weighted averages by project capacity/size (MW)

H2Hubs applicant electrolyzer cost data

In 2021, the Bipartisan Infrastructure Law appropriated $8B to the Office of Clean Energy Demonstrations (OCED) to fund H2Hubs demonstrating diversity in feedstocks (renewable energy, fossil fuel with carbon capture and storage, and nuclear power), end uses (industrial, transportation, power, and heating), and geography. The funding opportunity for the H2Hubs was announced 22 September 2022 and full applications were due 7 April 2023. While early in development, many applicants shared real world cost estimates for equipment and installation. Many of these cost estimates were provided as budgetary totals summarizing equipment and installation costs without detailed breakdowns. The aim of this record is to characterize cost trends observed in DOE's applicant pool.

Data on cost estimates from applications show higher near-term total installed costs for electrolyzer systems than those estimated in previous years – even when accounting for inflation. These trends align with data published by the Hydrogen Council, S&P, and other sources (see Figure 1).

[2] Range based on alkaline and PEM estimated costs, unless otherwise noted. Note the references shown were published in different years and inflation may have influenced cost fluctuations within those years. The costs shown in this figure have not been adjusted for a consistent dollar year because of uncertainty regarding the impacts of inflation within those years.
[3] Range based on alkaline and PEM estimated costs, unless otherwise noted (all 2022$)
[4] 100 MW project size, mean of 2020 and 2025 estimated costs used, 2021$
[5] >10 MW project size, 2020$
[6] 1 MW project size, 2018 estimated costs used, 2018$
[7] >10 MW project size, 2022 costs used, 2022$
[8] From 2023 DOE Clean H2 Liftoff Report. 2 MW electrolyzer size, assuming no economies of scale with project size, 2020$
[9] 100 MW project size
[10] 1 GW project size, range based on spread in survey responses and uncertainty in engineering analysis
[11] Based on weighted average of all DOE H2Hub applicants across all projects (average 350 MW), with range representing 25th and 75th percentile costs (see Appendix Figure 5). DOE H2Hubs "system" costs includes equipment costs associated with both the electrolyzer stack as well as balance of plant, resulting in higher system costs compared to other data sources. Note that applicants for PEM projects typically saw a larger project size (average 400 MW) and total installed costs trended lower (weighted average $1,900)
[12] 20 MW project size
[13] 250 MW project size

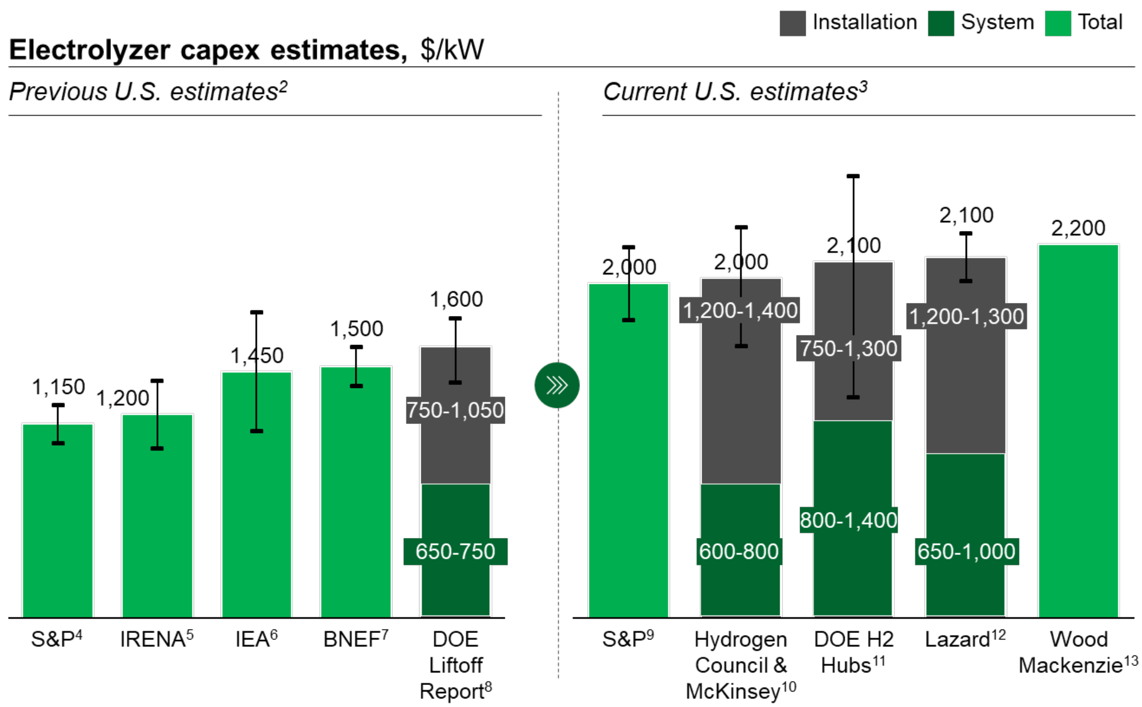


Figure 1.[14] *Estimated costs for electrolyzer installations up to year-end 2022 (left) compared to estimated costs for electrolyzer installations from 2023 onwards (right). Where available, system costs are shown in dark green and installation costs are shown in gray.*[15] *For bars with estimated ranges, the bar height represents the range midpoint. As a note, the DOE H2Hubs data includes balance of plant (BOP) in "system" costs (e.g., water treatment, power electronics, thermal management and drying), whereas the other sources only include electrolyzer/stack costs in "system" costs and classifies BOP costs as installation. McKinsey estimates these BOP costs to be ~$200-300/kW, which helps explain the difference in the split of system and installation costs between DOE H2Hubs data and others. DOE could not separate BOP equipment costs from electrolyzer/stack costs because of how applicant data was provided.*

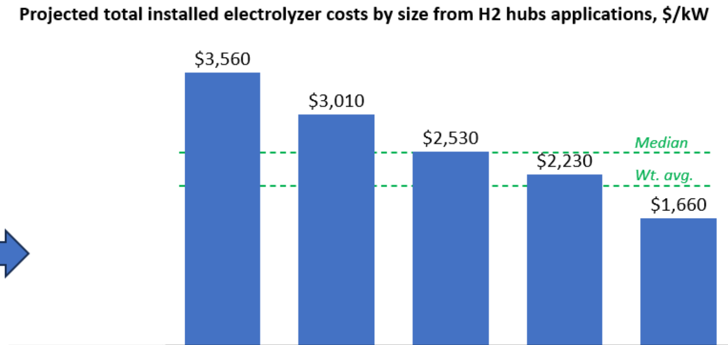
[14] **Sources:** S&P (2023 and 2024); International Renewable Energy Agency (IRENA) Green Hydrogen Cost Reduction report (2020); Lazard LCOH v2.0 (2021); International Energy Agency (IEA) "The Future of Hydrogen" (2019); Bloomberg New Energy Finance (BNEF) "2023 Hydrogen Levelized Cost Update" (2023); DOE Hydrogen Liftoff Report (March 2023); McKinsey Capital Analytics (2023); Survey of Hydrogen Council Member FEED studies; DOE Hydrogen Hubs applicant data (2023); Lazard LCOH v3.0 (2023); Wood Mackenzie "What the inflation reduction act means for production economics and carbon intensity" (2023) and corresponding calculations by Princeton University's Zero Lab (2023).

[15] Installation costs include labor costs, piping, transportation costs, permitting, contingency, EPC, and all other expenses incurred to bring the system to a condition where it can be used. DOE H2Hubs numbers include equipment costs associated with balance of plant (water treatment, thermal management, etc.) in system costs, while others include these costs in installation costs. The capitalization treatment of these installation and system costs should be governed by generally accepted accounting principles (GAAP) or other widely accepted accounting standards.

Projected total installed costs average ~$2,100, and vary with project size

*In general, projected total installed costs for electrolyzers decreased with larger installations. Across all electrolyzer types, weighted avg. costs were **$2,100/kW***

Key data	System size	Total cost
Wt. avg.	~350 MW	~$2,100/kW
Median	~215 MW	~$2,500/kW



Size (MW)	<50 MW	50-150 MW	150-300 MW	300-600 MW	>600 MW
Avg size (MW)	30 MW	100 MW	230 MW	450 MW	1500 MW
No. of Projects	~5	~10	~10	~5	~5
Cost range (max-min)	~$8.0k/kW	~$5.0k/kW	~$5.0k/kW	~$3.5k/kW	~$1.5k/kW

Figure 2*. Total estimated installed electrolyzer costs in $/kW by size across anonymized H2Hub applications received in April 2023. Cost estimates include data for PEM, alkaline, SOEC, and other/unspecified electrolyzers. Note that the installed costs estimated for unspecified electrolyzers was $3,750/kW compared to substantially lower costs for PEM systems of ~$1,900/kW.*[16,17]

Across approximately 35 proposed electrolyzer project applications to the H2Hubs program, the weighted average total installed cost for electrolyzers was ~$2,100/kW (Figure 2).[18,19] Two key observations based on the data are:

1) System costs are correlated with project size, with larger systems at substantially lower costs per kW than smaller systems. The deep dive on PEM systems in Figure 4 below highlights this trend.
2) The total installed cost estimates came in with a wide range (see "Cost range" row in Figure 2). This is likely driven by multiple factors:
    a. H2Hub applications were for early-stage projects, and the quality of estimates within the data set varies. Cost estimates were provided as budgetary totals summarizing equipment and installation costs without detailed breakdowns. Projects that specified technologies, e.g., PEM or alkaline, came in at generally lower total estimated costs than projects with an unspecified electrolyzer technology, and were likely higher quality estimates.
    b. This is a nascent industry where supply chains are still emerging and equipment costs have a wider variation, in contrast with more established markets.
    c. From the limited amount of data, we observed higher cost variation among smaller projects than larger projects.

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[16] Projects using other/unspecified electrolyzer technologies tended to be smaller projects, with an average size of ~170 MW

[17] Weighted average cost estimates for alkaline electrolyzers were similar to weighted average cost estimates of PEM. However average project sizes were ~270 MW vs ~400 MW respectively, and with minimal discrete alkaline data points, the sample size for alkaline projects is not large enough to draw meaningful conclusions from. H2Hub applications that reported insufficient data to derive nameplate capacity at the individual project level were not included in the analysis for this record.

[18] There were more than ~35 electrolyzer projects across H2Hubs applicants, but not every project provided granular cost data with nameplate capacity.

[19] Average weighted by installed nameplate capacity in MW.

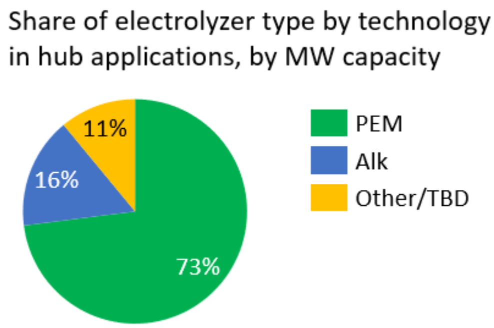

Figure 3. *Electrolyzer MW capacity by technology type across the H2Hub applications. Other/TBD includes SOEC.*

Deep dive on total installed costs for PEM electrolyzers: Among H2Hub applications with identified electrolyzer technologies (i.e., PEM, alkaline, etc.), PEM constituted ~60% of projects and 73% of capacity (Figure 3).[20] Since a relatively large number of PEM projects were proposed, an analysis of PEM costs specifically is presented in Figure 4. System costs (which include balance of plant costs) are generally lower for projects with larger capacities on a per kW basis. Weighted average size for PEM projects was 400 MW, with a median project size of ~150 MW.

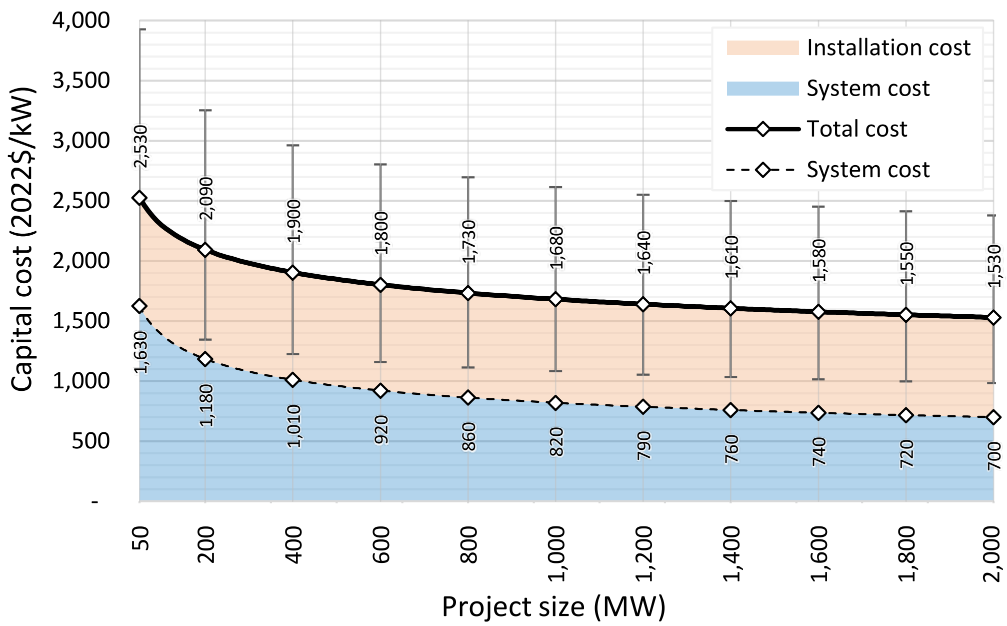

Figure 4*. PEM total costs (2022$/kW) by project size (MW) estimated using data from H2Hub applications. System costs (which include balance of plant costs, see footnote 15 on Figure 1) are indicated with blue shading, installation costs in orange shading, and total combined cost by a black line. At the average PEM electrolyzer size of 400 MW the total (installed) cost is $1,900/kW and the system (uninstalled) cost is $1,010/kW. Error bars show a 1 sigma cost range.[21] Installation accounts for ~half of total estimated cost for average sized PEM systems in the H2Hubs data set.*

Appendix: The appendix shares another view of the data discussed in Figure 2 and discusses the underlying calculation methodology to produce Figure 4.

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[20] Nameplate capacity weighted share of projects

[21] PEM costs by scaled modeled from the PEM projects within H2Hub applications that feature disaggregated system and installation costs. Two additional granular estimates from projects in development outside of OCED's H2Hubs program have been added to strengthen the data set.

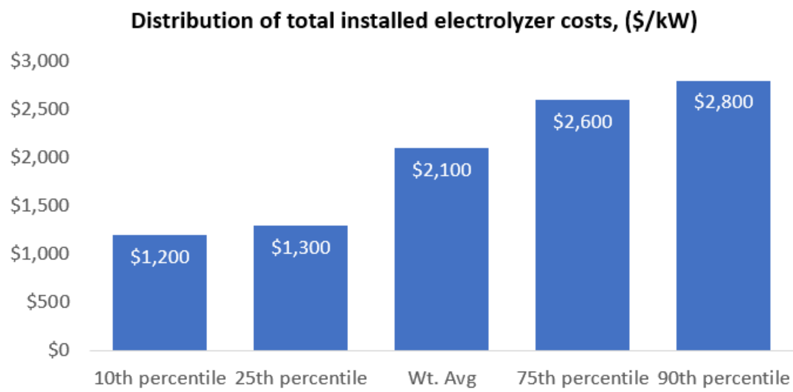

Figure 5*. Distribution of projected total installed electrolyzer cost estimates among H2Hubs applicant projects by percentile. Data is from applicant projects across all sizes and technology types. Percentiles are based on share total sample nameplate capacity.*

Calculation methodology for Figure 4: The "typical spread" of system capacities depicted was based on the distribution of project sizes derived from the PEM electrolyzer applications. These applications spanned project sizes of ~40 MW to over 3 GW and had an average project size of 400 MW and a median of 150 MW. As the median value was significantly below the average, two additional non-hub projects were added in the GW+ size range to help decrease statistical uncertainty of scaling at the GW class. The full data set of approximately 20 projects described above was used to derive an installed cost curve of electrolyzers.

Mathematically, the data was linearized by casting on a log-log basis of the total installed cost and the project capacities. The data was then fit with least squares method and uncertainty prediction interval was derived at a 68% confidence interval (±1σ). The resulting parameterization was then re-cast on the original basis of project size (kW) and total system cost (2022$). Lastly, parameters were generated for the system scaling equation below:

$$C_{tot}^{1} = C_{tot}^{0} \left[\frac{Q_{tot}^{1}}{Q_{eq}^{0}}\right]^{\alpha_{tot}}$$

Where:

- C_{tot}^{0} = 762,000,000 (2022$)
- Q_{tot}^{0} = 400,000 (kW)
- α_{tot} = 0.864 (scaling factor)
- Q_{tot}^{1} = Projected project size (kW)
- C_{tot}^{1} = equipment CapEx at Projected project size (2022$)

Similarly, the analysis was performed for uninstalled system cost. Notably, two applications did not report uninstalled system cost, so the statistical analysis relied on the remaining data points. Below is the resulting relationship of system cost to system power rating:

$$C_{eq}^{1} = C_{eq}^{0} \left[\frac{Q_{eq}^{1}}{Q_{eq}^{0}}\right]^{\alpha_{eq}}$$

Where:

- C_{eq}^{0} = $ 404,500,000 (2022$)
- Q_{eq}^{0} = 400,000 (kW)
- α_{eq} = 0.772 (scaling factor)
- Q_{eq}^{1} = Projected system size (kW)
- C_{eq}^{1} = equipment CapEx at desired projected system size (2022$)

Note that qualitatively, data spread appeared wider for smaller projects than for GW class systems. However due to the low number of systems in the data set, we did not have statistically significant amount of data to provide differentiated error bars by system size.