DOE Hydrogen Program Record		
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Title: Historical Cost Reduction of PEM Electrolyzers		
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Item

The uninstalled capital cost of proton exchange membrane (PEM) electrolyzer systems has been reduced by over 90% since 2001 (and 80% since 2005), as shown in Figure 1. This Record documents those historical cost reductions, which have been supported and enabled by research, development, and demonstration (RD&D) efforts funded by the Hydrogen and Fuel Cell Technologies Office (HFTO) of the U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE).

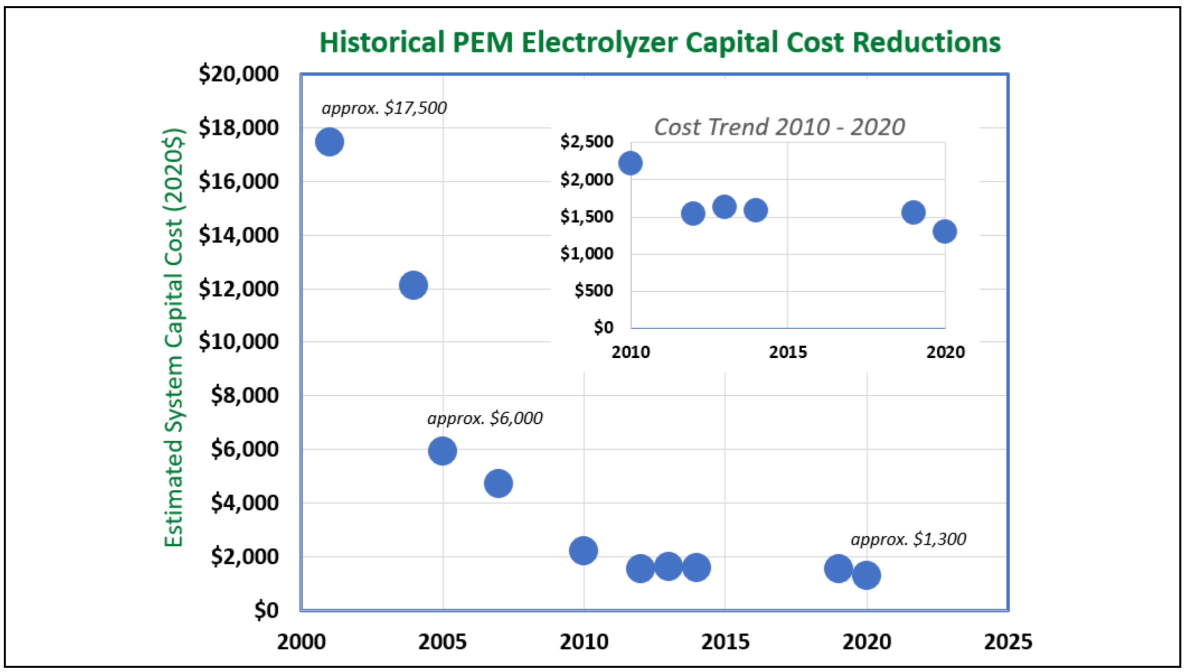

Figure 1 – Adjusted capital costs for PEM electrolyzer systems (in 2020 U.S. dollars) from 2000 to 2020.[1]

[1] Note: the period from 2010 to 2018 (see inset) has gaps in data and shows only modest cost reductions. This reflects limited/zero DOE funding in electrolyzer RD&D during this period. Also note that the data shown through 2020 represents the evolution and scale-up of relatively small electrolyzer systems (<1 MW); more-recent advances in stack and system scale-up offer opportunities for further cost reduction, especially for larger systems (>1 MW).

Summary

This Program Record documents the historical reductions in uninstalled capital costs of PEM electrolyzers reported by HFTO-supported projects over the past 20 years; and it highlights the important role that RD&D investments have played in enabling these cost reductions. The historical electrolyzer-cost data presented in Figure 1 was derived from HFTO-supported project reports as well as HFTO Program Records published over this time period [1-5], with adjustments for manufacturing volumes-of-scale and dollar-year-basis to enable consistent comparison.[2] HFTO Program Records track performance, durability, and cost in state-of-the-art PEM electrolyzer systems, and include data vetted by independent electrolyzer original equipment manufacturers (OEMs).

As seen in Figure 1, the estimated PEM electrolyzer system capital cost in 2020 of approximately $1,300/kW represents a greater than 90% reduction compared with the 2000 cost (~$17,500 kW), and almost an 80% reduction since 2005 (~$6,000/kW). These cost reductions have been enabled by RD&D innovations through DOE-supported projects with multiple PEM electrolyzer OEMs (including Giner, Inc. and Proton Onsite, among others [6]), largely focused on technology advancements and manufacturing innovations for PEM electrolyzer stacks.

Electrolyzer Stack Cost Reductions

Historically reported capital costs of electrolyzer stacks accounted for approximately 40-60% of the total system capital cost [7], and high-priority RD&D supported by HFTO focused on reducing stack costs, while at the same time improving performance and durability.

One example of successful HFTO-supported RD&D is illustrated in Figure 2, showing significant stack cost reductions between 2001 and 2012 in PEM electrolyzers at Giner, Inc. [1]. These lower costs were achieved through improved stack designs, which reduced costs in all stack elements, such as catalysts, membranes, anodes, cathodes, and frames (Figure 2a); and through manufacturing innovations, which reduced the number of parts per cell in the stack (Figure 2b).

[2] The methodology used to adjust data to reflect low-volume manufacturing system capital costs on a 2020 U.S. dollars basis is described in the Appendix.

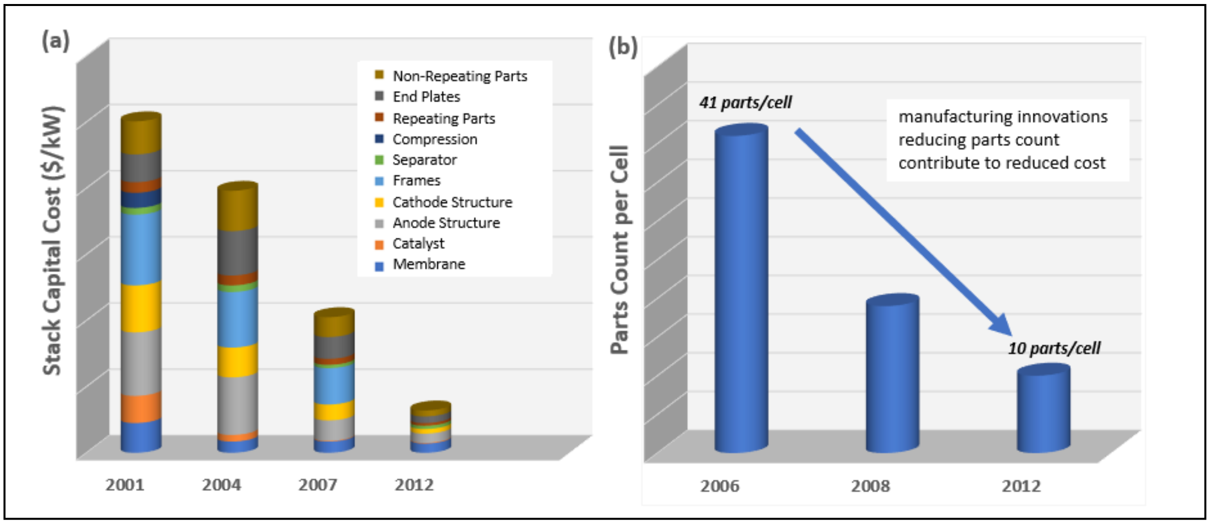

Figure 2 – Normalized reductions in electrolyzer stack cost and part count reported by Giner, Inc.[3]

Figure 3 illustrates the evolution of Giner's stack designs during this period [8], where reducing membrane thickness and catalyst loading contributed to cost reductions. At the same time, the newer designs improved power density and conversion efficiency, enabling a lower-cost, more-compact stack with fewer parts for a given power rating.

A key innovation in this stack evolution was Giner's development of Dimensionally Stabilized Membrane–Perfluorocarbon Sulfonic Acid (DSM-PFSA) membranes, which allowed for optimized performance at lower membrane thicknesses. By 2012, Giner demonstrated scaled-up 27-cell DSM-PFSA stacks (with a cell area of 290 cm²) producing more than 0.5 kg-H_2/hr at efficiencies >74% LHV (~88% HHV) and current densities ≥1500 mA/cm², with projected stack lifetimes of >60,000 hours. The Giner electrolyzer stack developed with HFTO support was commercialized and made available in 30-, 60-, and 100-cell configurations.

Efficiency (%HHV):	70	70	78	83	88	>88
Specific Energy (kWh/kg-H_2):	56	56	51	47	45	<45
Membrane Thickness (mils):	10	10	7	5	3 (DSM™)	<3
Temperature (°C):	50	50	55	80	80	80
Power Density (kW/kg):	<0.001	0.76	0.8	0.90	1.0	2.4

Figure 3 – Evolution of PEM stack designs at Giner, Inc., showing improvements in stack performance.[4]

[3] Reproductions based on figures in reference [1]
[4] Reproductions based on figures in reference [8]

Additional HFTO-supported RD&D innovations by other OEMs have complemented Giner's success and contributed additional reductions in PEM electrolyzer stack capital costs. For example, in 2014, Proton Onsite[5] achieved a greater-than-40% reduction in PEM stack cost from their 2011 legacy design. This was achieved using a large-active-area cell design (>650 cm^2), with cost reductions largely due to bipolar plate innovations achieved through DOE-funded work [9] (See Figure 4). These innovations enabled significant cost reductions in the flow fields and separators as well as in the balance of stack. The new large-active-area design was more compact and removed approximately 50% of the titanium from the cell, which was an important factor in lowering the cost. Importantly, the stack designs developed through this work have been instrumental in Proton's subsequent launch of their megawatt (MW)-scale commercial electrolyzer lines, which resulted in even further cost reductions from the 2014 design.

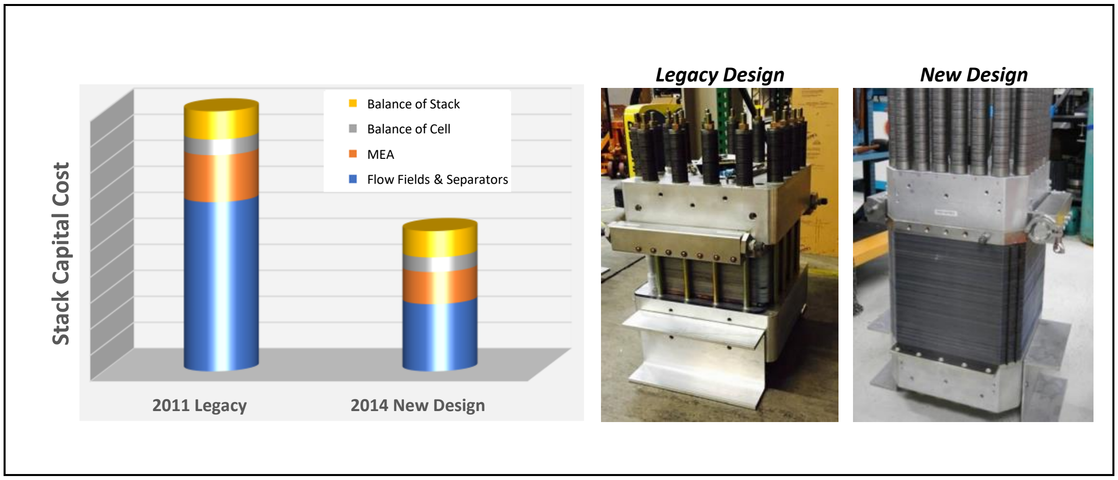

Figure 4 – Normalized reductions in electrolyzer stack capital cost reported by Proton Onsite, including images of the 2011 legacy stack design and the new, improved design implemented in 2014.[6]

Ongoing Efforts

As Figure 1 shows, the uninstalled capital costs of PEM electrolyzers have fallen dramatically, especially from 2000 to 2015, and this has been achieved in large part by RD&D advances made through DOE-supported projects—with Giner, Inc., Proton Onsite (now Nel), and other electrolyzer OEMs. These cost reductions were primarily due to improvements in electrolyzer stacks. Continued cost reduction efforts are underway, both in stacks and in the balance of system,[7] to enable meeting a clean hydrogen cost goal of $2/kg by 2026 (as specified in the *Infrastructure Investment and Jobs Act* [10]) and $1/kg by 2031 (the *Hydrogen Energy Earthshot* target [11]). Additional work is being done to improve electrolyzer efficiencies and lifetimes and to optimize integration with clean electricity generation sources. DOE's current portfolio of research, development, demonstration, and deployment is broadly addressing the necessary technology development, as well as manufacturing, scale-up, and supply chain issues relevant to affordable clean hydrogen production from electrolysis [12].

[5] Proton Onsite has since been acquired by Nel (in 2017)
[6] Reproductions based on figures in reference [9]
[7] Including cost savings enabled through recent developments in scale-up and optimization of integrated electrolyzer system configurations, based on stack and system sizes of 1 MW or greater.

References

[1] Hamdan M. "PEM Electrolyzer Incorporating an Advanced Low Cost Membrane." Final scientific and technical report for U.S. Department of Energy; August 29, 2013 (HFTO's Grant DE-FG36-08GO18065) https://www.osti.gov/servlets/purl/1091385

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[3] Ainscough, C.; Peterson, D.; Miller, E. (2014) "Hydrogen Production Cost from PEM Electrolysis." Record #14004. https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

[4] Peterson, D.; Vickers, J.; DeSantis, D. (2020). "Hydrogen Production Cost from PEM Electrolysis – 2019." Record #19009. https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf

[5] Vickers, J.; Peterson, D.; Randolph, K. (2020). "Cost of Electrolytic Hydrogen Production with Existing Technology." Record #20004. https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf

[6] See a more complete list of relevant projects in the HFTO Annual Merit Review and Peer Evaluation Meeting database at: https://www.hydrogen.energy.gov/annual_review.html

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[8] Hamdan, M., EERE Webinar: https://www.energy.gov/sites/prod/files/2014/03/f12/webinarslides052311_pemelectrolysis_hamdan.pdf

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[10] Also known as the *Bipartisan Infrastructure Law:* https://www.whitehouse.gov/bipartisan-infrastructure-law/. Hydrogen cost goal established by the Clean Hydrogen Electrolysis Program, 42 U.S.C. § 16161d.

[11] Also known as the *Hydrogen Shot*: https://www.energy.gov/eere/fuelcells/hydrogen-shot

[12] DOE Hydrogen Program Plan (2020). https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[13] The Chemical Engineering Plant Cost Index: https://www.chemengonline.com/pci-home

Appendix:

The adjusted data shown in Figure 1, for low-volume PEM system electrolyzer capital costs, is shown in Table 1 below.

Table 1. Electrolyzer Costs (2001 – 2020)

Year	Source	Stack High Volume (2016$)	System High Volume (2016$)	System Low Volume (2016$)	System Low Volume (2020$)
2001	Ref [1]	3,845	7,690	16,149	17,441
2004	Ref [1]	2,673	5,346	11,226	12,124
2005	Ref [2]	1,308	2,617	5,495	5,935
2007	Ref [1]	1,036	2,071	4,350	4,698
2010	Ref [2]	490	981	2,060	2,224
2012	Ref [2]	340	681	1,430	1,544
2013	Ref [2]	359	717	1,507	1,627
2014	Ref [3]	349	699	1,468	1,585
2019	Ref [4]	342	684	1,436	1,551
2020	Ref [5]	-	-	-	1,300

To estimate capital costs (at low-volume manufacturing) for electrolyzer systems in 2020 U.S. dollars, adjustments were made to the original data, including:

1) Cost projections for electrolyzer capital costs reported in references that were based on relatively high-volume manufacturing (1,500 MW/year) were converted to costs based on low-volume manufacturing (less than approximately 5 MW/year) using a ratio of 2.1:1, based on cost differences estimated by NREL [7].

2) Total electrolyzer *system* capital costs (for references only providing historical *stack* cost data) were estimated using a stack-to-balance-of-plant ratio of 1:1, as recommended by electrolyzer OEMs and generally consistent with the ratio estimated by NREL [7].

3) Dollar-year cost conversions applied to original source data (e.g., conversion to 2006 U.S. dollars and 2020 U.S. dollars) were based on standard consumer price index data [13].