Progress in Hydrogen and Fuel Cells Fact Sheet Citations

This document contains citations and additional background information for the examples in the "Progress in Hydrogen and Fuel Cells" fact sheet (January 2025). The fact sheet provides examples of industry investment and growth and describes how funding from the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office has spurred progress in several specific areas.

Download the fact sheet at https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-accomplishments-and-progress.

Quoted Figure	**Source / Additional Information**
25-fold increase in electrolyzer installations (planned and installed) since 2021—from 0.17 gigawatts (GW) in 2021 to 4.5 GW in 2024	Hubert, M., and V. Arjona. 2024. "Electrolyzer Installations in the United States." DOE Hydrogen Program Record #24001. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24001-electrolyzer-installations-united-states.pdf
>$40 billion in private-sector investment in the H2Hubs	DOE. 2023. "Biden-Harris Administration Announces $7 Billion For America's First Clean Hydrogen Hubs, Driving Clean Manufacturing and Delivering New Economic Opportunities Nationwide." U.S. Department of Energy. October. https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving
15 new or expanded manufacturing facilities announced for electrolyzers, fuel cells, and components—over $2.9 billion of investment	DOE. 2024. "Building America's Clean Energy Future." U.S. Department of Energy. Last updated December 2024. https://www.energy.gov/invest
Nearly **70,000 fuel cell forklifts** and **over 500 MW of backup power fuel cells** deployed—markets initiated and spurred by HFTO-supported deployments over 15 years ago	Satyapal, Sunita. 2024. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks." Slide 23. DOE Hydrogen Program 2023 Annual Merit Review and Peer Evaluation Meeting. May. https://www.energy.gov/sites/default/files/2024-05/amr-plenary-satyapal-2024-0.pdf

Data in cost-reduction graphic (bottom of page 1): • Electrolytic hydrogen production cost of ~$7/kg to ~$5/kg (low-volume estimate) • Thermal hydrogen production cost of ~$1.60 /kg to ~$1.30/kg (high-volume estimate) • HD fuel cell system cost of ~$300/kW (low-volume estimate) and f~$200/kW to ~$160/kW (high-volume projection) • Onboard hydrogen storage cost (700-bar) of ~$21/kWh (low-volume estimate) and ~$16/kWh (high-volume projection)	Satyapal, Sunita. 2024. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks." Slide 31. DOE Hydrogen Program 2023 Annual Merit Review and Peer Evaluation Meeting. May. https://www.energy.gov/sites/default/files/2024-05/amr-plenary-satyapal-2024-0.pdf Additional supporting information: • Graphs not drawn to scale and are for illustration purposes only. • Cost values incorporate different assumptions of volume production, economies of scale, and technology pathways. • Electrolysis cost numbers are in 2022 dollars, with renewables and no tax credits. • Thermal hydrogen production numbers are based on NETL analysis including projected modeled cost for SMR/ATR with CCS and technology advances at volume. • HD fuel cell system cost is based on "Heavy Duty Fuel Cell System Cost – 2023" (DOE Hydrogen Program Record #24004," https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/24004-hd-fuel-cell-system-cost-2023.pdf), adjusted to reflect cost of system that meets 25,000 hours durability. • Hydrogen storage costs based on "Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status" (DOE Hydrogen Program Record #19008, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19008_onboard_storage_cost_performance_status.pdf).
Accelerated hydrogen production R&D	Young, J., M. Steiner, H. Döscher, et al. 2017. "Direct Solar-to-Hydrogen Conversion via Inverted Metamorphic Multi-Junction Semiconductor Architectures." *Nature Energy* (2): 17028. https://www.nature.com/articles/nenergy201728.

Reduced the cost of electrolyzers by over 90% since 2001 and 80% since 2005	Hubert, M., D Peterson, E. Miller, et al. 2024. "Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology." DOE Hydrogen Program Record #24005. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf?sfvrsn=8cb10889_1.
Reduced the cost of compressed on-board hydrogen storage systems	Adams, J., C. Houchins, and R. Ahluwalia. 2019. "Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status." DOE Hydrogen and Fuel Cells Program Record #19008. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19008_onboard_storage_cost_performance_status.pdf.
Reduced the cost of compressed on-board hydrogen storage systems	Byerly, D., and C. Wilson. 2024. "Carbon Composite Optimization Reducing Tank Cost." DOE Hydrogen Program 2024 Annual Merit Review and Peer Evaluation Meeting. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/st237_byerly_2024_o.pdf.
Launched a first-in-the-U.S. facility to demonstrate 10 tons hydrogen storage capacity	Stetson, Ned. 2024. "HFTO H2 Infrastructure Technologies Subprogram Overview." Slide 21. May. 2024 Hydrogen Program Annual Merit Review and Peer Evaluation Meeting. Arlington, VA. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/in000_stetson_2024_o0e018332-9871-45a3-9c2c-67686e3fadab.pdf.
Launched a first-in-the-U.S. facility to demonstrate 10-ton hydrogen storage capacity	Leighton, Daniel. 2024. "DOE HFTO H2IQ Hour: NREL ARIES Flatirons Campus MW-Scale Hydrogen System Research." July. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy24osti/90601.pdf.
Demonstrated fast fueling of high-pressure H_2(700 bar), with 10 kg/min average rate and a peak rate of 27 kg/min	Martineau, R. 2022. Fast Flow Future for Heavy-Duty Hydrogen Trucks. National Renewable Energy Laboratory. June 8. https://www.nrel.gov/news/program/2022/fast-flow-future-heavy-duty-hydrogen-trucks.html.

Demonstrated that liquid organic hydrogen carriers	Breunig, H., F. Rosner, S. Saqline, et al. 2024. "Achieving Gigawatt-Scale Green Hydrogen Production and Seasonal Storage at Industrial Locations Across the U.S." *Nature Communications* (15): 9049. https://www.nature.com/articles/s41467-024-53189-2.
Reduced high-volume costs of fuel cells	Kleen, G., and W. Gibbons. 2024. "Heavy-Duty Fuel Cell System Cost – 2023." DOE Hydrogen Program Record #24004. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/24004-hd-fuel-cell-system-cost-2023.pdf.
Launched the L'Innovator with $2 million of HFTO funds enabling $160 million of private sector investment	HFTO. 2024. DOE's L'Innovator Pioneers a New Model for Jumpstarting Commercialization of Cutting-Edge Fuel Cell Technologies. U.S. Department of Energy. February. https://www.energy.gov/eere/fuelcells/articles/does-linnovator-pioneers-new-model-jumpstarting-commercialization-cutting.
Improved performance of platinum group metal PGM-free catalysts by 60%	D. Papageorgopoulos. 2023. "Fuel Cell Technologies Overview." DOE Hydrogen Program 2023 Annual Merit Review and Peer Evaluation Meeting. June. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/fc000_papageorgopoulos_2023_o.pdf.
Launched H2CIRC, a Recovery and Recycling Consortium for $64 million	AIChE. 2024. AIChE Selected by DOE to Lead New Hydrogen Electrolyzer and Fuel Cell Recycling Consortium. American Institute of Chemical Engineers. March. https://www.aiche.org/about/press/releases/03-15-2024/aiche-selected-doe-lead-new-hydrogen-electrolyzer-and-fuel-cell-recycling-consortium.
Launched H2CIRC, a Recovery and Recycling Consortium for $64 million	HFTO. 2024. Funding Selections for Clean Hydrogen Electrolysis, Manufacturing, and Recycling Activities under the Bipartisan Infrastructure Law. U.S. Department of Energy. March. https://www.energy.gov/eere/fuelcells/bipartisan-infrastructure-law-clean-hydrogen-electrolysis-manufacturing-and-0.
Supported the launch of seven Regional Clean Hydrogen Hubs for $7 billion	Office of Clean Energy Demonstrations. 2024. Regional Clean Hydrogen Hubs. U.S. Department of Energy. https://www.energy.gov/oced/regional-clean-

	hydrogen-hubs-0.
Launched SuperTruck III projects	DOE. 2021. "DOE Announces $162 Million to Decarbonize Cars and Trucks." U.S. Department of Energy. April. https://www.energy.gov/articles/doe-announces-162-million-decarbonize-cars-and-trucks.
Demonstrated the nation's first direct-coupled nuclear-to-hydrogen production facility	Office of Nuclear Energy. 2023. Nine Mile Point Begins Clean Hydrogen Production. U.S. Department of Energy. March. https://www.energy.gov/ne/articles/nine-mile-point-begins-clean-hydrogen-production.
Demonstrated steel decarbonization using hydrogen	O'Malley, R.J. 2023. "Grid-Interactive Steelmaking with Hydrogen (GISH)." DOE Hydrogen Program 2023 Annual Merit Review and Peer Evaluation Meeting. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/ta053_omalley_2023_o-pdf.pdf.
Demonstrated a first-of-its-kind MW-scale hydrogen fuel cell at a data center	HFTO. 2024. February H2IQ Hour: Hydrogen Fuel Cell Generator Demonstration at Microsoft Data Center. February. U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/february-h2iq-hour-hydrogen-fuel-cell-generator-demonstration-microsoft-data-center.
Demonstrated a first-of-its-kind MW-scale hydrogen fuel cell at a data center	HFTO. 2024. Spotlight on Success: First Megawatt-Scale Demonstration of Hydrogen Fuel Cells for Data Center Backup Power. U.S. Department of Energy. @H2Spotlight: Fall 2024. https://www.energy.gov/eere/fuelcells/h2spotlight-fall-2024#spotlights.
Launched H2Rescue fuel cell truck	HFTO. 2024. Hydrogen-Powered Heavy-Duty Truck Establishes New Threshold by Traveling 1,800 Miles on a Single Fill. Hydrogen and Fuel Cell Technologies Office. December. https://www.energy.gov/eere/fuelcells/articles/hydrogen-powered-heavy-duty-truck-establishes-new-threshold-traveling-0.
Launched "Station of the Future"	HFTO. 2024. Selections for Hydrogen and Fuel Cell Technologies Office Funding Opportunity Announcement to Advance the National Clean Hydrogen Strategy. U.S. Department of Energy. August 30. https://www.energy.gov/eere/fuelcells/selections-hydrogen-and-fuel-cell-technologies-office-funding-opportunity-0.

Informed code revisions	NFPA. 2023. *Hydrogen Technologies Code*. National Fire Protection Association. August. https://www.nfpa.org/codes-and-standards/nfpa-2-standard-development/2.
Developed an ASME code case that extends design life of storage vessels by up to 3X	Ronevich, J., and C. San Marchi. 2021. "Increased Design Life for High-Pressure Stationary Hydrogen Storage Vessels Through Development of Empirically Based Design Curves." DOE Hydrogen Program Record #21004. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/21004-increased-life-pressure-vessel-tanks.pdf?Status=Master.
Published a regulatory roadmap	Baird, A.R., B.D. Ehrhart, A.M. Glover, C.B. LaFleur. 2021. *Federal Oversight of Hydrogen Systems*. Albuquerque, NM: Sandia National Laboratories. SAND2021-2955. https://energy.sandia.gov/wp-content/uploads/2021/03/H2-Regulatory-Map-Report_SAND2021-2955.pdf.
Launched projects with NOAA	Watson, Christine. 2024. "Overview of DOE Activities Addressing Hydrogen Emissions." Hydrogen Emissions and Environmental Impacts Workshop. Irvine, CA. September 2024. https://www.energy.gov/sites/default/files/2024-11/h2-emissions-workshop-2-watson.pdf.
Launched projects in hydrogen sensor RD&D	HFTO. 2023. Selections for Funding Opportunity in Support of the Hydrogen Shot and a University Research Consortium on Grid Resilience. U.S. Department of Energy. May 22. https://www.energy.gov/eere/fuelcells/selections-funding-opportunity-support-hydrogen-shot-and-university-research.
Released H2Tools resources	Center for Hydrogen Safety. Hydrogen Tools Portal. PNNL. 2024. https://h2tools.org/.
Updated GREET	EERE. 2024. GREET. U.S. Department of Energy. https://www.energy.gov/eere/greet.
Established analysis models and tools now used worldwide H2A, H2A-Lite, H2FAST, HDSAM, HESET, HRSAM, StoreFAST	*H2A: Hydrogen Analysis Production Models*. NREL. https://www.nrel.gov/hydrogen/h2a-production-models.html; *H2A-Lite: Hydrogen Analysis Lite Production Model*. NREL. https://www.nrel.gov/hydrogen/h2a-lite.html; *H2FAST: Hydrogen Financial Analysis Scenario Tool*. NREL. https://www.nrel.gov/hydrogen/h2fast.html; *Hydrogen Delivery Scenario Analysis Model (HDSAM)*. ANL. https://hdsam.es.anl.gov/index.php?content=hdsa

	m; *Hydrogen Energy Storage Evaluation Tool (HESET)*. PNNL. https://eset.pnnl.gov/#/ourproducts/HESET; *Hydrogen Refueling Station Analysis Model (HRSAM)*. ANL. https://hdsam.es.anl.gov/index.php?content=hrsam; *StoreFAST: Storage Financial Analysis Scenario Tool*. NREL. https://www2.nrel.gov/storage/storefast.
Co-led the development of life cycle analysis best practices with the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)	IPHE Hydrogen Production Analysis Task Force. 2023. *Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen Version 3*. IPHE. July 2023. https://www.iphe.net/_files/ugd/45185a_8f9608847cbe46c88c319a75bb85f436.pdf.