Expert Assessments of the Expected Future Costs and Performance of Hydrogen Storage Systems for Vehicles

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Overview

To achieve widespread commercialization of fuel cell electric vehicles (FCEVs), improvements need to be made to the cost and technical performance of hydrogen storage systems. The U.S. DOE (1) highlights hydrogen storage cost, packaging, and durability as "...the major challenges facing hydrogen storage systems prior to widespread commercialization of hydrogen fuel cell systems." At 500,000 units/year, a compressed hydrogen storage system could cost upwards of $3,000, which is comparable to the cost of an automotive fuel cell system.[1] Hydrogen storage has become a of focus of public and private R&D. The U.S. DOE invested $15.6 million in FY 2017 to improve the technical and economic performance of physical and materials-based hydrogen storage technologies (2). The Fuel Cells and Hydrogen Joint Undertaking funds a three-year project, the Tank Hydrogen Automotive project, to develop a cost-competitive compressed gas system (3). Toyota reduced the weight and size of compressed gas tanks in their 2015 Mirai (4). Several physical and materials-based technologies, including cold and cryo-compressed gas, metal hydrides, adsorbents, and chemical storage, could rival compressed gas in the longer term (2). In our study, we (i) projected the future costs and performance of FCEV hydrogen storage systems, (ii) identified the most technically and economically viable hydrogen storage technologies in the near- and far-terms, and (iii) informed future hydrogen storage R&D funding.

Methods

We performed an expert elicitation to assess the expected future costs and performance of automotive hydrogen storage systems. We interviewed 30 experts across academia, government, and industry. We elicited experts' 2020, 2035, and 2050 assessments of hydrogen storage system cost, gravimetric capacity, and volumetric capacity. For reference, we provided experts with the DOE's current costs and capacities of compressed gas (5, 6), metal hydride, adsorbent, and chemical storage technologies (7). We describe our procedure in more detail in our previous work (8).

We asked experts to adopt technical and economic assumptions consistent with those in the Multi-Year Research, Development, and Demonstration (MYRD&D) Plan (1). We asked experts to define the gravimetric and volumetric capacities as the mass of usable hydrogen divided by the storage system's mass and volume, respectively. We asked experts to define the production cost as the system's total production cost divided by the lower heating value of usable hydrogen. Experts were asked to exclude any sales markup applied by the final system assembler for profit, overhead, and other business expenses, although experts could include markups applied by lower-tier suppliers. Experts were also asked to assume a production volume of 500,000 units/year (5).

In addition to eliciting experts' performance assessments, we asked experts to predict technology trajectories and recommend government R&D funding levels. When eliciting experts' technical and economic assessments, we asked experts to indicate the storage technology (or technologies) that they believed to be the most technically and economically viable in 2020, 2035, and 2050. To inform future hydrogen storage R&D, we asked experts to recommend the minimum amount of government R&D funding in FY 2018 that they thought would be necessary to achieve the MYRD&D Plan's hydrogen storage targets (1). Unless otherwise noted, the DOE values referenced hereafter are from the U.S. Drive's target explanation document (9).

[1] Assuming Ordaz, Houchins, and Hua's (5) estimate of $14.8/kWh for the hydrogen storage system and a stored amount of 5.6 kg_{H2}, the storage system would cost $3,190. Assuming the U.S. DOE's (10) estimate of $53/kW_{net}$ for the fuel cell system and a power output of 80 kW_{net}, the fuel cell system would cost $4,240. These costs assume a production volume of 500,000 units/year. We used the producer price index to convert published costs from 2007 USD to 2017 USD (11).

Results

Experts' hydrogen storage cost projections exceeded the DOE's targets from 2020–2050. On median, experts predicted that the 2020 cost would be \$16.4/kWh$_{H2}$, which is 60% greater than the DOE's 2020 target of \$10/kWh$_{H2}$. Experts predicted that the hydrogen storage cost would decline to \$10.5/kWh$_{H2}$ by 2050. However, most experts thought that the DOE's ultimate target, \$8/kWh$_{H2}$, would remain unmet.

Experts predicted that the gravimetric capacity of hydrogen storage would meet the DOE's 2020 target and come close to meeting the DOE's ultimate target. On median, experts predicted that the 2020 target of 0.045 kg$_{H2}$/kg$_{system}$ would be met. Experts predicted that the gravimetric capacity would reach 0.058 kg$_{H2}$/kg$_{system}$ by 2050. Several experts even predicted that the DOE's ultimate target, 0.065 kg$_{H2}$/kg$_{system}$, would be met by 2050.

Most experts predicted that the volumetric capacity of hydrogen storage would fall short of the DOE's targets from 2020–2050. On median, experts predicted that the 2020 gravimetric capacity would be 0.024 kg$_{H2}$/L$_{system}$, which falls short of the DOE's 2020 target of 0.03 kg$_{H2}$/L$_{system}$. Experts predicted the 2050 volumetric capacity to be 0.04 kg$_{H2}$/L$_{system}$, which falls short of the DOE's ultimate target of 0.05 kg$_{H2}$/L$_{system}$.

On median, experts recommended \$19.5 million in total funding. Experts allocated the most funding to materials development, followed in decreasing amount by advanced tanks, testing and analysis, and engineering. The middle 50% of experts recommended up to 2 times the DOE's FY 2017 appropriation for materials development and up to 5 times the appropriation for engineering. Most experts predicted that compressed gas would be the most technically and economically viable technology from 2020–2050. Several experts indicated that adsorbents, chemical storage, and cold compressed storage could become viable in 2035 and 2050.

Conclusions

We elicited 30 experts' assessments of the expected future costs and performance of automotive hydrogen storage systems. Experts' cost projections exceeded the DOE's targets from 2020–2050. Most experts predicted that the DOE's ultimate target, \$8/kWh$_{H2}$, would remain unmet in 2050. Experts generally agreed with the DOE's 2020 target for gravimetric capacity, and several experts predicted that the DOE's ultimate target would be met by 2050. Most experts provided volumetric capacity estimates that were lower than the DOE's 2020 and ultimate targets. To meet the DOE's hydrogen storage targets, experts recommended allocating the most funding to materials development, followed in decreasing amount by advanced tanks, testing and analysis, and engineering. Experts predicted that compressed gas would be the most technically and economically viable technology in the near and far-terms, though experts thought that materials-based storage could become viable in 2035 and 2050.

References

1. U.S. Department of Energy (2015) *Multi-year research, development, and demonstration plan: Hydrogen storage* Available at: https://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf.
2. Stetson NT (2017) Hydrogen storage program area. *Annual Merit Review Proceedings* (Washington, D. C.). Available at: https://www.hydrogen.energy.gov/pdfs/review17/st000_stetson_2017_o.pdf.
3. Fuel Cells and Hydrogen Joint Undertaking (2017) Tank Hydrogen Automotive. Available at: http://www.fch.europa.eu/project/tank-hydrogen-automotive [Accessed April 7, 2018].
4. Yamashita A, Kondo M, Goto S, Ogami N (2015) Development of high-pressure hydrogen storage system for the Toyota "Mirai." *SAE 2015 World Congress and Exhibition* doi:10.4271/2015-01-1169.
5. Ordaz G, Houchins C, Hua T (2015) *Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status 2015 (Record # 15013)* Available at: https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf.
6. McWhorter S, Ordaz G (2013) *DOE Fuel Cell Technologies Office record (Record # 13010)* Available at: https://www.hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf.
7. Anton DL, Motyka T (2016) Hydrogen storage engineering. *Annual Merit Review Proceedings* (Washington, D.C.). Available at: https://www.hydrogen.energy.gov/pdfs/review16/st004_anton_2016_o.pdf.
8. Whiston MM, et al. (2018) *Expert assessments of the costs and expected future performance of proton exchange membrane fuel cells for vehicles* (Manuscript submitted.).
9. U.S. Drive (2017) *Target explanation document: Onboard hydrogen storage for light-duty fuel cell vehicles* Available at: https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_targets_onboard_hydro_storage_explanation.pdf.
10. U.S. Department of Energy (2017) *Multi-year research, development, and demonstration plan: Fuel cells* Available at: https://energy.gov/sites/prod/files/2016/10/f33/fcto_myrdd_fuel_cells.pdf.
11. U.S. Department of Labor (2018) Producer Price Indexes [Date File]. Available at:https://www.bls.gov/ppi/.