DOE Hydrogen and Fuel Cells Program Record	
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Title: Current Status of Hydrogen Delivery and Dispensing Costs and Pathways to Future Cost Reductions	
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Item

This record establishes the levelized cost of hydrogen delivery and dispensing (excluding production) in 2017 as \$12-\$13/kg[1,2] (2016\$). Given research and development (R&D) accomplishments, the projected levelized cost of hydrogen delivery and dispensing has potential to reach \$5/kg by 2025 at stations supplied by liquid hydrogen tanker trucks.[3] Ultimately, given R&D accomplishments, aggressive market penetration of fuel cell vehicles, and a high-volume market for hydrogen fueling infrastructure technologies, the levelized cost of hydrogen delivery and dispensing also has potential to reach \$2/kg at stations supplied by pipelines.

Background

This record estimates the levelized cost of hydrogen delivery from centralized production to fueling stations, and dispensing into fuel cell electric vehicle (FCEVs) in current markets, and outlines examples of future pathways that could achieve the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's Fuel Cell Technologies Office's (FCTO) targets. It is important to note that the pathways analyzed for 2025 and ultimate scenarios are not forecasts or prescriptions; they are examples that have potential to meet FCTO's targets.

Several key criteria influence the levelized cost of hydrogen fuel delivery and dispensing (\$/kg), and are expected to evolve over the coming years, including:

1. Capital and operating costs of components

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[1] Each kilogram of hydrogen has approximately the same lower heating value as a gallon of gasoline, but fuel cells are about twice as efficient as gasoline engines. As a result, 1 kilogram of hydrogen will enable a car to travel about twice as far as a gallon of gasoline.

[2] This estimate is rounded to two significant digits, for sake of comparison with the aforementioned retail price of hydrogen.

[3] It is important to note that the "projected" cost refers to cost feasible if state-of-the-art laboratory-scale R&D achievements were scaled up and commercially adopted. This projection is not a forecast of actual costs likely to be commercially realized in the given timeframe. Actual costs will depend on many factors outside of the scope of this analysis, including the rate of technology adoption by industry, policies, and the rate at which economies of scale are achieved.

2. Capacities of fueling stations
3. Utilization rates of fueling stations
4. Economies of scale in component manufacturing

R&D innovations in hydrogen fuel production, hydrogen storage, fuel cells, and hydrogen infrastructure, will influence all of these parameters in the coming years. Examples of potential advancements include:

- R&D that enables reductions in station footprint, such that large-scale stations (e.g. 1,000 kg/day) are viable in urban areas.
- Reductions in the costs of capital-intensive equipment at fueling stations (e.g. compressors and liquid pumps).
- Reductions in the energy consumption of hydrogen delivery to fueling stations (e.g. energy consumed in hydrogen liquefaction).
- Improvements in the reliability of fueling components, to reduce maintenance costs.
- Reductions in the costs of fuel cell vehicles, which may result in greater market penetration of vehicles, and subsequent growth in both utilization rates of fueling stations and manufacturing volumes of fueling station components.

FCTO estimates the costs of hydrogen delivery (including compression into tube trailers or pipelines, liquefaction, long-term storage in caverns or at terminals, and transmission and distribution to fueling stations) and dispensing into fuel cell vehicles using the Hydrogen Delivery Scenario Analysis Model (HDSAM). [1] HDSAM is a bottom-up technoeconomic model that calculates the levelized costs of hydrogen delivery to fueling stations and dispensing into vehicles. The assumptions of technology costs and performance in HDSAM reflect state-of-the-art technologies that are currently commercially available. Certain key assumptions regarding the fueling station market and station design (e.g. penetration of fuel cell vehicles or method of hydrogen supply) are user-defined.

In this record, the costs of hydrogen delivery and dispensing in current markets are characterized, and examples of research paths that can achieve FCTO's near-term and ultimate targets for the cost of hydrogen fuel are identified. HDSAM was used to conduct the analysis in this record. It is important to note that the research paths described are not exclusive, or recommendations for future activities. FCTO's targets are summarized below:

- 2025 target for the cost of hydrogen fuel (produced, delivered, dispensed): $7/kg [2]
    - Current hydrogen production costs approximately $2/kg. [3] As a result, the near-term target allocated to hydrogen delivery and dispensing is $5/kg.

- Ultimate target for the cost of hydrogen fuel delivery and dispensing in mature markets: $2/kg

Delivery and dispensing costs have been calculated assuming early markets expected in the near-term, as well as mature markets expected in the long-term, wherein high-volume manufacturing (i.e., economies of scale) are expected to generate cost reductions beyond those achieved by R&D. Table 1 below summarizes these costs, and Sections I, II, and III describe them in greater detail. Each of the analysis years listed below corresponds to the year in which certain technological innovations are assumed to have driven reductions in cost. "High-volume" scenarios for those years project the costs achievable with the respective technologies if they were manufactured at economies of scale.

Table 1: Cost Estimates for Hydrogen Delivery and Dispensing in Fueling Scenarios Projected for 2017, 2025, and Ultimate Markets[4]

	Early-Market	High-Volume Manufacturing
2017	\$11.80-\$12.70/kg	\$7.95-\$8.80/kg
2025	\$4.90/kg	\$4.15/kg
Ultimate	\$2.95/kg	\$2.05/kg

I. 2017 Scenario for Hydrogen Delivery and Dispensing

Table 2a below enumerates the assumptions used to simulate the 2017 scenarios, and Table 2b describes the results of the simulations. As shown in Table 2b, the estimate for low-volume cost of hydrogen delivery and dispensing in 2017 is \$12/kg-\$13/kg.

Table 2a: Market Definition of 2017 Scenario

Hydrogen Supply Mode	Gaseous Tube Trailers and Liquid Tankers
Station Capacity	180 kg/day (tube trailers)[5] 350 kg/day (liquid tankers)[5]
Annual Station Utilization Rate	16% in year 1, increasing to 80% within 5 years[6]
Station Analysis Period	10 years
Analysis period for other delivery components (e.g. tube trailers, liquid tankers)	30 years
Station Discount Rate	7%[7]
Fuel Cell Vehicle Market Penetration	1% in a city with a population representing the median within the U.S.[8]
Federal Tax Rate	35%
Dollar Year of Estimate	2016\$

Extensive stakeholder feedback informed estimates of the costs of technologies used to deliver hydrogen to fueling stations (e.g. tube trailers and loading terminals), as well as components at stations; HDSAM documents these estimates.

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[4] The cost estimates in this table are direct outputs of HDSAM, given assumptions outlined in Tables 2a, 3a, 3b, 4a, and 4b. They have been rounded to the nearest 5 cents.

[5] 180 kg/day stations supplied by gaseous tube trailers and 350 kg/day stations supplied by liquid tankers are two of the designs that have been funded by the California Energy Commission (CEC), and a common assumption in station financial analysis. [4]

[6] As of 2017, the average rate of growth in utilization of stations in California would achieve 80% utilization within 5 years. These rates can range from 1 years to 10 years, depending in part on the capacity of the station. [4]

[7] 7% represents the "marginal pretax rate of return on an average investment in the private sector in recent years". [6]

[8] The city simulated was Indianapolis, IN in this analysis. The population of Indianapolis is approximately the median of the populations of the 30 largest cities in the U.S. [7]

Table 2b: Levelized Cost of Hydrogen Delivery and Dispensing Estimated for 2017 Scenario[9]

	180 kg/day Station Supplied by Gaseous Tube Trailers	**350 kg/day Station Supplied by Liquid Tankers**
Low-volume Manufacturing	$12.70/kg	$11.80/kg
High-volume Manufacturing	$7.95/kg	$8.80/kg

II. Delivery in Dispensing in 2025

Due to the anticipated growth in hydrogen demand and station utilization by 2025, it is expected that stations of at least 1,000 kg/day capacity will be of interest. [5] Liquid tankers are the most viable approach to supplying 1,000 kg/day stations in early markets. Liquid tankers are able to carry at least 5 times more hydrogen than tube trailers without exceeding U.S. Department of Transportation regulations regarding the gross weight of vehicles.[10] Use of liquid tankers is also significantly less capital intensive than installation of pipelines, which increases their value proposition in emerging markets.

Tables 3a and 3b below enumerate the market definition and R&D advancements used to simulate potential costs of delivery and dispensing in 2025, and Table 3c enumerates the results of the simulation.

Tables 3a, 3b, and 3c: Simulation of Hydrogen Fueling for 1,000 kg/day Stations in 2025

Table 3a: Market Definition of 2025 Scenario

Hydrogen Supply Mode	Liquid Tankers
Station Capacity	1,000 kg/day
Annual Station Utilization Rate	16% in year 1, increasing to 80% within 5 years
Station Analysis Period	10 years
Analysis period for other delivery components (e.g. tube trailers, liquid tankers)	30 years
Station Discount Rate	7%
Fuel Cell Vehicle Market Penetration	1%
Corporate Tax Rate	21%[11]
Dollar Year of Estimate	2016$

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[9] The figures in this table are direct outputs of HDSAM, given assumptions outlined in Table 2a. They have been rounded to the nearest 5 cents. These estimates reflect the projected cost of new hydrogen delivery and fueling infrastructure (e.g. new liquefaction plants, gaseous tube trailer terminals, and fueling stations). Today, hydrogen distribution leverages existing, amortized capital (e.g. liquefaction plants), and actual costs will therefore differ from these projections. For instance, the cost of hydrogen from a 350 kg/day liquid station may not exceed that from a 180 kg/day gaseous station (as shown in the table), because liquefaction plants that currently supply hydrogen fueling stations are likely to be fully amortized.

[10] Gaseous tube trailers currently commonly have capacities of <500 kg. However, the maximum capacity that they can achieve without exceeding U.S. DOT weight limits is estimated at 1,000 kg. The maximum capacity of liquid tankers is currently ~5,000 kg.

[11] The corporate tax rate is assumed to change to 21% due to the 2017 legislation "The Tax Cuts and Jobs Act".

Table 3b: Assumptions of R&D Accomplishments in 2025 Scenario[12]

Fueling Station Footprint	40% reduction by 2022, relative to 2016 baseline
Cost of Dispensers (Uninstalled)	$50,000/unit *(50% decrease from 2017 status)*
Cost of High-pressure (875-bar) Storage at Fueling Stations (Uninstalled)	$600/kg *66% decrease from 2017 status)*
Capital Cost of High-pressure Cryopumps (Uninstalled)	$380,000 *(50% decrease from 2017)*
Annual Maintenance Cost of High-pressure Cryopumps	2% of Capital Cost *(50% decrease from 2017)*
Capital Cost of Liquefier (Installed)	$19 million, 9 tonne/day plant *(50% decrease from 2017)*
Energy Consumption of Liquefier	5 kilowatt-hour/kilogram-H_2, 9 tonne/day plant *(50% decrease from 2017)*

Table 3c: Levelized Cost of Hydrogen Delivery and Dispensing Estimated for 2025 Scenario[13]

Low-volume Manufacturing	$4.90/kg
High-volume Manufacturing	$4.15/kg

Figure 1 below describes the impacts of each of the changes in assumptions between the 2017 and 2025 scenarios (Tables 2a, 3a, and 3b). Error bars reflect uncertainties in the costs of hydrogen dispensers, high-pressure storage, high-pressure cryopumps at fueling stations, and liquefaction.

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[12] It is important to note that these values reflect the costs feasible if state-of-the-art laboratory-scale R&D achievements as of 2025 were scaled up and commercially adopted. These assumption are not a forecast of actual costs likely to be commercially realized in the given timeframe. Actual costs will depend on many factors outside of the scope of this analysis, including the rate of technology adoption by industry, policies, and the rate at which economies of scale are achieved.

[13] The figures in this table are direct outputs of HDSAM, given assumptions outlined in Table 2a. They have been rounded to the nearest 5 cents.

Figure 1: Examples of Cost Reductions that Could Facilitate Low Cost of Hydrogen Delivery and Dispensing by 2025

Error bars reflect uncertainty in costs of forecourt compression, storage, dispensing, as well as liquefaction

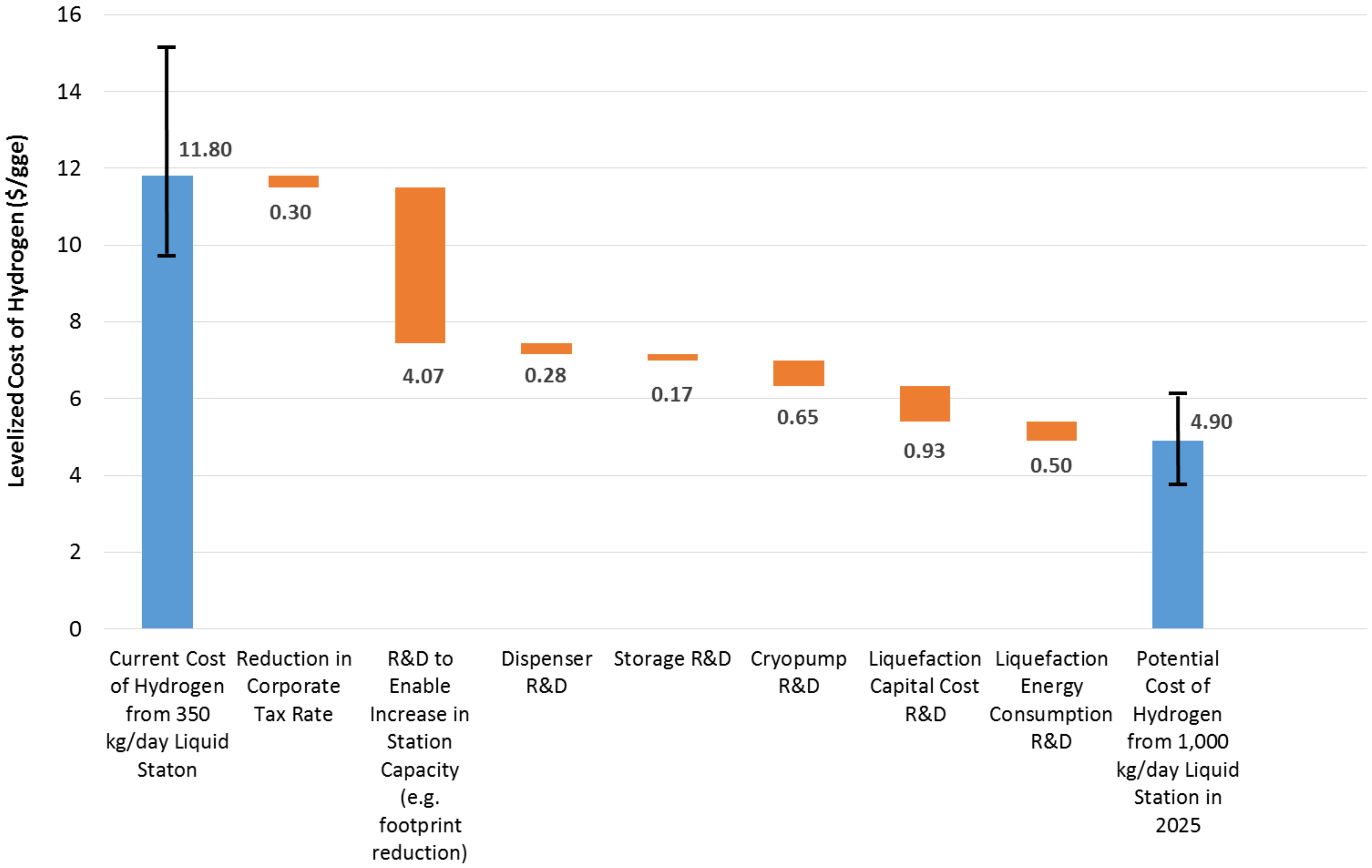

Table 3b enumerates the assumptions of R&D accomplishments that may be achieved by 2025. Ongoing R&D that FCTO is funding in these areas include:

- Characterization and quantitative modeling of liquid hydrogen behavior, to inform potential reductions in station footprint based on risk criteria and justifiable scientific analysis. [8]
- Chemical and structural evaluations of dispensing hoses, development of metal-free dispensing hoses from novel polymers, and development of high-accuracy hydrogen meters with advanced communications. [9], [10], [11]
- Development of wire-wrapped high-pressure storage vessels. [12]
- Exploration of novel early-stage concepts with potential to replace conventional compression and expansion equipment at liquefaction plants to reduce capital cost. [13]
- Evaluation of potential for non-mechanical concepts, such as use of magnetocaloric materials, to liquefy hydrogen at twice the efficiency of conventional cycles. [14]
- Thermodynamic analysis of liquid hydrogen handling processes to identify approaches to mitigate boil-off. [15]

III. Delivery and Dispensing in the Long-Term

Of the methods of hydrogen delivery currently feasible – tube trailers, liquid tankers, and pipelines – pipelines are an efficient and low-cost option when demand is substantial (hundreds of thousands of kilograms per day) and expected to remain stable for at least 30 years. [16] Pipelines are a viable approach to supplying 3,000 kg/day stations in the long-term. A scenario was identified with potential to meet FCTO's ultimate target for hydrogen delivery and dispensing of \$2/kg, [17] leveraging pipelines and 3,000 kg/day stations. This scenario and associated assumptions are described below.

Tables 4a, 4b, and 4c: Simulation of Hydrogen Fueling for 3,000 kg/day Stations

Table 4a: Market Definition of Ultimate Scenario

Hydrogen Supply Mode	Pipeline
Station Capacity	3,000 kg/day
Annual Station Utilization Rate	80%[14]
Station Analysis Period	10 years
Analysis Period for Other Delivery Components (e.g. pipeline)	30 years
Station Discount Rate	7%
Fuel Cell Vehicle Market Penetration	70%[15]
Corporate Tax Rate	21%[16]
Dollar Year of Estimate	2016$

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[14] Pipelines are assumed to only be deployed in regions where substantial utilization of fueling stations is immediately expected.

[15] It is expected that pipelines will primarily be deployed in regions with high demand for hydrogen. Currently, the only fueling station in the U.S. supplied by a hydrogen pipeline is located in Torrance, California; this pipeline was originally installed to supply high demands from petrochemical facilities. To simulate high demand for hydrogen in HDSAM, an aggressive penetration of fuel cell vehicles was assumed.

[16] The corporate tax rate is changed to 21% due to the 2017 legislation "The Tax Cuts and Jobs Act".

Table 4b: Assumptions of R&D Accomplishments in Ultimate Scenario

Cost of Dispensers	$50,000/unit *(50% decrease from 2017 status)*
Cost of High-pressure Storage at Fueling Stations	$600/kg *(66% decrease from 2017 status, assuming 67-kg capacity storage vessel)*
Capital Cost of Fueling Station Compressor (875-bar outlet, 60 kg/hr flow rate, 130 kW motor rating)	*$290,000* *50% decrease from 2017*
Annual Maintenance Cost of High-pressure Fueling Station Compressors	2% of Capital Cost *(50% decrease from 2017)*
Material Cost of Hydrogen Pipelines	$37,00/mile (1-inch pipeline) *(50% decrease from 2017)*
Labor Cost of Hydrogen Pipelines	$17,000/mile (1-inch pipeline) *(75% decrease from 2017)*
Operating Pressure of Hydrogen Pipelines	100 bar[17]
Capital Cost of High-Volume, High-Throughput Pipeline Compressors	$2,638,690 for 300,000 kg/day compressor (9,820 kW motor) *(50% decrease from 2017)*

Table 4c: Levelized Cost of Hydrogen Delivery and Dispensing Estimated for Ultimate Scenario[18]

Low-volume Manufacturing	$2.95/kg
High-volume Manufacturing	$2.05/kg

R&D efforts being funded by FCTO and industry to address the needs outlined in Table 4b include:

- Exploration of early-stage, non-mechanical concepts for high-pressure hydrogen compression. [18], [19], [20]
- Development of innovative strategies to operate fueling stations with gaseous hydrogen storage, to reduce capital costs of compression. [21]
- Characterization of the viability of high-strength modern steels in high-pressure hydrogen service, to reduce the capital and labor costs of pipelines. [22]
- Development of joints for fiber reinforced polymer (FRP) pipelines to improve reliability. [23]
- Early-stage, cross-cutting R&D on steel and polymeric materials for hydrogen delivery technologies. [24]
- Development of novel composite materials for high-pressure pipelines, to lower capital cost.
- Development of novel approaches to installation of fiber reinforced polymer (FRP), that allow for manufacturing on-site, dramatically reducing installation cost.

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[17] The operating pressure of hydrogen pipelines is currently a maximum of 70 bar. However, 100 bar is a future goal for operating pressure [[25]]. Additionally, as a result of a decade of research funded by FCTO, fiber reinforced polymer (FRP) pipelines are now accepted within the American Society of Mechanical Engineers (ASME) B31.12 Code for Hydrogen Piping and Pipelines for hydrogen service at pressures up to 170 bar [[26]].

[18] The figures in this table are direct outputs of HDSAM, given assumptions outlined in Tables 4a and 4b. They have been rounded to the nearest 5 cents.

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