DOE Hydrogen and Fuel Cells Program Record	
Record #: 12022	**Date:** November 29, 2012
Title: H_2 Delivery Cost Projections – 2011	
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Approved by: Rick Farmer and Sunita Satyapal	**Date:** July 12, 2013

Item:

Reported below are past 2005 and 2011 estimates, and target costs of delivering and dispensing (untaxed) H_2 to 10%-15% of the vehicles within a city population of 1.2M from a centralized H_2 production plant 100 km outside of the city gate. These projections are based on the H2A Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.3 projections and are employed as the basis for defining the technical targets in Tables 3.2.3 and 3.2.4 in the 2012 Delivery Sub-Program multi-year research, development and demonstration (MYRD&D) Plan [1]. Figure 1 shows the range of the hydrogen delivery cost projections in dollars per gallon of gas equivalent ($/gge) at 350 bar in 2005 and at 700 bar and 350bar in 2011. The large circles denote the 2015 and 2020 targets and the smaller circles denote the targets for 2005 and 2011 which have been extrapolated from the 2015 and 2020 targets.

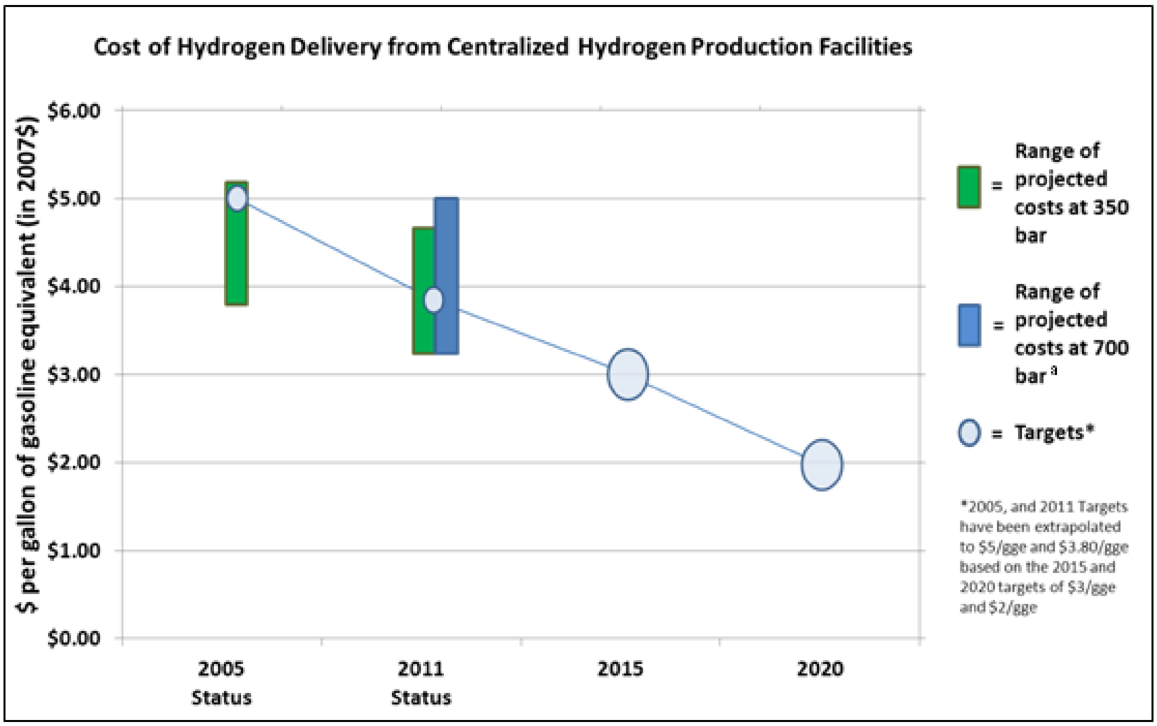

Figure 1: Range of HDSAM projected costs of hydrogen delivery from central production facilities in 2005 and 2011 along with the relevant targets.

[a] 2013 HDSAM updates will include revised precooling and 700 bar cost estimates

Data and Assumptions:

In fiscal year 2011, the Program's delivery analysis technical experts[b] updated HDSAM, to its current version, v2.3, including: establishing an economic baseline of $2007 for all costs, incorporating recent technology advances (such as increased pressure and capacity for new carbon fiber composite tube trailers and lower cost, more reliable pipeline compressors), more detailed and revised information on the costs of pipelines and large-scale liquefiers, and stakeholder feedback on the anticipated benefits of economies of scale (e.g. mass manufacturing) in reducing base cost for various process equipment.

Fourteen cases were developed for delivery pathways terminating with 350 bar dispensing and nineteen cases were developed for pathways terminating with 700 bar dispensing. Common assumptions for all of the cases included:

1. A city (based on Indianapolis) with a population 1.2 M was chosen because it represents an average city for the US and allows for informative rollout scenarios.
2. A mature fuel cell vehicle market penetration of 10%-15% that is served by the hydrogen infrastructure under study. It was found in previous studies that when delivery cost is plotted as a function of market penetration, the resulting curve begins to level off around 10%-15%; i.e. little cost reduction is gained by assuming market penetration above this level [2].
3. To negate the effects of inflation over various time periods and for consistency with the latest H2A models all costs were expressed in $2007.
4. An average refueling station capacity of 1000 kg of H_2/day at >95% utilization.
5. Mature economies of scale with respect to component manufacture for various unit operations.
6. Unless otherwise specified, the H_2 production plant is sited 100 km from the edge of the city, or city gate.

Among the 350 bar delivery scenarios, five were developed for pipeline transmission (from the production site to the city gate) and distribution (delivery within the city along a set of radial distribution lines) [3]; four were developed for pipeline transmission from the production site to terminals at the city gate, with distribution inside the city by tube trailer transport; and five were developed solely for tube trailer transport (transmission and distribution) from the production plant to the final refueling stations. These are denoted in Table 1 as: pipeline, pipeline – tube trailer, and tube trailer, respectively.

For each set of scenarios, delivery costs were calculated assuming an appropriate set of technologies (or technology readiness) for the time period considered as given in Table 2. For example, the 2005 tube trailer case assumes 180 bar steel tube vessels for transport and distribution (as Type 4 tanks were not available at that time). The 2020 tube trailer case assumes that 520 bar vessels will be developed and commercially available and therefore employs the performance and cost factors associated with this technology for that cost model. For the cases denoted as "target" in Table 1, assumptions were made to reduce cost as low as possible – essentially assuming stretch targets for various component technologies. Several of the target cases considered the effect of siting the production plant directly at the city gate; effectively eliminating long-distances transport. Outside of the technology readiness list provided in Table 2, the technology assumptions for each scenario and time period are too numerous to summarize here, but have been captured in the hydrogen delivery chapter of the MYRD&D Plan, [1]. The assumptions are also included in the delivery scenario runs referenced in Records 12022a, 12022b, and 12022c available at www.hydrogen.energy.gov/program_records.html.

[b] Delivery analysis technical experts are: Amgad Elgowainy (Lead), ANL, Marianne Mintz – ANL, Olga Sozinova – NREL, Daryl Brown – PNNL, and Mark Paster – Consultant

Among the 700 bar delivery scenarios, four were developed for pipeline transmission; three were developed for pipeline transmission from the production site to terminals at the city gate, with distribution inside the city by tube trailer transport; four were developed solely for tube trailer transport from the H_2 production plant; four were developed for pipeline transport from the production plant to a liquefier at the city gate, with liquid H_2 distribution within the city by tanker; and four were developed solely for liquid transmission and distribution by tanker from a co-located H_2 production site and liquefaction plant. The cases are denoted in Table 1 as: pipeline, pipeline – tube trailer, tube trailer, pipeline – liquid tanker, and liquid tanker, respectively. Again for each set of scenarios, delivery costs were calculated assuming technology readiness for a given time period and "target" cases included assumptions to reduce H_2 delivery as low as possible based on feasibility assumptions from technical experts. The 700 bar delivery scenario runs are shown in Table 1. Detailed cost breakdown (e.g. the costs of station compression, geologic storage, etc.) are included in Record #12021 [4]. Note that for the transport distance assumed (100 km), pipeline delivery does not offer the lowest cost delivery path. In fact, tube trailer transport does. This is due to the fact that pipeline infrastructure employed for intra-city distribution incurs high expense, largely because of high right-of-way and installation costs. Relative to the apportioned threshold cost for centralized Delivery in 2011 of $2.1/kg (or ~$2/kg) [5], the tube trailer based pathways appear to offer the best chance of meeting the Fuel Cell Technologies (FCT) Office fuel cost goals under the assumptions reported here.

Table 1: Hydrogen delivery cost as a function of dispensed gas pressure, delivery pathway, and technology readiness.

350 bar gas dispensing	**Delivery Costs†* ($/kg H_2 delivered and dispensed)**			
Pathway	**2005**	**2011**	**2020 Projection**	**2020 Target**
Pipeline	3.71	4.59	2.98	2.00
Pipeline-tube trailer	4.62	3.22	2.07	
Tube trailer	5.26	3.24	1.98	
700 bar dispensing	**Delivery Costs ($/kg H_2 delivered and dispensed)**			
Pipeline	No data**	5.00	3.27	2.00
Pipeline-tube trailer	No data**	3.59	2.29	
Tube trailer	No data**	3.61	2.22	
Pipeline – liquid tanker	No data**	3.73	2.99	
Liquid tanker	No data**	3.23	2.65	

* Assumes geologic H_2 storage with the exception of those pathways which use liquid tankers for delivery

** A 700 bar refueling option was not available in 2005.

† Cost results are estimates and are reported directly from HDSAM Model.

Table 2: Key technology components assumed in HDSAM v2.3 to have reached technology readiness in 2005, 2011, and 2020.

Delivery Component	Technology Year		
	2005	2011	2020
Refueling station compressors	Diaphragm (same used in HDSAM v2.2)	Ionic liquid	Ionic liquid, electrochemical (depending on capacity)
Refueling station gas storage	Steel vessels (same used in HDSAM v2.2)	Carbon fiber composite vessels	Lower cost carbon fiber composite vessels
Refueling station cryo-pumps	Liquid pumps (same used in HDSAM v2.2)	Cryopumps (same used in HDSAM v2.2)	Lower cost cryopumps
Cryogenic storage at station	Cryogenic vessels (same used in HDSAM v2.2)	Cryogenic vessels (same used in HDSAM v2.2)	Lower cost cryogenic vessels
Refueling station dispenser (gaseous)	CNG dispenser (same used in HDSAM v2.2)	H_2 dispensers	Lower cost H_2 dispensers
Refueling station dispenser (cryo)	CNG dispenser (same used in HDSAM v2.2)	H_2 dispensers	Lower cost H_2 dispensers
Tube-trailers	Steel tubes (same used in HDSAM v2.2)	High pressure carbon fiber composite tubes	Improved high pressure carbon fiber composite tubes
Liquefiers	Conventional liquefaction (same used in HDSAM v2.2)	Conventional liquefaction (updated)	Magnetic liquefaction, lower cost conventional liquefaction
Pipelines	Steel pipelines (same used in HDSAM v2.2)	Steel pipelines (updated)	Fiber reinforced polymer pipeline, steel pipeline (depending on capacity)
Pipeline compressors	Reciprocating (same used in HDSAM v2.2)	Centrifugal	Centrifugal

Note that data in Table 1 cannot be compared with cost projections calculated previously (before 2011) because: (1) the baseline economic year has changed from 2005 used in prior years (i.e. \$2005) to 2007 employed in the current analysis; (2) prior analyses assume 350 bar dispensing at the station, whereas current technology is now focused on 700 bar dispensing; and (3) the assumed market penetration has changed from 15% to 10% for a more accurate representation of near- to mid-term costs. As mentioned above, the data in Table 1 (from HDSAM v2.3) already incorporate our knowledge of past and present technologies for transmission, distribution, terminal operations, and station operations and makes assumptions regarding future technologies utilizing information from current R&D projects in the Delivery portfolio (e.g. magnetocaloric-based liquefaction) and cost projections of these based on stakeholder input. Thus, it can be stated that the recent advances in tube trailer vessel design have led to a 37% reduction in cost for an all-tube trailer delivery pathway with 350 bar dispensing. The recent decision by OEMs to move to 700 bar dispensing pressure lowers this gain to 30% because of the higher station costs incurred. However, the 2012 data from Lincoln Composites show an increased tube trailer capacity of 18% as a result of their new Titan 5 technology [6]. HDSAM analysis projects that this increased capacity will reduce the pathway costs by ~\$0.20 from the value in Table 1 (\$3.60/kg H_2; 700 bar dispensing, tube trailer).

References:

1. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2011–2020, Washington, DC: DOE, (2012) Section 3.2, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html.
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3. T-P. Chen, Nexant: "Hydrogen Delivery Infrastructure Options Analysis," DOE Award #DE-FG36-05GO15032, Appendix B, May 2008.Record 12021, November, 2012, "Cost Projections for Delivery Operations at a Distributed H_2 Production/Refueling Site", S. Weil, M. Ruth, S. Dillich and E. Sutherland. http://www.hydrogen.energy.gov/program_records.html
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5. 2012 Annual Merit Review Proceedings, Hydrogen Production and Delivery, "Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery", Don Baldwin, Lincoln Composites. http://www.hydrogen.energy.gov/pdfs/review12/pd021_baldwin_2012_o.pdf