DOE Hydrogen and Fuel Cells Program Record	
Record #: 13013	**Date:** September 26, 2013
Title: H_2 Delivery Cost Projections – 2013	
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Approved by: R. Farmer and S. Satyapal	**Date:** December 18, 2013

Item:

Reported herein are past 2005 and 2011 estimates, current 2013 estimates, 2020 projected cost estimates and the 2015 and 2020 target costs for delivering and dispensing (untaxed) H_2 to 10%-15% of vehicles within a city population of 1.2M from a centralized H_2 production plant located 100 km from the city gate. The 2011 volume cost estimates are based on the H2A Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.3 projections and are employed as the basis for defining the cost and technical targets of delivery components in Table 3.2.4 in the 2012 Delivery Sub-Program Multi-Year Research, Development and Demonstration (MYRD&D) Plan. [1] The 2013 estimated and the 2020 projected costs are based on a modified version of HDSAM V2.3 which includes two updates, detailed on page 3, required to reflect the status of the technology in 2013. Figure 1 shows the range of the hydrogen delivery cost projections in dollars per gallon of gasoline equivalent ($/gge)[a] at 350 bar in 2005 and at 700 bar and 350 bar in 2011 and 2013. The large circles denote the 2015 and 2020 targets and the smaller circles denote the targets for 2005, 2011 and 2013 which have been extrapolated from the 2015 and 2020 targets.

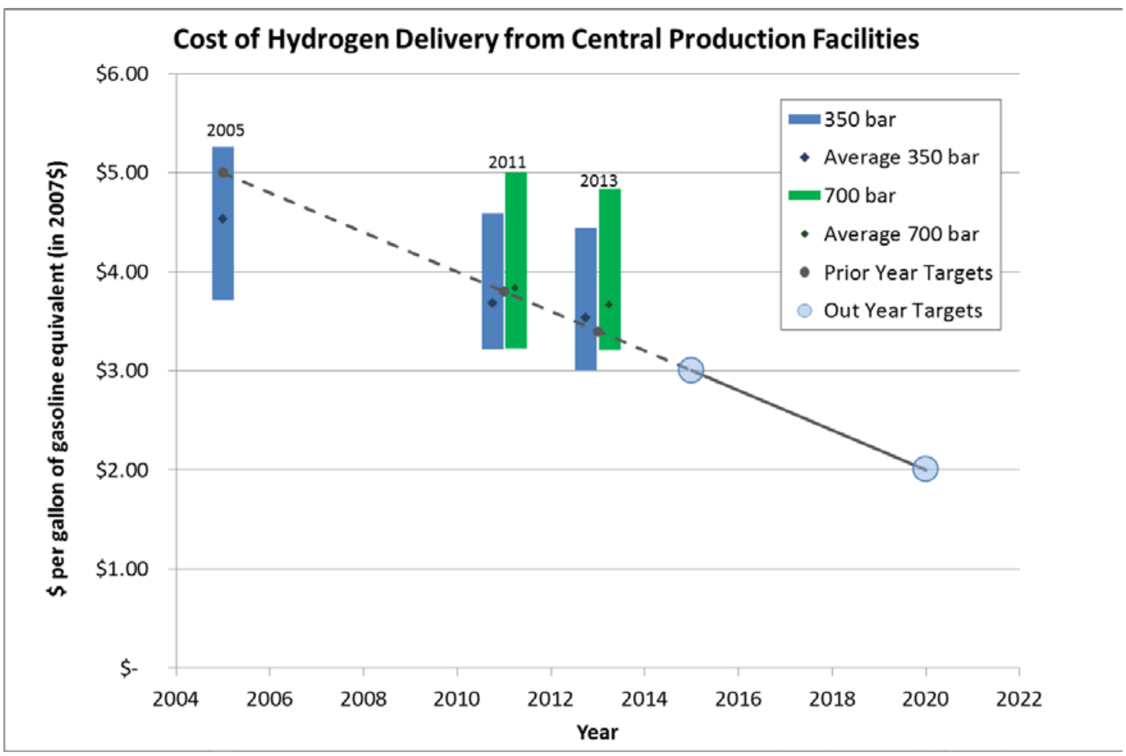

Figure 1: Range of HDSAM projected costs of hydrogen delivery from central production facilities in 2005, 2011, and 2013 along with the relevant targets.[b]

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[a] gge is approximately equivalent to kg of H_2 on energy basis and can be used interchangeably.
[b] Prior year targets have been extrapolated from the 2015 and 2020 targets.

Data and Assumptions:

In fiscal year 2011, the Program's delivery analysis technical experts[c] updated HDSAM, to its current public version, v2.3, including: establishing an economic baseline of 2007$ for all costs for consistency with the economic baseline of hydrogen threshold cost targets [2]; incorporating recent technology advances (such as increased pressure and capacity for 250 bar 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. Table 1 provides the key technology components in HDSAM v2.3 assumed to have reached technology readiness in 2005, 2011, and projected to reach technology readiness in 2020. This updated model is the basis for the scenarios presented here and in Record 12022. [3]

Three 350 bar delivery scenarios have been developed for the purpose of tracking the impacts of current technology advancements in delivery components on a projected high-volume levelized cost basis for hydrogen delivery. The cases developed are pipeline transmission (from the production site to the city gate) and distribution (delivery within the city along a set of radial distribution lines), pipeline transmission with distribution inside the city by tube trailer transport, and tube trailer transmission and distribution from the production plant to the refueling stations. [4] These are denoted in Table 2 as: "pipeline," "pipeline – tube trailer," and "tube trailer" respectively.

Likewise five hydrogen delivery scenarios have been developed for the purpose of projecting the impacts of current technology advancements in delivery and dispensing at 700 bar on high volume cost estimates. These include pipeline transmission and distribution, pipeline transmission and tube trailer distribution, tube trailer transmission and distribution, pipeline transmission and liquid tanker distribution, and liquid tanker transmission and distribution. These cases are labeled as "pipeline," "pipeline-tube trailer," "tube trailer," "pipeline-liquid tanker," and "liquid tanker" respectively in Table 2.

The three cases developed for delivery pathways terminating with 350 bar dispensing and five cases developed for pathways terminating with 700 bar dispensing have the following common assumptions:

1. A city (based on Indianapolis) with a population of 1.2 M was chosen because it represents an average city for the US, allows for informative large scale deployment scenarios and is consistent with previous DOE analysis.
2. A mature fuel cell electric vehicle (FCEV) 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 FCEV market penetration for a city with a population of 1 million, the resulting curve begins to level off around 10%-15%; i.e., little cost reduction is gained by assuming market penetration above this level. [5]
3. To negate the effects of inflation over various time periods and for consistency with the latest hydrogen cost target analysis and other H2A models, all costs were expressed in 2007$.
4. A refueling station capacity with average dispensing rate of 750 -1000 kg of H_2/day at 100% utilization.[d]

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

[d] For the 2005 analysis a market penetration of 15% and a station size of a 1000 kg/day were assumed. For the 2011 analysis and beyond, a market penetration of 10% and a station size of 750 kg/day were assumed for a more accurate cost comparison across pathways.

5. Mature economies of scale were assumed for component manufacturing cost based on industrial estimates for high volume of manufacturing.
6. Unless otherwise specified, the H_2 production plant is sited 100 km from the edge of the city, or city gate.

For each of the scenarios, delivery costs were calculated assuming an appropriate set of technologies (based on technology readiness and latest advances, including DOE funded technologies) for the time period considered as given in Table 1. 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 540 bar vessels will be developed and commercially available, and therefore employs the performance and cost factors associated with this technology for that delivery pathway. For the cases denoted as "2020 projection" in Table 2, assumptions were made to reduce cost as low as possible – essentially assuming MYRD&D targets for various component technologies [1]. Outside of the technology readiness list provided in Table 1, the technology assumptions for the 2011 and 2020 scenarios and time periods 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.

The key differences in the assumptions for the 2013 case in comparison to those of the 2011 case are as follows:

1. For pipeline distribution inside the city gate, the model was updated to assume the use of fiber reinforced polymer (FRP) pipeline. Steel pipeline is still assumed for the transport from the production plant (large diameter pipes are needed for large volume and long distance transport) to the city gate and the associated cost and performance assumptions have not changed.
2. The tube trailer information has been updated to assume 350 bar hydrogen delivery via composite tube trailer with a hydrogen capacity of 809 kg and a cost of $633,750 for the tube trailer. [6] Further for the tube trailer case the reduction in compression stages and associated buffer storage due to the higher pressure delivery was taken into account.

The updated 2020 projection also includes the reduction in onsite compression and storage based on higher pressure tube trailer delivery (540 bar). The hydrogen delivery analysis technical experts are expected to complete a new version of HDSAM in FY2014 and will include the updates described here along with other pathway updates.

As mentioned earlier for each set of scenarios, delivery costs were calculated assuming technology readiness for a given time period, and the "2020 projection" cases included assumptions to reduce H_2 delivery as low as possible based on DOE targets and feasibility assumptions from technical experts. The levelized cost of hydrogen delivery for 350 bar and 700 bar dispensing pathways are shown in Table 2. Note that for the assumed transport distance (100 km), pipeline delivery may not offer the lowest cost delivery path for the assumed FCEV market penetration scenario. High-pressure tube trailer transport appears to offer the lowest delivery cost option, although logistics of frequent deliveries to large capacity stations may pose a different challenge due to the limited trailer payload. 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 goal of $1-$2/kg for hydrogen delivery from central production in 2013 [7], the high pressure tube trailer based pathways (500 bar and above) appear capable of meeting the Fuel Cell Technologies (FCT) Office fuel delivery cost targets under the assumptions reported here.

Table 1: Key technology components in HDSAM v2.3 assumed to have reached technology readiness in 2005, 2011, and 2020.

Delivery Component	Technology Year			
	2005	2011	2013	2020
Refueling station compressors	Diaphragm (HDSAM v2.2)	Reciprocating and Diaphragm (HDSAM v2.3)	Average of available technologies and adjusted requirements for tube trailer delivery	Ionic liquid, electrochemical (assumed no backup due to improved reliability)
Refueling station gas storage	Steel vessels (HDSAM v2.2)	Steel and carbon fiber composite vessels (HDSAM v2.3)	Steel and carbon fiber composite vessels (same as HDSAM v2.3)	Lower cost carbon fiber composite vessels
Refueling station cryo-pumps	Liquid pumps (HDSAM v2.2)	High pressure cryopumps (HDSAM v2.3)	High pressure cryopumps (same as HDSAM v2.3)	Lower cost cryopumps
Cryogenic storage at station	Cryogenic vessels (HDSAM v2.2)	Cryogenic vessels (HDSAM v2.3)	Cryogenic vessels (same as HDSAM v2.3)	Lower cost cryogenic vessels
Refueling station dispenser (gaseous)	Based on CNG dispenser (HDSAM v2.2)	H_2 dispensers (HDSAM v2.3)	H_2 dispensers (same as HDSAM v2.3)	Lower cost H_2 dispensers
Precooling equipment	No data*	Sized to meet refueling demand at -40^{o}C **	Sized to meet refueling demand at -40^{o}C **	Sized to meet refueling demand at -40^{o}C **
Refueling station dispenser (cryo)	Based on CNG dispenser (HDSAM v2.2)	H_2 dispensers (HDSAM v2.3)	H_2 dispensers (same as HDSAM v2.3)	Lower cost H_2 dispensers
Tube-trailers	180 bar (300 kg payload) steel tubes (HDSAM v2.2)	250 bar (616 kg payload) carbon fiber composite tubes (HDSAM v2.3)	350 bar (809 kg payload) carbon fiber composite tubes	540 bar (1155 kg payload) carbon fiber composite tubes
Liquid tanker	17,000 gallon cryogenic tank (4000 kg payload) (HDSAM v2.2)	17,000 gallon cryogenic tank (4000 kg payload) (same as HDSAM v2.2)	17,000 gallon cryogenic tank (4000 kg payload) (same as HDSAM v2.2)	17,000 gallon cryogenic tank (4000 kg payload) (same as HDSAM v2.2)
Liquefiers	Conventional liquefaction (HDSAM v2.2)	Conventional liquefaction (HDSAM v2.3)	Conventional liquefaction (same as HDSAM v2.3)	Lower cost, higher efficiency liquefaction
Pipelines	Steel pipelines (HDSAM v2.2)	Steel pipelines (HDSAM v2.3)	Steel pipeline to city gate and FRP pipeline for distribution.	Steel pipeline to city gate and FRP pipeline for distribution.
Pipeline compressors	Reciprocating (HDSAM v2.2)	Centrifugal (HDSAM v2.3)	Centrifugal (as HDSAM v2.3)	Lower cost centrifugal technology

*Precooling is required for fast fills to 700 bar. A 700 bar refueling option was not available in 2005.

** Per SAE J2601 refueling protocol. Estimates will be refined in 2014.

Table 2: Hydrogen delivery cost as a function of dispensed gas pressure, delivery pathway, and year.

	Delivery Costs†* ($/kg H_2 delivered and dispensed)				
350 bar gas dispensing pathways	**2005**	**2011**	**2013**	**2020 Projection**	**2020 Target**
Pipeline	3.71	4.59††	4.44	3.67	2.00
Pipeline-tube trailer	4.62	3.22	3.16	2.49	
Tube trailer	5.26	3.24	3.00	2.26	
700 bar dispensing pathways	**Delivery Costs ($/kg H_2 delivered and dispensed)**				
Pipeline	No data**	5.00	4.84	3.96	2.00
Pipeline-tube trailer	No data**	3.59	3.21	2.53	
Tube trailer	No data**	3.61	3.29	2.32	
Pipeline – liquid tanker	No data**	3.73	3.73	3.19	
Liquid tanker	No data**	3.23	3.23	2.74	

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

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

†† Pipeline cost estimates were updated in 2011 for improved accuracy [8]

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

Note that data in Table 2 cannot be directly 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 in analyses conducted after 2011; (2) analyses before 2011 assumed 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% starting in 2011 for a better representation of near- to mid-term costs; (4) in 2013 the 2020 cost projections were also updated to be based on a 10% market penetration and a 750 kg/day station size. As mentioned above, the data in Table 2 (from HDSAM v2.3) already reflects current 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 Hydrogen Delivery portfolio (e.g. high pressure tube trailers) and their cost projections based on stakeholder input. Preliminary analysis has shown that the use of tube trailer consolidation algorithms at the forecourt could further reduce the cost of hydrogen delivery. It is estimated that a cost reduction of more than 20% compared to the 2013 status at the refueling station can be achieved by 2015. [9]

This record was peer-reviewed by industry and national laboratory experts.

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