Program Record (Offices of Fuel Cell Technologies)	
Record #: 11007	**Date:** March 25, 2011
Title: Hydrogen Threshold Cost Calculation	
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Approved by: Sunita Satyapal	**Date:** March 24, 2011

Description:

The hydrogen threshold cost is defined as the hydrogen cost in the range of \$2.00-\$4.00/gge (2007\$) which represents the cost at which hydrogen fuel cell electric vehicles (FCEVs) are projected to become competitive on a cost per mile basis with the competing vehicles [gasoline in hybrid-electric vehicles (HEVs)] in 2020. This record documents the methodology and assumptions used to calculate that threshold cost.

Principles:

The cost threshold analysis is a "top-down" analysis of the cost at which hydrogen would be competitive with gasoline in the light-duty vehicle (LDV) market. Because it is market-driven, it is pathway independent and provides a measure for assessing technology performance against market requirements. Projected improvements in vehicle technologies (both FCEVs and the competing HEVs) are included in the calculation through the incorporation of vehicle fuel economies and incremental costs.

Previous Target:

The previous hydrogen cost target of \$2.00-\$3.00/gge was calculated in 2005[1]. The previous cost target range was set in 2005 so the projected cost of the hydrogen FCEV was equivalent to the competing vehicle [HEVs were the competing vehicle for the lower end of the range and internal combustion engine (ICE) powered vehicles were the competing vehicle for its upper end]. The projected gasoline price (\$1.30/gal., untaxed) and the projected incremental ownership cost of the FCEV have significantly changed since then, thus requiring the cost target to be updated.

Calculation Methodology and Results:

The consumer's cost per mile for the FCEV is set to be equivalent to the cost of the competing technology (a gasoline HEV) on a per mile basis using the following equation:

$$\frac{Hydrogen\ threshold\ cost\ (\frac{\$}{gge})}{FCV\ fuel\ economy\ (\frac{mile}{gge})} + FCV's\ incremental\ cost\ \left(\frac{\$}{mile}\right) = \frac{Projected\ gasoline\ cost\ (\frac{\$}{gal})}{HEV\ fuel\ economy\ (\frac{mile}{gal})}$$

Neither the hydrogen threshold cost nor the projected gasoline cost includes sales or gasoline taxes. The FCEV's incremental cost is the difference in non-fuel ownership costs between the FCEV and the HEV. The incremental cost includes vehicle depreciation, financing, maintenance, tires, repairs, insurance, and registration costs as well as taxes, fees, and tax credits with all terms converted to a \$/mile basis.

Since the *Hydrogen threshold cost* is the desired result, the equation is manipulated to

$$Hydrogen\ threshold\ cost\ (\frac{\$}{gge}) = \left[\frac{Projected\ gasoline\ cost\ (\frac{\$}{gal})}{HEV\ fuel\ economy\ (\frac{mile}{gal})} - FCV's\ incremental\ cost\ \left(\frac{\$}{mile}\right)\right] * FCV\ fuel\ economy\ (\frac{mile}{gge})$$

A base set of assumptions was chosen using the best available projections for market and technology status in 2020. Those assumptions and comparison of them to the previous threshold calculation parameters are shown in Table 1.

The base case threshold cost for the current analysis is \$4.31/gge in 2007\$. Including a \$0.04/mile incremental cost for the FCEV reduces the threshold cost to \$2.01/gge (2007\$).

The hydrogen threshold cost in the previous analysis was calculated to be \$2.17/gge (2005\$) with the HEV as the competing technology and \$3.12/gge (2005\$) with the internal combustion engine (ICE) as the competing technology. Those were rounded to a range from \$2.00-\$3.00/gge (2005\$).

	Current Analysis (Base case)	Previous Analysis
Threshold cost	\$2.01-\$4.31/gge	\$2.17-\$3.12/gge
Reference year	2020	2015
Reference year dollars	2007	2005
Competing vehicles	Gasoline HEV	Gasoline ICE and HEV
Gasoline price (untaxed), \$/gal.	\$3.13/gal [2]	\$1.30/gal [3]
Energy Information Administration (EIA) Annual Energy Outlook (AEO) source year and case	2009 EIA AEO Reference Case	2005 EIA AEO Hi Oil Case
H_2 FCEV to ICE fuel economy ratio	Not used	2.40[4]
H_2 FCEV to gasoline HEV fuel economy ratio	1.4[5]	1.674
Source of vehicle performance projections	PSAT Simulations	NAS Report (2005)
Assumed lifetime mileage of all vehicles	150,000 miles	Not used
Incremental cost of vehicle ownership (not including fuel) for an FCEV over an HEV	\$0.00 - \$0.04 / mile	Not used

Table 1: Threshold Cost Calculation Parameters

Explanation of the values reported in Table 1 follow:

- The reference year of 2020 was chosen for this analysis to be consistent with targets set by other EERE programs.
- The currency year of 2007 was chosen because the 2009 AEO was used for fuel price projections and that document reports all prices in 2007 dollars.
- The HEV was chosen as the competing technology for light-duty vehicles because HEVs are advanced technology vehicles on the road today and can be used to represent one of the dominant fuel-efficient vehicles in 2020. In 2005, HEVs were being introduced and their future was uncertain so both HEVs and ICEs were used as competing technologies.
- The 2009 AEO reference case untaxed gasoline price projection of $3.13/gal was used for this analysis and the 2009 AEO reference case projection for crude oil price range in 2020 is $112-$115/bbl (2007$). For comparison, the high energy price case projection for untaxed gasoline in 2020 is $4.57/gal (2007$) with a corresponding crude oil price range of $181-$184/bbl. In the 2005 analysis, the high energy price case projection of $1.38/gal (2005$) was used.2
- For this analysis, 2020 projections of mid-size vehicle fuel economies were estimated by Argonne National Laboratory (ANL) using their Powertrain Systems Analysis Toolkit (PSAT). They estimated the FCEV's fuel economy to be 59 miles/gge and the HEV's fuel economy to be 42 miles/gal thus the calculated fuel economy ratio is 1.45. In the 2005 analysis, fuel economy ratios of 2.4 and 1.67 were used. Those ratios are based on the National Academy of Sciences 20054 report.
- The incremental cost of the FCEV was set at $0.00/mile for the base case analysis. Incremental costs were not considered in the 2005 analysis.

Each of the parameters used in the cost threshold calculation are known definitively so a probability range was used in additional calculations.

Analyses have been performed that show the cost of an FCEV is greater than that for a competing vehicle. One of those analyses was performed by the National Research Council in 2008 as part of their Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies. They estimated the incremental cost of an FCEV over a reference gasoline vehicle to range from $1,713 to $6,800 per vehicle and they reported the likely incremental cost to be $3,600/vehicle.[6] Other analyses in this area have not been published.

A simple estimate of the incremental cost for an FCEV can be made in the following manner. Presuming that achieving $30/kW for the fuel cell and $0.50/kWh for storage results in vehicle costs that are equivalent to HEVs, the following is true:

- achieving only $40/kW fuel cells increases the vehicle's incremental cost by $800
- achieving only $12/kWh storage increases the vehicle's incremental cost by $1900
- not achieving the fuel cell durability target and needed replacement of the fuel cell system once during the life of a vehicle increases the incremental cost by $3200 ($40/kW fuel cell system cost)

The sum of the above costs is $5900/vehicle. Assuming no financing cost, no time value of money, straight-line depreciation over 150,000 miles, and negligible differences in the cost of maintenance, tires, repairs, insurance, registration, taxes, and fees, the $5900 incremental cost is equivalent to $0.04 / mile. The assumptions above were considered conservative; therefore, the assumed range of incremental costs used in the study is $0.00-$0.04/mile. By incorporating an incremental cost of $0.04/mile into the base case calculation, the threshold cost becomes $2.02/gge.

Gasoline price projections also vary greatly. Figure 1 shows the effect of projected gasoline price on the hydrogen cost threshold. The base case is indicated by the vertical dashed line at the projected gasoline price of \$3.13/gal (untaxed, 2020 projection, 2007\$). That baseline price projection of \$3.13/gal is from the reference case reported in the 2009 AEO.2

Figure 1: Effect of Gasoline Price on Hydrogen Cost Threshold

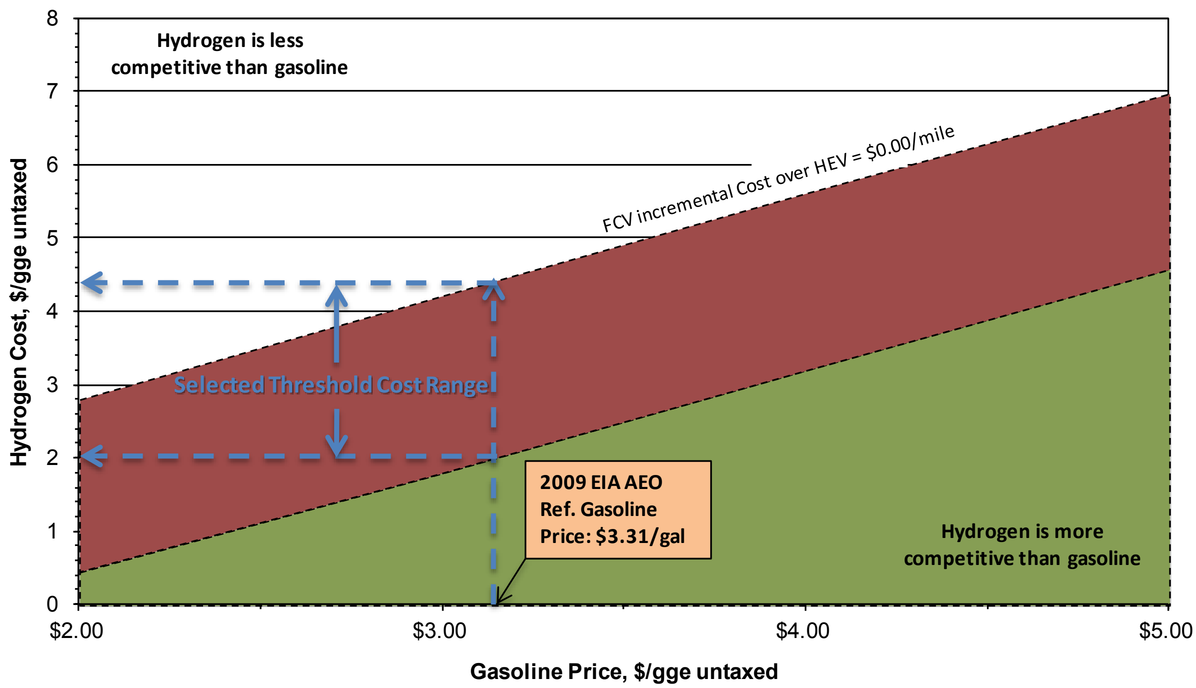


Figure 1 shows a cost range of roughly \$2 to \$4/gge based on gasoline price in 2020 (AEO 2009). Sensitivity analyses conducted by varying other parameters also show a similar cost range to be competitive with gasoline.

Stochastic analyses were performed so that the parameters of gasoline price and "incremental ownership cost compared over a HEV" could be varied simultaneously. The top two bars in Figure 2 show the effect of varying gasoline price and incremental ownership cost individually while keeping all the other parameters constant. The third bar shows the result of varying both simultaneously using Monte Carlo techniques. To generate the third bar, triangular probability density functions (PDFs) were defined and a Monte Carlo analysis was run.

The resulting threshold cost distribution is shown in the blue bar in Figure 2. The \$2-\$4 cost threshold range is from the 25th percentile to the 65th percentile. A histogram of the resulting hydrogen threshold costs is shown in Figure 3.

Figure 2: Sensitivities of Threshold Cost to Gasoline Price and Incremental Ownership Costs

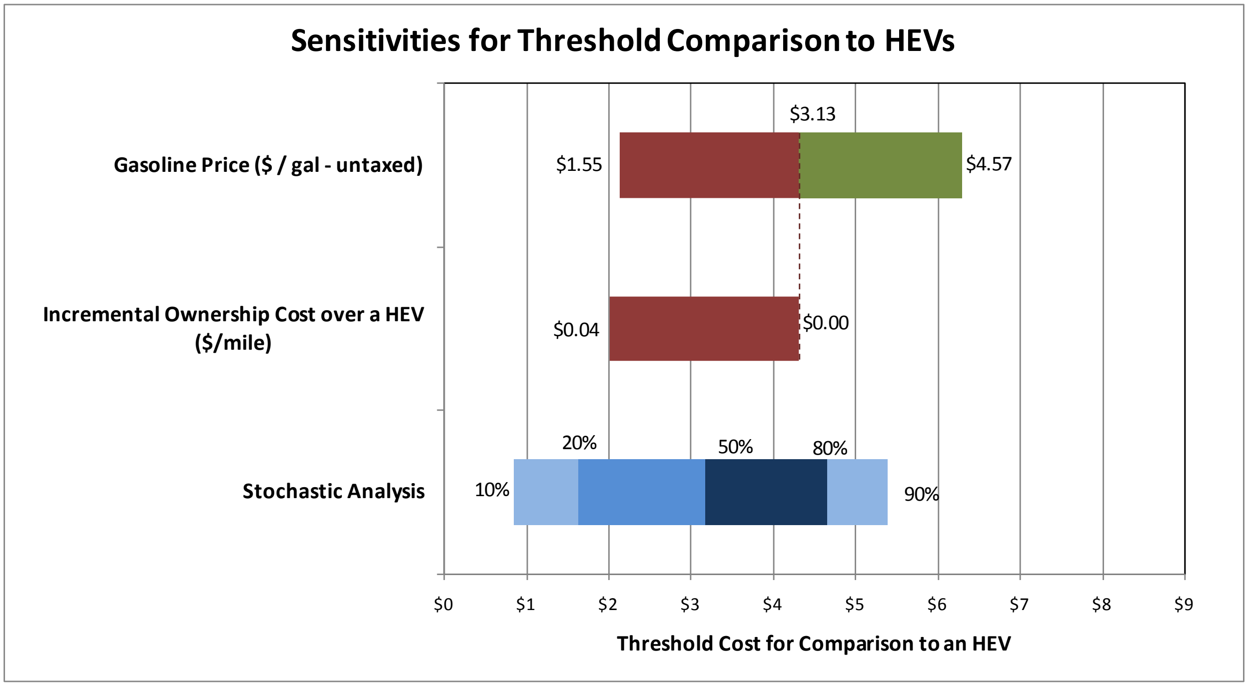
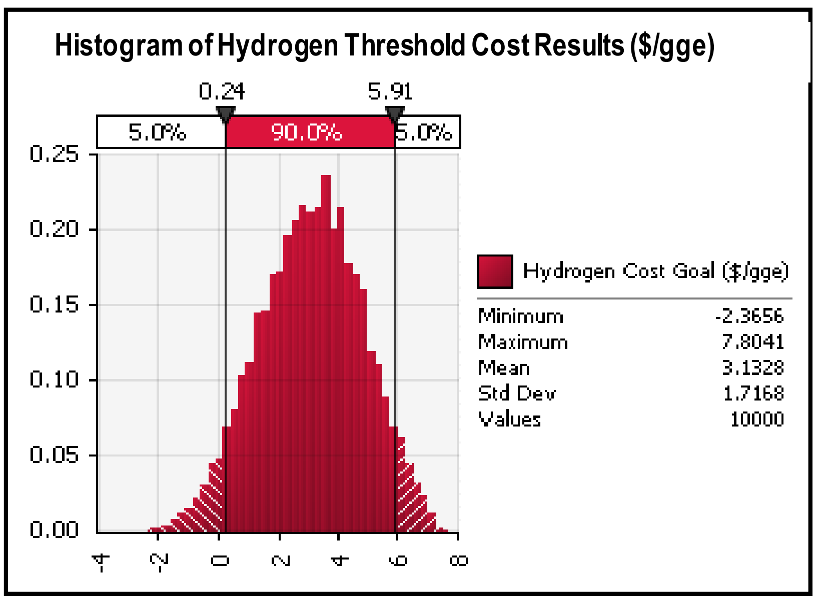


Figure 3: Histogram of the Hydrogen Threshold Cost Results



	10th Percentile	Most Likely	90th Percentile
Gasoline Price ($/gal)	$1.55	$3.13	$4.57
Incremental Ownership Cost ($/mile)	$0.00*	$0.00	$0.04

Table 2: Triangular Probability Density Function (PDF) definition for Stochastic Analysis with Constant Fuel Economy Ratio

* The minimum value was set to $0.00/mile instead of the 10th percentile

The ranges of the triangular distributions are shown in Table 2. The gasoline price PDF was defined such that the most likely value was \$3.13/gal (the AEO reference case value), the 10th percentile value was \$1.55/gal (the AEO low energy price case value which corresponds with a projected crude oil price of \$47-\$50/bbl), and the 90th percentile value was \$4.57/gal (the AEO high energy price case value). The incremental ownership cost PDF was defined such that both the lowest value and the most likely value were \$0.00/mile (the base case above) and the 90th percentile value was \$0.04/mile. The fuel economy ratio was kept constant.

Since the fuel economy projections also have uncertainty, a stochastic analysis where they are given PDFs in addition to those for gasoline price and incremental ownership cost was performed. The definition of the triangular distributions is shown in Table 3. The gasoline price and incremental ownership costs PDFs were the same as those used above. The fuel economy ranges were provided by ANL staff. The value they reported as the "low" adjusted fuel economy was input as the 10th percentile and the value they reported as the "high" adjusted fuel economy was input as the 90th percentile.

	10th Percentile	Most Likely	90th Percentile
Gasoline Price (\$/gal)	\$1.55	\$3.13	\$4.57
Incremental Ownership Cost (\$/mile)	\$0.00*	\$0.00	\$0.04
HEV Fuel Economy (mile / gal)	37.2	41.8	47.1
FCEV Fuel Economy (mile / gge)	51.9	57.5	63.3

Table 3: Triangular PDF definition for Stochastic Analysis with Constant Fuel Economy Ratio

* The minimum value was set to \$0.00/mile instead of the 10th percentile

The results of the second stochastic analysis are shown in Figure 4. The top four bars show the effect of varying each of the inputs individually while keeping all the other parameters constant. The blue, bottom bar shows the results of varying all four input parameters simultaneously using Monte Carlo techniques. The \$2-\$4 cost threshold range is from the 25th percentile to the 75th percentile. A histogram of the resulting hydrogen threshold costs is shown in Figure 35.

Figure 4: Sensitivities of Threshold Cost to Gasoline Price and Incremental Ownership Costs with Varied Fuel Economies

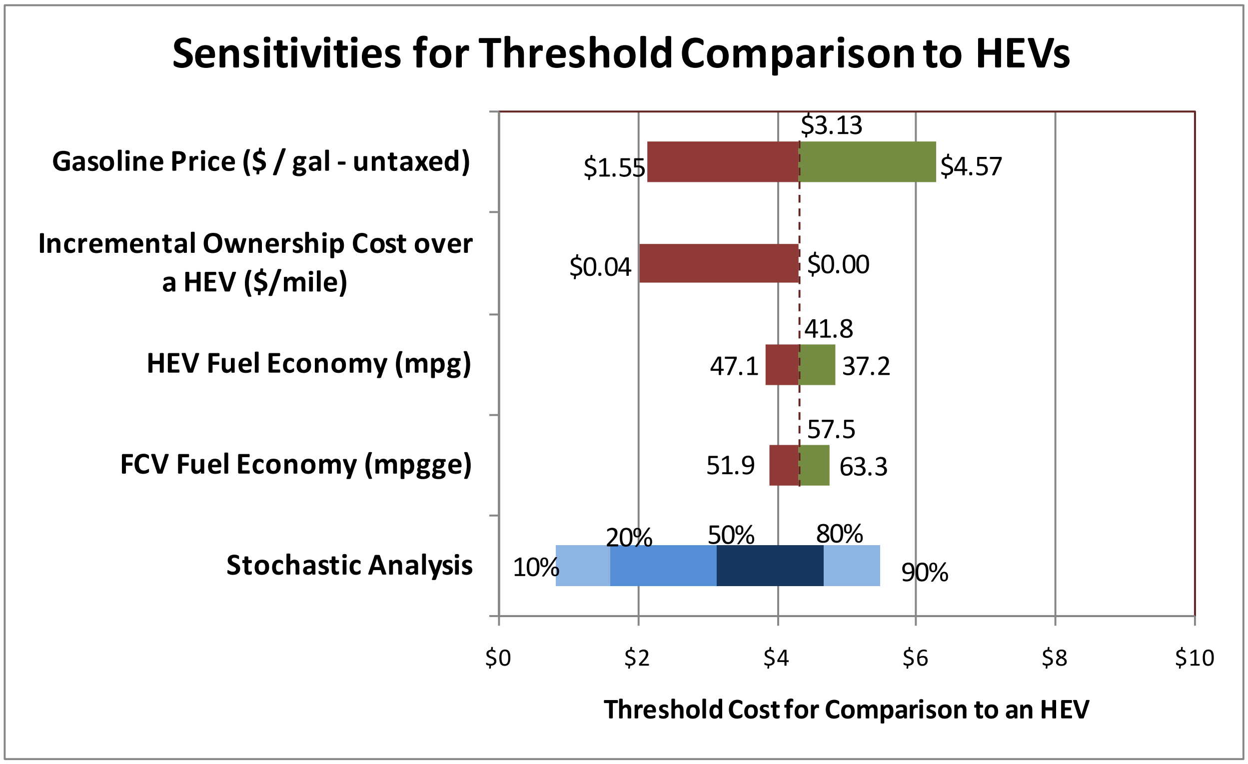
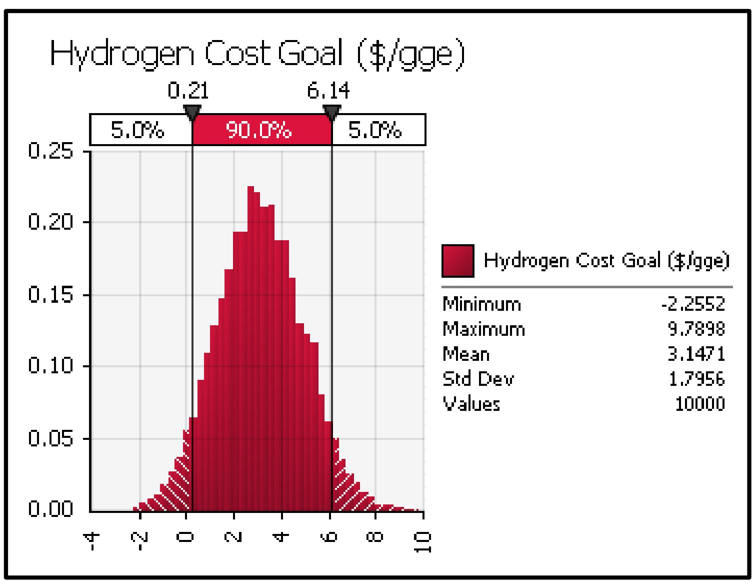


Figure 5: Histogram of the Hydrogen Threshold Cost Results with Varied Fuel Economies



Range Selection:

A cost threshold range of $2.00-$4.00/gge was selected for the following reasons:

- The upper end is near the base case results described below ($4.31/gge);

- The lower end is near the base case results with either the low price projection of gasoline or an incremental vehicle cost of $0.04/mile; and
- The range incorporates most of the range in each of the two stochastic results including the median in each case.

Review Process:

The cost threshold development underwent a rigorous review process including industrial and academic stakeholders, the Hydrogen and Fuel Cells Technical Advisory Committee (HTAC) and national laboratory experts. Formal feedback sessions were held with each of the following groups of stakeholders (in chronological order):

- DOE
- Directors and technical team members of the FreedomCar & Fuel Partnership
- Industrial gas companies, energy companies, automobile companies, electrical companies, national laboratories, and academia.
- International stakeholders
- National laboratory analysts and HTAC committee representatives.

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[1] DOE Hydrogen Program. Record 5013 "Hydrogen Cost Goal" http://www.hydrogen.energy.gov/pdfs/5013_h2_cost_goal.pdf. December 21, 2005.

[2] Energy Information Administration. "Annual Energy Outlook 2009, March 2009." http://www.eia.doe.gov/oiaf/archive/aeo09/index.html. DOE/EIA-0383 (2009). Table 12 lists a gasoline price of $3.60/gal and includes $0.47/gal taxes. The difference ($3.13/gal) was used as the untaxed price of gasoline.

[3] Energy Information Administration. "Annual Energy Outlook 2005 with Projections to 2025." http://www.eia.doe.gov/oiaf/archive/aeo05/index.html. DOE/EIA-0383 (2005). March 2005. Table 12 in the high energy price case lists a gasoline price of $1.71/gal and includes $0.41/gal taxes. The difference ($1.30/gal) was used as the untaxed price of gasoline.

[4] DOE Hydrogen Program. Record 5013 "Hydrogen Cost Goal" http://www.hydrogen.energy.gov/pdfs/5013_h2_cost_goal.pdf. December 21, 2005. The record states "FCVs are assumed to be 1.66 times more efficient than gasoline HEVs (The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 66) and 2.4 times more efficient than gasoline ICEVs(Ibid, p. 26)." In the NRC report, p.26 states that the committee selected the following fuel-economy improvement factors: 2.4 for FCEVs over baseline ICEs, 1.45 for gasoline HEVs over baseline ICEs, and 1.45 to 2.4 for diesel HEVs over baseline ICEs.

[5] Argonne National Laboratory. "Powertrain systems analysis toolkit (PSAT) - A Flexible, Reusable Model for Simulating Advanced Vehicles." Information available at http://www.anl.gov/techtransfer/pdf/PSAT.pdf. Referenced January 20, 2011. The HEV fuel economy of 41.8 mpg and the FCEV fuel economy of 57.5 mpgge were provided by Amgad Elgowainy in an email on August 1, 2010. However, sensitivity analysis was performed with a range of 37.2 to 47.1 mpg for HEVs and 51.9 to 63.3 mpg for FCEVs.

[6] National Research Council Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies. "Transitions to Alternative Transportation Technologies – A Focus on Hydrogen." http://www.nap.edu/catalog/12222.html. ISBN: 0-309-12101-9 (2008). Box 6.1 shows the incremental costs of FCEVs.