ORNL/TM-2008/30

Analysis of the Transition to Hydrogen Fuel Cell Vehicles & the Potential Hydrogen Energy Infrastructure Requirements

PREPARED BY

DAVID L. GREENE
PAUL N. LEIBY
BRIAN JAMES
JULIE PEREZ
MARGO MELENDEZ
ANELIA MILBRANDT
STEFAN UNNASCH
MATTHEW HOOKS

EDITED BY

SHAWNA MCQUEEN

DIRECTED BY

SIGMUND GRONICH

MARCH 2008

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via the U.S. Department of Energy (DOE) Information Bridge.

Web site http://www.osti.gov/bridge

Reports produced before January 1, 1996, may be purchased by members of the public from the following source.

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Web site http://www.ntis.gov/support/ordernowabout.htm

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange (ETDE) representatives, and International Nuclear Information System (INIS) representatives from the following source.

Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Web site http://www.osti.gov/contact.html

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-2008/30

Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements

David L. Greene
Paul N. Leiby
Oak Ridge National Laboratory

Brian James
Julie Perez
Directed Technologies, Incorporated

Margo Melendez
Anelia Milbrandt
National Renewable Energy Laboratory

Stefan Unnasch
Life Cycle Associates

Daniel Rutherford
Matthew Hooks
TIAX, LLC

EDITED BY

Shawna McQueen
Energetics, Incorporated

DIRECTED BY

Sigmund Gronich
U.S. Department of Energy, Retired

March 2008

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

Page

TABLES AND FIGURES

Table **Page**

Figure **Page**

ACKNOWLEDGMENTS

This report summarizes the results of the following analyses funded by the U.S. Department of Energy (DOE) to evaluate alternative scenarios for deployment of hydrogen fuel cell vehicles and fueling infrastructure in response to the requirements of Section 811 of the Energy Policy Act of 2005 and the recommendations of the National Academy of Sciences Report, *The Hydrogen Economy*, published in 2004.

Greene, David L. and Paul N. Leiby, “Integrated Analysis of Market Transformation Scenarios with HyTrans,” Oak Ridge National Laboratory, forthcoming (Draft March 2007).

James, Brian and Julie Perez, “Hydrogen Infrastructure Pathways Analysis Using HYPRO,” Directed Technologies Incorporated, April 02, 2007.

Melendez, Margo and Anelia Milbrandt, “Geographically Based Hydrogen Demand and Infrastructure Deployment Scenario Analysis,” National Renewable Energy Laboratory, March 14, 2007.

Unnasch, Stefan, Daniel Rutherford and Matthew Hooks, "Analysis of Incentive Options for Hydrogen Fueled Vehicles," TIAX, LLC, Draft Report for NREL, March 2007.

The report and supporting primary analyses were overseen by Sigmund Gronich and Frederick Joseck, of the DOE Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells & Infrastructure Technologies Program. The report was compiled and edited by Energetics, Incorporated, with contributions from Shawna McQueen, Pamela de los Reyes, Paget Donnelly, Richard Scheer, and Edward Skolnik.

EXECUTIVE SUMMARY

Achieving a successful transition to hydrogen-powered vehicles in the U.S. automotive market will require strong and sustained commitment by hydrogen producers, vehicle manufacturers, transporters and retailers, consumers, and governments. The interaction of these agents in the marketplace will determine the real costs and benefits of early market transformation policies, and ultimately the success of the transition itself.

The transition to hydrogen-powered transportation faces imposing economic barriers. The challenges include developing and refining a new and different power-train technology, building a supporting fuel infrastructure, creating a market for new and unfamiliar vehicles, and achieving economies of scale in vehicle production while providing an attractive selection of vehicle makes and models for car-buyers. The upfront costs will be high and could persist for a decade or more, delaying profitability until an adequate number of vehicles can be produced and moved into consumer markets. However, the potential rewards to the economy, environment, and national security are immense. Such a profound market transformation will require careful planning and strong, consistent policy incentives.

Section 811 of the *Energy Policy Act (EPACT) of 2005*, Public Law 109-59 (U.S. House, 2005), calls for a report from the Secretary of Energy on measures to support the transition to a hydrogen economy. The report was to specifically address production and deployment of hydrogen-fueled vehicles and the hydrogen production and delivery infrastructure needed to support those vehicles. In addition, the 2004 report of the National Academy of Sciences (NAS, 2004), *The Hydrogen Economy,* contained two recommendations for analyses to be conducted by the U.S. Department of Energy (DOE) to strengthen hydrogen energy transition and infrastructure planning for the hydrogen economy.

In response to the EPACT requirement and NAS recommendations, DOE's Hydrogen, Fuel Cells and Infrastructure Technologies Program (HFCIT) has supported a series of analyses to evaluate alternative scenarios for deployment of millions of hydrogen fueled vehicles and supporting infrastructure.

To ensure that these alternative market penetration scenarios took into consideration the thinking of the automobile manufacturers, energy companies, industrial hydrogen suppliers, and others from the private sector, DOE held several stakeholder meetings to explain the analyses, describe the models, and solicit comments about the methods, assumptions, and preliminary results (U.S. DOE, 2006a). The first stakeholder meeting was held on January 26, 2006, to solicit guidance during the initial phases of the analysis; this was followed by a second meeting on August 9-10, 2006, to review the preliminary results. A third and final meeting was held on January 31, 2007, to discuss the final analysis results. More than 60 hydrogen energy experts from industry, government, national laboratories, and universities attended these meetings and provided their comments to help guide DOE's analysis. The final scenarios attempt to reflect the collective judgment of the participants in these meetings. However, they should not be interpreted as having been explicitly endorsed by DOE or any of the stakeholders participating.

Methodology

The DOE analysis examined three vehicle penetration scenarios:

- **Scenario 1** – Production of *thousands* of vehicles per year by 2015 and *hundreds of thousands* per year by 2019. This option is expected to lead to a market penetration of 2.0 million fuel cell vehicles (FCV) by 2025.
- **Scenario 2** – Production of t*housands of* FCVs by 2013 and *hundreds of thousands* by 2018. This option is expected to lead to a market penetration of 5.0 million FCVs by 2025.
- **Scenario 3** – Production of *thousands of* FCVs by 2013, *hundreds of thousands* by 2018, and *millions* by 2021 such that market penetration is 10 million by 2025.

Scenario 3 was formulated to comply with the NAS recommendation:

> "DOE should map out and evaluate a transition plan consistent with developing the infrastructure and hydrogen resources necessary to support the committee's hydrogen vehicle penetration scenario, or another similar demand scenario (NAS, 2004, p. 4)."

Each of the scenarios was extensively discussed at the stakeholder meetings and each received support from industry. Although there was no consensus on a particular vehicle penetration rate, it was agreed that this set of scenarios is inclusive of industry expectations and could provide a basis to interpolate or extrapolate the results to other cases. The purpose of the DOE study was not to select any one scenario but to assess the costs and impacts of achieving each.

The major analyses summarized in this report (James and Perez, 2007; Melendez and Milbrandt, 2007; and Greene and Leiby, 2007; and Unnasch, Rutherford and Hooks, 2007) examined the following broad topics under the different vehicle penetration scenarios and corresponding hydrogen demand levels:

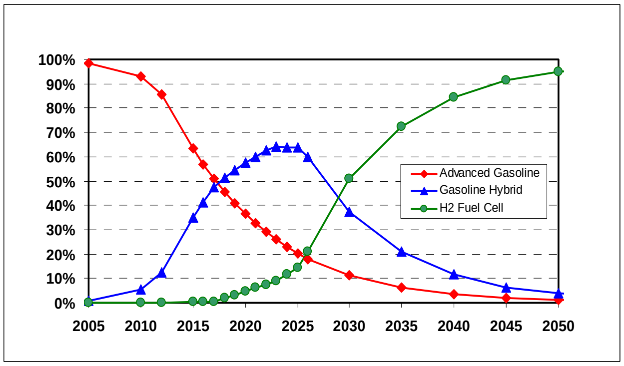
1. Hydrogen infrastructure analysis and deployment scenarios
2. Policy options for supporting hydrogen energy infrastructure and vehicle developments during the transition to the hydrogen fuel cell vehicles, and
3. Costs of implementing selected policy options to encourage the transition to hydrogen.

These analyses provide critical input for creating coherent and credible scenarios of paths to hydrogen powered transportation, and are essential to developing feasible plans. However, it must be stressed that analyses extending 20 to 45 years into the future entail multiple assumptions about technological progress and consumer behavior, which are necessarily replete with uncertainties. These uncertainties must be thoroughly understood, parametrically evaluated, and carefully monitored as the transition proceeds. This approach will help to ensure that government policies are effective and efficient in enabling industry to establish sustainable product lines by the conclusion of the transition process.

Major Findings

The Hydrogen Scenario Analysis indicates that *with targeted deployment policies in place* during 2012 to 2025, the fuel cell vehicle (FCV) market share could grow to 50% by 2030 and 90% by 2050 as shown in Figure ES-1. This would lead to a sustainable, competitive market for hydrogen FCVs beyond 2025, without a continuing need for policy support. This successful outcome assumes that the technical targets for FCVs in the DOE Multi-Year Program Plan (U.S. DOE, 2006b) are met (except for on-board hydrogen storage weight and volume targets) and that competing vehicle technologies also achieve their DOE targets in the same timeframe. Without policies in place to support development of a fueling infrastructure and bring down the cost of FCVs, the level of risk and investment that industry would have to bear would be too high for market forces to overcome, and hybrid electric vehicles would dominate the market. The scenario analysis evaluated the cost of alternative government policies to support a successful transition to hydrogen fuel cell vehicles. The costs for the three policy cases analyzed were estimated to range from $10 to $45 billion *cumulatively* over the 2012-2025 timeframe (14 years), with peak annual costs of between $1 and $6 billion.

Figure ES-1. Vehicle Technology Market Shares in Scenario 3



Source: Greene and Leiby, 2007

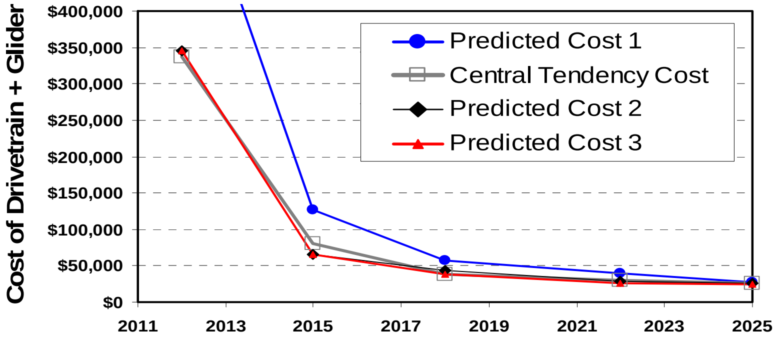
Major Factors Affecting Private and Public Sector Investment Needs

Technological Progress and Cost Reduction for Hydrogen Vehicles

The extent and rate of technological innovation in the automotive industry will be key factors in enabling progress toward the high-volume production levels required to reduce vehicle costs and investment needs during the move to hydrogen vehicles. As a prerequisite to proceeding with any scenario for higher-volume vehicle production, there is broad consensus that industry will need to demonstrate in the laboratory the capability to cost-effectively manufacture fuel cell vehicle systems in quantity (i.e., at $45/kW by 2010 and $30/kW by 2015, with a 5-year time lag between lab-demonstrated capabilities and implementation in a mass-produced product). Meeting these targets is deemed a key condition for proceeding with government policy and industry investment in the deployment of hydrogen vehicles and infrastructure.

However, until sufficient fueling infrastructure, vehicle demand, and industry supplier bases are in place, the fuel cell vehicle will still be more costly to produce than conventional new vehicle technologies. A major accomplishment of this scenario analysis is the development of a “composite learning curve” (see Figure ES-2) that represents the automotive industry’s best estimate of how production costs will decrease as a function of technological progress and production volumes.

Figure ES-2. Estimated Cost of FCVs as a Function of Learning Volume and Technical Progress: Scenarios 1, 2, and 3



Source: Greene and Leiby, 2007

Policies that provide industry support for moving down this learning curve are needed to foster industry development of a cost-competitive, market-ready product by 2025, and were found to represent the largest share of potential government costs during the early deployment period. This development requires producing tens of thousands of vehicles by as early as 2015, and increasing production to 1 to 2.5 million vehicles annually a decade later. Industry will need to perceive public policy as completely reliable throughout that ten-year period, or it may defer making the large investments necessary to bring the technology to market.

Sensitivity analyses that investigated technology shortfall cases for the fuel cell and storage system costs indicated a significant but reduced capacity for fuel cell vehicles to compete if the fuel cell vehicle systems cost is $60/kW vs. a target of $30/kW, and if the onboard hydrogen storage system cost is $8/kWh vs $2/kWh target. At $60/kW the market share for hydrogen fuel cell vehicles varies between 20% and 50%, and at $8/kWh for the hydrogen storage system costs it varies between 30% and 60%. The technological success of the fuel cell and storage costs are therefore important to the expected sustained market potential of fuel cell vehicles.

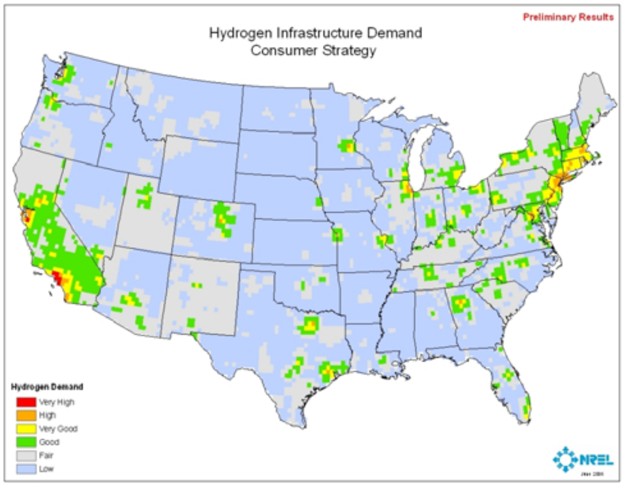
Location and Concentration of Nascent Fueling Infrastructure

The risk exposure of hydrogen fuel providers is particularly challenging during the early stages of deployment. Hydrogen fueling station developers will be faced with the evolution of different, competing alternative fuel options; potential for early obsolescence if hydrogen vehicles are not successful; and with the potential for stranded investments as more advanced, cost-effective hydrogen production technologies are developed. Customers will expect convenient access to fueling stations, necessitating the location of fueling stations near their homes and workplaces. The stations will initially be underutilized by FCV owners – a situation that would be greatly exaggerated if the early-development of fueling infrastructure is attempted on a national scale.

A key recommendation from the stakeholder meetings was to concentrate on establishing networks of fueling stations in a limited number of urban centers during the transition period. Strategically placing stations in major urban centers will maximize coverage and permit a cost-effective approach to providing the early infrastructure. The industry also recommended a complementary approach for the early introduction of vehicles, i.e., focusing sales of hydrogen fuel cell vehicles in these urban centers, so that vehicle sales are focused on areas where consumers will have convenient access to fueling stations and so that technical and maintenance support can be concentrated.

DOE's geographic deployment study (Melendez and Milbrandt, 2007) included an extensive demographic analysis, which confirmed that consumer demand for hydrogen fuel cell vehicles is greatest in major urban areas because of their high population densities and favorable population characteristics. Figure ES-3 shows the areas of the country ranked by their potential for early hydrogen demand. A phased urban roll-out, known as the "urban center concept," was employed to gradually create fueling networks serving 20 urban centers. Southern California and the Northeast (centered around New York City) were targeted for early infrastructure introduction (around 2012 to 2015) during Phase I ("Initial Introduction"). Their concentrated market potential and populations, numbering around 20 million people each, are significantly greater than other urban centers. The next phase, called Targeted Regional Growth, would focus on an additional eight selected cities with populations ranging from 4 to 10 million people. Three early corridors—Los Angeles-to-San Francisco; New York-Boston-Washington, DC; and Chicago-to-Detroit—are also recommended for inclusion in this phase. Phase III, Inter-Regional Expansion, expands the infrastructure to 10 additional urban centers with populations of 1.5 to 5 million and adds more corridors connecting the urban centers and enabling some cross country travel. Figure ES-4 shows what the fully deployed transition infrastructure might look like with red, blue and yellow representing deployment Phases I, II, and III, respectively.

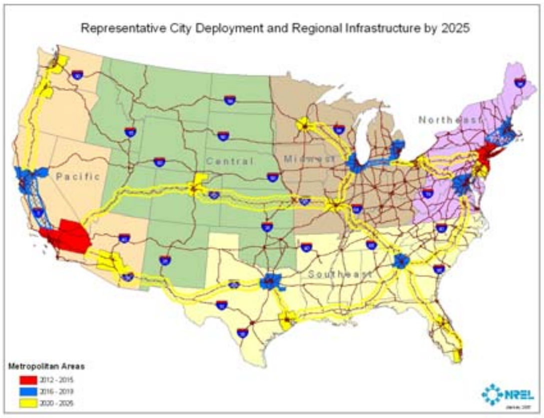
Figure ES-3. Areas of Projected Hydrogen Energy Demand



Source: Melendez and Milbrandt, 2007

This "urban center concept" obviates the need for an initial national system that could require 30,000 to 40,000 stations early in transition, permitting a more rational, affordable buildup of stations to a total of 4,000 - 8,000 stations by 2025.

Figure ES-4. Representative City Deployment and Regional Infrastructure



Source: Melendez and Milbrandt, 2007

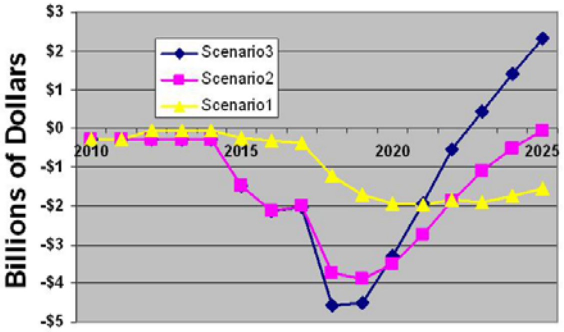
Impacts and Costs of Policies to Support a Hydrogen Vehicle and Infrastructure Deployment

The Hydrogen Scenario Analysis considered policies that could be used to help share the costs of bringing FCVs to market and address two key economic barriers: (1) lack of an existing fueling infrastructure and (2) the high cost of FCVs at low production volumes. The analysis evaluated policies that could *directly* incentivize the building of fueling stations, drive down the cost of producing fuel cell vehicles, and stimulate the purchase of FCVs. Candidate options included those authorized in existing federal legislation (e.g., EPACT Sections 805 and 808, clean fuel tax credits) and policies and incentives that are or have been offered by state and local governments, utilities, or other programs. Three alternative policy cases were developed that provide different strategies, with different allocations for sharing the costs between the private sector and the government over the 2012-2025 timeframe (a fourth, "no policy" case was also included as a point of comparison). While a representative set of policies were analyzed, the purpose of the study was not to prescribe or recommend any particular policy, but to use relevant, feasible policy options to determine the magnitude of the investment needed by government and industry to introduce hydrogen fuel cell vehicles as a viable commercial product by 2025.

DOE's integrated market simulation model (HyTrans) was used to evaluate the costs of the three policy cases (at cumulative scenario vehicle production levels of 2, 5, and 10 million hydrogen fuel cell vehicles by 2025). The *cumulative* government costs for the policy cases ranged from $10 billion to $45 billion over 2012-2025 (14 years) with peak annual costs for the three scenarios ranging between $1 billion and $6 billion. After 2025, the policies were discontinued to evaluate the sustainability of an unsubsidized market. In all three vehicle production scenarios, hydrogen FCVs are able to achieve and maintain market dominance without policy supports beyond 2025, such that by 2050 most new light-duty vehicles could be FCVs and the majority of fuel used by light-duty vehicles could be hydrogen.

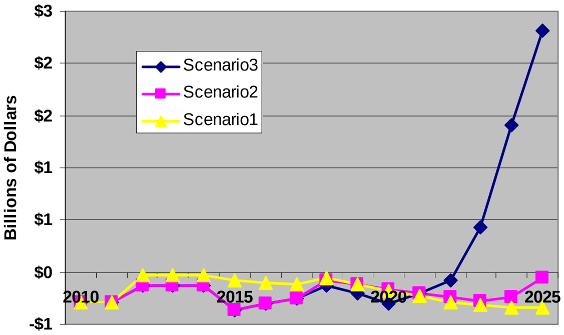
The figures below show the auto industry's simulated cash flow from the sales of FCVs, both with and without policy support. Without any government policy incentives in the years between 2010 and 2025 (Figure ES-5), the automotive industry would need to invest tens of billions of dollars and sustain billions in annual losses over more than a decade, with profitability delayed until 2022 or beyond. These losses are above the normal vehicle development and testing costs for a new vehicle model and require the extra risk of implementing a synchronized deployment of the hydrogen infrastructure. A no-policy scenario seems unlikely to induce the concerted effort or capital investment required to introduce sufficient vehicle models and hydrogen supply infrastructure to support a sustainable market.

Figure ES-5. Simulated Auto Industry Cash Flow from Sale of FCVs under No-Policy Case



Source: Greene and Leiby, 2007

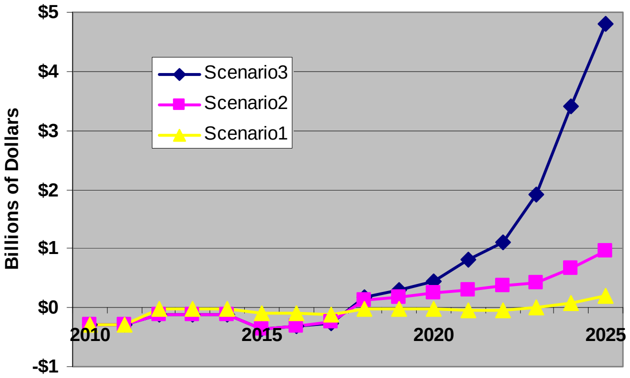
Figure ES-6. Simulated Auto Industry Cash Flow from Sale of FCVs under Policy Case 2



Source: Greene and Leiby, 2007

With policy incentives (and fuel cell vehicle technical success), the cost position of the automotive industry can be significantly improved. As shown in Figures ES-6 and ES-7, both Policy Cases 2 and 3 would provide enough cost sharing to reduce industry's annual losses to hundreds of millions of dollars in the early years. However, it still takes more than 10 years for industry to achieve a profit with Policy Case 2. Under Policy Case 3, the analysis suggests that industry could begin generating a profit as early as 2017. Policies would also help to reduce the cost of hydrogen to a level well below gasoline on a cost-per-mile basis, and encourage the build-out of hydrogen fueling stations.

Figure ES-7. Simulated Auto Industry Cash Flow from Sale of FCVs under Policy Case 3



Source: Greene and Leiby, 2007

1 INTRODUCTION

Section 811 of the EPACT (U.S. House, 2005) calls for the Secretary of Energy to report on measures to support the transition to a hydrogen economy, including the production and deployment of both hydrogen-fueled vehicles and the hydrogen production and delivery infrastructure needed to support those vehicles. In addition, the 2004 report of the National Academy of Sciences (NAS), *The Hydrogen Economy* (NAS, 2004), contains two recommendations calling for the U.S. Department of Energy (DOE) to conduct supporting analyses for infrastructure and transition planning for the hydrogen economy:

- "DOE should map out and evaluate a transition plan consistent with developing the infrastructure and hydrogen resources necessary to support the committee's hydrogen vehicle penetration scenario, or another similar demand scenario."
- "DOE's policy analysis should be strengthened with respect to the hydrogen economy, and the role of government in supporting and facilitating industry investments to bring a transition to the hydrogen economy needs to be better understood."

To address the EPACT requirement and NAS recommendations, DOE's Hydrogen, Fuel Cells and Infrastructure Technologies Program (HFCIT) supported and coordinated a series of analyses to evaluate alternative scenarios for the deployment of millions of hydrogen-fueled vehicles and the supporting hydrogen production and delivery infrastructure. To ensure that the market penetration scenarios were consistent with the thinking of automobile manufacturers, energy companies, industrial hydrogen suppliers, and others from the private sector, DOE held several stakeholder meetings to explain the analyses, describe the models, and solicit comments about the methods, assumptions, and preliminary results (U.S. DOE, 2006a). The first meeting was held on January 26, 2006, to solicit guidance during the initial phases of the analysis; this was followed by a second meeting on August 9-10, 2006, to review the preliminary results. A third and final meeting was held on January 31, 2007, to discuss the final analysis results. More than 60 hydrogen energy experts from industry, government, national laboratories, and universities attended these meetings and provided their comments to help guide DOE's analysis.

Overview of the Hydrogen Scenario Analysis

The Hydrogen Scenario Analysis examined the costs and benefits of ramping up large-scale production of hydrogen-powered fuel cell vehicles (FCVs) at different rates under three scenarios. All three scenarios assume that DOE technology readiness goals for hydrogen production and fuel cells are met in the laboratory in the 2010-2015 timeframe, including cost targets for compressed or liquid hydrogen storage.[1] The three vehicle penetration scenarios examined are as follows:

- **Scenario 1** – Production of t*housands* of vehicles per year by 2015, and *hundreds of thousands* by 2019. This option is expected to lead to a market penetration of **2 million FCVs by 2025**.

---

[1] Cost targets for compressed or liquid hydrogen storage were studied at $8/kWh, but weight and volume targets were set at 2010. Representatives from the automotive industry agreed that meeting 2010 goals in the lab is necessary for commercial-scale production of FCVs at rates of up to tens of thousands of vehicles per year by 2015.

- **Scenario 2** – Production of *thousands of* FCVs by 2013 and *hundreds of thousands* by 2018. This option is expected to lead to a market penetration of **5 million FCVs by 2025**.
- **Scenario 3** – Production of *thousands of* FCVs by 2013, hundreds of thousands by 2018, and *millions* by 2021, such that market penetration reaches **10 million FCVs by 2025**.

Scenario definitions began with the upper bound scenario (Scenario 3), which was constructed to correspond with the vehicle penetration scenario developed by the National Academies (NAS, 2004), which carried the optimistic assumption that infrastructure would not be an impediment to the deployment of vehicles. An examination of past and projected rates for the introduction of hybrid electric vehicles (HEVs) into the market found that HEVs (which are not fueling-infrastructure constrained) were introduced at about half the rate projected for FCVs in the NAS scenario. Therefore, the Hydrogen Scenario Analysis developed two additional, more conservative vehicle penetration scenarios, both of which follow the rate of introduction of hybrid vehicles. Scenario 2 initiates ramp-up earlier, in 2015, and Scenario 1 (the lower-boundary scenario) begins ramp-up three years later, in 2018. Figure 1 shows the three scenarios and also includes, as points of comparison, two sales projections of HEVs if they had been introduced in 2015 (HEV + 12 years) and 2018 (HEV + 15 years). The figure indicates that Scenarios 1 and 2 are reasonably consistent with historical and projected hybrid electric vehicle penetration rates.

Figure 1. Annual Hydrogen Vehicle Sales: Scenarios 1, 2, and 3

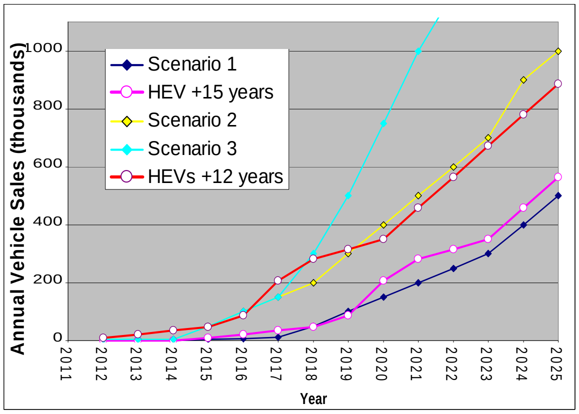


Table 1 shows the number of vehicles projected under each of the three scenarios, annually and cumulatively, over the period 2012-2025. Automobile manufacturers and energy suppliers submitted extensive comments on the scenarios. Some felt that the aggressive vehicle penetration rate described in Scenario 3 was necessary to achieve the economies of scale and number of models required to promote a sustainable market by 2025. Others felt that even Scenarios 1 and 2 were ambitious and optimistic. Although there was no consensus on a particular vehicle penetration rate, it was agreed that this set of scenarios is inclusive of industry expectations and could provide a basis to interpolate or extrapolate the

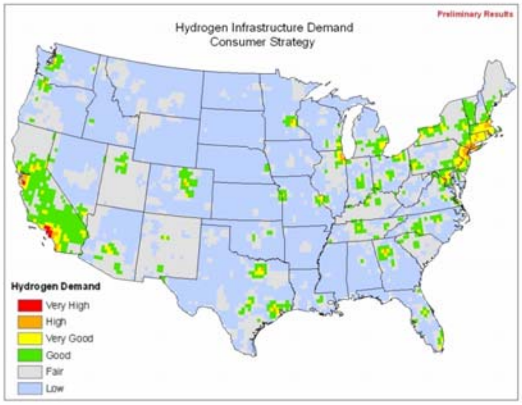
Table 1. Deployment of Hydrogen Fuel Cell Vehicles by Scenario (thousands)

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Scenario 1	0.0	0.0	0.0	3.0	4.8	7.2	50	100	150	200	250	300	400	500
Scenario 1 Cumulative	0.0	0.0	0.0	3.0	7.8	15.0	65	165	315	515	765	1,065	1,465	1,965
Scenario 2	0.5	1.0	1.0	30.0	60.0	60.0	200	300	400	500	600	700	900	1,000
Scenario 2 Cumulative	0.5	1.5	2.5	32.5	92.5	152.5	353	653	1,053	1,553	2,153	2,853	3,753	4,753
Scenario 3	0.5	1.0	1.0	30.0	60.0	60.0	300	500	750	1,000	1,200	1,500	2,000	2,500
Scenario 3 Cumulative	0.5	1.5	2.5	32.5	92.5	152.5	453	953	1,703	2,703	3,903	5,403	7,403	9,903

results to other cases. The purpose of the DOE study was not to select any one penetration scenario but to assess the costs and impacts of achieving each.

Automobile manufacturers and energy providers strongly endorsed a focused approach to fuel cell vehicle and fueling station roll-out as a way to manage resource requirements and provide adequate station networks to satisfy customer demand. The analysis adopted a phased urban network approach, in which vehicles and infrastructure are deployed in highly-populated cities, with the gradual addition of other cities and corridors connecting the cities. The analysis first considered the likely early markets for FCVs in the United States. An analysis of population statistics, such as income level, education, and car ownership, found that major urban areas tend to hold large concentrations of individuals likely to purchase hydrogen-fueled vehicles. Figure 2 shows the areas of the country containing urban areas believed to be good early markets for these vehicles.

Figure 2. Areas of Projected Hydrogen Energy Demand



Source: Melendez and Milbrandt, 2007

As shown in Figure 2, Southern California and several states in the Northeast represent the most attractive initial markets for hydrogen-fueled vehicles. Several of these states (e.g., California and New York) currently operate programs in hydrogen energy development and have established energy and environmental policies that are conducive to the deployment of clean energy technologies, including hydrogen-fueled vehicles.

Organization of this Report

This report summarizes the results of several studies of the transition to hydrogen fuel cell vehicles that DOE has supported and coordinated over the past several years (Brian and Perez, 2007; NREL 2007; Greene and Leiby, 2007; and Unnasch, Rutherford and Hooks, 2007). Chapter 2 summarizes the analysis of hydrogen infrastructure deployment and transition scenarios. The analysis finds that there are major advantages to focusing the early deployment of fueling station networks in major urban areas across the country. In the scenarios analyzed, 2012-2015 is the period for *initial introduction* in two major metropolitan areas, 2016-2019 is the period of *targeted regional growth* into an additional eight cities, and 2020-2025 is the period for *inter-regional expansion* into a total of 20 urban centers and the early introduction of hydrogen corridors permitting cross-country travel.

Chapter 3 presents results of an analysis that simulates the market response to advanced hydrogen technologies and estimates the costs of alternative policies to support the introduction of hydrogen FCVs and fueling infrastructure over the 2012-2025 timeframe. Three policy cases are analyzed, plus one "No-Policy" case. In Case 1, government and industry share the incremental costs of FCVs 50/50; in Case 2, government and industry share total FCV costs 50/50 until 2017, and tax credits cover the incremental cost of FCVs from 2018-2025; in Case 3, additional tax credits supplement market incentives in 2018-2025.

2 ANALYSIS OF INFRASTRUCTURE DEPLOYMENT SCENARIOS

To accomplish a successful transition to a hydrogen powered vehicles, it is critical to match as precisely as possible—in time and space—the available hydrogen supply with emerging hydrogen demand. This chapter describes results of analyses conducted on early infrastructure deployment scenarios, including the most cost-effective hydrogen production and delivery pathways and temporal and geographic deployment of the hydrogen refueling infrastructure, including the optimal siting of refueling stations in key locales.

The analysis considers the following questions:

1) What hydrogen production options are least expensive and most practical during the timeframe (2012-2025)?
2) What are the physical characteristics of the hydrogen fueling stations for siting considerations?
3) What level of hydrogen demand is generated in each of the three vehicle penetration scenarios, and how many stations are required to meet the demand?
4) Where do these stations need to be located to provide the user population with convenient access to fueling?
5) Are there enough feasible sites to accommodate this need for station infrastructure?

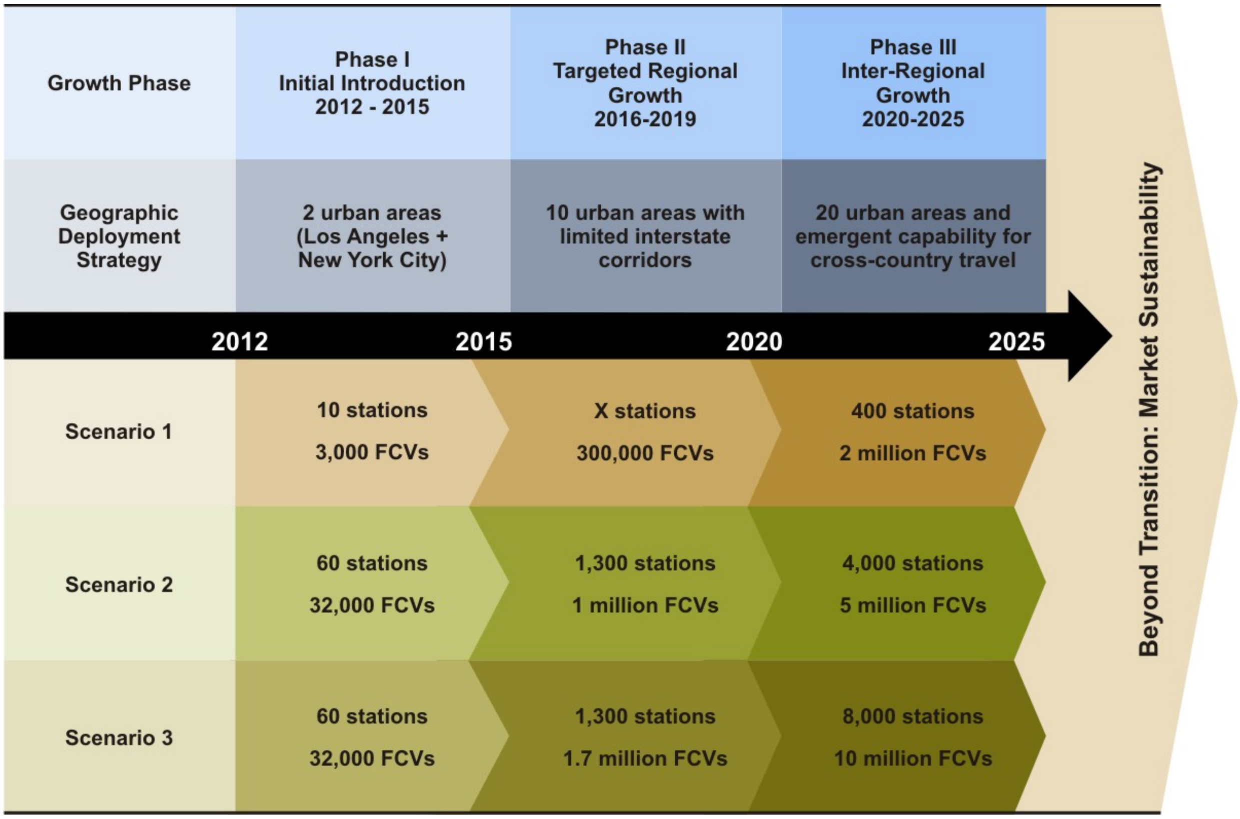
The analysis adopts a three-phase approach for developing hydrogen refueling station networks in urban centers with the highest projected demand for FCVs, and subsequently implementing corridors to connect those urban centers. The deployment of stations is aligned with projected growth in fuel cell vehicle sales under each of the three penetration scenarios, as summarized in Figure 3. In Phase I ("Initial Introduction," 2012 to 2015) stations are sited *only* in the Los Angeles and New York City urban areas. Phase II ("Targeted Regional Growth") corresponds to the 2016-2019 timeframe, and includes additional cities and an early interconnect system between several urban centers. The 2020-2025 time period represents Phase III ("Inter-Regional Expansion"), which includes more cities and enough stations along a basic interstate corridor system to permit cross-country travel.

The following sections summarize the infrastructure deployment analysis. The first section addresses hydrogen production strategies and associated fueling station characteristics and the second section addresses geographic location of these stations over space and time.

Comparative Infrastructure Costs

Infrastructure costs are a critical factor for the successful market penetration of hydrogen fuel cell vehicles. The ability to deliver low-cost hydrogen during this period is essential to gaining public acceptance and minimizing government investment. An analysis of hydrogen infrastructure pathway costs (Brian and Perez, 2007) evaluated the different options that could possibly be available in the 2012-2025 timeframe to produce, deliver, and dispense hydrogen to future FCVs, including use of biomass, water (electrolysis), natural gas, coal with sequestration, and nuclear energy (see Table 2 below). The analysis considered central and distributed production options. Central production is defined here

Figure 3. Cumulative Fuel Cell Vehicle and Station Deployment, by Scenario and Phase



Growth Phase	Phase I Initial Introduction 2012 - 2015	Phase II Targeted Regional Growth 2016-2019	Phase III Inter-Regional Growth 2020-2025
Geographic Deployment Strategy	2 urban areas (Los Angeles + New York City)	10 urban areas with limited interstate corridors	20 urban areas and emergent capability for cross-country travel
Scenario 1	10 stations 3,000 FCVs	X stations 300,000 FCVs	400 stations 2 million FCVs
Scenario 2	60 stations 32,000 FCVs	1,300 stations 1 million FCVs	4,000 stations 5 million FCVs
Scenario 3	60 stations 32,000 FCVs	1,300 stations 1.7 million FCVs	8,000 stations 10 million FCVs

as plants producing greater than 100 tons of hydrogen per day and located 30-60 miles beyond the city limits, with hydrogen delivered to terminals and filling stations via truck or pipeline. Distributed (or forecourt) production plants are small (up to 3.0 tons of hydrogen per day) facilities that produce hydrogen on the same site as the vehicle filling station.

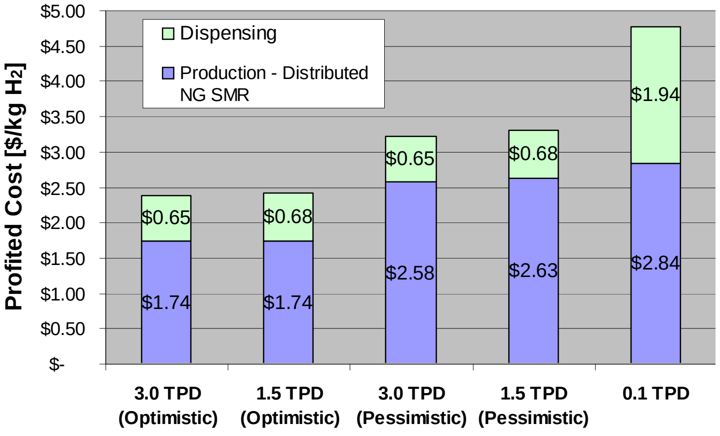
Table 2. Production Options Considered for Hydrogen Scenario Analysis

Feedstock	Process	Plant Size	Location
Natural Gas	Steam Methane Reforming	0.1 TPD, 1.5 TPD, 3.0 TPD 379 TPD	Distributed Central
Coal	Gasification	316 TPD	Central
Biomass	Gasification	155 TPD	Regional
Nuclear	Sulfur Iodine Thermo chemical Water Splitting	767 TPD	Central
Ethanol	Reforming	1.5 TPD	Distributed
Water	Electrolysis	0.1 TPD, 1.5 TPD	Distributed

Source: DTI 2007

The production options were analyzed using a model developed by DTI called HYPRO, which generates a "profited cost of production" from each pathway and then projects the least-cost hydrogen production pathways for meeting specified hydrogen demand levels over time. Figures 4, 5, and 6 provide the profited cost of production of the most viable near-term production pathways at constant high demand with all anticipated technology advancements implemented (year 2030 performance). The pathways for electrolysis and nuclear were determined to be too costly in this time period, and so are not included here.

Figure 4. Distributed Steam Methane Reforming: Total Pathway Costs*



* Production costs include on-site hydrogen storage and compression.

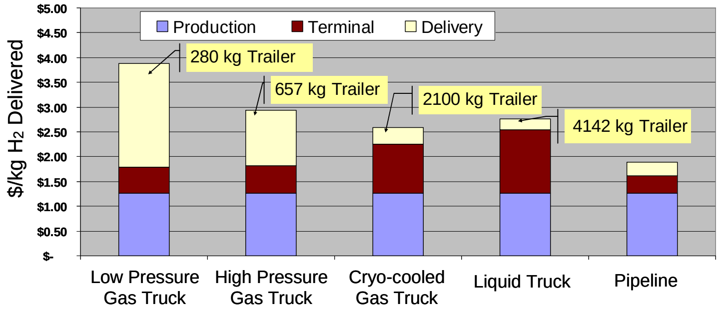
Source: James and Perez, 2007

The total pathway costs for distributed steam methane reforming (on-site reforming of natural gas) for different plant/station sizes are shown in Figure 4. The small plant (0.1 tons per day [TPD]) costs for hydrogen are prohibitively high, at nearly $5 per kg of hydrogen dispensed at 5000 psi (untaxed). The 1.5 ton per day and the 3.0 ton per day plants have equivalent price perspectives, at between about $2.50 and $3.50/kg (untaxed at the dispenser at 5000 psi gas). Because there is wide dispersion in the expected installed capital cost of forecourt steam methane reforming equipment, both a low ("optimistic") and a high ("pessimistic") cost case is shown. The optimistic case assumes advances in Design for Manufacturing and Assembly that reduce manufacturing and field installation costs, as well as technical innovations that allow for smaller and cheaper production units.

It will be important to provide consumers with as many station locations as possible during the early deployment period. The number of stations that can be provided in any geographic region is maximized by siting smaller stations that do not require as much land. (This will be explained in more detail in the next section.) Therefore, the 1.5 TPD-size distributed production plant was selected as the prototype for the analysis because it leads to the largest number of stations that can be deployed in the shortest amount of time.

Central hydrogen production pathways include additional costs for transporting the hydrogen from the plant to its point of use within the city. For the Hydrogen Scenario Analysis, delivery via conventional, low-pressure gas truck, high-pressure gas truck, cryo-compressed gas truck, conventional liquid truck, and gas pipeline were considered. Figure 5 shows that while the cost to produce hydrogen at central plants is low (between about $1.00 and $1.50/kg), the terminal and delivery costs add significantly to the total. The terminal costs in Figure 5 include compressors, pumps, liquefiers (for liquid pathways), evaporators, trucking bays and storage vessels (all located at the central production plant). Delivery costs include the material and labor costs of either truck or pipeline delivery from the terminal to the fueling station. Because truck delivery costs vary inversely with trailer capacity (shown in kilograms in Figure 5), liquid truck delivery is the least costly of the truck delivery

Figure 5. Hydrogen Transport Costs from Alternative Delivery Pathways

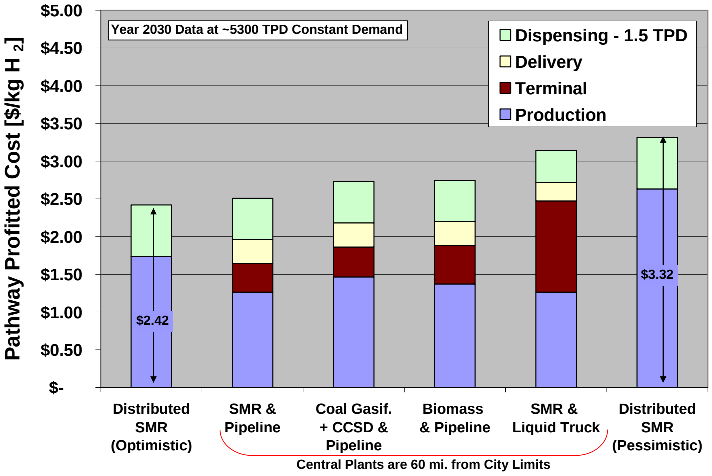


* Hydrogen production mode is central steam methane reforming

Source: James and Perez, 2007

options. A large part of the costs for the liquid truck pathway are associated with the high cost of liquefying hydrogen at the terminal. While cryo-gas (cold compressed gas) truck delivery costs appear to be slightly lower than liquid trucks, the technology is unproven, costs are speculative, and high-pressure storage is required at the station, which complicates siting. For this reason, liquid trucks are selected in this analysis as the preferred truck-based mode of hydrogen delivery from remote hydrogen production facilities. Pipeline delivery also offers a high capacity and relatively low costs when fully utilized, but it may take many years to build this level of hydrogen demand. Therefore, this mode of delivery is also selected, but does not emerge until later in the early deployment period. While all of the above options are included in the model as viable alternatives, their projected implementation will depend on which pathway offers the lowest-cost option for that particular point in time, demand level, and geographic location.

Figure 6. Total Pathway Costs for Lowest-Cost Hydrogen Infrastructure Pathways



Source: James and Perez, 2007

Figure 6 summarizes the results of this analysis by showing the total pathway costs for the lowest-cost hydrogen infrastructure pathways for the early deployment period. The optimistic and pessimistic forecourt provide the low- and high-end pathway costs, at between $2.50 and $3.25/kg (untaxed, 5000 psi). The coal option includes a $0.46/kg penalty for carbon sequestration; improved sequestration methods may lower the cost of this option. The biomass option considered here is gasification of switchgrass. In addition to these options, hydrogen could also be provided, in limited amounts and in niche locations, by excess capacity at existing hydrogen production facilities (i.e., petrochemical refineries and merchant gas producers). This would be the lowest-cost option for delivered hydrogen, where available. One important point to note about central steam methane reforming with liquid delivery is that the current liquefaction process is electricity-intensive and would be carbon-intensive if provided by the existing electricity grid fuel mix.

Geographic Deployment Analysis

One of the greatest challenges to the introduction of hydrogen vehicles nationwide is development of a logical strategy for deploying both the vehicles and the supporting infrastructure. Some studies have looked at a national vehicle deployment scenario that could require as many as 30,000 to 50,000 hydrogen fueling stations to meet customer demand. However, such a large deployment of stations is neither economically nor practically feasible. Automakers have also expressed a strong preference for focusing the early sales of FCVs in limited urban areas with the largest markets in order to limit the need to support a diffuse and low-utilization technical support and maintenance network. A key finding of this study is that vehicle deployment and fueling station deployment should be synchronized and *rolled out in a phased approach that starts in areas of high potential demand for FCVs.*

An analysis was conducted (Melendez and Milbrandt, 2007a) to identify the areas of highest FCV demand, and then assess how many stations would be needed to fuel these vehicles and where they might realistically be located. As a first step, a literature search and interviews with vehicle technology experts were conducted to identify key demographic attributes affecting hydrogen vehicle adoption in consumer markets. The following attributes were selected for assessing the relative merits of different geographic areas for early deployment of hydrogen vehicles: households with two or more vehicles, hybrid vehicle registrations, education, household income, commute distance, state incentives, clean city coalitions, and zero emission vehicle (ZEV) mandates.

The analysis showed that major urban centers are the best early markets for hydrogen FCVs (see Figure 2). New York and Los Angeles were identified as particularly good areas, with population centers of about 20 million. Next-best are cities with populations between 5 and 10 million, such as Boston, Chicago, San Francisco/Sacramento, and Dallas. Cities with populations between 2 and 5 million (e.g., Houston, Seattle, Phoenix, Denver, Cleveland, and Miami) were also considered promising for deployment of hydrogen refueling stations. In all, 20 cities in five different regions were identified as promising candidates in a phased roll-out (see Table 3 and Figure 7).

The Oak Ridge HyTrans model was used to calculate the total number of fueling stations required to meet demand in each of the three different scenarios (Greene and Leiby, 2007). The analysis assumes deployment of 1.5 TPD distributed hydrogen production and central production with liquid truck and gaseous pipeline delivery, as described in the previous section. The total number of stations was then allocated among the 20 selected urban areas. In the

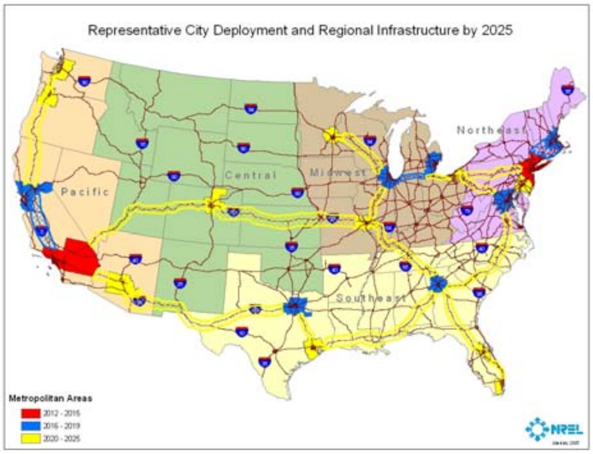
Table 3. Projected Hydrogen Fueling Station Deployment 2012 -2025 (Scenarios 2 and 3)

	Phase I	Phase II	Phase III	
Urban Area*	**2012-2015 Stations**	**2016-2019 Stations**	**Scenario 2 2020-2025 Stations**	**Scenario 3 2020-2025 Stations**
New York	20	200	554	1,227
Los Angeles	40	400	751	965
Chicago		135	316	699
Washington			265	586
San Francisco/ Sacramento		78	181	401
Philadelphia**		58	136	302
Boston		127	296	656
Detroit		90	210	465
Dallas		92	215	477
Houston			192	425
Atlanta**		74	173	382
Miami			50	111
Seattle		27	63	140
Phoenix			99	219
Minneapolis/ St. Paul			98	217
Cleveland			83	183
Denver			88	196
St. Louis			85	188
Portland			55	123
Orlando			35	77
Total	**60**	**1,281**	**3,945**	**8,039**

*Ranked by Population shown in Table 3.
** Cities selected and reranked for geographic diversity within analysis
Colors indicate phase in which infrastructure development is initiated in HyTrans:
Red: 2012-2015, Blue: 2016-2019, Green: 2020-2025

first phase of deployment (2012–2015), stations are sited only in the Pacific and Northeast regions, in the urban areas of Los Angeles and New York. In Phase II, Targeted Regional Growth (2016–2019), stations are sited in eight additional cities and two additional regions, with limited corridors between a few cities (see heavy blue lines in Figure 7). By Phase III (2020–2025), stations are deployed in all 20 cities and all five regions, with nascent capacity for cross-country travel, as shown by the yellow network in Figure 7. Table 3 shows the breakdown of fueling station deployment over time for Scenarios 2 and 3. The number of stations in Scenarios 2 and 3 is similar until Phase III, at which point the two scenarios are projected to diverge.

Figure 7. Representative City Deployment and Regional Infrastructure



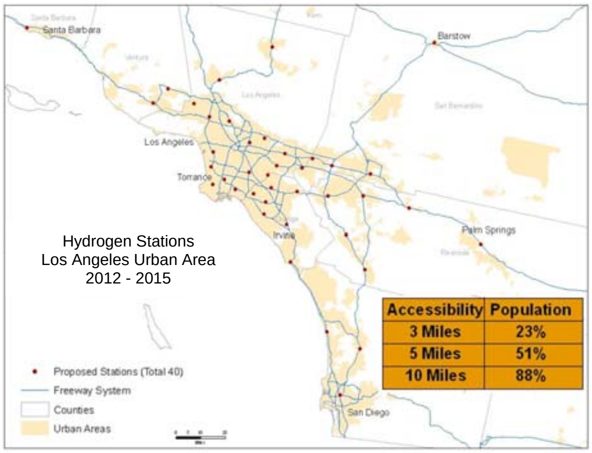
Source: Melendez and Milbrandt, 2007

Within each city or urban area, feasible station locations were identified using the following criteria:

- Along roads with traffic flow above 200,000 vehicles per day
- In census tracts with 3,000 or more registered vehicles
- Near retail centers
- Along major and secondary roads
- Balanced station coverage
- Near major civic airports

Stations have also been sited such that FCV customers can get to and from popular local destinations or commuter communities. Figures 8-13 show the results of this analysis for

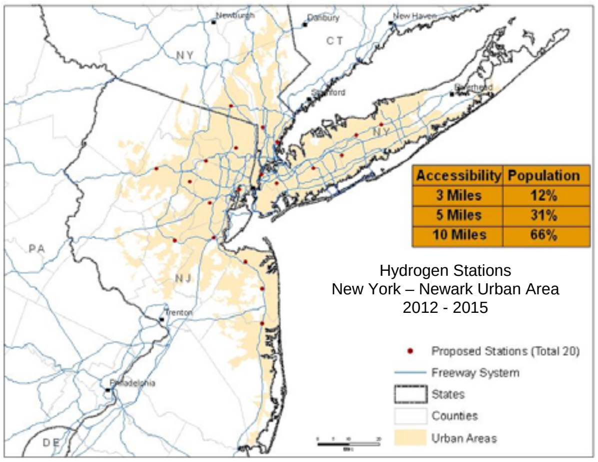
Figure 8. Hydrogen Refueling Stations in the Los Angeles Urban Area during Phase I (Scenarios 2 and 3)



Accessibility	Population
3 Miles	23%
5 Miles	51%
10 Miles	88%

Source: Melendez and Milbrandt, 2007

Figure 9. Hydrogen Refueling Stations in the New York Urban Area during Phase I (Scenarios 2 and 3)

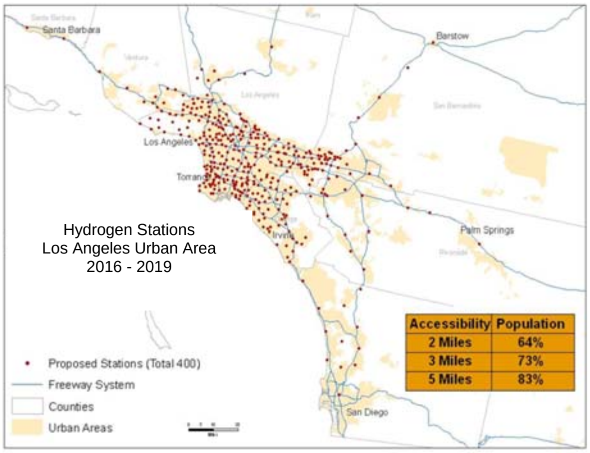


Accessibility	Population
3 Miles	12%
5 Miles	31%
10 Miles	66%

Source: Melendez and Milbrandt, 2007

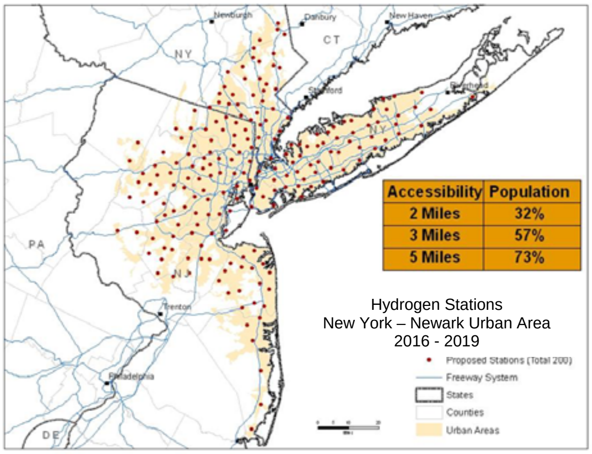
the urban centers of Los Angeles and New York. In Phase I a total of 60 stations are built—40 in the Los Angeles urban area and 20 in the New York area. More stations are initially deployed in Los Angeles, since local and state regulations and incentives are expected to stimulate a more rapid market penetration of fuel cell vehicles in that area. As shown in Figures 8 and 9, 51% of the population of Los Angeles and 31% of the population of New York are expected to be within five miles of these early stations. The stations are generally located on major arteries and are expected to provide adequate coverage for the hydrogen demand projected during this timeframe.

Figure 10. Hydrogen Refueling Stations in the Los Angeles Urban Area during Phase II (Scenarios 2 and 3)



Source: Melendez and Milbrandt, 2007

Figure 11. Hydrogen Refueling Stations in the New York Urban Area during Phase II (Scenarios 2 and 3)



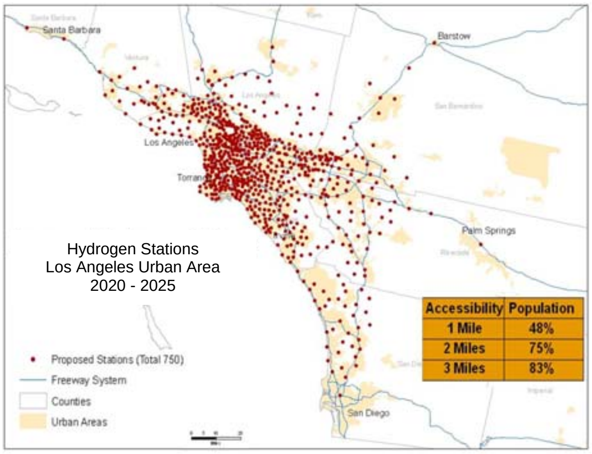
Source: Melendez and Milbrandt, 2007

During Phase II stations are placed in eight additional cities to meet growing projected demand (see Table 3). About half of the 1,280 stations are located in Los Angeles and New York, with the remainder in the other cities. Figures 10 and 11 shows how the station locations might expand during Phase II in Los Angeles and New York. With this level of station coverage, 64% of the population in Los Angeles will live within 2 miles of a hydrogen station and 83% will live within 5 miles. For New York the respective figures are 32% and 73%. Additional stations are provided just beyond the city centers to provide people with greater driving ranges, but hydrogen demand is not high or widespread enough at this point to make fueling stations in long distance corridors economically viable (except between Los Angeles-San Francisco, New York-Boston Washington D.C., and Chicago-Detroit).

Phase III, the Inter-Regional Expansion phase, marks the threshold to an adequate and interconnected national hydrogen infrastructure. During this 2020-2025 timeframe, hydrogen station deployment is projected to spread to all 20 selected cities and all regions of the country. This outcome would be highly dependent on how many vehicles are actually produced and sold. If automakers aggressively pursue a receptive consumer market and can meet the FCV sales levels assumed for this timeframe in Scenario 3, then this kind of station deployment would be needed. Scenario 3 places over 8,000 stations during Phase III (or about 15% of the total number of existing gasoline stations). Almost 6,000 of these are located outside the urban centers of Los Angeles and New York. Scenario 2 establishes about half as many stations during the same timeframe, with over 2,500 of these located in other cities. The 4,000 stations deployed by the end of Phase III in Scenario 2 equates to about 7% of existing gas stations.

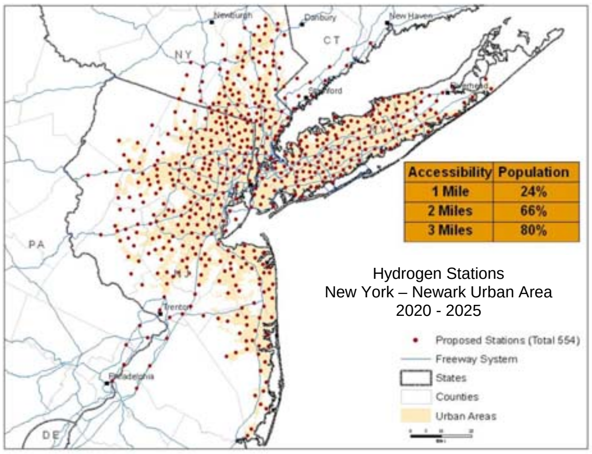
Figures 12 and 13 show the placement of stations in Los Angeles and New York during Phase III (Scenario 3). This level of station coverage brings more than 80% of the Los Angeles metro population within 3 miles of a station and almost 50% within one mile. In New York, only about a quarter of the population is within one mile of a station, but about 80% is within 3 miles. An analysis of driving distances and times (Welch, 2007b) in Los Angeles concluded that the station coverage in Scenarios 2 and 3 were both adequate to meet consumer expectations (less than 3 minutes driving time in Scenario 3 and less than 4 minutes in Scenario 2, as shown in Figure 14).

Figure 12. Hydrogen Refueling Stations in the Los Angeles Urban Area during Phase III (Scenario 3)



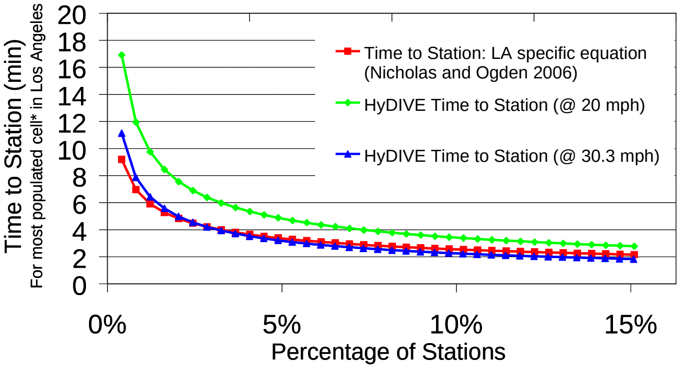
Source: Melendez and Milbrandt, 2007

Figure 13. Hydrogen Refueling Stations in the Los Angeles Urban Area during Phase III (Scenario 3)



Source: Melendez and Milbrandt, 2007

Figure 14. Comparison of Time to Station Projections



* 15.4 x 16.5 mile cell with 490 gas stations

Source: Welch, 2007

As a final step in the geographic deployment analysis, the possibilities for actual station placement at the identified locations were assessed. A model station footprint was developed for a 1.5 ton per day steam methane reforming (SMR) fueling station. Land requirements ranged from 6,700 – 12,800 square feet, depending on the setback required for nearby buildings, sidewalks, parking lots, etc. The analysis first considered the feasibility of siting the SMR facilities at existing gas stations, since this represents the lowest cost option. Based on an assessment of existing gas stations in Los Angeles, New York City and Dallas (40 stations per city), only a small number (less than 20) were clearly feasible for on-site SMR. Therefore, the analysis was extended to consider locating fueling stations at "big box" stores, such as Wal-Mart and Costco. These locations are attractive because they have large parking lots that could accommodate SMR equipment, and several of the corporate chains have expressed interest in participating in clean energy projects. Their share of fuel sales is also growing; in 2005, gas stations at big box retailers and grocery stores accounted for only 2-3% of stations, but nearly 8% of gasoline sales nationwide. However, the number of these retail centers is limited. The shortage of feasible distributed SMR sites in urban areas means that central plants with pipeline delivery systems may need to be in place by 2020 or earlier to meet the kind of hydrogen demand that would be generated by either Scenarios 2 or 3.

Key Findings and Conclusions: Infrastructure Deployment Analysis

- The lowest-cost hydrogen production pathways for the early deployment period are:
  - Liquid hydrogen delivered by truck from existing hydrogen production facilities (available in very limited quantity to niche locations)
  - Distributed steam methane reforming (SMR) on a scale of 1.5 tons per day (1,050 kg of hydrogen dispensed per day)
  - Liquid hydrogen delivered by truck or gaseous hydrogen delivered by pipeline from central (about 300 tons per day) plants located 30-60 miles from the city (coal with sequestration, biomass or natural gas)

  All options are considered viable; the lowest-cost option will depend on the particular economic conditions at that specific time and place.
- Urban areas represent the best early markets for FCVs (with Los Angeles and New York City being the top 2 early markets in the United States)
- An "urban center" approach to deployment was recommended by industry, in which vehicle sales and fueling infrastructure build-out are focused on a limited number of cities, with fueling networks radiating out and gradually connecting additional cities
- A phased roll-out concept, that focuses first on areas of highest potential demand for FCVs, will enable strategic location of fueling stations to maximize the coverage early for least cost and enable automakers to concentrate technical and maintenance support resources
- Between 4,000 and 8,000 stations are needed to meet the hydrogen demand from FCV sales assumed in Scenarios 2 and 3, respectively, by 2025. While this represents only 7-15% of the number of existing gasoline stations, strategic deployment of stations will meet customer demands for convenience (assuming 3-mile travel distances)
- On-site SMR fueling stations have a footprint of between 6,700 and 12,800 square feet. Because of space constraints at existing gasoline stations and the limited number of "big box" store locations (which are not as space-constrained), there appears to be a shortage of feasible locations for distributed SMR facilities. Therefore, there may be a need to consider gaseous pipeline delivery before 2020.

3 ANALYSIS OF SCENARIO COSTS AND SUSTAINABILITY

This chapter presents the results of analysis that simulates the market response to advanced hydrogen technologies and estimates the cost of alternative polices to support a market transformation to hydrogen fuel cell vehicles (Greene and Leiby, 2007). The analysis uses an integrated market simulation model (HyTrans) representing the economic decisions of vehicle manufacturers, energy suppliers and consumers to estimate market outcomes through 2050. For the Hydrogen Scenario Analysis, the three vehicle penetration scenarios are evaluated to assess their costs in comparison to a business-as-usual or “null” scenario. The HyTrans model calculates the added costs of achieving these scenarios both in terms of infrastructure, and fuel and vehicle production. The costs above the null scenario represent economic hurdles for investors, and are assumed to be shared by the government and private sector through policy incentives designed to foster a competitive environment, as described below. The level of FCV penetration that is actually achieved will depend on the abilities of the several stakeholders to educate the public, market and sell fuel cell vehicles, and deliver hydrogen to consumers in a competitive marketplace. After 2025, the HyTrans model is run to 2050 to determine whether, in the absence of further policy initiatives, a sustainable transition to hydrogen powered vehicles would be likely to continue to completion.

The Hydrogen Scenario Analysis considered policies that could be used by government to help foster market conditions in which FCVs could effectively compete. The policies address two key economic barriers: (1) lack of an existing fueling infrastructure, and (2) the high cost of FCVs at low production volumes. The analysis evaluated policies that could *directly* incentivize the building of fueling stations, drive down the cost of producing fuel cell vehicles, and stimulate the purchase of FCVs. Three alternative policy cases were developed that provide different options for doing this, with different allocations for sharing the costs between the private sector and the government. The cost of each policy case is estimated for the three scenarios over the 2012-2025 timeframe, with a “no-policy case” included as a point of comparison. The following sections describe the results of the scenario and policy cost analysis.

Projected Market Sustainability of Scenarios 1-3

On the vehicle manufacturing side, the HyTrans model represents technological progress towards the DOE’s goals for advanced automotive technologies, cost reduction via learning-by-doing, and economies of scale in vehicle production. More information on the fuel cell vehicle cost projections within each scenario is presented below.

On the energy supply side HyTrans includes a range of hydrogen production processes and delivery options derived from DOE’s H2A hydrogen production and delivery models, and is generally consistent with the hydrogen production pathway analysis described in Chapter 2. In the early stages of the deployment, hydrogen is produced predominantly by distributed SMR or from existing hydrogen plants. As the demand for hydrogen grows, central production from biomass and coal (with sequestration) with liquid truck and pipeline delivery become important sources in higher-demand markets. The hydrogen is calculated as a delivered cost, and includes all the infrastructure necessary for production, delivery, and refueling. Several pathways appear to be able to deliver hydrogen at very similar costs. Small changes in assumptions can therefore produce large changes in the hydrogen production mix. For example, central production may appear earlier than is predicted here, depending on relatively minor changes in assumptions. As a consequence, it is not meaningful to emphasize the precise mix of hydrogen production pathways predicted by the HyTrans model. The key implication is that hydrogen is likely to be produced via a variety of pathways at competitive costs. More information on the cost of hydrogen versus gasoline, on a cost-per-mile-driven basis, is presented in the section addressing policies and costs.

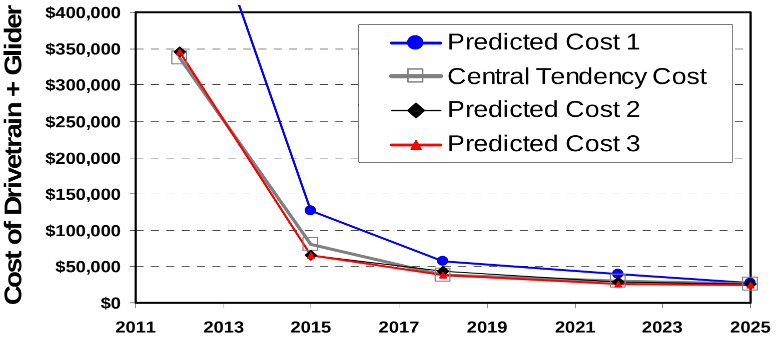
On the demand side, the HyTrans model represents consumers' choices and fuel use among competing vehicle technologies, taking into consideration the projected availability and price of fuel, fuel economy, and the diversity and number of vehicle makes and models to choose from. The U.S. is divided into markets consistent with the phased geographic deployment scenarios presented in Chapter 2. As previously mentioned, for this study the model follows the vehicle penetration rates for the three scenarios until 2025.

Fuel Cell Vehicle Cost Projections

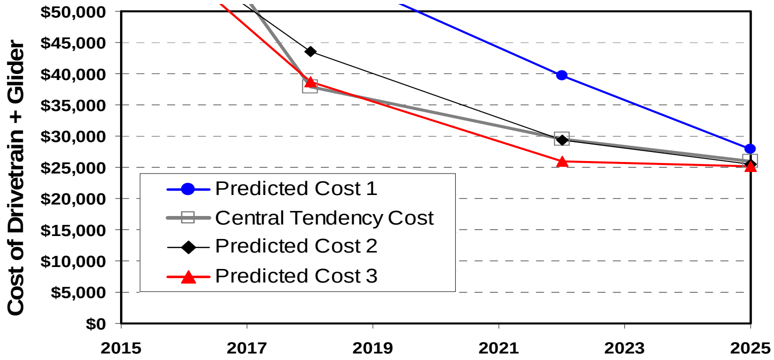
Initially, fuel cell vehicles will be very expensive. Costs will decline as a function of technological progress, learning-by-doing, and manufacturing scale economies, all of which are represented in the HyTrans model. Figures 15a and 15b show the fuel cell vehicle cost estimates calculated by the model, along with an averaged "central tendency" or "composite" cost curve based on proprietary cost estimates provided by OEMs for different years and production volumes. The calculated cost estimates assume that DOE's 2010 and 2015 R&D goals for cost reductions are met and incorporated into mass-produced technology five years later. Note that the FCV cost estimates do not include the normal development costs that automobile manufacturers invest to produce and test vehicles for mass production and consumer acceptance.

Figure 15. Estimated Cost of FCVs in Scenarios 1, 2 and 3 as a Function of Learning, Volume, and R&D Progress

15a. Predicted FCV Costs: 2011-2025



15b. Estimated FCV Costs: 2017-2025



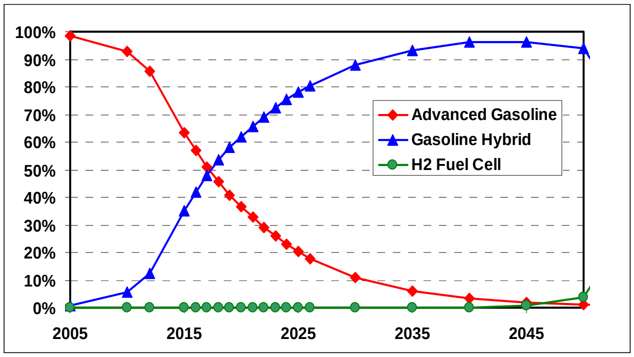
Source: Greene and Leiby, 2007.

On a scale showing the entire 2012-2025 timeline, FCV costs in Scenarios 2 and 3 are barely distinguishable from one another and from the OEM "composite" cost estimate. The lower production volumes in Scenario 1 result in a higher cost for the first few years. Expanding the scale to show only the time period after the cost of the vehicle has gone below $50,000 (Figure 15b), more of the differences between the scenarios can be seen. These differences have a big affect on the OEMs' cash-flow conditions during this period, which are discussed in more detail later in the report.

Market Simulations for Hydrogen Fuel Cell Vehicles

The market simulations for the different scenarios assume the following: 1) all key light-duty vehicle technologies[2] achieve their DOE cost and performance goals and 2) world oil prices are consistent with the Energy Information Administration's high world price projections (i.e., $90/barrel in 2030). Technology success for FCVs assumes that the hydrogen fuel cell power train meets its cost target of $30/kW by 2015 and is incorporated into commercially available vehicles by 2020. Sensitivity analyses were also conducted to test the impacts of technology shortfalls, lower oil prices, and competing demands for biofuels under an expanded national biomass initiative.

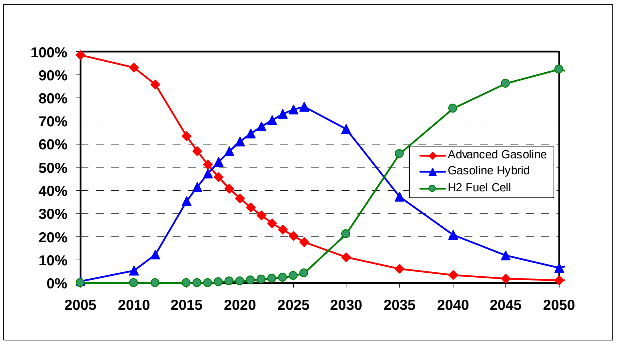
Figure 16. Vehicle Technology Market Shares in Null Scenario



Source: Greene and Leiby, 2007

Figure 16 shows the simulation of the light-duty vehicle market with no direct policies in place to stimulate the production or sales of FCVs (the Null Scenario). These results are important, because they suggest that even with technology success, high world oil prices, and a CO_2 tax in place, market forces alone will not drive a market shift to hydrogen powered vehicles until, perhaps, well after 2050. The market barriers and industry investments for FCVs are too large to overcome and advanced gasoline and diesel hybrid vehicles (which do not face the same market barriers) will dominate.

Figure 17. Vehicle Technology Market Shares in Scenario 1



Source: Greene and Leiby, 2007

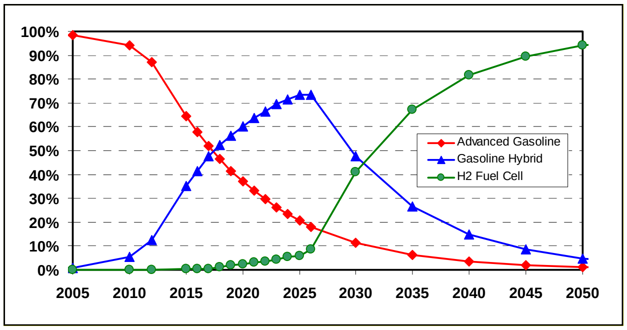
The HyTrans market simulations for Scenarios 1, 2, and 3 (shown in Figures 17-19) indicate that achieving any one of these vehicle penetration scenarios over the 2012-2025 timeframe (which, again, is dependent on the actual sales of vehicles by auto companies) is able to accomplish a sustainable changeover to hydrogen powered vehicles after 2025. The scenarios differ with respect to the rate and degree of market penetration beyond 2025. Although risk has not been explicitly included in this analysis, it is probably a critical factor in achieving a successful market transformation. It is likely that those scenarios that quickly drive down

---

[2] Competing light-duty vehicle technologies include fuel cell vehicles, advanced conventional gasoline and diesel vehicles, advanced hybrid gasoline and diesel vehicles, and future hydrogen internal combustion engine vehicles.

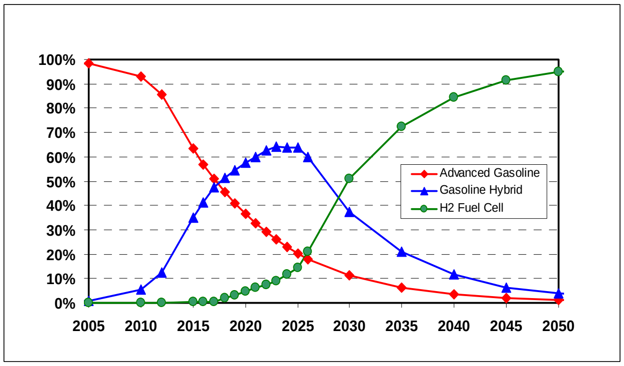
FCV costs and establish an extensive hydrogen infrastructure will inspire a greater degree of confidence in the ultimate success of the conversion to hydrogen and have a higher chance for success.

Figure 18. Vehicle Technology Market Shares in Scenario 2



Source: Greene and Leiby, 2007

Figure 19. Vehicle Technology Market Shares in Scenario 3



Source: Greene and Leiby, 2007

Sensitivity analyses showed that the achieving DOE's goals for fuel cell and storage costs are very important to ensuring a stable, sustainable market transformation. If all of the technologies achieve only "intermediate" goals (which for FCVs equates to $60/kWh for fuel cell systems vs $30 and/or $8/kWh for on-board hydrogen storage vs $2), then the ability for FCVs to effectively compete is reduced and generally share about 40% of the marketplace. An analysis using a lower price for oil (the EIA Annual Energy Outlook Reference Case) indicated that even with oil prices at $50/barrel in 2030 (and assuming technology success for FCVs), a sustainable market shift to FCVs would occur. Likewise, an expanded biofuels policy (which assumes biofuels replace 15% of gasoline use by 2017 and 22% by 2030) does not impact the long-run market transformation to hydrogen, but does change the mix of hydrogen production pathways.

Selection of Policy Options

As the previous section indicated, without some direct policy intervention to help overcome significant market barriers, it is unlikely that a changeover to hydrogen FCVs will occur. However, with policy support to share the private sector's costs for producing a fuel cell vehicle that is cost-competitive in the marketplace, a sustainable market transformation is possible. As requested by Congress (in U.S. House, 2005) and the National Academies, this study evaluates the cost of policy options that could help to overcome these barriers. An analysis was conducted to identify the best options for consideration in the Hydrogen Scenario Analysis study (Unnasch, Rutherford and Hooks, 2007). Candidate options included those authorized in existing federal legislation (e.g., EPACT Sections 805 and 808, clean fuel tax credits) and policies and incentives that are or have been offered by state and local governments, utilities, or other programs. The leading candidates (shown in Figure 20) were assessed for their strengths and weaknesses in directly addressing the

Figure 20. Policy Options: Candidates Considered in the Analysis

50/50 vehicle cost share
Infrastructure loan guarantees
Accelerated depreciation
Infrastructure cost share
Producer fuel payment
Fleet purchase program
Consumer tax credit

market barriers to FCV manufacturing and fuel infrastructure development. Vehicle production mandates and broader policy options such as renewable fuel portfolio standards and carbon taxes were also evaluated and rejected as policy candidates since they do not directly address the economic barriers faced by private sector investors and car buyers. The analysis was presented at DOE stakeholder meetings and discussed with industry representatives.

The three policy cases ultimately selected for consideration and the manner in which they are implemented over the time period of the study are shown in Table 4. The emphasis is on policies that could (1) reduce the cost of FCVs and hydrogen fuel to consumers (both commercial fleet operators and individual car buyers); and (2) reduce the risk for private investors (vehicle manufacturers and fueling station providers) by lowering the investment costs to levels more consistent with normal development costs and providing a reasonable time horizon for revenues. The three policy cases provide some level of policy support through 2025, at which time the policy supports are removed to determine if the FCV market is sustainable beyond 2025.

Table 4. Scenarios of Government Support for Hydrogen Fuel Cell Vehicles and Infrastructure:
Three Policy Cases

Policy Case	Time Period	Vehicle Policies		Fueling Infrastructure Policies	
		Fuel Cell Vehicle Cost Sharing	**Fuel Cell Vehicle Tax Credits**	**Station Cost Sharing (for Distributed Hydrogen Production)**	**Hydrogen Fuel Subsidy (Production Tax Credit)**
Case 1	2012 - 2017	50% of incremental FCV costs	None	$1.3 Million/Station	$0.50/kg
	2018 - 2021	50% of incremental FCV costs	None	$0.7 Million/Station	Decreases linearly From 2018 to $0.30/kg in 2025
	2022 - 2025	50% of incremental FCV costs	None	$0.3 Million/Station	$0.30/kg in 2025
Case 2	2012 - 2017	50% of total FCV costs	None	$1.3 Million/Station	$0.50/kg
	2018 - 2021	None	100% of incremental cost	$0.7 Million/Station	Decreases linearly From 2018 to $0.30/kg in 2025
	2022 - 2025	None	100% of incremental cost	$0.3 Million/Station	$0.30/kg in 2025
Case 3	2012 - 2017	50% of total FCV costs	None	$1.3 Million/Station	$0.50/kg
	2018 - 2021	None	100% of incremental cost plus $2,000/vehicle	$0.7 Million/Station	Decreases linearly From 2018 to $0.30/kg in 2025
	2022 - 2025	None	100% of incremental cost plus $2,000/vehicle	$0.3 Million/Station	$0.30/kg in 2025

All three policy cases encourage the development of refueling infrastructure by providing government cost sharing for the capital cost of distributed SMR stations, in a descending amount over time as shown in Table 4. The total capital cost of a 1.5 ton per day distributed SMR station is estimated to be 3.3 million in 2012, declining as a result of learning-by-doing to $2.0 million by 2025. Each of the policy cases also includes a fuel subsidy for hydrogen equaling $0.50/kg from 2012 through 2017 and declining linearly thereafter to $0.30/kg by 2025. This subsidy would be in the form of a tax credit to hydrogen producers, similar to the credits received for ethanol and biodiesel under current law.

The incentives provided to lower the costs of fuel cell vehicles varies with the three policy cases. Policy Case 1 provides for *50/50 sharing of the incremental costs* of fuel cell vehicles between government and industry throughout the entire time period with no vehicle tax credits. Incremental costs are calculated as the cost above the price of the FCV's closest competitor (assumed to be the advanced gasoline-electric hybrid).

Policy Case 2 modifies the vehicle cost sharing to split not just the incremental but the *total cost of FCVs* 50/50 between government and industry through the year 2017. This policy would be consistent with EPACT of 2005 Section 808 provisions for demonstration programs. After 2017 Case 2 includes a 100% tax credit to industry on the incremental costs of FCVs through the remainder of the time period. Policy Case 3 is exactly the same as Case 2, but adds a $2,000 tax credit (split 50/50 between the vehicle manufacturer and the car buyer) between 2018 through 2025, to provide additional incentives to consumers and industry.

Analysis of Policy Costs

The costs of the policy cases were calculated for the three vehicle market penetration scenarios in order to estimate 1) the annual costs to the government, 2) the cumulative costs to the government, and 3) the simulated cash flow of vehicle manufacturers.[3] A "No Policy Case" is also included, which maintains the baseline assumption that a carbon mitigation policy is in place, but which does not include any policies for cost sharing by the government.

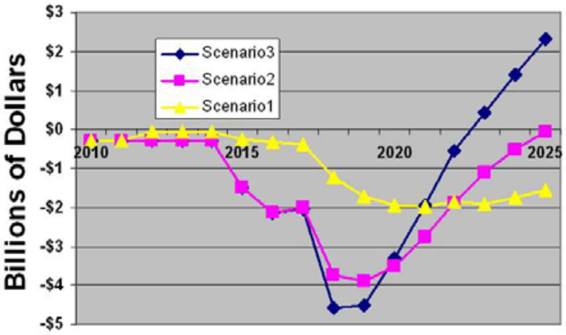
---

[3] Assumptions used for the OEM cash flow simulations include: 1) manufacturers are assumed to make a 6.5% profit on the long-run retail price of an FCV; 2) manufacturers' losses are estimated by subtracting the incremental cost above the long-run retail cost from the estimated profit and multiplying by the number of FCVs sold, plus the available amount of government cost sharing; 3) for Policy Case 3, it is assumed that the $2,000/vehicle tax credit is split equally between consumer and manufacturer, and so $1,000 times the number of FCVs sold is added in Policy Case 3; 4) . Normal product development costs to produce and test commercial vehicles are not included in these analyses. Cash flow simulations for fueling station providers are not presented, since the fueling infrastructure policies are the same in all three policy cases and were designed to permit the fuel provider to be profitable during the early deployment period.

No Policy Case

As shown in Figure 21, without any cost sharing by the government, the automobile industry would sustain significant losses if it were to introduce FCVs at the rates depicted in Scenarios 1, 2 and 3. While the annual losses are lower in Scenario 1, the sales volume never reaches a high enough level for the industry to break even or turn a profit. The higher production volumes in Scenarios 2 and 3 reduce the per-vehicle cost and stimulate the market, creating a net-zero or positive cash flow by 2025. However, the cost of getting there is very high. Figure 21 clearly illustrates the "valley of death," which has peak industry costs of close to $5 billion per year and roughly $25 billion in cumulative losses between 2015 and 2022. These costs represent the amount that industry would have to invest *over and above* normal vehicle development costs that automobile manufacturers invest to bring new vehicles to the mass market. Note that these losses are for the auto industry as a whole, and assumes that there are five companies producing hydrogen fuel cell vehicles over this time period. These losses are a large part of the reason why a transition to hydrogen does not occur in the "Null Scenario" case (see Figure 16).

Figure 21. Simulated Auto Industry Cash Flow from Sale of FCVs under No-Policy Case



Source: Greene and Leiby, 2007

Policy Case 1

In Policy Case 1, the government assumes a substantial share of the additional costs of early deployment. As mentioned previously, Policy Case 1 supports FCVs by providing a 50% cost share for the incremental cost of FCVs over the entire 2012-2025 transition timeframe. Table 5 shows the breakdown of government costs for Policy Case 1 under the three vehicle penetration scenarios (the entire cost curves are shown in Appendix A, Figures A1a-c). Here, as with all three policy cases, the largest share of government cost sharing goes to bring down the cost of hydrogen fuel cell vehicles. Fuel and infrastructure subsidies increase with the number of hydrogen vehicles on the road, so these costs

Table 5. Cost to Government of Cost Sharing and Subsidies for Fuel Infrastructure and Fuel Cell Vehicles: Policy Cases 1, 2 and 3*

	Peak Annual Cost ($ billion)			Cumulative Cost 2012 - 2025 ($ billion)		
	Fuel	Vehicle	Total	Fuel	Vehicle	Total
Policy Case 1						
Scenario 1	0.2	0.8	1.0	1.5	6.5	8.0
Scenario 2	0.3	1.8	2.1	4.0	11.0	15.0
Scenario 3	0.4	2.1	2.5	7.0	10.0	17.0
Policy Case 2						
Scenario 1	0.2	1.7	1.9	1.5	12.5	14.0
Scenario 2	0.3	3.7	4.0	4.0	21.0	25.0
Scenario 3	0.4	4.4	4.8	8.0	18.0	26.0
Policy Case 3						
Scenario 1	0.7	1.8	2.5	5.0	13.0	18.0
Scenario 2	1.0	3.7	4.7	13.0	21.0	34.0
Scenario 3	1.7	4.3	6.0	27.0	18.0	45.0

* Costs in $2004. Cumulative costs are undiscounted. See also see Appendix A.

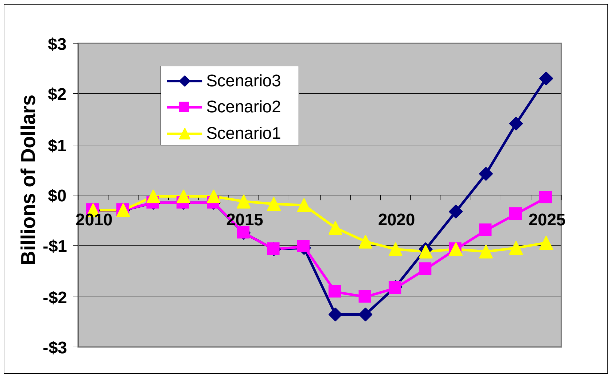
generally increase each year and are highest in Scenario 3. The government's peak annual costs for Policy Case 1 are $2-2.5 billion per year, with cumulative costs reaching up to $17 billion by 2025.

The simulated automotive industry cash flows from Policy Case 1, shown in Figure 22, have the same general shape as the no-policy case, but the magnitude of the loss is about halved. Break even points are about the same as in the no-policy case. This case would still present a prospect of long continued investments by industry with profitability delayed for more than a decade.

Policy Case 2

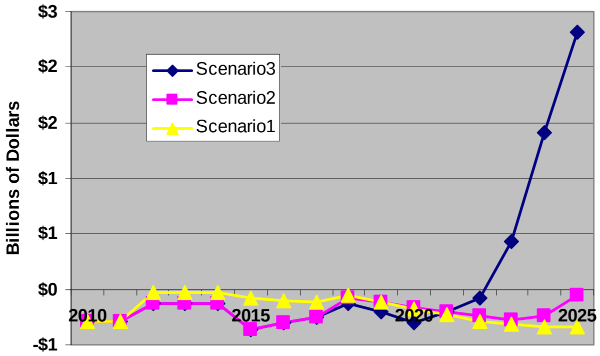
In Policy Case 2 the government supports a greater amount of cost sharing for hydrogen fuel cell vehicles. Here the government provides 50% of the *total* cost of FCVs through 2017, and then provides a tax credit to vehicle manufacturers equal to 100% of the FCV's incremental cost in 2018-2025. The cost breakdown for Policy Case 2 under the three vehicle penetration scenarios is shown in Table 5 and Appendix A (Figure A2). The government costs for FCVs under Policy Case 2 are nearly double those of Policy Case 1, peaking at $4.5-5 billion/year, and reaching cumulative costs of up to $25 billion by 2025. The annual cost sharing for vehicles peaks in 2018-2020, and (for Scenarios 2 and 3) declines to almost nothing in the 2023-2025 timeframe. This happens because the higher production volumes in Scenarios 2 and 3 bring vehicle costs down to the point where incremental costs of FCVs are almost zero. Fueling infrastructure costs are a smaller percentage of overall costs, and are about the same as in Policy Case 1.

Figure 22. Simulated Auto Industry Cash Flow from Sale of FCVs under Policy Case 1



Source: Greene and Leiby, 2007

Figure 23. Auto Industry Cash Flow from Sale of FCVs under Policy Case 2



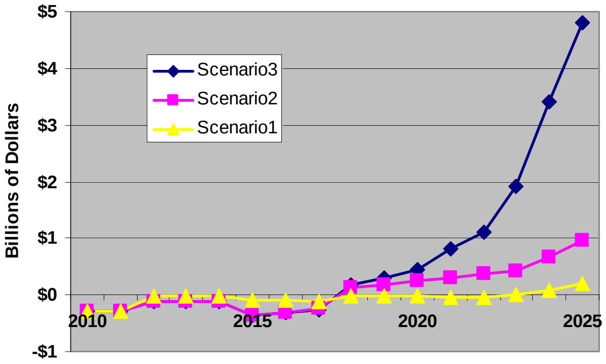
Source: Greene and Leiby, 2007

The government's larger role substantially reduces losses to the industry. The cash flow analysis for Policy Case 2 (Figure 23), suggests that this level of cost-sharing will keep the auto industry's losses below $1 billion for all scenarios in all years. Although this makes the level of industry investment required beyond normal development costs more reasonable, the losses must still be sustained for more than 10 years. This represents a long time for industry to invest to achieve a profit.

Policy Case 3

Policy Case 3 is identical to Case 2 but provides an additional $2,000 per vehicle tax credit incentive starting in 2018 and continuing through 2025. This additional incentive increases the cost to government, particularly in the later years when the vehicle subsidy remains in place for a growing number of vehicles produced and sold. As shown in Table 5 and in Appendix A (Figure A3), this Policy Case produces peak costs of $4.5 and $6 billion annually for Scenarios 2 and 3, with cumulative costs reaching as much as $45 billion. As with Policy Case 2, the vehicle cost sharing peaks in the 2018-2020 timeframe. Even though Scenario 3 places twice as many vehicles on the road as Scenario 2 (10 million vs. 5 million), the aggressiveness of Scenario 3 enables industry to achieve economical production volumes more quickly, and results in slightly lower cumulative costs to the government for vehicle subsidies than Scenario 2.

Figure 24. Simulated Auto Industry Cash Flow from Sale of FCVs under Policy Case 3



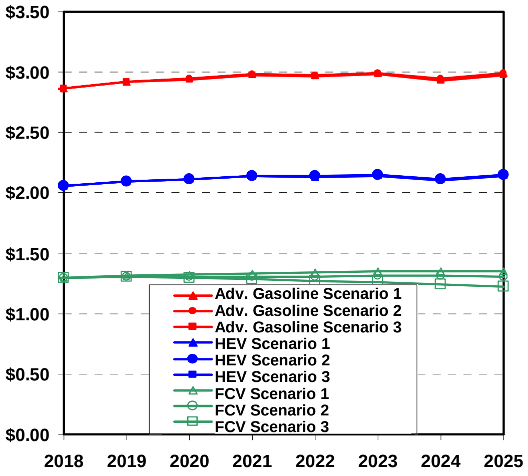
Source: Greene and Leiby, 2007

The additional tax incentive provided in Policy Case 3 is assumed to be divided between the vehicle manufacturer and the car buyer, with each getting a $1,000 tax credit. This improves the cash-flow position of the auto manufacturers, as shown in Figure 24. The negative cash-flow sustained by the industry is reduced to the order of hundreds of millions of dollars during the early years, with profits generated by 2017 in both Scenarios 2 and 3.

Hydrogen Cost Projections

The FCV penetration rate used in Scenario 3 moves the cost of hydrogen down from $3.00/kg to $2.50/kg (untaxed and unsubsidized) by 2025, due to higher fuel production volumes.[4] When the incentives for fueling infrastructure discussed above are included, the cost of hydrogen drops well below the price of gasoline on a dollar-per-distance-traveled basis. Figure 25 compares the cost of fuel for an FCV, hybrid electric vehicle (HEV) and advanced gasoline vehicle, taking into account hydrogen's higher energy content and the greater efficiency of the fuel cell. Adjusted for the difference in energy efficiency, gasoline is projected to cost about 60% more than hydrogen. This cost advantage for hydrogen would provide strong

Figure 25. Efficiency-Adjusted Costs of Hydrogen and Gasoline*



* All taxes and policies included; Los Angeles region. Advanced gasoline costs presented in $/gallon; advanced hybrid electric vehicles (HEV) and fuel cell vehicles (FCV) presented in $/equal distance traveled.

Source: Greene and Leiby, 2007

---

[4] The assumption is that through 2025, all vehicular hydrogen comes from either distributed SMR or from central plants (natural gas or biomass, or from coal if sequestration costs can be reduced) with liquid or pipeline delivery.

incentives for building fueling infrastructure. A retail price advantage for hydrogen would also provide an incentive for potential purchasers of FCVs.

Policy Cases 1-3: Cost Implications

There are several important conclusions that can be inferred from analysis of the policy cases. First, the cost to government is not inordinate or out of line with the level of public support provided for other programs that support national goals. The highest total annual government expenditure under the policy cases was about $6 billion, which is the same magnitude of spending expected to be provided by the ethanol tax credit in 2012.

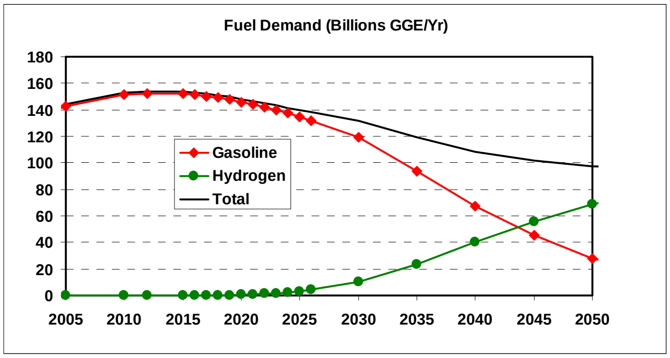
Consistent, credible policies appear to be essential to overcome the initial economic barriers to hydrogen powered transportation. This seems to be true even if hydrogen and fuel cell technology is superior to an advanced hybrid internal combustion vehicle. Establishing a refueling infrastructure that will initially be underutilized, moving down the learning curve for FCV manufacturing, and achieving both economies of scale and diversity of choice for hydrogen vehicles present private sector investors with the prospects for losses that would be very difficult to bear. In light of this, some policies to share the costs of the early deployment appear to be necessary to obtain the public benefits of clean, secure, and sustainable energy for transportation.

The policies evaluated in this analysis were designed to assist automakers and fuel providers in lowering their costs during the early deployment period, so that they can bring a cost-competitive product to consumers. Since the response of the market (and the aggressiveness of the private sector) is impossible to predict, it will be important to closely monitor actual FCV sales and hydrogen fueling infrastructure development over the course of the changeover so that policies can be modified as appropriate.

Environmental and Energy Security Benefits

The scenarios also show that hydrogen powered light-duty vehicles can dramatically reduce petroleum use and significantly decreases overall energy use by light-duty vehicles. By 2050, in Scenario 3, petroleum use by light-duty vehicles would be reduced to less than 30 billion gallons per year (a savings of 15 million barrels per day), on its way towards zero (see Figure 26). Without a successful move to hydrogen fuel cell vehicles, gasoline consumption would be held fairly steady in the 2030-2050 timeframe, at about 140 billion gallons of gasoline a year, due to the higher efficiency of hybrid-electric vehicles (Greene and Leiby, 2007).[5]

Figure 26. Light-Duty Vehicle Fuel Use by Type: Scenario 3, No Carbon Policy



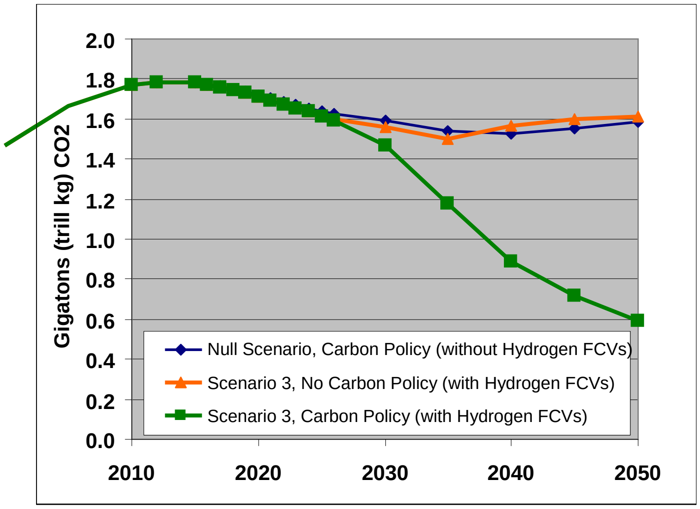
Source: Greene and Leiby, 2007

---

[5] These calculations do not consider the potential for biofuels to displace a significant fraction of gasoline.

The market transformation to hydrogen FCVs combined with carbon mitigation policies to ensure that centrally produced hydrogen is carbon-free results in a dramatic reduction in CO_2 emissions from light-duty vehicles. Figure 27 shows the full fuel cycle carbon emissions of light-duty vehicles in the U.S. under different assumptions about the future. In Future 1 (the "null scenario"), there are no policies in place to foster fuel cell vehicles or the deployment of hydrogen infrastructure. In this scenario, even with a carbon tax[6] in place, carbon emissions from light duty vehicles rise through 2015 but then begin to decline as more efficient advanced hybrid technologies penetrate the market. As illustrated by the "Scenario 3, No Carbon Policy" future shown in Figure 26, if hydrogen is produced from carbon-intensive sources (e.g., coal without sequestration), there will be no significant difference in carbon emissions from the light-duty vehicle sector, even with FCV market success. Only a future that combines carbon policy with a strong market transformation strategy causes CO_2 emissions to continue to decline, reaching about one third of the initial level by 2050.

Figure 27. Impact of Carbon Policy and FCV Market Success on CO2 Emissions from Light-Duty Vehicles



Key Findings and Conclusions: Scenario Costs and Sustainability

- Directed policies of cost sharing and tax credits over a decade would enable the industry to bring competitive automotive and infrastructure products to the marketplace by 2025 if fuel cell and storage cost targets are met.
- Without such policy actions, it does not appear that the industry would have a compelling business case to introduce hydrogen vehicles in the marketplace or that a coordinated vehicle and infrastructure program could be implemented.
- The actual scenario of car introduction will depend on the industry's ability to reduce the cost of the fuel cell power-train and the willingness of the public to purchase the vehicles which will be significantly dependent on the infrastructure.
- The government's peak annual costs for policy support could range from \$1 to \$6 billion, with cumulative costs of \$10 to \$45 billion over 14 years.
- Low cost hydrogen fuel can be a factor in the public purchasing hydrogen fuel cell vehicles.

---

[6] Carbon dioxide tax starting at \$10/ton in 2010 and increasing linearly to \$25/ton by 2025.

REFERENCES

(U.S. DOE) U.S. Department of Energy, Hydrogen, Fuel Cells & Infrastructure Technologies Program. 2006a. "2010-2025 Scenario Analysis for Hydrogen Fuel Cell Vehicles and Infrastructure." http://www1.eere.energy.gov/hydrogenandfuelcells/analysis/scenario_analysis.html

(U.S. DOE) U.S. Department of Energy, Hydrogen, Fuel Cells & Infrastructure Technologies Program. 2006b. "Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2004-2015." http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

DOE/EIA 2006. U.S. Department of Energy, Energy Information Administration. *Annual Energy Outlook 2006.* DOE/EIA-0035(2006/12). February 2006.

James, Brian and Julie Perez. 2007 . "Hydrogen Infrastructure Pathways Analysis Using HYPRO." Directed Technologies Incorporated. April 02, 2007.

U .S. House, 109th Congress, 1st Session. 2005. *Energy Policy Act of 2005* (Public Law No: 109-058), retrieved April 6, 2007, from http://thomas.loc.gov.

Greene, David L. and Paul N. Leiby. 2007. "Integrated Analysis of Market Transformation Scenarios with HyTrans." Oak Ridge National Laboratory. Forthcoming (Draft March 2007).

(NAS) National Research Council and National Academy of Engineering, Committee on Alternatives and Strategies for Future Hydrogen Production and Use. 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (Washington, DC: National Academies Press, 2004). http://www.nap.edu/books/030909/632/html.

Melendez, Margo, and Anelia Milbrandt. 2007. "Geographically Based Hydrogen Demand and Infrastructure Deployment Scenario Analysis." National Renewable Energy Laboratory. March 14, 2007.

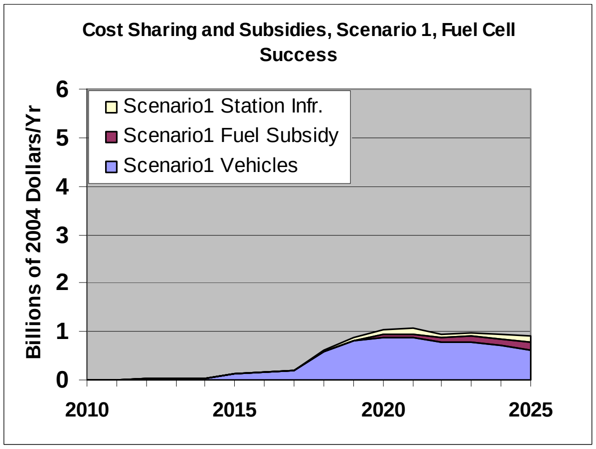
Welch, Cory. 2007. "Hydrogen Scenario Analysis Using HyDIVE™." National Renewable Energy Laboratory. Draft Technical Report: March 2007.

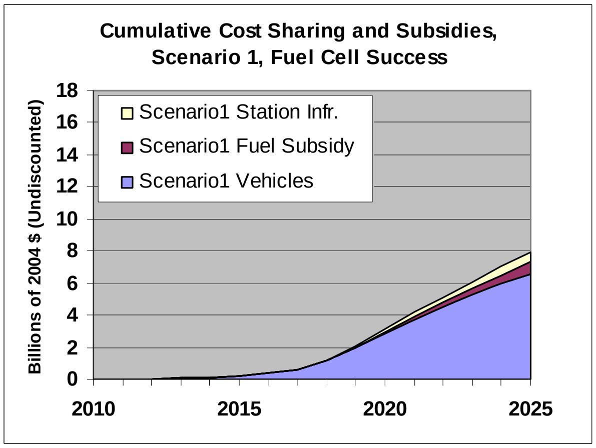
Unnasch, Stefan, Daniel Rutherford, and Matthew Hooks. 2007. "Analysis of Incentive Options for Hydrogen Fueled Vehicles. TIAX, LLC. Draft Report for the National Renewable Energy Laboratory: March 2007.

APPENDIX A. GOVERNMENT COSTS OF ALTERNATIVE POLICY CASES

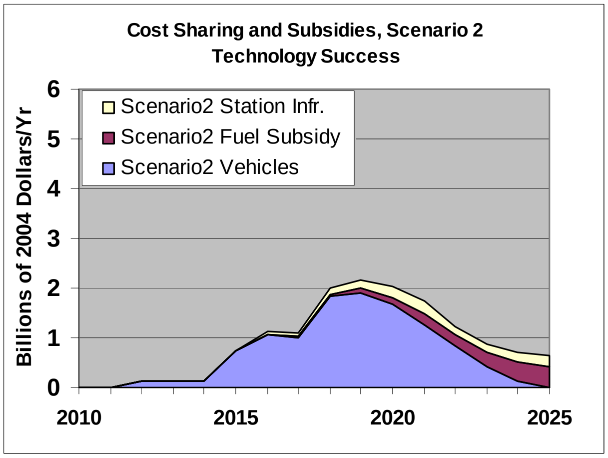
Figures A1a-c. Cost To Government: Policy Case 1

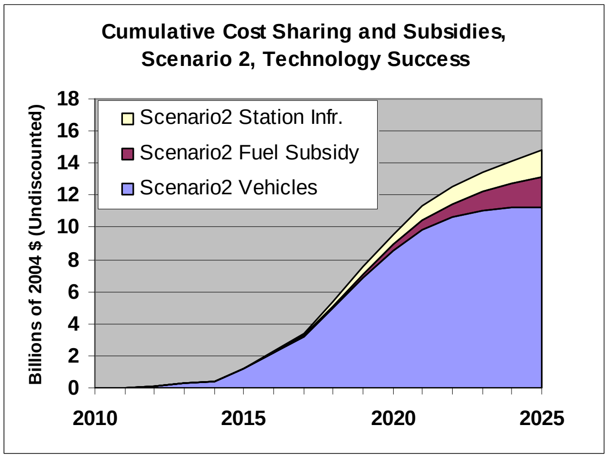
A1a. Policy Case 1, Scenario 1


Cost Sharing and Subsidies, Scenario 1, Fuel Cell Success


Cumulative Cost Sharing and Subsidies, Scenario 1, Fuel Cell Success

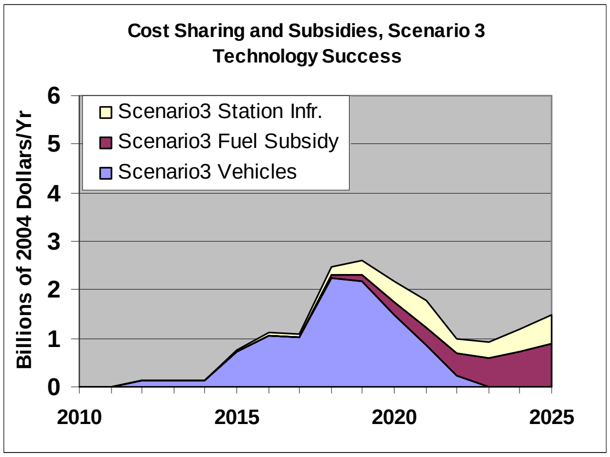
A1b. Policy Case 1, Scenario 2

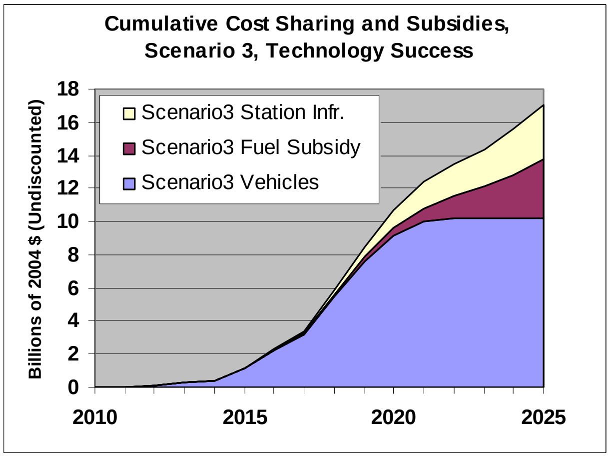

Cost Sharing and Subsidies, Scenario 2 Technology Success


Cumulative Cost Sharing and Subsidies, Scenario 2, Technology Success

Source: Greene and Leiby, 2007

A1c. Policy Case 1, Scenario 3

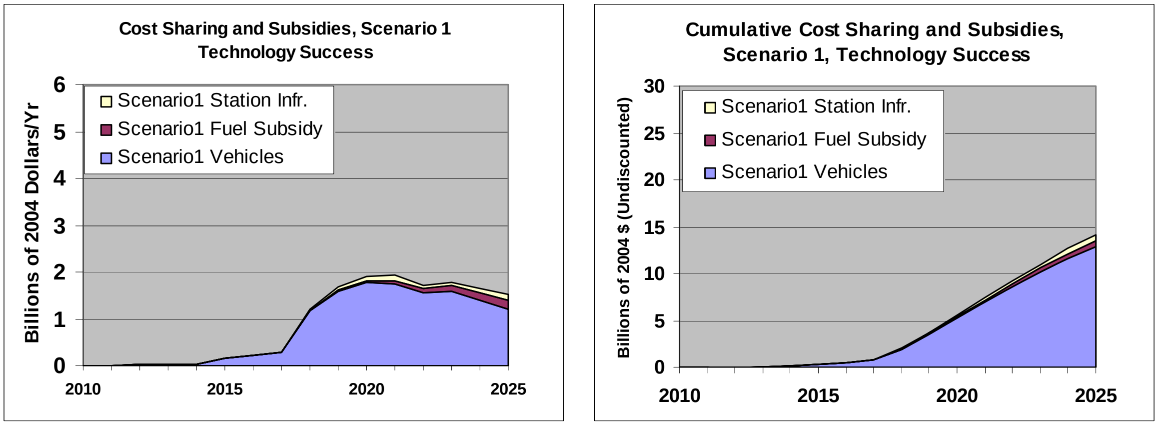

Cost Sharing and Subsidies, Scenario 3 Technology Success


Cumulative Cost Sharing and Subsidies, Scenario 3, Technology Success

Source: ORNL 2006

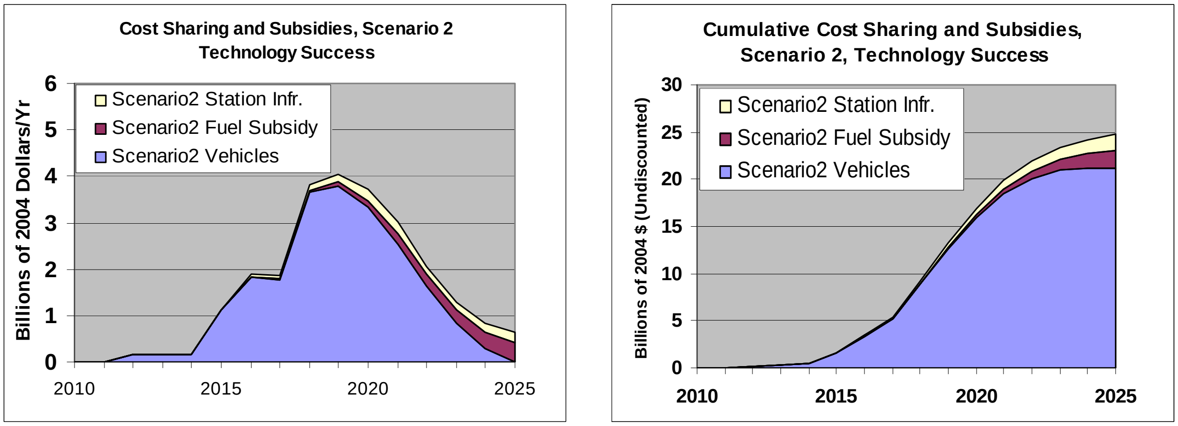
Figures A2a-c. Cost To Government: Policy Case 2

A2a. Policy Case 2, Scenario 1



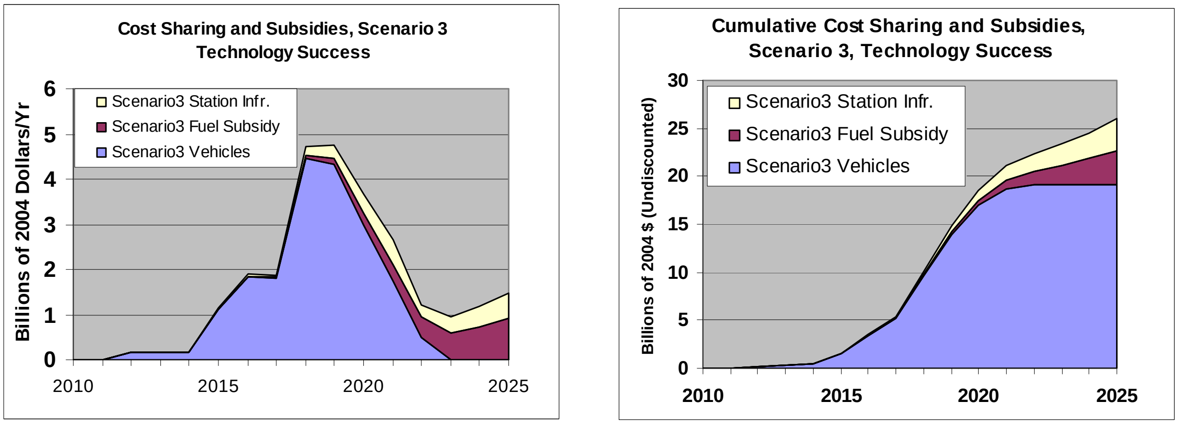
Source: Greene and Leiby, 2007

A2b. Policy Case 2, Scenario 2



Source: Greene and Leiby, 2007

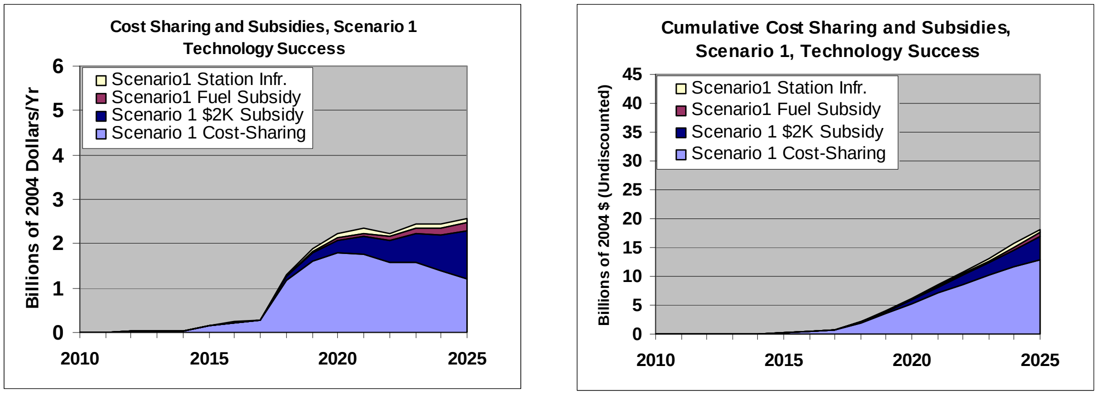
A2c. Policy Case 2, Scenario 3



Source: Greene and Leiby, 2007

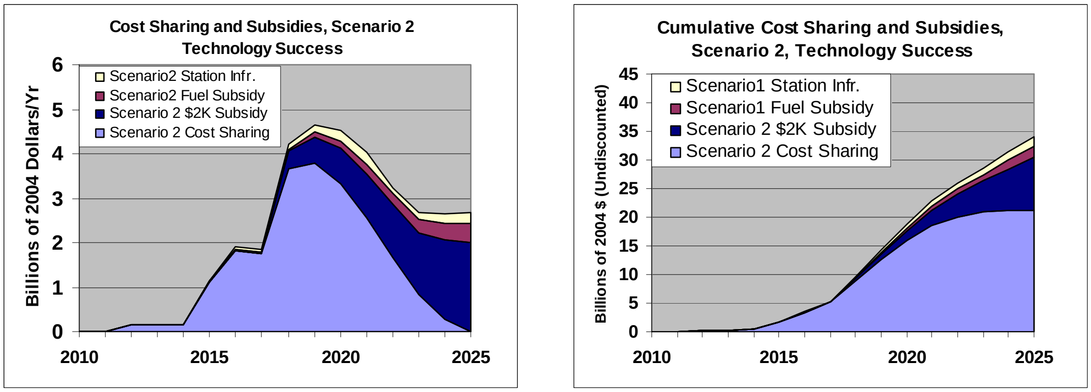
Figures A3a-c. Cost To Government: Policy Case 3

A3a. Policy Case 3, Scenario 1



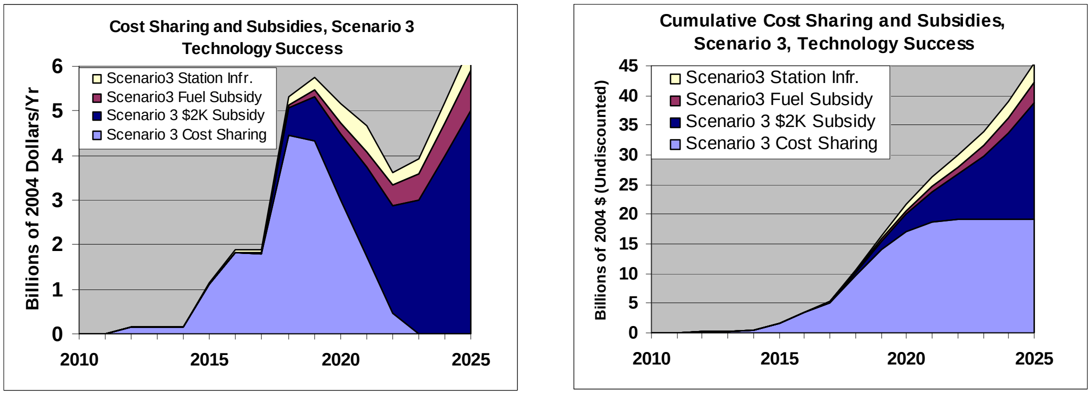
Source: Greene and Leiby, 2007

A3b. Policy Case 3, Scenario 2



Source: Greene and Leiby, 2007

A3c. Policy Case 3, Scenario 3



Source: Greene and Leiby, 2007

APPENDIX B. PARTICIPANTS IN STAKEHOLDERS' MEETINGS

DOE and FreedomCAR & Fuel Partnership
Hydrogen Delivery and On-Board Storage Analysis Workshop
Washington, DC
January 25, 2006

Rajesh Ahluwalia	Argonne National Laboratory
Arlene Anderson	U.S. Department of Energy, HFCIT
Jim Campbell	Air Liquide
Ed Casey	ConocoPhillips
Tan-Ping Chen	Nexant
Keith Cole	General Motors Corporation
Peter Devlin	U.S. Department of Energy, HFCIT
Karl Fiegenschuh	Ford Motor Company
Dale Gardner	National Renewable Energy Laboratory
Donald Gardner	ExxonMobil
Britta Gross	General Motors Corporation
Bhadra Grover	Air Liquide
Glyn Hazelden	Gas Technology Institute
Fred Joseck	U.S. Department of Energy, HFCIT
Greg Keenan	Air Products & Chemicals, Inc.
Edward Kiczek	Air Products & Chemicals, Inc.
Winnie Kwok	Energetics Incorporated
Stephen Lasher	TIAX LLC
Johanna Levene	National Renewable Energy Laboratory
Shawna McQueen	Energetics Incorporated
Margo Melendez	National Renewable Energy Laboratory
Marianne Mintz	Argonne National Laboratory
Henk Mooiweer	Shell Hydrogen
Graham Moore	Chevron Technology Ventures LLC
Kazuo Nagashima	Nissan Technical Center
Joan Ogden	University of California, Davis
Mark Paster	U.S. Department of Energy, HFCIT
Damodaran Raghu	Shell Global Solutions
Mark Richards	Gas Technology Institute
Matt Ringer	National Renewable Energy Laboratory
Mark Ruth	National Renewable Energy Laboratory, SI
Sunita Satyapal	U.S. Department of Energy, HFCIT
James Simnick	BP
George Thomas	U.S. Department of Energy, SNL
Elzbieta Tworek	Oak Ridge National Laboratory
James Uihlein	BP
Stefan Unnasch	TIAX LLC
Michael Wang	Argonne National Laboratory
Elvin Yuzugullu	Sentech
Giorgio Zoia	BP

PARTICIPATING BY PHONE:

Chris Aardahl	Pacific Northwest Laboratory
Salvador Aceves	Lawrence Livermore National Laboratory
Gene Berry	Lawrence Livermore National Laboratory
Carolyn Elam	U.S. Department of Energy, HFCIT
Amgad Elgowainy	Argonne National Laboratory
Henry Fowler	McNeil Technologies/U.S. Department of Energy
Jill Gruber	U.S. Department of Energy, HFCIT
James Kegerreis	ExxonMobil
Leo Klawiter	Rohm and Haas
George Parks	ConocoPhillips
Keith Parks	National Renewable Energy Laboratory
Scot Rassat	Pacific Northwest National Laboratory
John Shen	U.S. Department of Energy

DOE Hydrogen Transition Analysis Workshop
Washington, DC
January 26, 2006

Arlene Anderson	U.S. Department of Energy, HFCIT
Klaus Bonhoff	DaimlerChrysler AG
Ed Casey	ConocoPhillips
Steve Chalk	U.S. Department of Energy, HFCIT
Tan-Ping Chen	Nexant
Peter Devlin	U.S. Department of Energy, HFCIT
K. G. Duleep	Energy and Environmental Analysis, Inc.
Karl Fiegenschuh	Ford Motor Company
John Garbak	U.S. Department of Energy, HFCIT
Dale Gardner	National Renewable Energy Laboratory
Donald Gardner	ExxonMobil
David Greene	Oak Ridge National Laboratory
Sigmund Gronich	U.S. Department of Energy, HFCIT
Britta Gross	General Motors Corporation
Brian James	Directed Technologies, Inc.
Fred Joseck	U.S. Department of Energy, HFCIT
Gregory Keenan	Air Products & Chemicals, Inc.
Edward Kiczek	Air Products & Chemicals, Inc.
Winnie Kwok	Energetics Incorporated
Stephen Lasher	TIAX LLC
Paul Leiby	Oak Ridge National Laboratory
Johanna Levene	National Renewable Energy Laboratory
Shawna McQueen	Energetics Incorporated
Margo Melendez	National Renewable Energy Laboratory
Marianne Mintz	Argonne National Laboratory
Henk Mooiweer	Shell Hydrogen
Graham Moore	Chevron Technology Ventures LLC
Kazuo Nagashima	Nissan Technical Center North America
Joan Ogden	University of California, Davis
Keith Parks	National Renewable Energy Laboratory
Mark Paster	U.S. Department of Energy, HFCIT
Bill Reinert	Toyota Motor Sales, U.S.A.
Mark Richards	Gas Technology Institute
Matthew Ringer	National Renewable Energy Laboratory
Mark Ruth	National Renewable Energy Laboratory/SI
Ichiro Sakai	Honda
Sunita Satyapal	U.S. Department of Energy, HFCIT
James Simnick	BP
George Thomas	U.S. Department of Energy, SNL
Elzbieta Tworek	Oak Ridge National Laboratory
James Uihlein	BP
Stefan Unnasch	TIAX LLC
Harry Vidas	Energy and Environmental Analysis, Inc.
Michael Wang	Argonne National Laboratory
Keith Wipke	National Renewable Energy Laboratory
Robert Wimmer	Toyota Motor North America

Frances Wood	OnLocation, Inc.
Elvin Yuzugullu	Sentech
Stephen Zimmer	DaimlerChrysler Corporation
Giorgio Zoia	BP

PARTICIPATING BY PHONE:

Salvador Aceves	Lawrence Livermore National Laboratory
Gene Berry	Lawrence Livermore National Laboratory
Anthony Burrell	Los Alamos National Laboratory
Keith Cole	General Motors Corporation
Guenter Conzelmann	Argonne National Laboratory
Kant Desai	RCF Economic and Financial Consulting Incorporated
Carolyn Elam	U.S. Department of Energy, HFCIT
Henry Fowler	McNeil Technologies, U.S. Department of Energy
Jill Gruber	U.S. Department of Energy, HFCIT
Donald Jones	RCF Economic and Financial Consulting Incorporated
James Kegerreis	ExxonMobil
Matt Miyasato	South Coast Air Quality Management District
George Parks	ConocoPhillips
Julie Perez	Directed Technologies, Inc.
Peter Schmidt	Directed Technologies, Inc.
John Shen	U.S. Department of Energy
Lea Yancey	McNeil Technologies

2010-2025 Scenario Analysis for Hydrogen Fuel Cell Vehicles and Infrastructure
Review and Discussion of Preliminary Results
Washington, DC
August 9-10, 2006

Arlene Anderson	U.S. Department of Energy
Howard Andres	Energetics Incorporated
Klaus Bonhoff	DaimlerChrysler AG
Brian Bonner	Air Products
Chris Bordeaux	Air Liquide (Consultant)
Ethan Brown	Ballard Power Systems
Kwontae Cho	Hyundai America Tech Center Inc.
Pete Devlin	U.S. Department of Energy
K. G. Duleep	Energy and Environmental Analysis, Inc.
Catherine Dunwoody	California Fuel Cell Partnership
Carolyn Elam	U.S. Department of Energy
Kathi Epping	U.S. Department of Energy
Tara Faherty	Energetics Incorporated
Karl Fiegenschuh	Ford Motor Company
Stuart Funk	LMI
Linda Gallaher	Chevron Technology Ventures
John Garbak	U.S. Department of Energy
Paul Gilman	Consultant
David Greene	Oak Ridge National Laboratory
Sig Gronich	U.S. Department of Energy
Britta Gross	General Motors Corporation
Tom Gross	U.S. Department of Defense
Doug Hooker	U.S. Department of Energy, Golden Field Office
Brian James	Directed Technologies Incorporated
Donald Jones	RCF Economic and Financial Consulting
Fred Joseck	U.S. Department of Energy
Edward Kiczek	Air Products
Winnie Kwok	Energetics Incorporated
Paul Leiby	Oak Ridge National Laboratory
Johanna Levene	National Renewable Energy Laboratory
Valri Lightner	U.S. Department of Energy
Margaret Mann	National Renewable Energy Laboratory
Shawna McQueen	Energetics Incorporated
Margo Melendez	National Renewable Energy Laboratory
JoAnn Milliken	U.S. Department of Energy
Marianne Mintz	Argonne National Laboratory
Matt Miyasato	South Coast AQMD
Henk Mooiweer	Shell Hydrogen LLC
Graham Moore	Chevron Technology Ventures
Kazuo Nagashima	Nissan Technical Center North America
Joan Ogden	University of California, Davis
George Parks	ConocoPhillips
Keith Parks	National Renewable Energy Laboratory
Mark Paster	U.S. Department of Energy
Philip Patterson	U.S. Department of Energy

Julie Perez	Directed Technologies Incorporated
Jason Perron	BMW of North America, LLC
Elizabeth Pfeiffer	BMW of North America, LLC
Jerry Rogers	General Motors Corporation
Mark Ruth	National Renewable Energy Laboratory
Ichiro Sakai	American Honda Motor
Sunita Satyapal	U.S. Department of Energy
Rich Scheer	Energetics Incorporated
Peter Schmidt	Directed Technologies Incorporated
Craig Scott	Toyota
Tom Sheahen	National Renewable Energy Laboratory
John Shen	U.S. Department of Energy
Lee Slezak	U.S. Department of Energy
John Stamos	U.S. Department of Energy
Margaret Steinbugler	UTC Fuel Cells
Jeroen Struben	Massachusetts Institute of Technology
Brinda Thomas	Sentech, Inc.
James Uihlein	BP
Stefan Unnasch	TIAX LLC
Laura Verduzco	Sentech, Inc.
Cory Welch	National Renewable Energy Laboratory
Frances Wood	OnLocation, Inc.
Ye Wu	Argonne National Laboratory
Elvin Yuzugullu	Sentech, Inc.
Stephen Zimmer	DaimlerChrysler Corporation
Giorgio Zoia	BP
James Zucchetto	National Academy of Sciences

U.S. DOE Scenario Analyses of a Nascent National Hydrogen Transportation System Meeting
Honolulu, HI
November 13, 2006

Hideaki Akamatsu	Foreign Correspondents' Club of Japan
Steven Alber	State of Hawaii Strategic Industries Division
Bhaskar Balasubramanian	Chevron
Thomas Benjamin	Argonne National Laboratory
Sebastian Blanco	AutoblogGreen
Ashok Damle	RTI International
Mark Debe	3M Fuel Cell Components Program
Janusz Dmochowski	Kielce University of Technology
William Ernst	Plug Power
Bradford Fleming	UTC Power
Peter Friebe	DaimlerChrysler Corporation
Don Gervasio	Arizona State University
Jay Gore	Purdue University
Sig Gronich	U.S. Department of Energy, HFCIT
Justin Hawkes	United Technologies Research Center
Michael Hickner	Sandia National Laboratories
Bill Holtzcheiter	Savannah River National Laboratory
Brian James	Directed Technologies Incorporated
Nicholas Josefik	U.S. Army Corps of Engineers
Kathleen Judd	Battelle
Tsutom Kawashima	Panasonic
Jong Hee Kim	POSCO/Stainless Research Group
John Kopasz	Argonne National Laboratory
Balaji Krishnamurthy	Chevron
Romesh Kumar	Argonne National Laboratory
Won Ho Lee	LG Chem, Ltd/Research Park
Paul Leiby	Oak Ridge National Laboratory
Melissa Lott	Alliance Technical Services, Inc.
William Lueckel	Renewable Fuels Association
Wayne Mabry	Mitsubishi Caterpillar Forklift America
Kathya Mahadevan	Battelle
Robert Mammarella	Fujifilm Manufacturing USA
David Martin	Membrane Reactor Technologies
Michael Martin	EMTEC
Stewart McKenzie	Columbian Chemicals
Margo Melendez	National Renewable Energy Laboratory
George Miley	University of Illinois
George Mitchell	DaimlerChrysler Corporation
Hiroyuki Nagai	Panasonic
Masafumi Nakamura	Mitsubishi Research Institute, Inc.
Pinakin Patel	FuelCell Energy
Julie Perez	Directed Technologies Incorporated
David Peterson	U.S. Department of Energy, Golden Office
Gilles Platen	Imphy Alloys

Art Pontau	Sandia National Laboratories
Peter Rolfe	U.S. Air Force
Robert Rose	U.S. Fuel Cell Council
Craig Scott	Toyota
Susan Shaheen	University of California, Berkeley, California PATH
Asako Suzuki	Mitsubishi Canada Limited
George Sverdrup	National Renewable Energy Laboratory
Maria Tome	State of Hawaii, DBEDT - SID - EEB
Doanh Tran	DaimlerChrysler Corporation
Takatada Usami	Takatada
Silvia Wessel	Ballard Power Systems
Keith Wipke	National Renewable Energy Laboratory
Takeshi Yamaguchi	Nissan Motor Company, LTD
Akira Yamanaka	Trans-Pac Sales Corporation
Takuji Yoshimaru	Engineering Advancement Association of Japan
Makoto Yoshimura	FujiFilm

2010-2025 Scenario Analysis for Hydrogen Fuel Cell Vehicles and Infrastructure
Review and Discussion of Draft Results
Washington, DC
January 31, 2007

Arlene Anderson	U.S. Department of Energy
Brian Bonner	Air Products & Chemicals, Inc.
Ethan Brown	Ballard Power Systems
James Brown	Superprotonic, Inc.
Andrew Chew	Sentech, Inc.
Raj Choudhury	General Motors Corporation
Alan Crane	National Research Council
Maria Curry-Nkansah	BP
Pete Devlin	U.S. Department of Energy
Kathleen Dooley	U.S. Department of Energy
Jeff Dowd	U.S. Department of Energy
Kathi Epping	U.S. Department of Energy
Scott Freeman	DaimlerChrysler Corporation
Peter Froeschle	DaimlerChrysler Corporation
Linda Gallaher	Chevron
John Garbak	U.S. Department of Energy
Nancy Garland	U.S. Department of Energy
David Greene	Oak Ridge National Laboratory
Adam Gromis	California Fuel Cell Partnership
Sig Gronich	U.S. Department of Energy
Britta Gross	General Motors Corporation
Thomas Gross	Transportation Energy Partnership
C.J. Guo	Shell Hydrogen LLC
Brian James	Directed Technologies Incorporated
Charles Jennings	BCS Inc.
Donald Jones	RCF Economic and Financial Consulting, Inc.
Fred Joseck	U.S. Department of Energy
Mauricio Justiniano	Energetics Incorporated
Edward Kiczek	Air Products and Chemicals, Inc.
Benjamin Knight	Honda R&D Americas, Inc.
Melissa Lott	Alliance Technical Services, Inc.
Jason Marcinkoski	U.S. Department of Energy
Patrice Marshall	Texas H2 Coalition
Shawna McQueen	Energetics Incorporated
Margo Melendez	National Renewable Energy Laboratory
Marianne Mintz	Argonne National Laboratory
Bill Murphy	Praxair Inc.
Kazuo Nagashima	Nissan Technical Center North America
Joan Ogden	University of California, Davis
Grace Ordaz	U.S. Department of Energy
George Parks	ConocoPhillips
Mark Paster	U.S. Department of Energy
Philip Patterson	U.S. Department of Energy
Julie Perez	Directed Technologies Incorporated

Todd Ramsden	National Renewable Energy Laboratory
Carole Read	U.S. Department of Energy
Gerald Roussel	Ford Motor Company
Mark Ruth	National Renewable Energy Laboratory
Daniel Rutherford	TIAX LLC
Craig Scott	Toyota
Tom Sheahen	National Renewable Energy Laboratory
John Shen	U.S. Department of Energy
Margaret Steinbugler	UTC Power
Jeroen Struben	Massachusetts Institute of Technology
Laura Verduzco	Sentech, Inc.
James Volk	Shell Hydrogen
Cory Welch	National Renewable Energy Laboratory
Robert Wimmer	Toyota Motor North America
Keith Wipke	National Renewable Energy Laboratory
Matthias Wolsteiner	DaimlerChrysler Corporation
Frances Wood	OnLocation, Inc.
Elvin Yuzugullu	Sentech, Inc.
Giorgio Zoia	BP
James Zucchetto	National Academy of Science

2360 Cherahala Boulevard
Knoxville, TN 37932
P 865-946-1311
F 865-946-1314