HYDROGEN VEHICLES: IMPACTS OF DOE TECHNICAL TARGETS ON MARKET ACCEPTANCE AND SOCIETAL BENEFITS

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Abstract

Hydrogen vehicles (H2V), including H2 internal combustion engine, fuel cell and fuel cell plug-in hybrid powertrains, could greatly reduce petroleum consumption and greenhouse gas (GHG) emissions in the transportation sector. The U.S. Department of Energy has adopted targets for vehicle component technologies to address key technical barriers to widespread commercialization of H2Vs. This study estimates the market acceptance of H2Vs and the resulting societal benefits and subsidy in 41 scenarios that reflect a wide range of progress in meeting these technical targets. Important results include: (1) H2Vs could reach 20%-70% market shares by 2050, depending on progress in achieving the technical targets. With a basic hydrogen infrastructure (~5% hydrogen availability), the H2V market share is estimated to be 2%-8%. Fuel cell and hydrogen costs are the most important factors affecting the long-term market shares of H2Vs. (2) Meeting all technical targets on time could result in about an 80% cut in petroleum use and a 62% (or 72% with aggressive electricity de-carbonization) reduction in GHG in 2050. (3) The required hydrogen infrastructure subsidy is estimated to range from $22 to $47 billion and the vehicle subsidy from $4 to $17 billion. (4) Long-term H2V market shares, societal benefits and hydrogen subsidies appear to be highly robust against delay in one target, if all other targets are met on time. R&D diversification could provide insurance for greater societal benefits. (5) Both H2Vs and plug-in electric vehicles could exceed 50% market shares by 2050, if all targets are met on time. The overlapping technology, the fuel cell plug-in hybrid electric vehicle, appears attractive both in the short and long runs, but for different reasons.

Keywords: hydrogen, alternative fuel vehicle, energy, greenhouse gas, public policy, electric vehicle

1 Introduction

The current petroleum-dependency of the U.S. transportation sector poses threats to the environmental, energy and economic security of the United States. Nearly 70% of U.S. petroleum consumption occurs in the transportation sector. Petroleum use in the transportation sector produces emissions that contribute to air pollution and climate change. Meanwhile, half of the U.S. petroleum consumption is imported [1], raising concerns about wealth transfer to other countries and vulnerability of the economy to oil price shocks [2].

Hydrogen vehicles[1] (H2V) could greatly reduce petroleum consumption in the transportation sector. A study by the National Academies estimated that the use of H2Vs could reduce gasoline consumption by 24% in 2035 and 69% in 2050 [3]. According to the same study, no single technology is capable of completely eliminating the use of gasoline by 2050, but with a portfolio of technologies including H2Vs, a 69% reduction in gasoline use by 2035 and 100% by 2050 are possible, if these technologies are widely accepted by the market.

But at present, the widespread market acceptance of H2Vs still faces technological, economic and institutional challenges. The U.S. Department of Energy's (DOE's) Fuel Cells Technologies Office (FCTO) was launched to address *"key technical challenges for fuel cells and hydrogen production, delivery, and storage and the institutional barriers…*" [4, page 1-1]. Currently, FCTO is governed by its multi-year research, development and demonstration (RD&D) plan, which describes technical targets through 2020 for "*hydrogen production, delivery, and storage; fuel cells for transportation, portable, and stationary applications; technology validation; codes and standards; safety; education; systems analysis; systems integration; manufacturing and market transformation.*" [4, page 1-12]

Significant progress has been made toward achieving these technical targets. For example, the capital cost of electrolyzer stacks has been reduced by more than 80% since 2001 [4]. Since 2002, the estimated high-volume manufacturing cost of automotive fuel cell systems has been reduced by 80% (Figure 1) [4b]. However, some technical targets have proved to be more difficult to meet. For example, the previous target of $2/kWh for on-board hydrogen storage systems is believed to be too difficult to achieve and is currently under review for revision [6].

[1] H2Vs refer to vehicles that are powered by hydrogen, regardless the architecture of the powertrain. They include hydrogen ICE, fuel cell, and fuel cell plug-in hybrid powertrains.

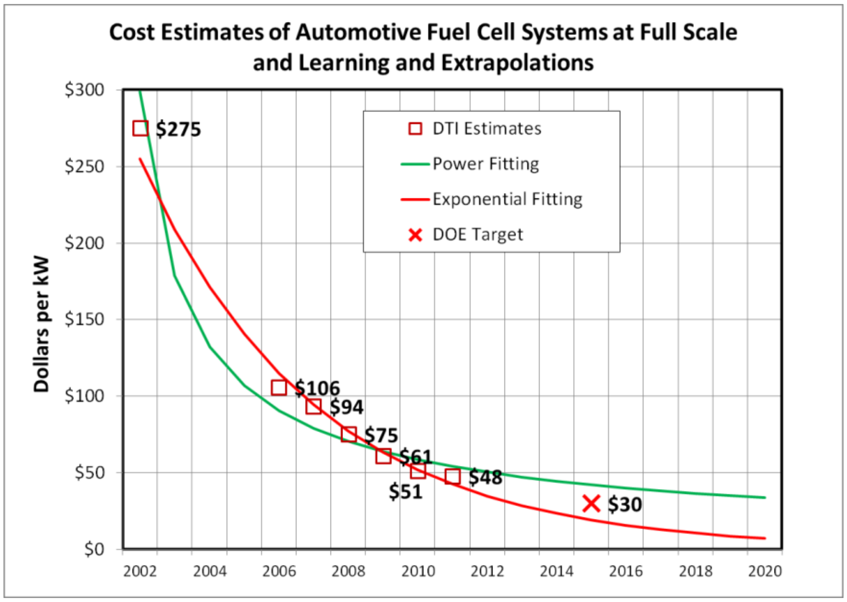

Figure 1. Fuel Cell System Cost—Target and Historical Progress. (DOE Target from [4], DTI Estimates from [5])

The following research questions are raised and addressed in this study.

- How important are FCTO technical targets to the market acceptance of H2Vs and to the associated societal benefits?
- How sensitive are the market acceptance and societal benefits of H2Vs to delays in meeting the targets?
- What are the key barriers for the H2V market?
- How much public subsidy is needed for a market transition to H2Vs?

This study analyzes the impacts of the DOE technical targets for powertrain components (FC, battery, motor and control, hydrogen on-board storage) on the market acceptance and societal benefits of H2Vs, including hydrogen (H2) internal combustion engine (ICE) vehicles, fuel cell electric vehicles (FCEV), and FC plug-in electric vehicles (FC PHEV) with 10-, 20-, and 40-mile battery electric range (FC PHEV10, FC PHEV20, FC PHEV40). The modeling approach is explained in the next section of the paper, followed by results of the impacts of meeting the technical targets. Discussions of results focus on H2V market prospects, societal benefits, public investments, infrastructure roll-out strategies, R&D policies, and synergy between FC and plug-in batteries.

2 Approach

2.1 Overview

The overall modeling approach is illustrated in Figure 2. A total of 41 scenarios are constructed to reflect different combinations of H2 prices, costs, and vehicle component progresses relative to the DOE technical targets. In each scenario, based on exogenous settings of vehicle attributes, consumer segmentation, energy prices, infrastructure deployment, and policies, the Market Acceptance of Advanced Automotive Technologies (MA3T) model estimates annual sales of various vehicle technologies from 2010 to 2050, as well as vehicle stock, energy use (gasoline, diesel, natural gas, hydrogen and electricity), well-to-wheel greenhouse gas (GHG) emissions, and vehicle subsidy. The Hydrogen Infrastructure Cash Flows (HICF) model takes hydrogen availability[2], hydrogen price, and full-utilization hydrogen cost from the exogenous inputs and the projected hydrogen use estimated by MA3T, and calculates the required infrastructure subsidy that balances the difference between hydrogen price and under-utilization (or breakeven) hydrogen cost.

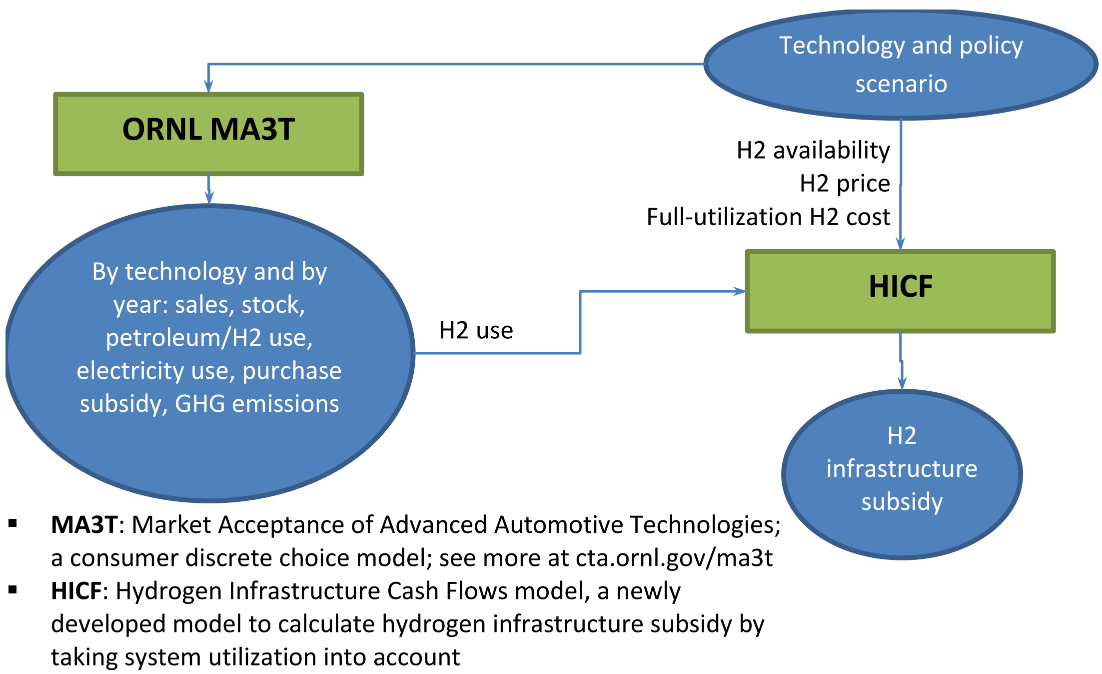

Figure 2. Illustration of Overall Approach.

2.2 The ORNL MA3T Model

Funded by U.S. DOE Vehicle Technologies Office (VTO), the ORNL MA3T model [7, 8] was developed to estimate demand for a range of vehicle powertrain technologies.

[2] Hydrogen availability is defined as the ratio of the number of optimally located hydrogen stations to the current number of gasoline stations.

MA3T simulates market demand for advanced vehicle powertrain technologies by representing relevant attributes of technologies and consumer behavior such as technological learning by doing, range anxiety, access to recharging points, daily driving patterns, and willingness to accept technological innovation. Forty vehicle choices are included, consisting of 20 powertrain technologies for each of two vehicle size classes—passenger cars and light duty trucks. U.S. household vehicle users are divided into 1,458 segments based on 6 dimensions: census divisions, residential areas, attitudes toward novel technologies, driving patterns, home recharging situations, and work recharging situations. The projection period is from 2010 to 2050. The temporal interaction between market penetrations and product diversity and risk is considered. MA3T characterizes daily driving distance variation with the Gamma distribution, which has been validated with real-world high-resolution travel data [9]. MA3T explicitly quantifies range anxiety for electric vehicles and reflects the effect of charging and refueling infrastructure on the appeal of plug-in electric vehicles and alternative fuel vehicles [10].

The core of the model is a nested multinomial logit model that predicts purchase probabilities among 40 choices by each of the 1,458 consumer segments based on value components associated with vehicle attributes, user behavior, infrastructure, energy prices, and policies (Figure 3). The segment purchase probabilities are translated into market penetrations, sales, vehicle stock, petroleum use, and GHG emissions. Some of the outputs serve as feedback signals and, together with other exogenous inputs from various sources, affect the purchase probabilities. More details on the MA3T methodology can be found in an earlier report [7].

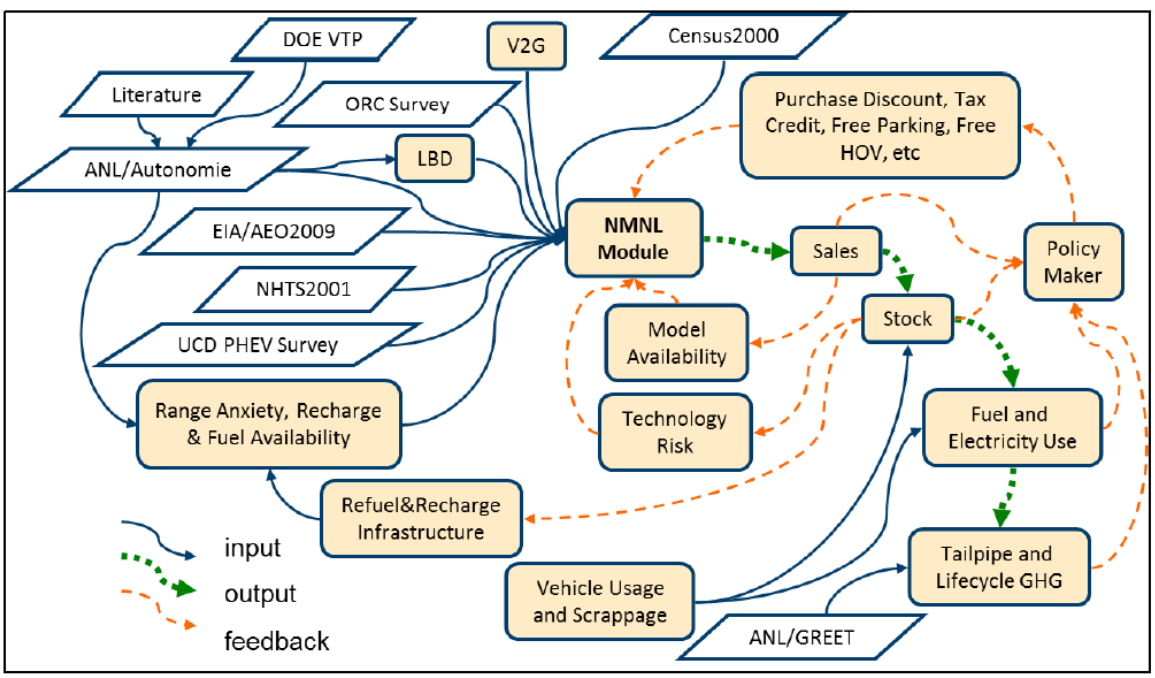

Figure 3. Framework of the ORNL MA3T Model.

The American Recovery and Reinvestment Act of 2009 (ARRA) provides tax credits for plug-in electric vehicles, represented in MA3T as vehicle purchase subsidies. The ARRA subsidy provides at least a $2,500 tax credit for plug-in electric vehicles and $417 per each additional kilowatt-hour of plug-in battery capacity, up to $7,500 in total. The ARRA subsidy begins to phase out for a manufacturer's vehicles when at least 200,000 qualified vehicles have been sold in the United States since December 31, 2009. Given the spirit of the ARRA subsidy, this study assumes $7500 tax credit for all zero-emission vehicles, including battery electric vehicles (BEVs) and all H2Vs. The spark-ignition (SI) PHEV tax credit is calculated based on battery capacity and the actual law. The MA3T model assumes six manufactures, so in MA3T, the ARRA subsidy expires when the cumulative sales of qualified vehicles exceed 1.2 million. This 1.2-million quota is up for competition among all qualified types. For simplicity, the within-year phase-out process is ignored. When the cumulative sales of a qualified powertrain type reach or exceed the 1.2-million quota, the ARRA subsidy ends, starting from the next year. As a result, the total of subsidized vehicles may exceed 1.2 million by a certain quantity that is determined by the sales in the last qualified year.

2.3 The Hydrogen Infrastructure Cash Flows Model

The HICF model was developed to calculate the hydrogen infrastructure subsidy required to offset the gap between hydrogen price and breakeven hydrogen cost. Hydrogen price, full-utilization hydrogen cost, and hydrogen availability are exogenously assumed for each scenario. Hydrogen use is endogenously estimated by MA3T and is used to calculate infrastructure supply capacity and utilization. Based on these 6 variables, the under-utilization (or breakeven) hydrogen cost is then calculated, reflecting scale economies and capacity utilization.

The HICF model can be described by Equations (1)-(6), where a lower-case variable denotes an endogenous or intermediate variable, while an upper-case variable represents an exogenous input. As in Equation (1), the required subsidy (rs), i.e., the net present value of annual infrastructure subsidy, is a function of the breakeven hydrogen cost (bhc), the hydrogen price (HP), and the hydrogen use (hu) during the year i. Equation (2) states that the breakeven hydrogen cost (bhc) equals the breakeven hydrogen cost at maximum utilization (bhcmu) when the infrastructure utilization (u) reaches the maximum utilization (MU) level (MU=0.90 is assumed); otherwise, a lower utilization (u) leads to a higher breakeven hydrogen cost (bhc). Equation (3) states that bhcmu equals the hydrogen cost (HC) when the supply capacity (sc) reaches the maximum supply capacity (MSC); otherwise, bhcmu is increased according to the scaling factor (SF, assumed to be 0.88 based on NRC [11] and H2A [12]). MSC is assumed to be 180,000 metric tons per day, representing the hydrogen sc at 100% hydrogen availability. But the breakeven hydrogen cost at maximum utilization (bhcmu) can increase only up to the cost cap (CC), which is assumed to be $4.0/kg after tax, representing the max-utilization delivered cost with distributed steam-methane-reforming. As in Equation (4), for a given hydrogen availability (HA) and the number of hydrogen stations at MSC and the maximum station size (MaxSta, assumed to be 1500 kg/day), the sc is proportional to the average station size (ss), but is not less than the amount required to meet the hydrogen use (hu) at the maximum utilization (MU). As in Equation (5), the average station size (ss) is assumed to be constrained between the minimum station size (MinSta, assumed to be 100 kg/day) and the maximum station size (MaxSta), and depends on the hydrogen availability (HA) relative to the minimum and maximum availability (MinHA=5% and MaxHA=80%, by assumption). Equation (6) defines the infrastructure utilization (u) as the ratio of the hydrogen use to the sc.

$$rs = \sum_{i=2010}^{2050} \frac{(bhc_i - HP_i) \cdot hu_i}{(1+R)^{i-2010}} \tag{1}$$

$$bhc_i = bhcmu_i \cdot \frac{MU}{u_i} \tag{2}$$

$$bhcmu_i = MIN\left(CC, HC_i \cdot \left(\frac{MSC}{sc_i}\right)^{1-SF}\right) \tag{3}$$

$$sc_i = MAX\left(HA_i \cdot \frac{MSC}{MaxSta} \cdot ss_i, \frac{hu_i}{MU}\right) \tag{4}$$

$$ss_i = \begin{cases} MinSta & \text{if } HA_i < MinHA \\ \frac{MaxSta - MinSta}{MaxHA - MinHA} \cdot (HA_i - MinHA) & \\ MaxSta & \text{if } HA_i > MaxHA \end{cases} \tag{5}$$

$$u_i = hu_i / sc_i \tag{6}$$

As shown in Figure 2, the hydrogen price (HP) is an exogenous input to both MA3T and HICF. A higher hydrogen price will not necessarily reduce the annual infrastructure subsidy, because the resulting higher energy cost for H2V will reduce the demand for H2Vs and hydrogen and therefore reduce the utilization of the infrastructure. Lower infrastructure utilization increases the breakeven hydrogen cost (bhc).

2.4 Scenario Settings

Full-utilization hydrogen cost, hydrogen availability and costs of six powertrain components are used to characterize the technological progress in each scenario relative to the DOE technical targets (including those set by FCTO and VTO). Here, full-utilization hydrogen cost refers to the delivered cost from a fully-utilized (at the maximum 0.90 utilization level) infrastructure and should be distinguished from the under-utilization (or breakeven) hydrogen cost, which is required to balance the costs of an underutilized infrastructure and therefore is higher than the full-utilization cost. Unless specified otherwise, hydrogen price is assumed to be \$3.8/kg after tax, or the same as the full-utilization hydrogen cost, whichever is lower. The 6 powertrain components and their labels are: FC system, onboard hydrogen storage system (H2S), PHEV40 battery (P40Bat), hybrid electric vehicle battery (HEVBat), BEV battery (BEVBat), and electronics and motor system (EMC). Full-utilization hydrogen cost is labeled as H2Cost. When all the DOE technical targets are met on time, the costs of hydrogen and the 6 components are illustrated in Figure 4. The costs are expressed in terms of ratios to their 2010 levels, which are shown on the legend of Figure 4. It should be noted that DOE does not set targets for each year. The assumptions shown on Figure 4 combine DOE targets, estimates from credible sources for years for which DOE targets are not available, and interpolated estimates for years for which both DOE targets and literature estimates are not available. For example, the analysis assumes DOE reaches its fuel cell cost target of \$30/kW by 2015. The fuel cell cost is assumed to decrease to \$18/kW in 2045, according to a National Research Council study [3], and then assumed to stay constant beyond 2045.

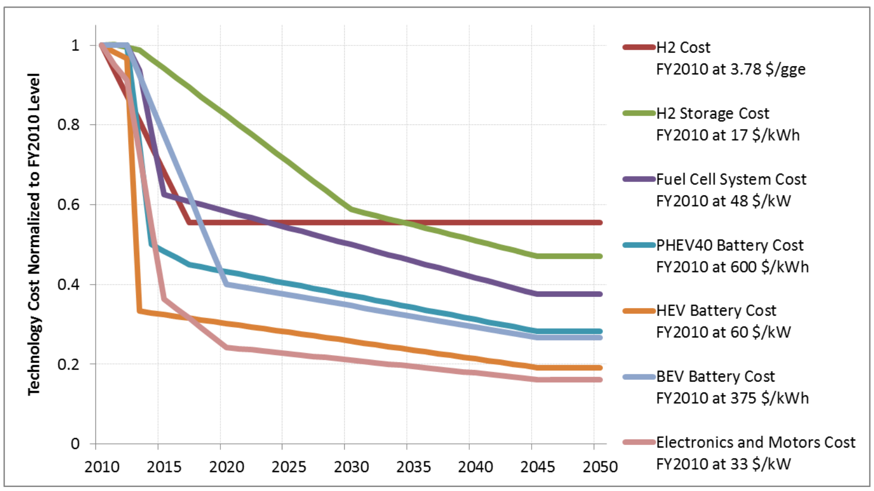

Figure 4. DOE Technical Targets—Hydrogen and Component Costs.

These technical targets, when met on time, reduce the prices of advanced vehicles relative to the Base case in MA3T. These reductions in vehicle prices in 2045 are illustrated in Figure 5. Note that “ProgramGoal” is the label for the scenario where all DOE FCTO and VTO technical targets are met on time, while “Base” represents the default scenario in MA3T where no significant technology progress is achieved.

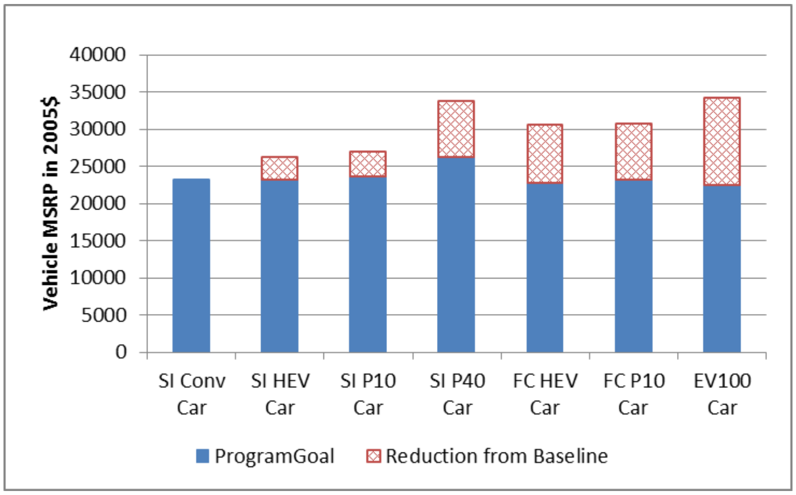

Figure 5. Vehicle Retail Prices in 2045—Base vs ProgramGoal.

In terms of infrastructure, it is assumed that the availability of both public charging[3] (ChgInfra) and hydrogen refueling (RefInfra) increases linearly to 50% by 2050 in the ProgramGoal case. The infrastructure deployment in the Base case is 10 years slower than the ProgramGoal case, i.e., linearly increasing from 0.1% in 2021 to 37.2% in 2050. Such an assumption on infrastructure is somewhat arbitrary, but with two reasons. First, the DOE targets do not include infrastructure availability. Second, studies show that hydrogen availability has a diminishing impact and makes little incremental impact when it reaches 50% [13].

Including **Base** and **ProgramGoal**, a total of 41 scenarios are simulated in MA3T. These scenarios represent a range of mixed progress in meeting the technical targets. These scenarios are labeled according to the following definitions.

- **PG-X-db5** and **PG-X-db10**: all components meet the technical targets on time, except the component X is delayed by (db) 5 and 10 years relative to ProgramGoal, respectively. X=H2S, FC, P40Bat, HEVBat, BEVBat, EMC, H2Cost, ChgInfra, and RefInfra. The purpose of these 18 scenarios is to reveal the impact of delaying a specific component progress.
- **Base+X**: all components follow the progress in the Base case, except that component X meets the DOE technical target on time. There are 9 of these scenarios. They are intended to show the marginal impact of a specific component's progress.
- **PGdb10+X**: progress of all components is delayed by 10 years relative to ProgramGoal, except the component X which meets its target on time. There are 9 of these scenarios. The comparison between PGdb10+X and Base+X scenarios is expected to illustrate the importance of pursuing progress for all components while emphasizing a particular technology, even if the progress of other component progress is delayed.

3 Charging availability is defined as the probability of a PEV driver being able to access a public charger when the driver conduct personal or business activities at public places outside the driver's home or workplace. An average of one hour parking on public places per day is assumed.

- **Base+$2H2by2020**: Base case, except that hydrogen price is forced at $2/gge from 2010 to 2020 and then merges to the full-utilization cost or $3.8/kg, whichever is lower.
- **PGdb10+$2Hby2020**: all progress is delayed by 10 years, and the same hydrogen price scheme as in Base+$2H2by2020.
- **PG+$2Hby2020**: all targets are met on time and the same hydrogen price scheme as in Base+$2H2by2020.

All 41 scenarios assume the deployment of hydrogen refueling infrastructure, whether delayed or not. No meaningful H2V sales are observed when there is no hydrogen refueling infrastructure, regardless how much progress is achieved for H2V components. All 41 scenarios assume energy prices that are consistent with the Reference case of Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2011 [14].

Carbon dioxide (CO2) associated with electricity used to power vehicles is included in calculation of well-to-wheel GHG emissions. Electricity generation and associated carbon dioxide emissions collected and projected by EIA's National Energy Modeling System (NEMS) model in its Reference case for 2009-2035 for each of 22 Electricity Market Modules (EMM) [15] are mapped with the 9 census divisions in MA3T. Non-CO2 GHG emissions from electricity generation are excluded in this study. This results in estimates of average emission factors for 2009-2035 by census divisions that are used to calculate upstream GHG emissions of plug-in electric vehicles. Emission factors are assumed unchanged beyond 2035. The estimated emission factors for 9 census divisions for the year 2010 and 2035 are shown as the blue and red-pattern bars in Figure 6. These emission factors reflect very slow progress in grid de-carbonization. The most aggressive grid-decarbonization scenario in the AEO 2012 is the GHG25 case, which estimates a 76% reduction in CO2 emissions from the electric power sector from the 2010 levels. This scenario is represented by the green-pattern bars in Figure 6. Although the GHG25 scenario is not used in model runs, it will be used in result discussions.

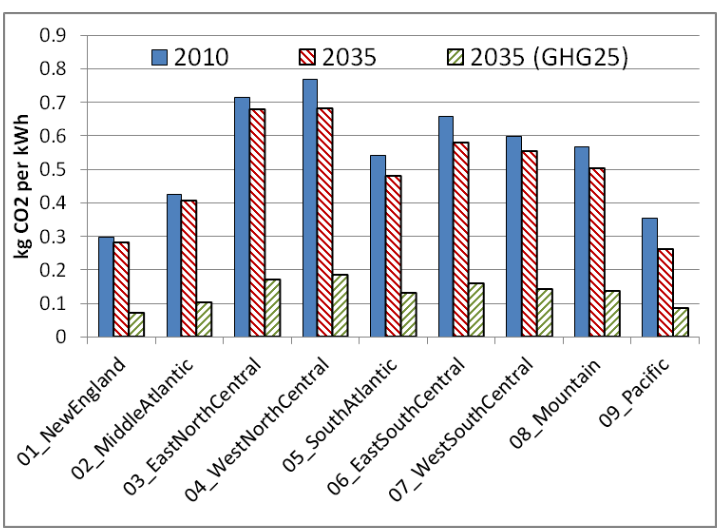

Figure 6. CO2 Emission Factor for Electricity Generation.

GHG emissions associated with H2Vs are mainly from the upstream supply of hydrogen. The emission factor associated with hydrogen supply is assumed to decrease linearly from 12.13 kg CO2eq/kg H2 in 2010 to 1.3 in 2050. The hydrogen supply technologies behind these two emission factors are—distributed steam reforming of natural gas with current technologies (12.13 kg CO2eq/kg H2) and central steam reforming of natural gas coupled with pipeline distribution and carbon sequestration with future technologies (1.3 kg CO2eq/kg H2) [11]. However, these two numbers are intended as simplified boundaries. Like in the HICF model, this study does not explicitly characterize hydrogen supply technologies, but instead uses simplified models to obtain reasonable assumptions for emissions. It is possible that a future national hydrogen infrastructure would consist of multiple supply pathways with varied emission factors, resulting in an average that is below or above 1.3 kg CO2eq/kg H2. More scenarios of carbon intensity in hydrogen supply could be included in future studies. For references, the National Research Council [11] estimated 2.2 kg CO2eq/kg H2 for hydrogen supply from central coal gasification with carbon capture and sequestration in the future.

3 Results

3.1 Market Prospect of H2Vs

The H2V market shares of the 41 scenarios are plotted in Figure 7. The lower and upper black curves represent the Base and ProgramGoal cases, respectively. The cluster of red curves includes scenarios where only one component matches the progress of the ProgramGoal case (i.e., the Base+X scenarios), and the Base+$2H2by2020 scenario. The blue curves include scenarios where only one component is consistent with ProgramGoal and the others are delayed by 10 years (i.e., the PGdb10+X scenarios), and the PGdb10+$2Hby2020 scenario. The green curves include PGdb10+$2Hby2020 and those where all components are consistent with ProgramGoal except one being delayed by 5 or 10 years (the PG-X-db5 and PG-X-db10 scenarios).

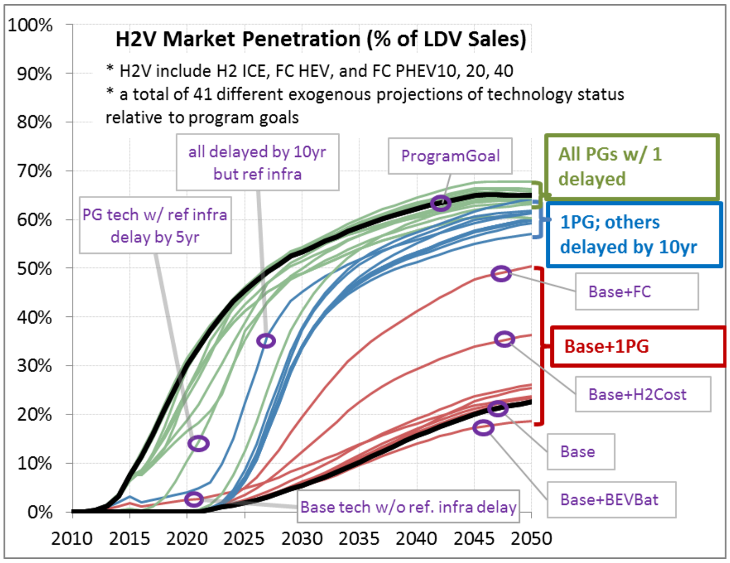

Figure 7. H2V Market Penetration.

Several things can be inferred. First, the estimated H2V market shares in 2050 range from 20% to 70%, mostly depending on how well the technical targets are met. Such a range of market shares indicates robustness of H2V market success. Note that the 41 scenarios in Figure 7 include those where only the targets of battery technologies are met on time and the FC technology remains at the Base case level. This indicates how attractive H2Vs have become, thanks to significant reduction in the costs of FCs and on-board hydrogen storage, as resulting from the investments in R&D by DOE and the industry. The lowest H2V market share in 2050 is with the Base+BEVBat scenario, where all other technologies stay on the Base level except that BEV battery reaches its technical target on time. This is the only scenario that results in a H2V market share lower than Base, because the progress of BEV battery is assumed, for simplicity, to be independent of the batteries used in FCV and FC PHEV. But even with Base+BEVBat, H2Vs still capture 18.7% of the market in 2050. The 2050 H2V market share of Base+P40Bat is actually higher than Base, which means the progress in PHEV battery facilitates market acceptance of not only SI PHEVs, but also FC PHEVs (one type of H2Vs). All these together suggest that, as long as hydrogen infrastructure is developed, even at a slow pace, it is very likely that H2Vs will exceed a 20% market share by 2050.

FC costs and hydrogen costs have the biggest impacts on H2V market shares. The estimated H2V market share in 2050 is 22.6% in Base, 36.3% in Base+H2Cost, and 50.4% in Base+FC. On-time progress for other technologies, including on-board H2 storage and PHEV battery, does not have as large a marginal impact. With 5% hydrogen availability at local levels by 2025, achieving only the hydrogen cost target or the FC cost target increases the H2V share by 2025 from 1.88% to 3.55% and 5.09%, respectively, assuming all other components following the baseline progress.

According to the modeling results, the more technical targets are met on time, the higher the H2V market share, but the market dominance (i.e., more than 50% market share) of

H2V does not require all DOE technical targets to be met on time. H2Vs can still capture 50% of the market if (1) any single one component is delayed by 10 years and all others progress on time, i.e., ProgramGoal, PG-X-db5 and PG-X-db10 (green curves in Figure 7); or (2) any single one component progresses on time and all others are delayed by 10 years, i.e., PGdb10+X (blue curves in Figure 7). These results do not mean that H2V market dominance is easy to obtain. What is relevant is that pursuing all component technologies can better ensure the market dominance by H2Vs and the resulting societal benefits, because H2V market dominance in the long term seems to be robust against delay of one or multiple components.

3.2 Hydrogen Infrastructure—The Enabler of H2V Market

A minimum level of infrastructure deployment is needed to enable the emergence of the H2V market. As shown in Figure 8, which contains 6 of the 41 scenarios in Figure 7, the H2V market starts emerging only after the hydrogen infrastructure deployment begins. By 2025, even with only 5% hydrogen availability and the Base technologies, H2V can capture nearly 2% of the light duty vehicle (LDV) market. In ProgramGoal, where all technical targets are met on time and hydrogen infrastructure is deployed faster, a 5% hydrogen availability by 2015 is accompanied a 7.6% market share by H2V. In general, with 5% hydrogen availability at local levels, H2Vs are estimated to capture 2%-8% of the market, depending on progress on reaching component technical targets.

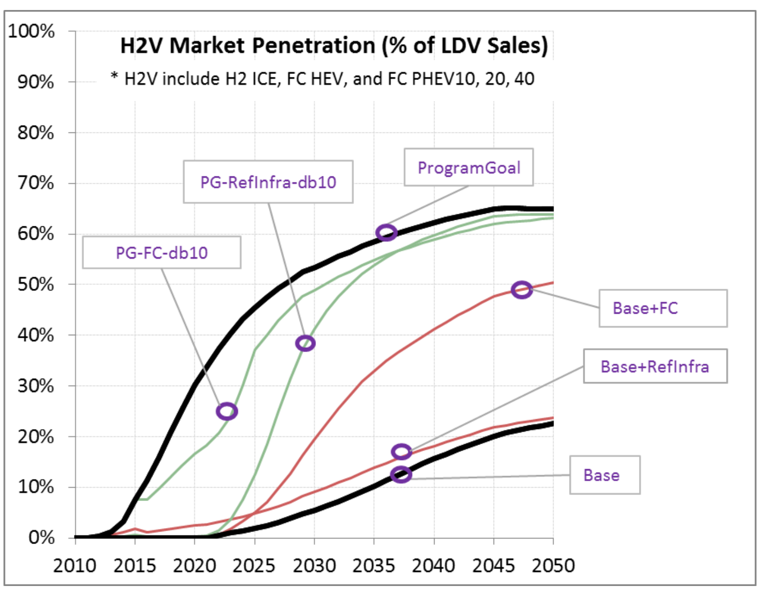

Figure 8. Infrastructure Impact on Market Penetration.

Improving the core H2V technologies can increase the long-term H2V market share, but does little to accelerate the onset of the H2V market in the absence of infrastructure (see “Base” vs “Base+FC” on Figure 8). Even if all components progress on time, the H2V market may not emerge until minimum hydrogen availability (5% or so) is provided (see

“PG-RefInfra-db10” on Figure 8). Earlier development of the infrastructure can advance the market onset, accelerate technology learning and bring more H2V to the road (see “Base” vs “Base+RefInfra” on Figure 8). After 5% hydrogen availability is reached, H2V sales are estimated to emerge, regardless of component progress, but the speed of H2V sales growth does depend on component progress. Faster progress on related components, such as FCs, is predicted to cause faster growth of H2V market shares after 5% hydrogen availability is achieved (see “ProgramGoal” vs “PG-FC-db10”, or “Base” vs “Base+FC” on Figure 8).

The modeling results show that market shares of H2V become less sensitive after hydrogen availability passes 5%. When all targets are met on time and hydrogen availability grows to 50% in 2050, the market share of H2V in 2050 is estimated to be 64.9%. When all targets are met on time but hydrogen infrastructure is delayed by 5 or 10 years (so the hydrogen availability grows to 43.6% and 37.2% in 2050, respectively), the 2050 market share of H2V is 64.4% and 63.8%, respectively. The impact of infrastructure on H2V market shares appears to quickly diminish after the 5% threshold.

3.3 Fuel Cell and Battery—Competition or Co-Existence

Between FC and plug-in battery, which one will succeed or dominate the market? Under what progress relative to the DOE targets? To address these questions, market shares of H2ICE, FCV, FC PHEV, BEV, SI PHEV, HEV, and commercial vehicle (CV) are analyzed for 4 of the 41 scenarios (Figure 9)—Base, Base+FC, Base+P40Bat, and ProgramGoal. The market share of FC refers to the combined shares of FCVs and FC PHEVs. The market share of plug-in battery refers to the combined shares of FC PHEV, BEV, and SI PHEV, shown as the three stacked areas with pattern fills in Figure 9.

The results of the 4 scenarios indicate that FC and plug-in battery could co-exist and both succeed. In Base (Figure 9), in 2050, plug-in battery captures more than 35% of the LDV market, while FC captures nearly 20%, a little better than HEV. The market share of CV continuously declines over time. The share of HEV peaks around 2025, exactly the year when hydrogen availability reaches 5%, and then slowly decreases over time. FC and plug-in battery, on the other hand, keep gaining more market share over time.

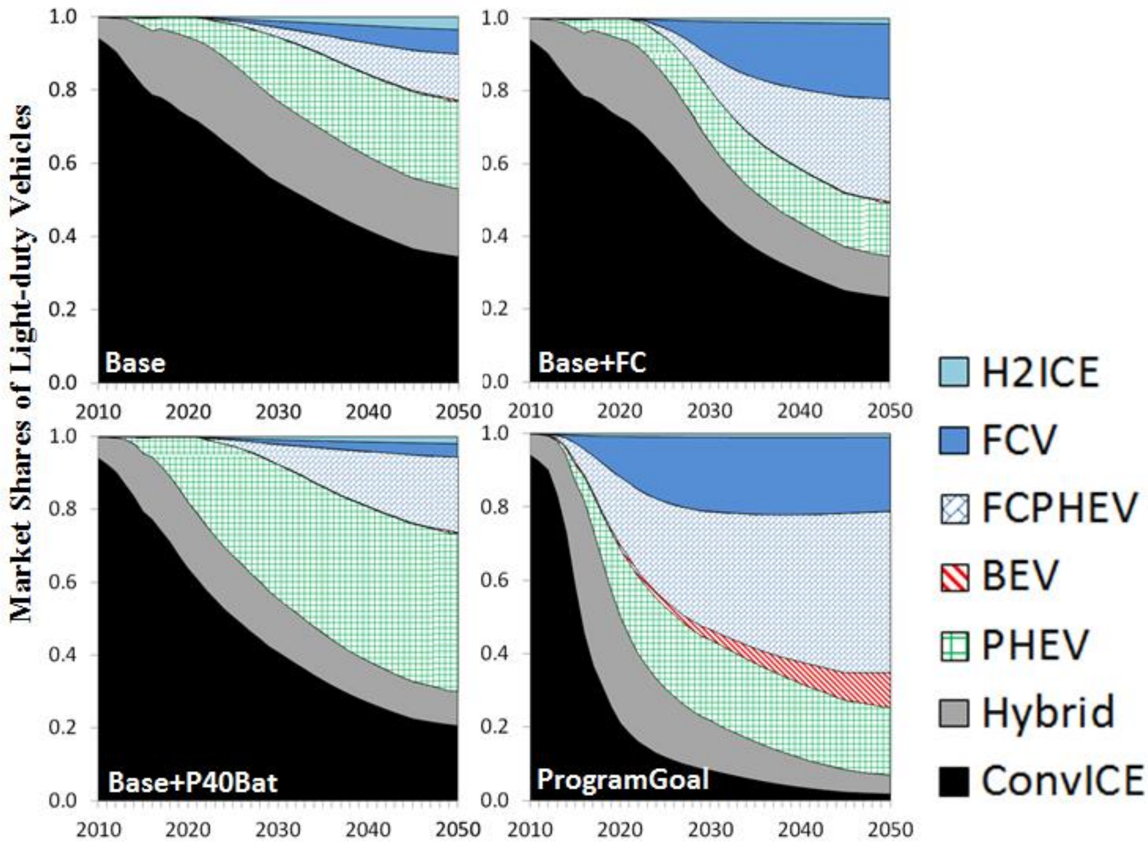

Figure 9. Market Shares of Four Scenarios by Technology Category.

Both FC and plug-in battery could dominate the LDV market, meaning both capture more than a 50% market share (due to the overlapping FC PHEV). If all DOE technical targets are met on time (ProgramGoal case in Figure 9), FC could capture about 64% of the market, while plug-in battery could gain about 72%. Note that oil prices of the AEO2011 Reference case are assumed. HEV is severely squeezed out of the market, not to mention conventional ICE. Similar to Base, the ProgramGoal scenario results in continuous growth of market shares of both fuel cell and plug-in battery through 2050. What is not observed, importantly, is the direct competition between FC and plug-in battery, even when both dominate the market. It seems that the LDV market has sufficient room for both FC and plug-in battery to grow together by 2050.

The synergy between FC and plug-in battery is remarkable in two ways. Besides the common growth as previously observed in Base and ProgramGoal cases, mutual promotion is also observed—i.e., technological improvement of one increases the market shares of both. According to the results, on-time progress of PHEV battery increases, expectedly, the market share of plug-in battery in 2050 from 37% to 64% (Base+P40Bat vs. Base in Figure 9). Somewhat surprising is that the market share of FC also increases, solely as a result of PHEV battery progress, from 19% to 24%, both in 2050. Similarly, on-time progress of FC increases its market share from 19% to 49% and that of plug-in battery from 37% to 43%, all in 2050.

The remarkable synergy between FC and plug-in battery is mainly due to the shared powertrain option—FC PHEVs, which appear to be competitive across all scenarios, both in the short term and the long term, but for common and different reasons. Low energy cost is the common reason. FC PHEVs have lower energy costs than SI PHEVs by relying on a cheaper (partly due to subsidy) and more efficient fuel (hydrogen). Compared to FCVs, FC PHEVs also achieve lower energy costs by fueling some miles with slightly cheaper electricity. The other reason for FC PHEVs to be attractive in the short-term market is its less severe range barrier. FC PHEVs consume less hydrogen fuel and thus require less frequent refueling trips, which is an important advantage in the early market with low hydrogen availability. Over time, this advantage diminishes as the hydrogen infrastructure expands, but the long-term advantage emerges—a competitive vehicle price of FC PHEVs due to progress of both FC and plug-in battery. As illustrated by Figure 5, the price of FC PHEV10s in 2045 is even a little lower than that of a SI PHEV10s, if all technical targets are met on time. The competition among SI PHEVs, FCVs and FC PHEVs reflects tradeoff among vehicle price, energy cost, and refueling inconvenience. This topic is worth of further investigation because the knowledge about how consumers value energy costs and fuel availability is still insufficient.

3.4 Societal Benefits

Societal benefits of the DOE technical targets are examined with respect to the annual petroleum use in 2050 (Figure 10), annual GHG emissions in 2050 (Figure 11), cumulative sales of zero-emission vehicles (ZEV) by 2050 (Figure 12), and cumulative sales of grid-connected vehicles (GCV) by 2050 (Figure 13), for 16 scenarios out of the 41. The "Base+X" scenarios show the impact of having one component meeting DOE technical targets on time. The "PG-X-db10" scenarios show the impact of one being delayed by 10 years.

Achieving the DOE technical targets could result in significant societal benefits in the long run. If all targets are met on time, the transition to electric drive (including H2Vs and PEVs) could cut LDV petroleum use in 2050 by about 80% and well-to-wheel GHG emissions by about 62%, relative to the 2010 Base level (see ProgramGoal in Figure 10 and Figure 11). These estimates exclude the likely minor use of petroleum in hydrogen and electricity supply. Due to upstream emissions from electricity generation and hydrogen production, the reduction in GHG emissions is not as great as in petroleum use. If coal gasification with carbon capture and sequestration is the dominant long-term hydrogen supply technology, the GHG cut would be about 59% instead of 62%. The cut in 2050 relative to 2010 would be only 12% (assuming 16.7 kgCO2eq /kg H2), if coal gasification dominates hydrogen supply without carbon capture and sequestration. Although such a scenario seems very unlikely, it does highlight the importance of decarbonizing hydrogen supply. Deeper cuts would be possible if renewable electricity, renewable hydrogen production, and biofuels are included in the scenarios. The GHG25 grid de-carbonization assumptions from AEO 2012 (as shown in Figure 6) would boost the GHG emission cut by 2050 to 72%. A total de-carbonization of hydrogen supply would further increase the cut to over 76%. Also in ProgramGoal, about 53% of all LDVs sold during 2012-2050 are estimated to be ZEVs, including H2 ICEs[4], FCEVs, FC PHEVs, and BEVs. About 52% are GCVs, including SI PHEVs, BEVs, and FC PHEVs.

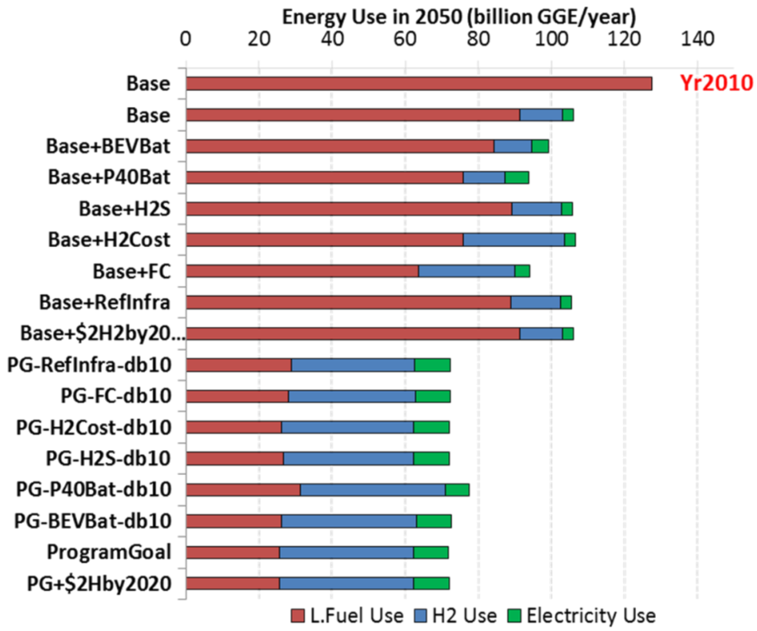

Figure 10. Long-Term Impact on Petroleum Use.

[4] H2 ICE still emits a small amount of nitrogen oxide, but compared to conventional gasoline vehicles, H2 ICE vehicles are regarded as nearly-zero regulated emissions vehicles.

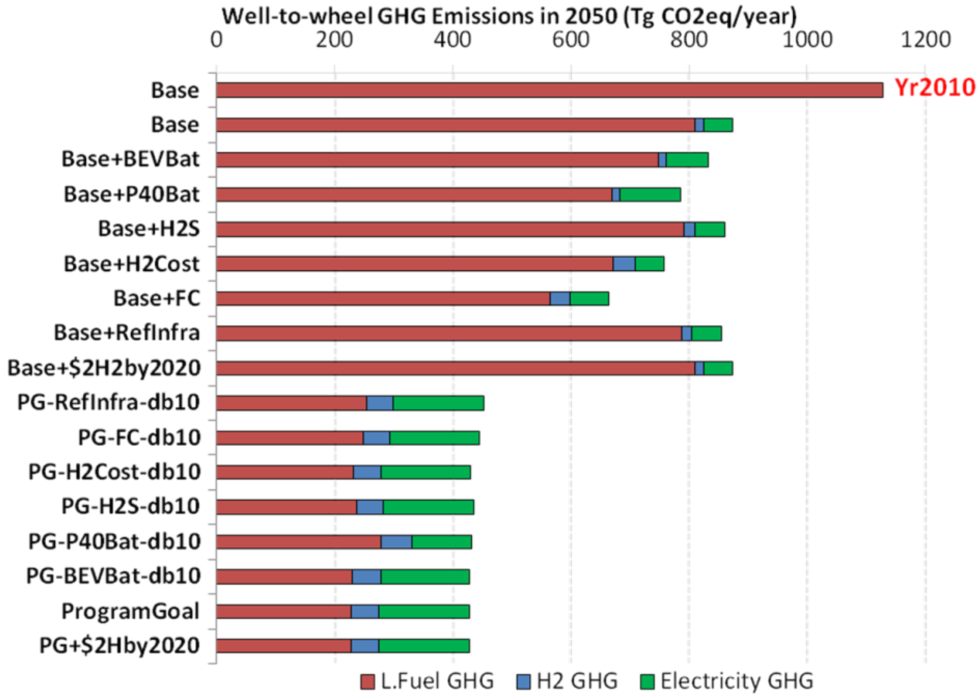

Figure 11. Long-Term Impact on GHG Emissions.

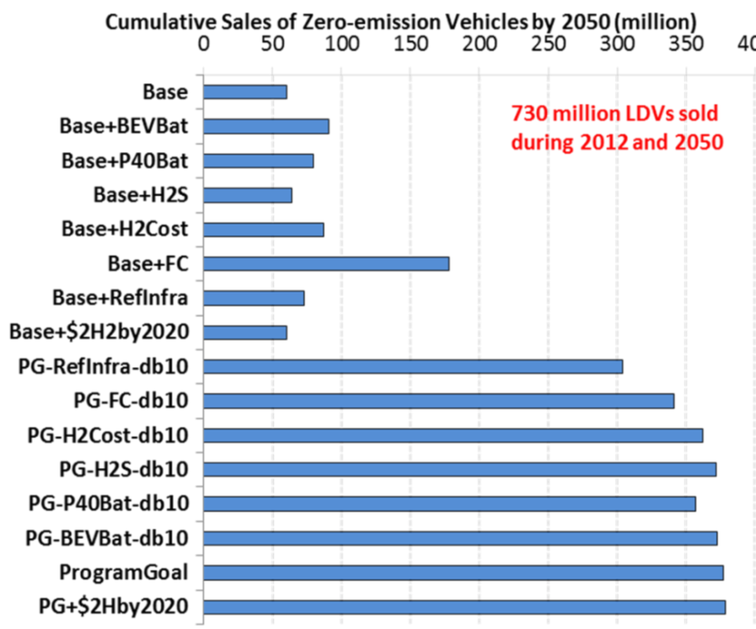

Figure 12. Long-Term Impact on ZEV Population.

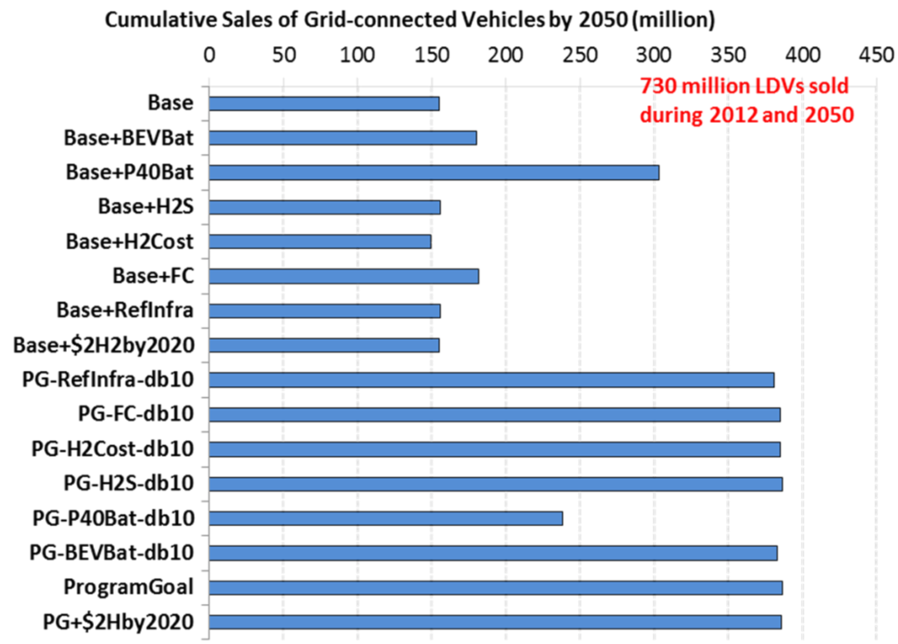

Figure 13. Long-Term Impact on GCV Population.

The magnitude of societal benefits in 2050 appears to be robust against delay in meeting one technical target, if all the others are met on time. One target delay could reduce the 80% petroleum cut by 0.3~4.3 percentage points and could reduce the 62% GHG cut by 0.1~2.3 percentage points. On the other hand, if no other targets are pursued, the failure in meeting the single target that is being pursued could be much more consequential. For example, although achieving the PHEV battery target alone could reduce the 2050 petroleum use by about 41% and the 2050 GHG emissions by about 30%, these significant benefits are very sensitive to the on-time progress of PHEV battery. The progress of each component adds a marginal societal benefit to the total. The results in Figure 10 and Figure 11 indicate that the marginal benefit of a component depends on the progress of other components. As other components improve, the marginal benefit of any single component could diminish, and so could the sensitivity of prospective societal benefits to any single component. That is, success of more components provides insurance for future societal benefits, although it may require larger R&D investments.

Among all component targets, meeting the FC cost target results in the largest impact on petroleum savings, GHG emission reduction, and cumulative ZEV sales (see Base+X in Figure 10 - Figure 13), while PHEV battery has the largest impact on cumulative GCV sales.

3.5 Required Subsidy

Two forms of subsidy are calculated—hydrogen infrastructure subsidy and vehicle purchase subsidy, as previously explained in the “Approach” section. The calculated subsidies are not intended to be optimal but are instead a consequence of the scenario assumptions. It might be possible to achieve equal results with smaller subsidies. Even so, as will be shown, the subsidies are not large relative to the societal benefits they induce.

The hydrogen infrastructure subsidy associated with the same 16 scenarios varies widely from \$3.4 billion to \$52.7 billion, in terms of net present value at the beginning of 2012 at a 7% annual discount rate (Figure 14). The variation in hydrogen subsidy can be explained by three intertwined factors—hydrogen cost-price gap, hydrogen use, and discounting, as formulated in Equation (1). An earlier onset of the H2V market could result in early-year hydrogen subsidies that are less discounted and therefore increase the net present value of subsidies, as illustrated by ProgramGoal, PG-X-db10 (except PG-RefInfra-db10), and Base-RefInfra in Figure 14. A large amount of subsidy could be caused by a large gap between hydrogen cost and price, due to low infrastructure utilization (such as Base-RefInfra in Figure 14), low hydrogen price, or slow progress in hydrogen cost reduction. A large subsidy caused by high demand for hydrogen could be desirable, because more hydrogen use generally means greater societal benefits (such as ProgramGoal in Figure 14).

If technological progress is slow, as in the Base case, early deployment of hydrogen infrastructure could result in large subsidy costs for small societal benefits. For example, the extremely high subsidy from Base+RefInfra is not very desirable, as its resulting societal benefits are not very compelling (see "Base+RefInfra" on Figure 10 through Figure 13). This is a warning sign. Although the authors have pointed out the importance of having an infrastructure in place to allow H2V sales to emerge, the high subsidy cost and small societal benefits of Base+RefInfra indicates bad timing between hydrogen infrastructure deployment and progresses of H2V-related technologies. Apparently, with Base+RefInfra, the technological progress of FC, on-board storage, plug-in battery, and H2 cost are too slow and consequently the H2V sales and H2 demand are too low, making the infrastructure utilization low and the required subsidy high.

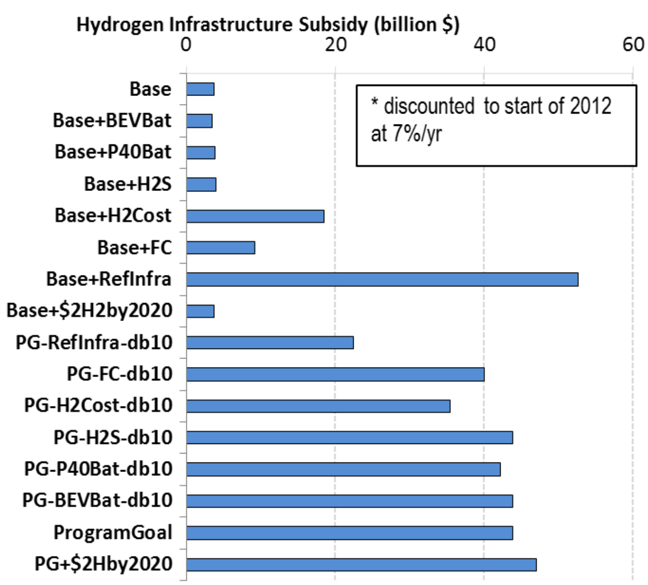

Figure 14. Subsidy for Hydrogen Infrastructure.

If all components achieve the technical targets on time or only one is delayed by 10 years, the required H2 subsidy as estimated ranges from $22.4 billion to $47.1 billion. In particular, if all components meet the DOE technical targets on time, the estimated H2 subsidy is about $43.9 billion. Although these are at the higher end of the included scenarios, the estimated societal benefits are also much larger (Figure 10 through Figure 13). Again, the variation of H2 subsidy is due to different technological progress, causing differences in H2 demand, infrastructure utilization, and breakeven hydrogen cost.

In general, more successful components increases H2V sales and hydrogen use, resulting in more hydrogen subsidy as well as more societal benefits.

The ARRA subsidy ranges from $4.0 billion to $16.5 billion[5] (Figure 15). The Base+X scenarios result in low ARRA subsidy, ranging from $4.0 to $5.3 billion. In these scenarios, the majority of subsidized vehicles are PHEV10, each of which receives $2500 of tax credit. But in the ProgramGoal and most of the PG-X-db10 scenarios, the majority of subsidized vehicles are H2V, each qualified for $7500 tax credit by assumption. This substantially increases the total subsidy amount. With PG-RefInfra-db10, where hydrogen infrastructure deployment is delayed by 10 years, sales of H2V are suppressed, driving most of ARRA subsidy toward PHEV and BEV. When hydrogen is priced lower at $2/kg for the first 10 years (PG+$2Hby2020), the total sales of H2V during the first 4 qualified years go up and exceed the 1.2 million quota, ending the ARRA subsidy one year earlier.

[5] Technically, even all subsidized vehicles receive the maximum $7,500 each, the total is $9.75 billion for 1.2 million qualified vehicles. As previously explained, when the 1.2 million quota is reached in the middle of the year, the total number of subsidized vehicles will exceed the quota, resulting in more subsidies.

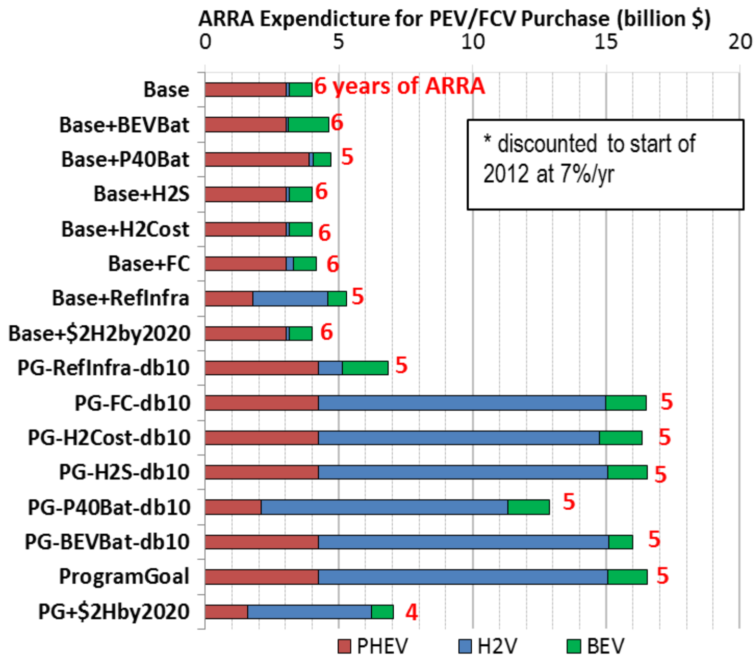

Figure 15. Subsidy for Purchase of PEV and ZEV.

3.6 Subsidy Cost-Effectiveness

Putting together the societal benefits and the required subsidy, we can estimate the cost-effectiveness of subsidy. Two metrics are examined—Tg CO2 equivalent of emissions reduced per $1 million subsidy and million barrel of petroleum use reduced per $1 million subsidy. The marginal societal benefits and marginal subsidy costs of a given scenario are calculated in relative to the no-H2 Base, which is the same as the Base scenario, except that the hydrogen infrastructure is not deployed. For the no-H2 Base case during 2011-2050, the total GHG emissions are estimated to be 41 Pg CO2e, the total petroleum use, 110.4 billion barrel of oil equivalent, and the total subsidy, $4.2 billion. Figure 16 and Figure 17 shows the two metrics for the same 16 scenarios. The inverses of the two metric are also plotted as the red-pattern bars, in terms of dollar per metric ton CO2 equivalent and dollar per barrel, respectively.

Overall, the Base and Base+X scenarios have higher cost-effectiveness than the ProgramGoal and PG-X-db10 scenarios, but higher cost-effectiveness is not necessarily more desirable. With equal societal benefits, higher cost-effectiveness is more desirable. If additional societal benefits can be gained at a marginal cost of public support that is lower than the marginal social cost (not quantified in this study), then the additional public support should be recommended.

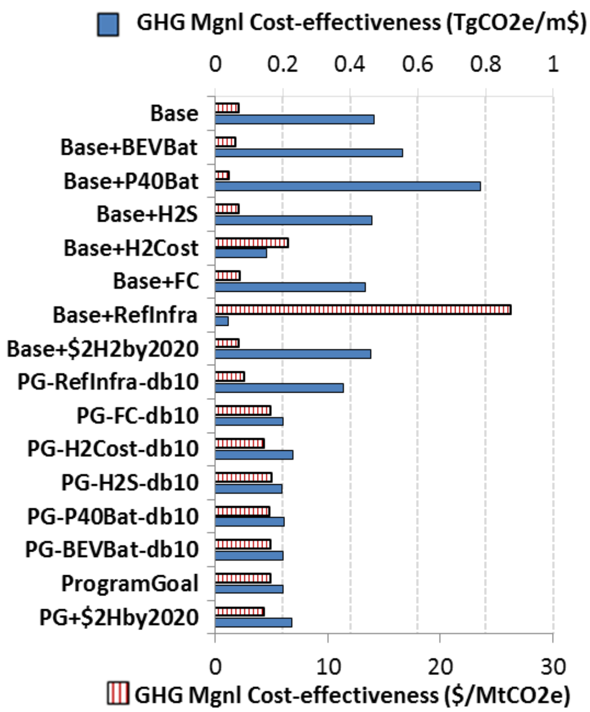

Figure 16. GHG Cost-Effectiveness of Subsidy.

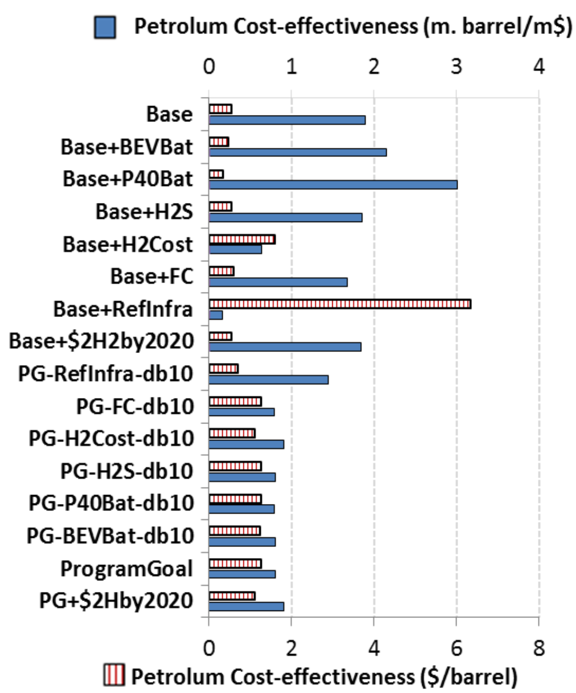

Figure 17. Petroleum Cost-Effectiveness of Subsidy.

The public and private investments in R&D to achieve the DOE targets have not been considered here. Therefore, these two metrics do not offer the whole picture of public investment cost-effectiveness. On the other hand, the calculated subsidies may not be optimal. Furthermore, these two metrics do not include air quality, energy security, and employment benefits. For a specific scenario where component progress is exogenously determined, these two metrics offer valuable information on whether it is desirable to expand the public subsidy to gain more societal benefits. For example, with all technical targets met on time (ProgramGoal case), each million dollar of subsidy is associated with 0.2 Pg CO2e of GHG avoided and 0.8 million barrels of oil saved. The questions, not yet analyzed in this study, are—what is the social cost of the next ton of GHG emission and the next million barrel of oil use, so that more or less public subsidy can be justified? What is the optimal amount of public subsidy?

4 Summary

This study estimates and analyzes market shares of H2Vs (including H2 ICE, FCV and FC PHEV) and the resulting societal benefits and required subsidy under 41 scenarios that describe varied progress in meeting the DOE technical targets for vehicle powertrain components. The estimation is based on assumptions of projected energy prices, vehicle attributes, consumer behavior, infrastructure deployment and policies and the use of the MA3T and HICF models.

The first caveat of this study is exclusion of scenarios that reflect more aggressive adoption of biofuel and natural gas, possibly resulting in underestimates of societal benefits. Second, our understanding of consumer behavior, infrastructure roll-out and technology evolvement is still weak. Therefore, the quantitative results from the two models are scenario analyses, not predictions of the future. Third, our cost-effectiveness assessment of public investments is limited in scope, both on the cost side as we have not quantified the investments in R&D and other activities (such as regulation process), and on the benefit side as we have not quantified the benefits related to air quality, energy security, and economic development. Forth, without optimization, the calculated subsidies may be overestimates of the actual amounts needed.

Nevertheless, the modeling results appear to have provided some important insights and raised new questions about transitions to electric drive vehicles.

H2Vs could have a high probability of market success, if hydrogen infrastructure is deployed. Among the 41 scenarios, the estimated market share of H2V in 2050 ranges from 20% to 70%, depending on progress in meeting the DOE technical targets. Even with the Base technology and delayed infrastructure deployment, H2Vs could still capture about 23% of the LDV market, thanks to technological progress that has been realized by government and industry efforts in recent years.

It seems certain that a basic level of hydrogen availability (probably 5%) will need to precede the onset of a H2V market. Consistently across all 41 scenarios, virtually no demand for H2V exists before a hydrogen infrastructure starts to be built. The market share of H2V is estimated to be from 2% to 8% when hydrogen availability reaches the 5%

basic level. After that, the market share of H2V becomes less and less sensitive to hydrogen availability as infrastructure expands. This points to a “fast-then-adaptive” infrastructure roll-out strategy—quickly establishing a basic hydrogen infrastructure (e.g. at about 5% availability) and thereafter expanding it in response to hydrogen demand while emphasizing on high infrastructure utilization.

Meeting all DOE technical targets on time could result in significant societal benefits at a relatively small cost. By 2050, annual well-to-wheel GHG emissions from LDVs are estimated to be cut by about 62% (or 72% with aggressive electricity de-carbonization) and annual petroleum use by LDVs cut by 80%, both relative to the 2010 level, due to deep penetrations of H2Vs and plug-in electric vehicles. The required subsidy for hydrogen infrastructure is estimated to be $43.9 billion at net present value. Additional $16.5 billion of subsidy is estimated for vehicle purchase under the current ARRA tax credit policy. The combined amount of $60 billion appears to be a very cost-effective investment—each million dollar of subsidy is associated with 0.2 Pg CO2e of GHG avoided and 0.8 million barrels of oil saved. Admittedly, the investments in R&D to achieve these targets and the benefits on air quality, energy security and economy development, not estimated in this study, could change the cost-effectiveness ratios.

There is no guarantee that all the DOE technical targets will be met on time and that the resulting vast societal benefits will be harvested in whole. However, pursuing a portfolio of technologies including both FC and plug-in battery could provide insurance for societal benefits. When all other DOE targets are met on time, a 10-year delay in meeting one target cause less than 5 percentage points in petroleum saving benefits and less than 3 percentage points in GHG mitigation benefits. The magnitude of societal benefits appears to be robust against delay in meeting one technical target, if all the others are met on time.

If either or both are successful in meeting DOE targets, FC and plug-in battery could not only increase societal benefits, but also enhance the market strength of each other. First, the LDV market is large enough for both to grow together. Among all 41 scenarios, a common pattern of market shares from 2010 and 2050 is that the share of conventional ICE keeps falling, the HEV share peaks at some point and thereafter keeps falling, and the shares of both FC and plug-in battery keep growing. There is no exception, although the pace of these changes and the timing of HEV peaking vary with different progress in meeting DOE targets. Second, between FC and plug-in battery, the success of one in meeting DOE targets always increases the market share of the other (and that of itself, of course), according to the modeling results.

The synergy between FC and plug-in battery lies in the availability of FC PHEV, a powertrain that marries the two components. During the near term when hydrogen availability is low, the plug-in battery helps reduce the refueling inconvenience for FC PHEV users. In the long run, FC becomes cheaper and FC PHEV becomes a competitive powertrain, in addition to SI PHEV, to help plug-in battery capture market shares from conventional ICE and HEV.

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6 References

[1] Davis SC, Diegel SW, Boundy RG. Transportation energy data book, edition 31, Oak Ridge National Laboratory, Oak Ridge, TN; 2012.

[2] Greene DL. Measuring energy security: Can the United States achieve oil independence? Energy Policy 38(4), 1614-21; 2010.

[3] National Research Council. Transitions to alternative transportation technologies: A focus on hydrogen, National Academies Press, Washington, DC; 2008.

[4] US Department of Energy, Fuel Cells Technologies Program. Fuel Cell Technologies Office multi-year research, development and demonstration plan; 2009.

[5] Brian D. James, Jeff Kalinoski, Kevin Baum. Manufacturing Cost Analysis Of Fuel Cell Systems. DOE 2011 Annual Merit Review presentation, Project# FC018. Washington DC, May 12, 2011.

[6] National Research Council. Review of the research program of the FreedomCAR and fuel partnership: Third report, Washington, DC: The National Academies Press; 2010.

[7] Lin Z, Greene DL. "A plug-in hybrid consumer choice model with detailed market segmentation," TRB 10-1698, 89th Annual Meeting of the Transportation Research Board, Washington, DC; 2010.

[8] Lin Z. MA3T model: Modeling the market acceptance of advanced automotive technologies, Center for Transportation Analysis, Oak Ridge National Laboratory, http://cta.ornl.gov/ma3t/; 2012.

[9] Lin Z, Dong J, Liu C, Greene DL. Estimation of energy use by plug-in hybrid electric vehicles: Validating gamma distribution for representing random daily driving distance. Transportation Research Record, 2287(1), 37-43; 2012.

[10] Lin Z, Greene DL. Promoting the market for plug-in hybrid and battery electric vehicles: Role of recharge availability. Transportation Research Record, 2252(1), 49-56; 2011.

[11] National Research Council. The hydrogen economy: Opportunities, costs, barriers, and R&D needs. Washington, DC: The National Academies Press; 2004.

[12] Department of Energy, the Hydrogen Analysis (H2A) Project. http://www.hydrogen.energy.gov/h2a_analysis.html, accessed on Feb 1, 2013

[13] Zhenhong Lin, Joan Ogden, Yueyue Fan, Chien-Wei Chen, The fuel-travel-back approach to hydrogen station siting, International Journal of Hydrogen Energy, Volume 33, Issue 12, June 2008, Pages 3096-3101

[14] Energy Information Administration. Annual Energy Outlook 2011. DOE/EIA-0484(2011), U.S. Department of Energy, Washington, DC; 2011.

[15] Energy Information Administration. The electricity market module of the national energy modeling system—Model documentation report, DOE/EIA-M068(2011); 2011.