XI.4 Analysis of the Effects of Developing New Energy Infrastructures

David Reichmuth
Sandia National Laboratories
P.O. Box 969
Livermore, CA 94551-0969
Phone: (925) 294-3393
E-mail: dreichm@sandia.gov

DOE Manager
HQ: Fred Joseck
Phone: (202) 586-7932
E-mail: Fred.Joseck@ee.doe.gov

Subcontractor:
Andy Lutz, Alamo, CA

Project Start Date: December 1, 2007
Project End Date: September 30, 2012

Fiscal Year (FY) 2011 Objectives

- Develop models of interdependent energy infrastructure systems.
- Analyze the impacts of widespread deployment of a hydrogen fueling infrastructure and hydrogen fuel cell vehicle fleet.
- Analyze the impacts of stationary fuel cell systems for distributed power.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Future Market Behavior
(B) Stove-Piped/Siloed Analytical Capability
(E) Unplanned Studies and Analysis

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE milestones from the Systems Analysis section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 5**: Complete analysis and studies of resource/feedstock, production/delivery and existing infrastructure for various hydrogen scenarios. (4Q, 2010)
- **Milestone 7**: Analysis of the hydrogen infrastructure and technical target progress for the hydrogen fuel and vehicles. (2Q, 2011)
- **Milestone 8**: Complete analysis and studies of resource/feedstock, production/delivery and existing infrastructure for technology readiness. (4Q, 2014)

Accomplishments

- Sandia National Laboratories developed a dynamic tool for analyzing the potential impact of an emergent hydrogen fuel infrastructure on the existing energy infrastructures.
- Developed models of the behavior of natural gas, refined petroleum, hydrogen, and electricity generation cost for eight geographic regions in the U.S.
- Incorporated a light-duty vehicle adoption model for hydrogen fuel cell (HFCV), plug-in hybrid electric (PHEV), battery electric (BEV) and a new generation of conventional vehicles that meet the 2016 Corporate Average Fuel Economy regulation [1]. Added market segmentation to assign alternative vehicles to three vehicle classes: small cars, large cars, and trucks.
- Quantified the impact of large-scale HFCV adoption on key metrics such as petroleum use and carbon emissions and analyzed the relative benefits of BEV and HFCV. Our analysis shows that HFCVs could enable nearly 10-fold larger savings in petroleum use, as compared to BEVs.
- Examined impact of combined power and hydrogen production from stationary fuel cells on early HFCV market.

✧ ✧ ✧ ✧ ✧

Introduction

This systems analysis task is designed to examine the impact of emerging hydrogen infrastructure and fuel cell vehicles on key metrics, such as petroleum use and carbon emissions. To make a meaningful assessment of the benefits of fuel cell technologies, potential competing technologies must be included in the analysis. For this reason, we include multiple hydrogen and electricity production pathways and a range of vehicle sizes and powertrain combinations. It is also important to consider the time scale for technology development and deployment. Therefore our analysis includes time-dependent data for the deployment of potential fuel production and delivery pathways along with the evolution of the light-duty vehicle fleet.

Sandia National Laboratories (SNL) developed a system dynamics (SD) model for studying the competition of

HFCVs, PHEVs, BEVs, and advanced gasoline vehicles and the resulting impact on energy infrastructures. In addition, our model includes the possible adoption of stationary fuel cell systems for distributed power and hydrogen fuel production. To demonstrate the utility of the SD approach, in FY 2009 and 2010 SNL analyzed the likely impact on the California markets for gasoline, natural gas, and electricity. This state was selected because it is home to one or more "lighthouse" cities for early hydrogen adoption, and because of the interdependencies between electricity and natural gas infrastructures (a significant fraction of electricity generation is derived from natural gas boilers and gas turbines). Our current work expands on the analysis to the national scale, with a regionally differentiated model that can examine geographic differences in vehicle fleet composition and transportation energy sources.

Approach

We use an SD model to simulate the future vehicle fleet composition [2]. The model is comprised of three main submodules: energy sources, fuels, and vehicles. The vehicle portion of the model calculates the changing composition of the vehicle fleet, in part due to the cost of fuel calculated by the fuel submodule. The cost of the fuels changes in response to changing demand from the vehicle model, with both positive and negative feedback elements. Positive feedbacks include factors such as decreasing cost of hydrogen delivery with increasing infrastructure utilization, while negative feedback elements include competition and exhaustion of primary energy sources. We consider multiple pathways to generate hydrogen and electricity, and the model uses a cost-based choice function to allocate new production capacity. For hydrogen production, we currently model natural gas distributed steam-methane reforming and centralized electrolysis from wind power.

The SD model chooses future vehicle sales by applying a multinominal logit choice model based on the amortized purchase cost, penalty factors (e.g. for low vehicle range) and the annual fuel cost [3]. This choice function allocates sales among the various combinations of vehicle powertrains and sizes included in the model. The cost of fuels and the purchase cost of the vehicles change over time, which causes the distribution of powertrain choice to evolve over time. A summary of vehicle efficiency assumptions is shown in Table 1. The model allows for analysis of the sensitivity to input assumptions by using multiple model runs with variation of input parameters, using Latin hypercube sampling of the input space.

Results

The projected evolution of the light-duty vehicle (LDV) fleet over time is shown in Figure 1. Our baseline case assumes moderate growth in the vehicle fleet, at a net rate of 0.9%, equal to the estimate for overall U.S. population growth [4]. The overall growth rate is a result of an annual vehicle sales rate of 6.9% per year and a scrap rate of 5.8% per year. The baseline case also assumes that the price of crude oil starts at \$90/barrel and increases (in constant dollars) \$3/barrel per year. In this baseline case, alternative fuel vehicles (AFVs) make up approximately 50% of the LDV fleet by 2050. The dominant AFV in 2050 is the HFCV, with nearly 100 million vehicles in service. The PHEV40 and BEV vehicles' market penetration is lower in large part due to unavailability of larger-sized vehicles, while PHEV10

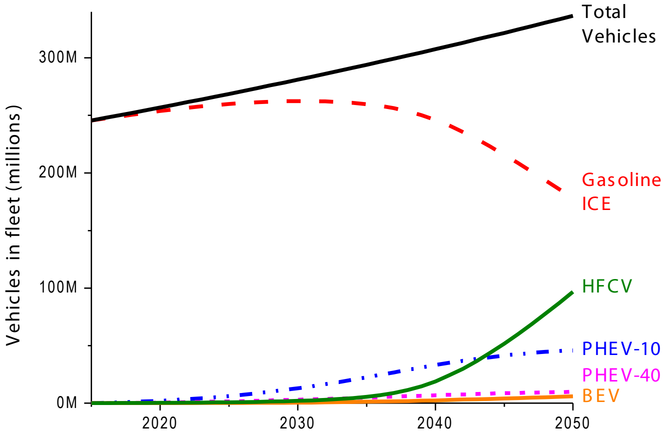

FIGURE 1. LDVs in the U.S. by powertrain for the baseline case. By 2050, approximately 50% of the vehicles in the fleet are AFVs.

TABLE 1. Analysis Assumptions for Vehicle Fuel Efficiency in 2010, 2016, and 2035

MPGe in 2010/2016/2035	Gasoline ICE	HFCV	PHEV10 Gas (77%) Elect (23%)	PHEV40 Gas (37%) Elect (63%)	BEV
Small Car	36/42/45	69/71/76	41/45/56 (gas) 84/102/136	30/34/47 (gas) 94/110/148	99/110/148
Large Car	18/30/39	69/71/76	35/39/47 72/87/116	25/29/40 80/94/126	N/A
Truck	18/30/39	69/71/76	20/23/28 42/51/68	N/A	N/A

MPGe – miles per gallon equivalent; ICE – internal combustion engine; N/A – not applicable vehicles enter into the fleet in significant numbers due to their lower purchase price. The vehicle sales for the baseline case are shown in Figure 2. PHEVs initially make up most of the AFV sales, however HFCV sales greatly increase, starting in 2035. By 2050, HFCV sales make up over half of all new LDV sales. The shape and timing of the HFCV sales curve is consistent with prior studies by Greene *et al* [5]. It is important to note that the sales of HFCV are highly dependent on the assumption of rising petroleum prices. If crude oil prices remain constant at $90/barrel, our results show little (<5%) penetration of AFVs (data not shown).

The impact of the significant AFV sales in the baseline case is shown in Figure 3. Both LDV carbon emissions and gasoline consumption show significant decreases (42% and 56%, respectively) relative to the start of the simulation, despite the fact that the total number of vehicles rises 37% over the 35-year simulation run. By 2050, LDV gasoline consumption has dropped to less than 60 billion gallons per year. This level of emissions and petroleum reductions is enabled by AFVs, however predicted improvements to conventional gasoline vehicles are responsible for a large portion of the savings. Gasoline vehicle improvements alone would result in 25% reductions in both gasoline use and carbon emissions in 2050 (relative to 2015).

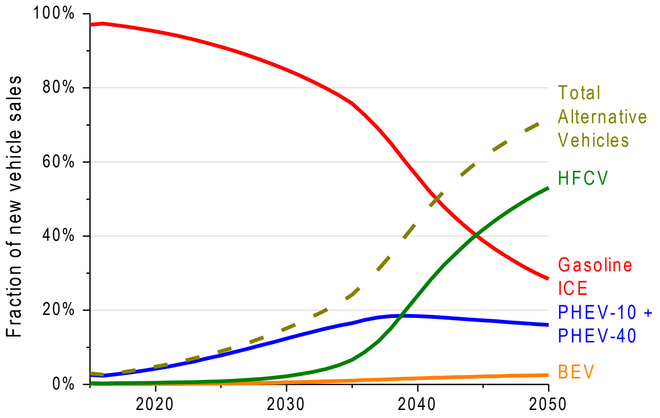

FIGURE 2. Fraction of LDV sales by powertrain for the baseline case. PHEVs are the dominant AFV at the start of the simulation, however HFCV sales rise quickly starting in 2035.

In the baseline case, we assume all AFV powertrains (PHEV10, PHEV40, BEV, and HFCV) are available. However, AFV technologies require substantial infrastructure investment and research and development progress, and it is possible that not all AFV powertrains will reach large-scale commercial viability. We examine the effects of powertrain unavailability in Figure 4 and Table 2. These data show the effect of not having BEVs, HFCVs or both on key metrics. As shown in Figure 4, the reduction in carbon emissions due to HFCV availability is over 5-fold greater than the reduction due to BEV. In Table 2, the impact of powertrain availability on LDV gasoline consumption is shown and the HFCVs show almost an order of magnitude greater reduction.

Conclusions and Future Directions

Under our baseline case of moderate oil price increases, our analysis predicts 50% hydrogen fuel cell and electric vehicles by 2050. The large-scale market penetration of HFCVs would allow significant greenhouse gas emission and gasoline use reductions, with over 50% decrease in gasoline use in 2050 (relative to 2015 levels). Increasing oil prices

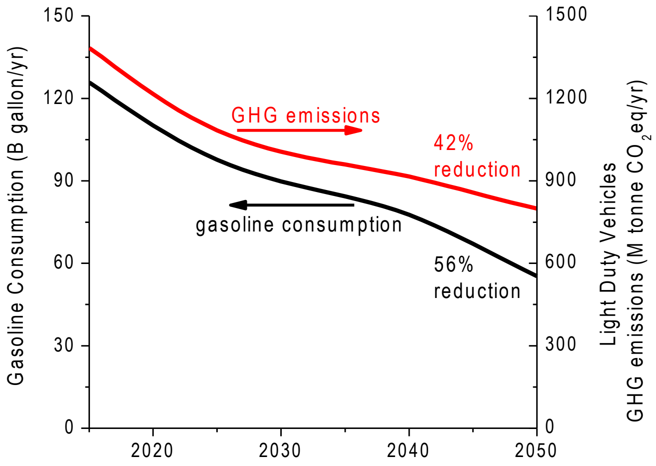

FIGURE 3. Gasoline consumption and carbon emissions from the LDV fleet in the baseline case. Reductions shown are relative to the values in 2015.

TABLE 2. Annual LDV Gasoline Consumption under Different Assumptions for Gasoline Price Projections (Constant Dollars) and Vehicle Powertrain Availability

Oil Price, 2015→2050	ICE+PHEV	ICE+PHEV+BEV	ICE+PHEV+HFCV	ICE+PHEV+HFCV+BEV
$90/bbl, no increase	92.7 B gal/yr	92.6 B gal/yr	91.4 B gal/yr	91.3 B gal/yr
$90/bbl → $195/bbl	84.5 B gal/yr	82.6 B gal/yr	56.2 B gal/yr	55.3 B gal/yr
$90/bbl → $265/bbl	79.6 B gal/yr	75.6 B gal/yr	40.5 B gal/yr	39.2B gal/yr

bbl - barrel

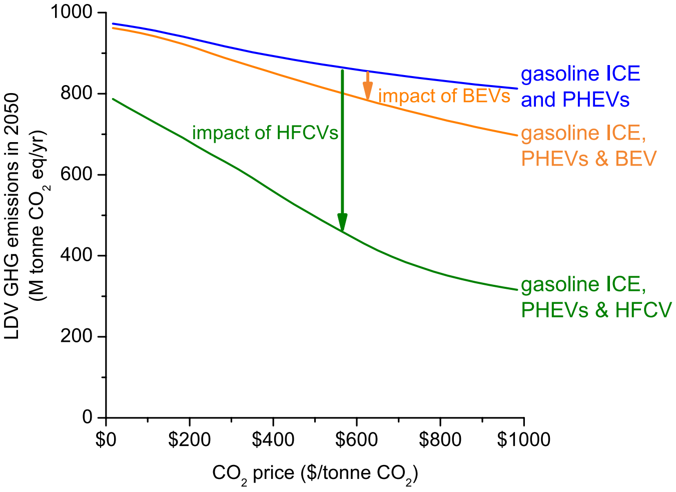

FIGURE 4. Carbon emissions as a function of carbon price in cases with different powertrain availability. The highest emissions are for the scenario in which only gasoline ICE and PHEVs are available (no HFCVs or BEVs). The middle line shows the emissions with gasoline ICE, PHEV and BEV vehicles (no HFCVs), and shows moderate reductions in carbon emissions due to BEV availability. The lowest line corresponds to the scenario with gasoline ICE, PHEV and HFCV vehicles (no BEVs). The impact of HFCV availability is much greater than BEV availability.

(and/or policies that give a price to carbon) are needed for significant numbers of HFCVs (or AFVs) to penetrate the LDV fleet. Our analysis predicts HFCVs will have much larger effect than BEVs on both gasoline consumption and LDV carbon emissions.

The model described in this report analyzes a subset of possible hydrogen production pathways, limiting our ability to model hydrogen infrastructure development and also limiting analysis of carbon-neutral transportation options. Future work will include more energy sources and production processes, with an emphasis on low-carbon hydrogen production options, so that infrastructure requirements and potential limiting factors for hydrogen fuel cell technologies will be better understood.

Acknowledgements

We acknowledge helpful discussions and assistance from the SNL “Transportation Energy Pathways” Laboratory Directed Research and Development team, led by Dawn Manley and Todd West. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

FY 2011 Publications/Presentations

1. Annual Merit Review, Washington, D.C., May 2011.

2. D.S. Reichmuth and J.O. Keller, “Impact of Hydrogen Resource and Vehicles on U.S. Greenhouse Gas Emissions and Petroleum Use,” 9th Fuel Cell Science, Engineering, and Technology Conference, Washington, D.C., August 2011.

References

1. Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule. In Envionmental Protection Agency, Department of Transportation,, Ed. Federal Register: 2010; Vol. 40 CFR 85,86,600 49 CFR 531,533,536,537.

2. Lutz, A. and Reichmuth, D., “Analysis of Energy Infrastructures and Potential Impacts from an Emergent Hydrogen Fueling Infrastructure”, DOE Hydrogen Program FY 2009 Annual Progress Report.

3. Struben, J. and Sterman, J., “Transition challenges for alternative fuel vehicle and transportation systems.” *Environment and Planning B*. 35, 1070-1097. (2008)

4. Population Division, U.S. Census Bureau,*Projections of the Population and Components of Change for the United States: 2010 to 2050*; 2008.

5. Greene, D., Leiby, P., James, B., Perez, J., Melendez, M., Milbrandt, A., Unnasch, S., Hooks, M., “Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements”, ORNL/TM-2008/30, March 2008.