VII.6 Analysis of Energy Infrastructures and Potential Impacts from an Emergent Hydrogen Fueling Infrastructure

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Objectives

- Develop models of interdependent energy infrastructure systems.
- Analyze the impacts of widespread deployment of a hydrogen fueling infrastructure.
- Identify potential system-wide deficiencies that would hinder infrastructure growth.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Hydrogen, Fuel Cells and Infrastructure 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 Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) 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, 2009)
- **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 market behavior of natural gas (NG), refined petroleum, hydrogen, and electricity generation in California (CA).
- Incorporated a vehicle adoption model based on the Struben and Sterman [1] formulation for hydrogen fuel cell vehicles (HFCVs) and plug-in hybrid electric vehicles (PHEVs).
- Performed analysis of vehicle penetration scenarios to project increased demand and prices for hydrogen, NG, and electricity.

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Introduction

The HFCIT program envisions the transition to hydrogen vehicles will begin by taking advantage of the existing infrastructure for NG. Since hydrogen production by steam-methane reforming (SMR) is currently the most economical production pathway [2], we start with a study of the impact of hydrogen vehicles on demand for NG. Natural gas demand comes from several sectors, so growing demand from hydrogen production can potentially affect sectors such as electricity generation. Understanding the potential impacts of a hydrogen refueling infrastructure requires a model that couples the markets for natural gas and electricity.

In addition to hydrogen vehicles, PHEVs may provide an alternative to conventional gasoline vehicles. Competition between HFCVs and PHEVs will depend on their relative performance and cost, including the costs of hydrogen, electricity, NG, and gasoline.

Approach

We use the system dynamics approach to simulate the interaction of vehicle adoption and infrastructure for hydrogen, electricity, NG, and gasoline. The model formulation considers vehicle sales to occur according to a driver's willingness-to-adopt the alternative vehicles, which is parameterized by factors for the effectiveness of advertising and word-of-mouth [1]. Given a willingness-to-adopt, drivers will purchase the alternative vehicles when the performance of the vehicle, measured here as an operating cost (per mile), favors the alternative. The performance relative to conventional vehicles depends on the incremental sales cost spread over the vehicle life, as well as the fuel cost and mileage. The assumptions for vehicle performance are listed in Table 1.

TABLE 1. Vehicle Model Assumptions

Gasoline vehicle mileage	20 mpg
PHEV	
Gasoline mileage	48 mpg
Electric mileage	0.35 kWh/mi
Fraction electric mode	2/3
Electric range	40 miles
HFCV Mileage	65 miles/kg
Total vehicle sales rate	6%/yr
Total vehicle scrap rate	5%/yr

The model considers the energy infrastructure for California, because the state is a "lighthouse" region expected to lead the way in adopting HFCVs. The infrastructure model computes fuel demand from the vehicles and balances this with supplies to estimate price variations. The model uses traditional elasticity parameters to represent the price of NG and refined gasoline, which for CA is a unique blend not available from out-of-state refiners. The gasoline price uses the projected oil price and adds a refining margin that varies with a supply elasticity. The demand for NG comes from electricity generation and vehicles, which couples these HFCVs and PHEVs, because the reformed hydrogen and the variable electricity demand both consume NG. The assumptions for the energy markets are listed in Table 2.

Results

The model simulates the market adoption of PHEVs and HFCVs to replace conventional gasoline vehicles in time. The parameters in the adoption model are adjusted to capture the vehicle sales fractions suggested by Scenario #1 of the Greene *et al* [3] study; we use this team's study of potential vehicle adoption as a reference case upon which to begin evaluating the impact of the vehicles on the infrastructure. A departure from Greene *et al* is that we substitute PHEVs for gasoline hybrids. Figure 1 shows the simulated number of vehicles on the road for this reference scenario. The PHEVs are adopted before the HFCVs, because the incremental cost

TABLE 2. Infrastructure Model Assumptions

Natural Gas	
Supply:	Imports and in-state production
Demand:	• Electric generation • H_2 demand from SMR • Industrial, commercial, and residential are constant
Price:	• Varies with market elasticity • Initial value: $8/GJ
Hydrogen	
Demand	HFCV
Price	• Computed from NG price via SMR at 70% efficiency • Includes $1/kg fixed cost • Initial value: $3/kg
Electricity	
Supply:	• Imports: 31% of total 54% of imports from coal • Must-run generation: nuclear, hydro, other renewable • Variable generation: NG
Demand:	• Load data with hourly resolution (Cal-ISO over 1 yr, 2007) • PHEV charging at night
Price:	• Weighted average of fixed and variable generation costs • Initial value: 12 ¢/kWh
Gasoline	
Supply:	• Refinery capacity for CA compliant gasoline
Demand:	• Conventional and PHEV consumption
Price:	• Oil price rises linearly from $65/bbl to $140/bbl in 2030 • Refining mSargin market elasticity • Initial value: $2.50/gallon

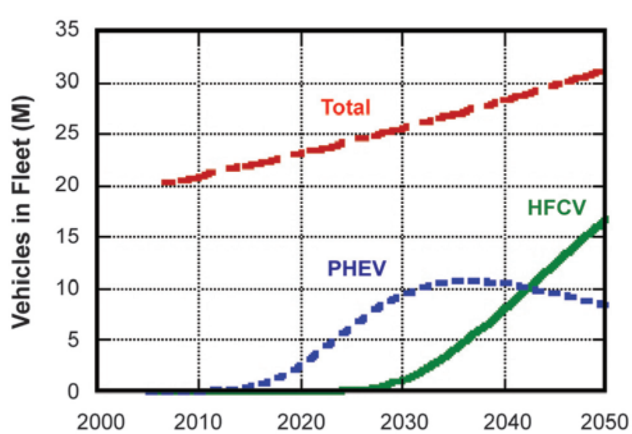

FIGURE 1. Number of PHEVs (dotted curve), HFCVs (solid curve), and total vehicles (dot-dashed curve) in California during the reference case simulation.

of the HFCVs includes an exponentially decaying cost per mile that makes the fuel cell vehicles too expensive until about 2020, consistent with the learning curve used by Greene *et al* [3].

The increasing demand for NG – from both PHEVs and HFCVs – causes the price to increase 150% by mid-century. Figure 2 shows the increase in price for the fuels during time, relative to the initial prices given in Table 2. The hydrogen price tracks the NG price, because SMR is the only path to hydrogen; however, the relative increase is not the same, because there is a fixed cost of $1/kg added to the contribution from NG. The NG price increases by a larger fraction than electricity, because of the extra demand of the HFCV; note that this reference case holds the other electricity demand fixed at the 2007 level.

The gasoline price shows an interesting dynamic caused by the reduced demand. Despite the linearly increasing oil price, the gasoline price flattens out during the decade following 2020 due to the reduced refining margin. After the refining margin reaches a minimum, the price rises again with the assumed linearly increasing oil price. While this gasoline price reduction is plausible, the model may not be realistic at extremely low demand for gasoline, because the oil price would probably not continue to increase on the world market.

The dynamic model can be used to examine the effects of a variety of parameters. For example, what if the HFCVs do not achieve DOE HFCIT program targets? Decreasing the HFCV mileage to only 55 mile/kg means that PHEVs maintain a majority of market share by 2050. What if conventional vehicles increase their efficiency? Increasing the conventional vehicles over time to 30 mpg decreases the market adoption of PHEV in the near term, but the HFCVs are adopted at about the same rate in the longer term. What about the effect of a cost for carbon emissions? Imposing a carbon dioxide cost of $200/tonne, which is about $1.75/gallon of gasoline, increases the PHEVs on the road by about 4 million vehicles, because the electricity used by the PHEVs for two-thirds of their travel has lower average carbon emissions than gasoline. Interestingly, the simulation suggests about the same population of HFCVs as the reference case, because the carbon cost on the SMR path adds $1.85/kg to the hydrogen price, but adds only 3 ¢/mile to the operating cost.

The dynamic model suggests that the most critical component of the CA energy infrastructure will be the capacity for importing NG. Figure 3 shows the fraction of the supply capacity that must be used to import the NG to meet demand under three scenarios. The reference scenario considers the increased adoption of vehicles only, without any growth in other electricity demand; this scenario suggests the existing import pipeline capacity will not be exceeded by mid-century – although operation at 95% of capacity will likely have problems supplying seasonal variations. However, the electric growth alone will likely stress the NG supply system much sooner; electric demand growth of 1% per year will exceed NG import capacity by 2035. Adding the reference case penetration of alternative vehicles exacerbates the NG supply problem by moving the critical point up about a decade.

Conclusions and Future Directions

The dynamic model for the CA energy markets predicts significant price increases for NG and electricity if an aggressive scenario of PHEV and HFCV adoption occurs. The coupling of plug-in and hydrogen vehicles supplied by SMR links both vehicles to the supply of NG. The simulations suggest that understanding the CA energy market in the coming decades requires predicting the supply and price of NG.

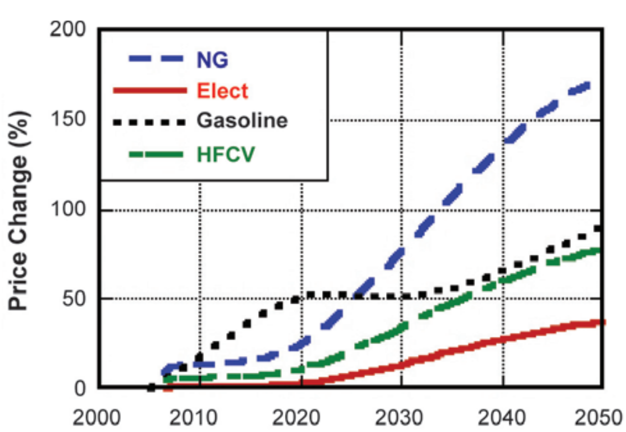

FIGURE 2. Price change (in percent) from the beginning of the dynamic simulation for electricity (solid curve), NG (dashed curve), gasoline (dotted curve), and hydrogen (dot-dashed curve).

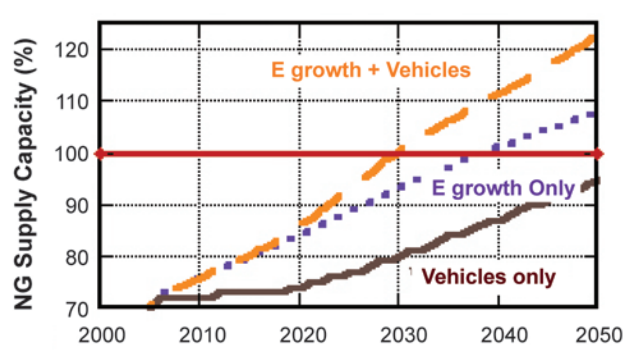

FIGURE 3. Fraction of the NG pipeline capacity necessary to import NG into California to meet demand for three cases: reference case for alternative vehicles only (solid curve); electricity growth at 1%/yr but without alternative vehicles (dotted curve); and the combination of electricity growth and alternative vehicles (dashed curve).

The plan for future work includes more dynamic modeling of the NG flows into the state and providing an electrolysis option for hydrogen production, coupled to increased renewable electricity to meet California's Renewable Portfolio Standard. Next year's work will focus on applying the influence of stationary fuel cell systems for production of electricity and hydrogen.

FY 2009 Publications/Presentations

1. MIT/Ford/Shell Research Workshop on Strategies for Market Transitions to Alternative Energy and Transportation Systems, Detroit, MI, June 9, 2009.

2. Fuel Pathways Integration Technology Team, Golden, CO, June 16, 2009.

References

1. Struben, J. and Sterman, J., "Transition challenges for alternative fuel vehicle and transportation systems, *Environment and Planning B: Planning and Design*, Vol 35, pp 1070-1097, 2008.

2. James, B and Perez, J, "Hydrogen Pathway Analysis using HyPro", DOE HFCIT Annual Merit Review, May 2007.

3. 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.