X.17 Analysis of Energy Infrastructures and Potential Impacts from an Emergent Hydrogen Fueling Infrastructure

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Objectives

SNL has developed and has access to a number of software simulations and analysis tools for studying critical infrastructures and their interdependencies. Production and delivery of energy to the transportation sector is accomplished through complex networks of interdependent systems, and decision makers need reliable information detailing the likely impacts of an emergent hydrogen fueling infrastructure on these existing systems.

- Analyze the impacts of deploying a widespread hydrogen fueling infrastructure on existing infrastructures.
- Identify potential system-wide deficiencies that would otherwise hinder infrastructure evolution.
- Identify mitigation strategies that would promote adoption of hydrogen-fueled vehicles.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section (4.5) 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 (4.7, Task 1) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 5:** 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:** Analysis and studies of resource/feedstock, production/delivery and existing infrastructure for technology readiness. (4Q, 2014)

Accomplishments

SNL developed a dynamical model to analyze the likely impact of hydrogen derived from methane reforming on the petroleum, natural gas (NG), and electricity markets in California (CA).

- Developed system dynamics (SD) model that describes the complex market behavior of interconnected infrastructures in CA (NG, refined petroleum [RP], and electricity).
- Incorporated Bass [1] technology diffusion approach to predict hydrogen-fueled vehicle (HFV) demand (no need to impose technology adoption scenarios).
- Performed preliminary analysis of HFV rollout in CA under two limiting assumptions (*high* and *low* technology adoption rates) and two extremes of NG demand (baseline and an increased demand from the electric power sector).

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Introduction

This project supports the DOE Hydrogen, Fuel Cells, and Infrastructure Technologies Program by analyzing the potential impact of an emergent hydrogen fuel infrastructure on existing infrastructures, and by providing technical guidance as systems evolve over time. Production and delivery of energy to the transportation sector is accomplished through complex networks of interdependent systems comprised of energy sources, coupled to conversion and distribution systems, which deliver fuel and electricity. In order to effectively navigate infrastructure evolution, decision makers need reliable information detailing the impact of public policy and capital investment on future markets and infrastructure reliability. This is especially critical in the future of hydrogen-powered transportation where rapid introduction of new technology will be an important driver. The goal of this task is to use dynamic models of interdependent infrastructure systems (NG, coal, electricity, petroleum, etc.) to analyze the impacts of widespread deployment of a hydrogen fueling infrastructure, identify potential system-wide deficiencies that would otherwise hinder infrastructure evolution, and formulate mitigation strategies that will support growth and acceptance of HFV technologies.

Approach

Consistent with SD methodologies developed at SNL through Department of Homeland Security funded projects, this infrastructure analysis task was initiated by addressing fundamental questions surrounding the rollout of hydrogen fueling stations in urban settings. Using CA as a contextual backdrop, an SD model representing the aggregate behavior of NG, RP, and electric power (EP) markets was formulated with sufficient fidelity to simulate the effects of large scale steam methane reformer (SMR)-derived hydrogen on regional supply and demand. It was anticipated that fueling support for a successful HFV adoption plan would likely perturb these systems, and that response functions dependent upon feedback loops would yield complex or non-intuitive behaviors. A key aspect of this approach begins with formulating questions pertinent to infrastructure assurance and vehicle acceptance, such as: 1) to what extent will the demand for SMR-derived hydrogen impact the NG market, 2) are there interdependencies between the NG and EP systems in CA that could have a negative impact on HFV adoption rates, and 3) are the existing infrastructures capable of supporting a large number of HFVs?

The SD model was assembled within the Vensim (Ventana Systems, Inc.) environment which allows for graphical representation and assembly of the system of non-linear differential equations that constitute the behavioral model. The dynamics are representative of a traditional stock and flow approach where flows and capacities (either transmission into CA or internal generation) of NG, RP, and EP are represented. The dynamics of HVF adoption were incorporated endogenously in order to account for market forces that reflect the temporal demand for hydrogen, and subsequent impact on the price of NG and RP, using a Bass [1] diffusion approach. Figure 1 shows a schematic illustration of key variables endogenous to the model. Data needed to initialize the model and recover accurate flow rates were taken from various sources including the Federal Energy Information Administration and the California Public Utilities Commission. In brief, the model focuses on interactions over time between sectors/infrastructures resulting from the production of hydrogen needed to satisfy the demand of HFVs. These interactions are governed by economic theory inclusive of market elasticity, market latency, and appropriate recovery margins. At this point in model development there are many limiting assumptions, most important are: 1) resource capacities and CA population are exogenous and held static (not accounting for growth or infrastructure development), 2) the model does not resolve geospatial features, and 3) elasticity factors remain fixed.

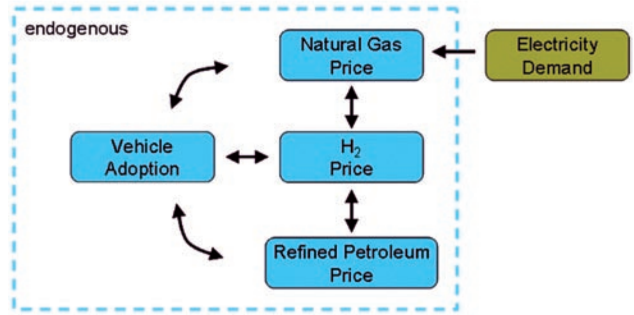

FIGURE 1. Schematic of the SD model concept illustrating key variables endogenous to the model as well as those that are currently exogenous but will be integrated in future revisions.

Results

Preliminary analysis focused on two extreme cases of technology adoption rates and a single perturbation in the NG demand by the EP sector under these two extremes. Figure 2 presents the number of HFVs and the associated demand for NG predicted as a function of time for a *high* rate of vehicle adoption. Figure 3 presents this same information for a *low* rate of vehicle adoption. The *high* and *low* rate outcomes were achieved by adjusting model parameters that control advertising effectiveness, vehicle reliability, and fuel efficiency. Baseline cases where derived from current estimates to resource capacity and demand for each sector. The baseline gasoline price was arrived at by adjusting the world price for oil to match current prices at the pump in CA (roughly $150/barrel), which remained fixed throughout the simulation. The high EP case assumed an instantaneous increase of 35% above baseline for NG by the EP sector (effectively simulating growth without NG infrastructure improvement).

Figure 2 indicates that a modestly successful HFV rollout (displacing 3.5 MM gasoline-fueled cars) would not significantly increase the demand for NG in CA, only adding an additional 3% above current levels. Currently

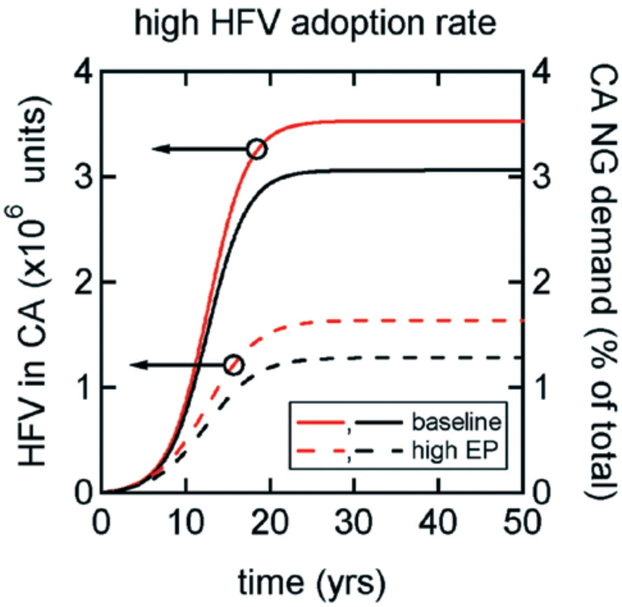

FIGURE 2. Number of HFVs in CA (left) and the associated demand for NG (right) as a function of time for a simulation with *high* technology adoption rates. Solid lines are for the baseline case, broken lines are for increased competition for NG resources imposed by an expanded EP sector (see text).

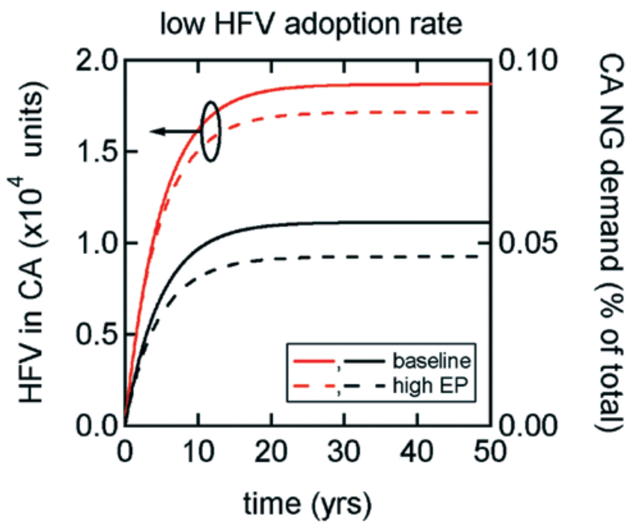

FIGURE 3. Number of HFVs in CA (left) and the associated demand for NG (right) as a function of time for a simulation with *low* technology adoption rates. Solid lines are for the baseline case, broken lines are for increased competition for NG resources imposed by an expanded EP sector (see text).

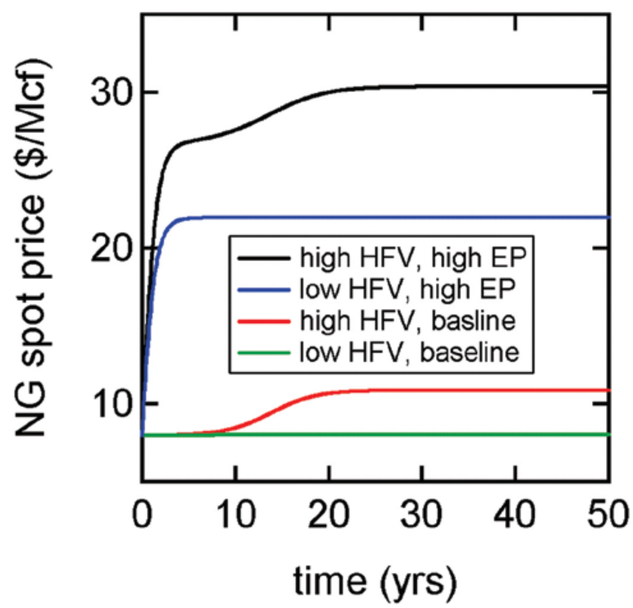

FIGURE 4. Spot price for NG as a function of time predicted by the SD model for various technology adoption rates and NG demand assumptions.

the compressed natural gas vehicle fleet accounts for approximately 0.5% of total demand and is considered a successful alternative fuel technology, so these results seem plausible. The predicted rollout behavior is significantly impacted if a future situation exists where the EP sector expands by 35% without improving the NG infrastructure. While the model behavior does not predict failure or die out of the HFV technology (perhaps because this dynamic is not adequately represented by the constitutive equations), the results do indicate fewer HFVs adopted. This is mainly due to higher NG spot prices for the high EP case, which in turn increases the cost of hydrogen fuel relative to gasoline making HFV technologies less attractive to consumers (spot NG prices as a function of time for all four scenarios are presented in Figure 4 and mirror the ratio of H_2 to gasoline price). The high EP case does not impact the low rate of HFV adoption scenario as strongly, presumable due to other cost factors that are more significant for low volume acceptance.

Another notable market behavior that may negatively impact HFV adoption is the effect on the spot price for NG resulting from a high rate of vehicle acceptance. The red solid curve in Figure 4 indicates that the spot price for NG increases by 36% (from $8/Mcf to nearly $11/Mcf) with only a 3% in crease in NG demand. This behavior is representative of a supply system near capacity, as is the case for NG, RP, and EP sectors in CA. Due to market elasticity factors, operating near capacity can result in unanticipated effects as was witnessed in CA during the power crisis of 2000-2001. While these results are preliminary, and more work is needed to refine the method and evaluate sensitivities to model parameters, it does illustrate the utility of SD approaches in that unexpected behavior may arise that would otherwise go unnoticed using conventional market projection or equilibrium methods.

It is clear from the preliminary analysis that the current CA NG infrastructure can absorb the additional demand imposed by millions of HFVs on the road, especially if the transition is accompanied by infrastructure improvements (as would be expected in a growing or developing marketplace). As the project moves forward, we expect to resolve less intuitive behaviors by assessing near term impacts on infrastructure stability and reliance given that utilization levels are extremely high for all three energy supplies (NG, RP, and EP), and systems operating at or near capacity can exhibit problematic behavior.

Conclusions and Future Directions

An SD model was developed and used to analyze the CA energy infrastructures (NG, RP, and EP) as they respond to the added demand of providing SMR-derived hydrogen to fuel vehicles. Results indicate:

- A successful rollout of HFVs will not dramatically increase demand for NG.
- NG and EP systems in CA running near capacity may exhibit undesirable market behavior induced by marginal demand increases.
- Given sufficient time for infrastructure improvement or expansion, these effects can be mitigated.

Future Work

- Fully integrate EP distribution dynamic into model.
- Resolve key dynamical behaviors resulting from infrastructure interdependencies.
- Identify system vulnerabilities that may hinder HFV rollout.
- Develop a resource utilization metric to quantify system perturbations.
- Assess and analyze other U.S. regions.
- Investigate issues stemming from coal-to-hydrogen in regions dependent on coal-derived electrical power.

References

1. Bass, FM; *Management Science*, **15**(5), p 215, 1969.