VII.2 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.
- 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 market behavior of natural gas (NG), refined petroleum, hydrogen, and electricity generation in California.
- Incorporated a vehicle adoption model for hydrogen-fueled vehicles, plug-in hybrid electric vehicles, and a new generation of conventional vehicles that meet the Corporate Average Fuel Economy (CAFE) regulation through the 2016 ruling.
- Incorporated a model for the impact of stationary fuel cell systems with distributed generation of electricity by combined with the provision of heat or cooling to a building, and potential co-production of hydrogen for vehicles.

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Introduction

The DOE Hydrogen Program envisions the transition to hydrogen vehicles will begin by using the existing infrastructure for NG to produce hydrogen by steam-methane reforming (SMR). In addition, the transition to widespread use of hydrogen in fuel cells is expected to benefit from development of the market for stationary fuel cells (SFCs). Previously, we developed a model for the adoption of hydrogen-fueled vehicles (HFVs) and plug-in hybrid electric vehicles (PHEVs). The model showed that adoption of either of these alternative fuel vehicles (AFVs) effectively couples transportation to the markets for hydrogen, electricity, and NG.

The present work investigates the coupling of hydrogen and electricity further by adding the adoption of SFC distributed to buildings. The model is now able to examine the reduced load on the grid from distributed SFC, as well as the potential benefits of combined heat (or cooling) and power. Lastly, the application of high-temperature SFC systems allow for the potential co-production of hydrogen, for local refueling of HFVs.

Approach

We use the system dynamics approach to simulate the adoption of SFCs for a selection of buildings within the state of California, which is expected to lead the adoption of HFVs. The adoption of SFCs is specified based upon estimates of the potential for applying combined heat and power (CHP) provided by the California Energy Commission [1]. The penetration of SFCs is not modeled as a competitive adoption based on economics, so the model serves to estimate the potential impact that SFC systems can have on the electricity and fueling infrastructure.

The simulated operation of the SFC follows daily load profiles for the electricity, heating, and cooling for various buildings taken from the DOE database [2]. The hourly loads for the buildings are combined with the total electricity load for the state from California Independent System Operator data [3]. The distributed electricity provided by the SFC reduces the total state demand, which is filled by a simple dispatch model developed previously [4]; the model approximates the state electricity mix for baseload power, but assumes that all marginal electricity is provided by NG generation. Consequently, distributed electricity reduces the demand for NG generation.

The SFCs are sized for buildings and homes to operate with about a 75% capacity factor. A daily load profile for a type of building–large office, for example–is considered for each of the four seasons; the simulation timestep is a quarter of the year, so the integrated operation over a day in each season represents an average for the quarter. When the SFC can meet the building electric load, its electricity reduces the demand on the grid. When the building load exceeds the SFC capacity, the excess load is taken from the grid. Similarly, the useful heat provided by the SFC in CHP mode offsets NG demand for a combustion-driven heater. In combined cooling and power (CCP) mode, the waste heat from the SFC is used in an absorption chiller to provide cooling, thereby offsetting electricity that would have otherwise provided the air-conditioning.

The details of the SFC operation are summarized in Table 1. The model considers two types of SFCs: large, high-temperature systems and small, low-temperature proton exchange membrane fuel cells (PEMFCs). The high-temperature systems have sufficient waste heat to operate either in CHP or CCP mode, depending on which mode the building load demands for the season of year. In addition, the model allows the potential to provide combined heat and hydrogen production (CHHP mode) for fueling HFVs. For the CHHP mode, the electrical efficiency is reduced from 47% to 40%, consistent with the operational data of an example molten carbonate fuel cell system [5].

TABLE 1. Model Assumptions for SFC Applications

<table>
<tr><td rowspan="9">Large Scale</td><td colspan="2">250–500 MW high temperature</td></tr>
<tr><td colspan="2">NG fuel with internal reforming</td></tr>
<tr><td colspan="2">Commercial building applications</td></tr>
<tr><td rowspan="2">CHP mode</td><td>47% NG to electric efficiency</td></tr>
<tr><td>30% NG to useful heat</td></tr>
<tr><td rowspan="2">CCP mode</td><td>47% NG to electric efficiency</td></tr>
<tr><td>10% NG to displaced electric</td></tr>
<tr><td rowspan="2">CHHP mode</td><td>40% NG to electric efficiency</td></tr>
<tr><td>15% NG to H_2</td></tr>
<tr><td rowspan="4">Small Scale</td><td colspan="2">2–5 kW PEMFC</td></tr>
<tr><td colspan="2">NG fuel with integrated reformer</td></tr>
<tr><td rowspan="2">CHP mode</td><td>40% NG to electric efficiency</td></tr>
<tr><td>30% NG to useful heat</td></tr>
</table>

The SFC systems distributed in buildings by size and type, as described in Table 2, displace both electricity demand from the grid and NG demand for heating. These demands are coupled to the vehicle model and the markets for NG and gasoline, which adjust the prices via elasticity models. The electricity cost is computed using fixed costs for each type of generation in the mix, including distributed SFC generation. The hydrogen cost is related to the NG cost by the efficiency of SMR and a fixed cost to represent the fueling station.

TABLE 2. SFC Application to Buildings

	Units	Size (kW)	Capacity (GW)
Offices	7,000	400	2.7
Hotels	8,000	250	1.9
Homes	1,300,000	4	5.2

Results

The projected impacts of SFCs and vehicles on the overall CO_2 emissions (including all sectors) for California (CA) are shown in Figure 1. Starting from the top-most curve, the solid curve shows the continuation of existing electricity generation and vehicle travel. The business-as-legislated (BAL) curve shows the impact of two regulations: the CA Renewable Portfolio Standard (33% by 2020) and the CAFE regulation (35.5 mpg by 2016). These two existing regulatory changes will reduce CO_2 emissions by 18% below the unregulated emissions by mid-century.

The next simulation adds the impact of SFC to the BAL scenario to see that there is only a minor effect–about 2% further reduction in CO_2 emissions. The impact is small because the SFCs displace NG plants with distributed generation that is only marginally

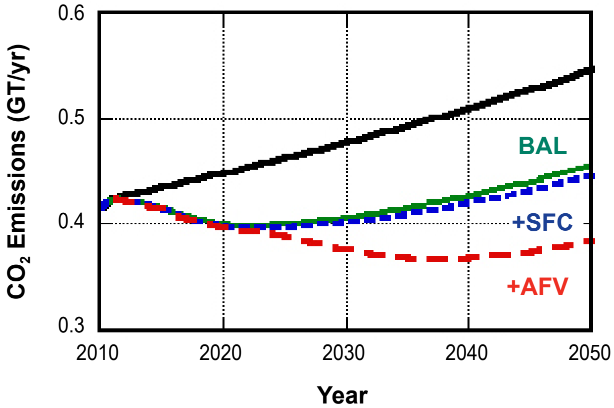

FIGURE 1. Total CO_2 emissions (giga-tonnes per year) for California in the scenarios: solid black curve is business-as-usual following current trends; dotted green curve is business-as-legislated for the state's Renewable Portfolio Standard for electricity and the national CAFE regulation on vehicles; dashed blue curve adds SFCs; long-dashed red curve adds AFVs, including HFVs and PHEVs.

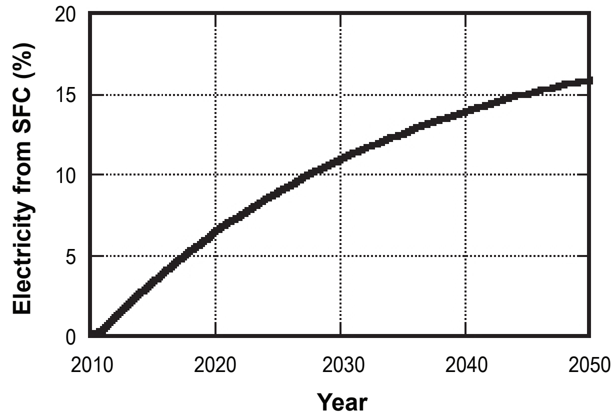

FIGURE 2. Fraction of California's electricity generation from SFC systems for the SFC scenario in Figure 1.

more efficient. The large SFC systems operate with an electrical efficiency that is about 7% better than conventional generation (~40%). The PEMFC systems have approximately the same electric efficiency as the conventional NG generation. The combined benefits of heat or cooling are marginal, because on average only about one-half of the available heat is matched to the daily heating or cooling demand; the other heat is not useable, due to mismatch in the timing of the electricity load and the heating load. Figure 2 shows the fraction of the total electricity supplied to the state by the SFCs. By mid-century, the SFC systems provide 16% of CA's electricity. The total SFC capacity is 10 GW for the state load that varies from 30 to 70 GW.

Turning now to the impact of AFVs–both PHEVs and HFVs–which replace conventional and CAFE-compliant gasoline vehicles as shown in Figure 3. The penetration of HFVs and PHEVs were adjusted previously [4] to reflect the projections by Greene et al. [6]. The performance assumptions for vehicle performance are listed in Table 3. The impact of the large number of AFVs entering the state on-road fleet is much larger than that of the SFCs, adding a further 14% reduction from the SFC scenario. Since hydrogen from SMR without sequestration brings about the same CO_2 per energy content as gasoline, the gain from HFVs is due to the greater fuel economy.

While the SFC systems do not provide a large impact on CA's CO_2 emissions, there is the potential for distributed co-production of hydrogen for vehicles. In the AFV scenario, the hydrogen demand grows to 3 billion kg per year, of which the large-scale SFC could potentially provide 11%, or enough to fuel about 2 million vehicles per year. Early market-adoption of SFCs could potentially help support the initial HFV refueling infrastructure.

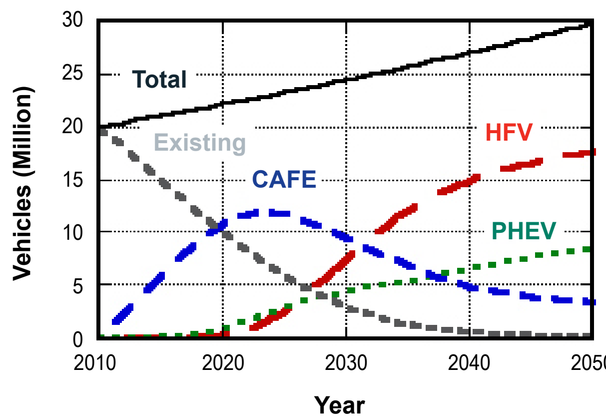

FIGURE 3. Number of vehicles on the road in California in the AFV scenario of Figure 1. Total vehicles are solid curve; existing conventional vehicles are grey short-dashed curve; vehicles complying with the new CAFE regulation are the blue dashed curve; PHEVs are the dotted green curve; HFVs are the red long-dashed curve.

TABLE 3. Vehicle Model Assumptions

Gasoline vehicle mileage	20 mpg
CAFE vehicle mileage	35 mpg by 2016
PHEV	
Gasoline mileage	48 mpg
Electric mileage	0.35 kWh/mi
Fraction electric mode	2/3
Electric range	40 miles
HFV mileage	70 miles/kg
Total vehicle sales rate	6% / yr
Total vehicle scrap rate	5% / yr

mpg – miles per gallon

Conclusions and Future Directions

The dynamic model for the CA infrastructure shows a limited impact of an optimistic penetration of stationary fuel cell systems on the overall CO_2 emissions. The benefits of CHP are also limited by the matching of local building loads for electricity and heat (or cooling). However, the adoption of AFVs–primarily HFVs, but also PHEVs–brings a CO_2 reduction nearly equivalent to the expected impact of existing regulations. The potential for CHHP to supply HFV in the state is significant if the SFC adoption occurs concurrently with the vehicles.

These conclusions regarding the impact of SFC with CHP are limited to the state of CA. Future work will apply the model to a region of the country where coal-fired electricity generation is dominant. Preliminary simulations suggest that the effect of SFC will be significant. Further development of the model will engage industry and utility partners to enhance the fidelity of the electricity dispatch model.

Acknowledgements

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FY 2010 Publications/Presentations

1. Fuel Pathways Integration Technology Team, Golden, CO, July 21, 2010.

References

1. "Assessment of California CHP Market and Policy Options for Increased Penetration", Electric Power Research Institute report to California Energy Commission, April 2005, CEC-500-2005-060-D.

2. Buildings Energy DataBook, US DOE/EERE http://buildingsdatabook.eren.doe.gov/, accessed April, 2010.

3. California Independent System Operator data (http://www.caiso.com/outlook/SystemStatus.html) accessed April 2009.

4. 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.

5. Heydorn, E., Patel, P., Jahnke, F., "Development of a Renewable Hydrogen Energy Station", National Hydrogen Assoc. Conference, April 2010.

6. 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.