XI.12 Analysis of Community Energy

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Project Start Date: September 2011
Project End Date: Project continuation and direction determined annually by DOE

Overall Objective

Evaluate the potential benefits of integrating renewable (photovoltaic [PV]) electricity generation with hydrogen-based transportation fueling

Fiscal Year (FY) 2013 Objectives

- Model performance and economics of hydrogen production and storage for capturing peak PV generation and fueling hydrogen-powered vehicles
- Compare system based on PV-generated hydrogen fueling fuel cell electric vehicles (FCEVs) versus system based on PV-generated electricity fueling battery-electric vehicles (EVs)
- Produce draft report of analyses

Technical Barriers

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

(B) Stove-piped/Siloed Analytical Capability

(D) Insufficient Suite of Models and Tools

(E) Unplanned Studies and Analyses.

Contribution to Achievement of DOE Systems Analysis Milestones

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

- Milestone 1.5: Complete evaluation of hydrogen for energy storage and as an energy carrier to supplement energy and electrical infrastructure. (4Q, 2012)
- Milestone 1.17: Complete analysis of program technology performance and cost status and potential to enable use of fuel cells for a portfolio of commercial applications. (4Q, 2018)

FY 2013 Accomplishments

- Created two distributed PV/vehicle-fueling system models: one using PV to supply electricity to buildings and produce hydrogen for FCEV fuel, and one using PV to supply electricity to buildings and produce electricity for EV fuel.
- Performed hourly modeling of all system energy flows using modeled building load and measured solar resource data, highlighting the time-dependent impacts of distributed PV generation.
- Analyzed realistic grid impacts for three levels of PV electricity generation (1,200-, 4,000-, and 7,000-m^2 PV systems) “behind the meter,” showing that the largest PV system provides the best vehicle-fueling economics, especially for the hydrogen/FCEV system.
- Showed that capturing PV-generated energy for vehicle fueling could eliminate reverse flow of electricity to the grid.
- Compared performance and economics of hydrogen/FCEV system versus electricity/EV system, finding, in the best-case scenario, a vehicle-fueling cost of $0.19/mile for FCEVs versus $0.13/mile for EVs; the EV economics are better largely because EVs use less energy per mile than FCEVs, but the hydrogen/FCEV system provides potential for greater flexibility than the electricity/EV system[1].

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INTRODUCTION

Because PV generation is intermittent, strategies must be implemented to integrate high levels of PV into the electricity system. In particular, high penetration of distributed, residential rooftop PV systems could affect loading and capacity margins for community-level electricity-distribution systems. PV output typically peaks slightly before the

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[1] Hydrogen vehicle: midsize 2012 Honda FCX Clarity, 60 miles/GGE (approx. 55.6 kWh/100 miles), 240 mile range. Electric only vehicle: midsize 2013 Nisson Leaf, 29 kWh/100 miles, 75 miles/charge. Source: Fueleconomy.gov accessed 6/20/2013.

peak daily electricity demand, and this offset could cause overloading of local distribution equipment at high PV penetration.

Hydrogen and fuel cell technologies offer possible PV-integration strategies that could enhance the economic viability—and thus deployment—of both distributed PV and hydrogen/fuel cell technologies. This study modeled and analyzed the costs and benefits of using PV-generated electricity to power homes and produce hydrogen fuel for FCEVs. The study also compared this system to a system that powers homes and stores PV-generated electricity in batteries to fuel EVs.

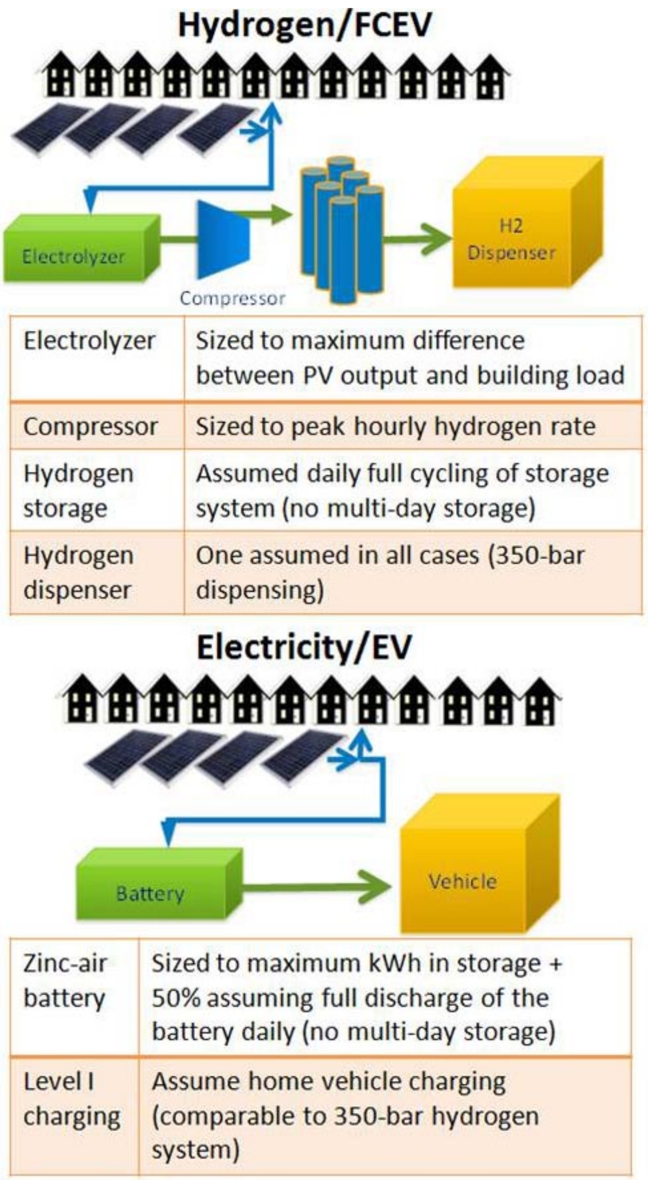
APPROACH

First, simulated systems integrating PV with hydrogen/FCEV and electricity/EV fueling were created using a modified version of DOE's Fuel Cell Power Model. The PV provides electricity to the buildings and all the electricity for vehicle fuel; when PV output is less than building load, the grid supplies the difference. In addition to PV systems of three different sizes (1,200, 4,000, and 7,000 m^2), the hydrogen/FCEV system includes an electrolyzer, compressor, storage, and dispenser, and the electricity/EV system includes battery storage and a charger (Figure 1).

An hourly building load profile for about 100 single-family homes was established based on modeled load data for a hotel (which has a load profile similar to housing) in Boulder, Colorado. Empirical solar resource data for this location were used to determine PV output for each modeled PV system. Vehicle-fueling profiles and hydrogen and battery system performance and costs were developed from a variety of sources [1-11]. Two fueling cases were analyzed. In Case 1, all PV output in excess of building load is directed to vehicle fueling. In Case 2, all PV output before noon plus all output in excess of building load is directed to vehicle fueling. Finally, hourly energy flows—PV output, electricity to buildings (from PV and the grid), electricity to storage (from PV), and stored electricity to vehicles—were modeled for the simulated systems, and system electricity and fuel costs were calculated.

RESULTS

Figure 2 shows an example of system energy flows for a day in July for Case 1 with the 4,000-m^2 PV system. Both building and vehicle peak demands are offset from the peak PV output. During the PV peak, the system draws no electricity from the grid and produces hydrogen or electricity for storage, which is then used to supply the later-peaking vehicle demand. In this example, PV produces the equivalent of 167% of building electricity demand while directly supplying 47% of building demand; the grid supplies the remaining 53% of building demand. Table 1 summarizes the energy flows for the 4,000-m^2 PV Case 1 systems.



Electrolyzer	Sized to maximum difference between PV output and building load
Compressor	Sized to peak hourly hydrogen rate
Hydrogen storage	Assumed daily full cycling of storage system (no multi-day storage)
Hydrogen dispenser	One assumed in all cases (350-bar dispensing)

Zinc-air battery	Sized to maximum kWh in storage + 50% assuming full discharge of the battery daily (no multi-day storage)
Level I charging	Assume home vehicle charging (comparable to 350-bar hydrogen system)

FIGURE 1. Schematics of Hydrogen/FCEV and Electricity/EV Systems

Figure 3 and Figure 4 show the total system capital costs for Case 1 and Case 2, respectively. The PV system dominates the capital costs followed, for the larger systems, by the electrolyzer. When the PV system costs are excluded, the electrolyzer accounts for 16% (1,200-m^2 PV system), 40% (4,000-m^2 system), and 45% (7,000-m^2 system) of the hydrogen system costs. For the smallest PV system, hydrogen storage accounts for the largest capital cost (22%). Hydrogen system capital costs are higher for Case 2 than for Case 1. However, this difference decreases as the PV system size increases because the difference in annual hydrogen production between the two cases (and thus the difference

TABLE 1. Energy Flows for Hydrogen/FCEV and Electricity/EV Systems, Case 1, 4,000-m^2 PV

Equipment/ System	System Size	Yearly Output	Capacity Factor (% of max output during operation [hrs/year])	Percent of Building Load
PV System	4,000 m^2 (~611 kW peak rated output)	955,681 kWh	18	167 (total) 47 (direct supply)
Electrolyzer (H_2 system)	560 kW input	14,564 kg	40 [3,265]	—
Hydrogen Storage (H_2 system)	85 kg	~ 1 cycle per day	—	—
Vehicle Electricity (battery system)	—	500,755 kWh	—	—
Battery Storage (battery system)	2,954 kWh	~ 1 cycle per day	—	—
Grid	—	303,744 kWh	—	53

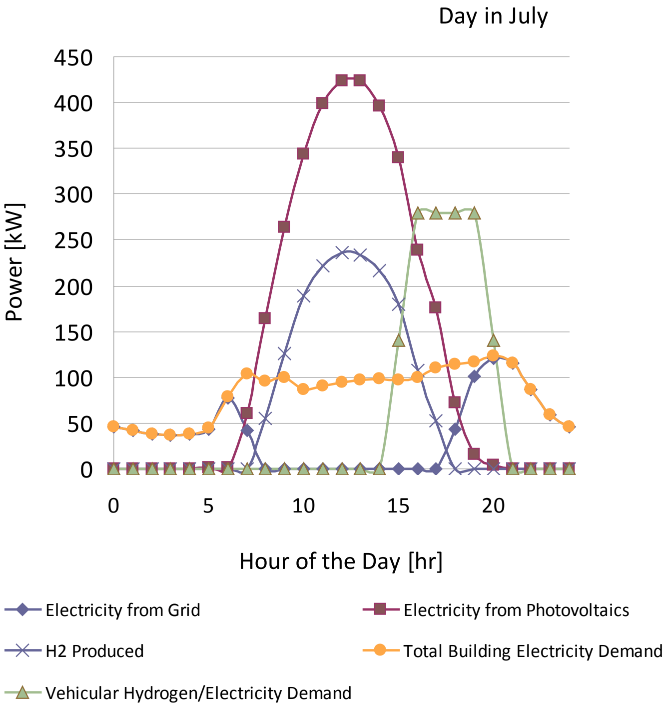
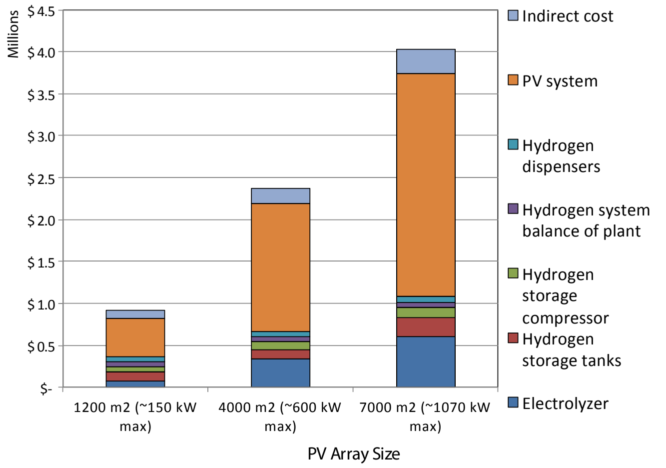


FIGURE 2. Building Electricity Demand, Vehicular Hydrogen/Electricity Demand, PV and Grid Electricity Supply, and Hydrogen Produced (or Electricity to Storage) During a Typical Day in July (4,000-m^2 PV system), Case 1

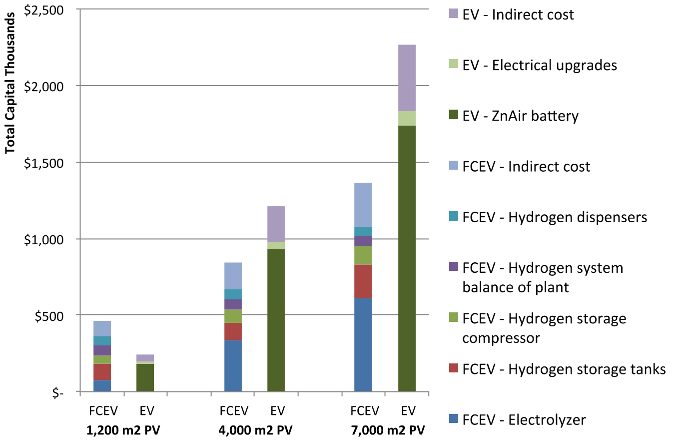


PV system is largest cost item @ $2.50/watt

Other System Cost Assumptions (installed):

- Dispensers: $64,000
- Compressor: $2,600 - $11,000/kW (depending on size)
- H2 storage: ~$1,400/kg
- Electrolyzer: ~$600/kWin ($750/kW incl indirect costs)

FIGURE 3. Total Hydrogen/FCEV System Capital Costs, Including PV Panels, Case 1



Battery system produces ~3% more energy than hydrogen system because of its higher efficiency.

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- Compressor: $2,600 - $11,000/kW (depending on size)
- H2 storage: ~$1,400/kg
- Electrolyzer: ~$600/kWin ($750/kW incl indirect costs)
- Battery: $315/kWh

FIGURE 4. CapitalCosts of Hydrogen/FCEV and Electricity/EV Systems, Case 2

in the size of the required hydrogen production and storage components) decreases as the PV system size increases. For the 7,000-m^2 system, the Case 1 and Case 2 capital costs are almost identical.

The vehicle-refueling analysis shows the potential for community-level hydrogen refueling using only renewably generated electricity. Table 2 summarizes the Case 1 and Case 2 cost results for both the hydrogen/FCEV and electricity/EV systems. With the 4,000-m^2 PV system, the number of FCEVs served (70–80) roughly matches the modeled community size (100 households). The levelized hydrogen cost ranges from $34/kg ($1.01/kWh) for the 1,200-m^2 Case 1 system to $11/kg ($0.34/kWh) for the 7,000-m^2 Case 2 system. The cost of battery storage of electricity for electric vehicles ranges from $0.57/kWh–$0.39/kWh, also decreasing with increasing system size. The hydrogen system cost reduction for the larger systems is due to better utilization of the equipment. The hydrogen system configuration is also more flexible than the battery system because there are more independent pieces of equipment. For small systems, this is a disadvantage, but for larger systems the increased flexibility reduces costs because an incremental increase in hydrogen storage capacity per kWh (hydrogen tank) is less expensive than an incremental (per kWh) increase in electrochemical storage. Even though the hydrogen system is lower cost than the battery system for the largest storage case, the electric vehicle is less expensive on a fuel ¢/mile basis because of its higher efficiency in this scenario in comparison to the FCEV.

In both cases for both the hydrogen and battery systems, diverting more electricity from the PV system for vehicle fueling improves the economics; this effect is more pronounced for the hydrogen/FCEV system than for the battery/EV system. The best hydrogen cost is from the Case 2, 7,000-m^2 PV system. In this scenario, about 90% of the PV output goes to hydrogen production or battery storage, and the PV system supplies 28% of the building load. The hydrogen system produces about 32,000 kg of hydrogen per year (about 90 kg/day), enough to supply 159 vehicles at a cost of $11/kg or $0.19/mile.

CONCLUSIONS AND FUTURE DIRECTIONS

This analysis shows that community-level hydrogen fueling using only PV-generated electricity could be accomplished. For the 4,000-m^2 PV system case, the number of FCEVs that could be fueled roughly matches the total number of vehicles expected for the community size modeled (100 households). By capturing excess peak PV electricity generation as vehicle fuel (instead of feeding excess electricity back onto the grid), the system also provides the smoothing of PV/grid interactions that could be vital for integrating high levels of distributed PV. Although the analysis did not explicitly address seasonal variations in production or demand, it is likely that the additional storage modeled would be sufficient to accommodate them.

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TABLE 2. Summary of Vehicle Fueling Cost Results

Hydrogen for FCEVs								
	Case 1 (Excess Electricity)				Case 2 (Excess Electricity + Morning Output)			
PV Size (m^2) [% of bldg load]	Production (kg H_2/yr)	Vehicles Served	H_2 Cost ($/kg)	H_2 Cost (¢/mi)	Production (kg H_2/yr)	Vehicles Served	H_2 Cost ($/kg)	H_2 Cost (¢/mi)
1,200 [~50%]	1,804	9	34	56	3,541	17	22	38
4,000 [~170%]	14,564	72	13	22	16,985	84	12	21
7,000 [~300%]	29,274	146	12	20	31,898	159	11	19
Electricity for EVs								
	Case 1 (Excess Electricity)				Case 2 (Excess Electricity + Morning Output)			
PV Size (m^2)	Production (kWh/yr)	Vehicles Served	Elec. Cost ($/kWh)	Elec. Cost (¢/mi)	Production (kWh/yr)	Vehicles Served	Elec. Cost ($/kWh)	Elec. Cost (¢/mi)
1,200	61,726	17	0.57	17	121,936	35	0.45	13
4,000	500,755	143	0.41	12	585,475	168	0.40	12
7,000	1,008,212	289	0.39	11	1,100,877	316	0.39	11

Note: ¢/mile values are for fuel only and do not include vehicle cost or maintenance.

Thus this analysis does not present a compelling economic case for community-scale hydrogen fueling for very small systems in comparison to battery storage and EV charging. However, several characteristics of hydrogen/FCEV systems could be attractive despite the higher cost. The hydrogen/FCEV system provides more flexibility in its configuration than the electricity/EV system because the power (per kW) component (the electrolyzer) is decoupled from the capacity (per kWh) component of the system (the hydrogen storage tanks). In the battery storage system, the power-to-capacity ratio is fixed, so the system configuration is less flexible, and additional storage is more expensive on a per-kWh basis than additional hydrogen storage capacity. Overall system costs are highly dependent on the relationships between component sizes/capacities, so a more flexible system may prove to be more cost effective when carefully optimized for the particular situation and goals.

Future work in this area could include the following:

- Explore more realistic scenarios for addressing seasonal variation in PV output
- Explore methodologies for optimizing hydrogen system configuration
- Explore the impact of incentives and net metering for system economics

FY 2013 PUBLICATIONS/PRESENTATIONS

1. Steward, Analysis of Community Energy; Project ID AN043, Poster presentation at the U.S. Department on Energy Office of Energy Efficiency and Renewable Energy Fuel Cell and Vehicle Technologies Annual Merit Review. Washington DC May 13–17, 2013.

2. Hydrogen Community Energy; Hydrogen Energy Storage and Community-Level Refueling for Grid Integration of Distributed PV (Expected publication September 2013).

REFERENCES

1. Barbose, G.; Darghouth, N.; Wiser, R. (November 2012). *Tracking the Sun V: An Historical Summary of the Installed Cost of Photovoltaics in the United States from 1998 to 2011.* Berkeley, CA: Lawrence Berkeley National Laboratory.

2. DOE Independent Review. (September 2009). *Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis*. NREL/BK-6A1-46676. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy10osti/46676.pdf.

3. FCPower Model. (2012). Molten Carbonate Fuel Cell, version 1.2 (Excel file). http://www.hydrogen.energy.gov/fc_power_analysis.html.

4. Field, K.; Deru, M.; Studer, D. (2010). *Using DOE Commercial Reference Buildings for Simulation Studies*. Preprint. SimBuild 2010. Golden, CO: National Renewable Energy Laboratory.

5. H2A Production Model. (2012). Current Forecourt Grid Electrolysis 1500 kg per day version 3.0 (Excel file). http://www.hydrogen.energy.gov/h2a_prod_studies.html.

6. HTAC. (September 2011). HTAC Energy Storage Working Group discussions.

7. James, B. D.; Perez, J.; Baum, K.N.; Spisak, A.; Sanders, M. (May 2011). *Low Temperature PEM Stationary Fuel Cell System Cost Analysis: Preliminary Results*. DTI Subcontract Report; page 35.

8. "Fuel Cell Power Model Case Study Data." (2009). National Renewable Energy Laboratory. http://www.hydrogen.energy.gov/cf/fc_power_analysis_model_data.cfm.

10. Rastler, D. (December 2010). *Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits*. EPRI Technical Update.

11. Steward, D.; Saur, G.; Penev, M.; Ramsden, T. (November 2009). *Lifecycle Cost Analysis of Hydrogen versus Other Technologies for Electrical Energy Storage*. NREL/TP-560-46719. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy10osti/46719.pdf.