VII.12 Fuel-Cycle Analysis of Hydrogen-Powered Fuel Cell Systems with the GREET Model

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Objectives

- Expand and update the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model for hydrogen production and delivery pathways and for applications involving fuel cell vehicles (FCVs) and other early market fuel cell (FC) systems.
- Examine well-to-wheels (WTW) energy and greenhouse gas (GHG) emission effects of plug-in hybrid electric vehicles (PHEVs).
- Conduct fuel-cycle analysis of early market FC systems for combined heat, hydrogen, and power (CHHP) as well as combined heat and power (CHP) applications.
- Provide WTW results for DOE Office of Hydrogen, Fuel Cells, and Infrastructure Technologies activities such as the Hydrogen Posture Plan and the Multi-Year Program Plan.
- Engage in discussions and dissemination of information on the energy and environmental benefits of hydrogen FCVs and other FC systems.

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:

(C) Inconsistent Data, Assumptions, and Guidelines
(D) Suite of Models and Tools
(E) Unplanned Studies and Analyses

Contribution to Achievement of DOE Systems Analysis Milestones

This project contributes to achievement of the following DOE milestone from the Systems Analysis section of the Hydrogen, Fuel Cells, and Infrastructure Technologies Program Multi-Year Research, Development, and Demonstration Plan:

- **Milestone 11:** Complete environmental analysis of the technology environmental impacts for the hydrogen scenarios and technology readiness.

Accomplishments

- Completed the analysis of energy use and GHG emissions of polymer electrolyte membrane (PEM) FC application to forklifts, which showed that significant reductions in energy use and GHG emissions can be accomplished by displacing fossil fuels in internal combustion engine (ICE) forklifts and replacing battery-powered forklifts with those powered by FCs using hydrogen from steam reforming of natural gas or from coke oven gas.
- Completed the analysis of energy use and GHG emissions associated with various FC technologies for distributed power generation, which showed that FC technologies approaching or exceeding the DOE target electrical efficiency of 40% offered a significant reduction in energy use and GHG emissions compared to combustion generation technologies and U.S. grid generation mix.
- Conducted a WTW analysis of PHEVs, including FC PHEVs, which showed that PHEVs offered significant reduction in petroleum energy use and GHG emissions relative to a conventional ICE vehicle that used gasoline.
- Conducted energy and GHG effects of FC systems for CHHP generation, which showed that CHHP FCs offer significant reduction in energy use and GHG emissions compared to CHP FCs and distributed combustion generation technologies.

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Introduction

The pathway to the application of PEM FCs in hydrogen vehicles will likely be preceded by the introduction of PEM FCs in markets with fewer technical challenges than automobiles. Forklifts and distributed power generation are near-term markets in which PEM FC can be successful. The application of FCs to distributed power generation has the potential to produce excess hydrogen at a relatively low cost for local utilization. The excess hydrogen may be stored locally and used to refuel FC forklifts in a nearby facility or to refuel hydrogen FCVs during their early introduction in the marketplace. Recently, PHEVs received significant attention for their potential of reducing the dependence of the U.S. transportation sector on petroleum by using off-peak excess electric generation capacity and increasing the energy efficiency of vehicles. While PHEVs offer the potential for reductions in petroleum energy use and GHG emissions, these potential benefits need to be thoroughly examined by including the upstream energy and emissions penalties associated with the electricity generation needed to recharge PHEV batteries. The implications of the upstream marginal electricity generation mix as well as the PHEV's powertrain technology, fuel source, and all-electric range (AER) rating can be fully understood through a WTW assessment of energy use and GHG emissions.

The GREET model has been expanded to address the fuel-cycle energy use and GHG emissions associated with the application of CHP and CHHP FCs and to examine the WTW energy use and GHG emissions of PHEVs. In March 2009, Argonne released version 1.8c of the GREET model. As of the latest release, more than 10,000 researchers worldwide have become registered GREET users.

Approach

GREET obtains data needed for simulating different fuel cycles and WTW pathways from the open literature, simulation results from Hydrogen Analysis (H2A) production and delivery models, the H2A Power model, and process engineering simulation models such as Advanced System for Process Engineering (ASPEN). GREET uses simulation results from the Powertrain System Analysis Toolkit (PSAT) model to estimate fuel economy for hydrogen FCVs, PHEVs, and other advanced fuel/vehicle technologies. GREET researchers also interact with industry sources and users to obtain data on the performance characteristics of systems and components associated with the simulated pathways. Then, the GREET model was expanded and updated to conduct WTW and fuel-cycle simulations for the pathways of interest. GREET examines fuel-cycle energy use and emissions for baseline and alternative technologies by tracking the energy use and emission occurrences throughout the upstream processes to the primary source of energy for each technology. The fuel cycle includes the production and transportation of the primary energy source or feedstock (e.g., crude oil or natural gas [NG]) to the fuel production plant, the conversion of the primary energy source in the production plant to a fuel suitable for each technology (e.g., NG to hydrogen [H_2] or NG to electricity), the conditioning of the fuels (e.g., H_2 compression, direct current-to-alternating current electricity inversion, etc.), and the end use of the conditioned fuels (e.g., H_2 in forklifts or NG in distributed power generators).

Results

The fuel-cycle results for various distributed generation technologies were examined based on estimates of annual production and consumption of energy streams as produced by National Renewable Energy Laboratory's H2A Power Model for different facility types in different climatic regions. Two different approaches for fuel-cycle analysis were considered: a total demand approach and a displacement approach. The total demand approach compared the impact of various technologies in satisfying a facility's demand for electric and heat energy, which includes the onsite generation of power, heat, and hydrogen in addition to typical technologies for producing supplemental heat, hydrogen, and the grid power. The displacement approach examined different technologies for onsite generation of electricity and evaluated credits for the co-products of heat and hydrogen. Figures 1 and 2 show the fuel-cycle GHG emissions associated with different generation technologies for a hospital in Chicago using the total demand approach and the displacement approach, respectively. The relative benefits of the CHP and CHHP systems depend on the efficiency and carbon intensity of the displaced grid mix. In general, CHHP FCs are shown to provide more reduction in energy use

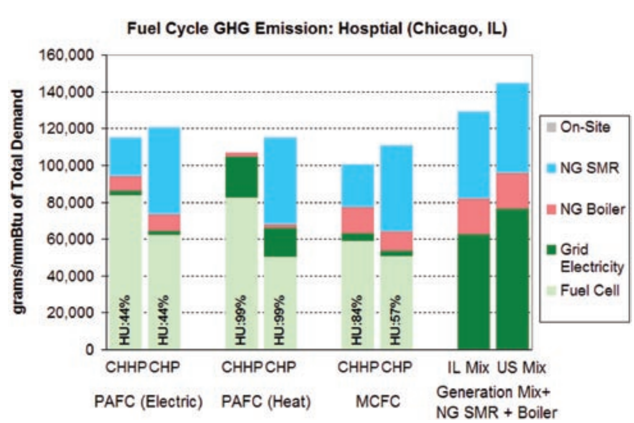

FIGURE 1. Fuel Cycle GHG Emissions for a Hospital in Chicago Using the Total Demand Approach

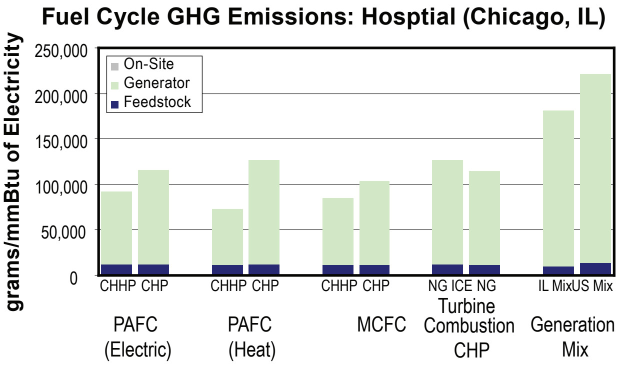

FIGURE 2. Fuel Cycle GHG Emissions for a Hospital in Chicago Using the Displacement Approach

and GHG emissions compared to CHP FC systems. Utilization of co-produced heat is critical to the overall energy and emission performance of FC systems. CHHP FCs provide better utilization of the coproduced heat compared to CHP FC systems.

Three North American Electric Reliability Corporation regions (4, 6, and 13) were selected for the WTW analysis of PHEVs, because they encompassed large metropolitan areas (Illinois, New York, and California, respectively) and provided significantly different marginal generation mixes for recharging PHEVs. The electricity generation for PHEV recharging also included the U.S. generation mix and electricity from renewable sources in examining cases of average and clean mixes, respectively. For an AER between 10 mi and 40 mi, PHEVs that employed petroleum fuels (gasoline and diesel), a blend of 85% ethanol and 15% gasoline (E85), and hydrogen offered a 40–60%, 70–90%, and more than 90% reduction in petroleum energy use and a 30–60%, 40–80%, and 10–100% reduction in GHG emissions, respectively, relative to an ICE vehicle that used gasoline, as shown in Figure 3. The spread of WTW GHG emissions among the different fuel production technologies and grid generation mixes was wider than the spread of petroleum energy use due to very different carbon intensities of the diverse fuel production technologies and feedstock sources for the fuels considered in this analysis. Figure 3 also shows that PHEVs offered reductions in petroleum energy use compared to regular hybrid electric vehicles (HEVs). More petroleum energy savings could be realized as the AER increased, except when the marginal grid mix was dominated by oil-fired power generation, such as the marginal mix estimated for the region covering New York. Similarly, more GHG emissions reductions could be realized at higher AERs, except when the marginal grid generation mix was dominated by oil or coal. Electricity from renewable sources realized the largest reductions in petroleum energy use and GHG emissions for all PHEVs as the AER increased.

Conclusions and Future Directions

Conclusions

- FC technologies for distributed power generation approaching or exceeding the DOE target electrical efficiency of 40% offer significant reduction in energy use and GHG emissions compared to combustion technologies and the U.S. grid generation mix.
- Application of the PEM FC to forklifts offers significant reductions in energy use and GHG emissions compared to ICE forklifts and battery-powered forklifts charged through U.S. grid power.
- PHEVs offer significant reductions in petroleum energy use and GHG emissions relative to a conventional ICE vehicle that uses gasoline.
- CHHP FCs offer significant reductions in energy use and GHG emissions compared to FCs and distributed combustion technologies for CHP applications.

Future Work

- Conduct fuel-cycle analysis of criteria pollutant emissions for distributed combustion technologies and various FC system technologies for CHP and CHHP generation.
- Examine benefits of waste-based fuel production pathways such as landfill gas and potentially biogas from waste water treatment plants.
- Incorporate the newly developed pathways into the public version of GREET.

FY 2009 Publications/Presentations

1. Elgowainy, Amgad, Andrew Burnham, Michael Wang, John Molburg, and Aymeric Rousseau, 2009, *Well-To-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles*, ANL/ESD/09-2, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, February.

2. Elgowainy, Amgad, Andrew Burnham, Michael Wang, John Molburg, and Aymeric Rousseau, 2009, "Well-To-Wheels Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles," 2009-01-1309, SAE World Congress.

3. Elgowainy, A., L. Gaines, and M. Wang, 2009, "Fuel-Cycle Analysis of Early Market Applications of Fuel Cells: Forklift Propulsion Systems and Distributed Power Generation," *International Journal of Hydrogen Energy* 34(9): 3557–3570.

4. Elgowainy, A., and M. Wang, 2008, *Fuel Cycle Comparison of Distributed Power Generation Technologies*, ANL/ESD/08-4, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, November.

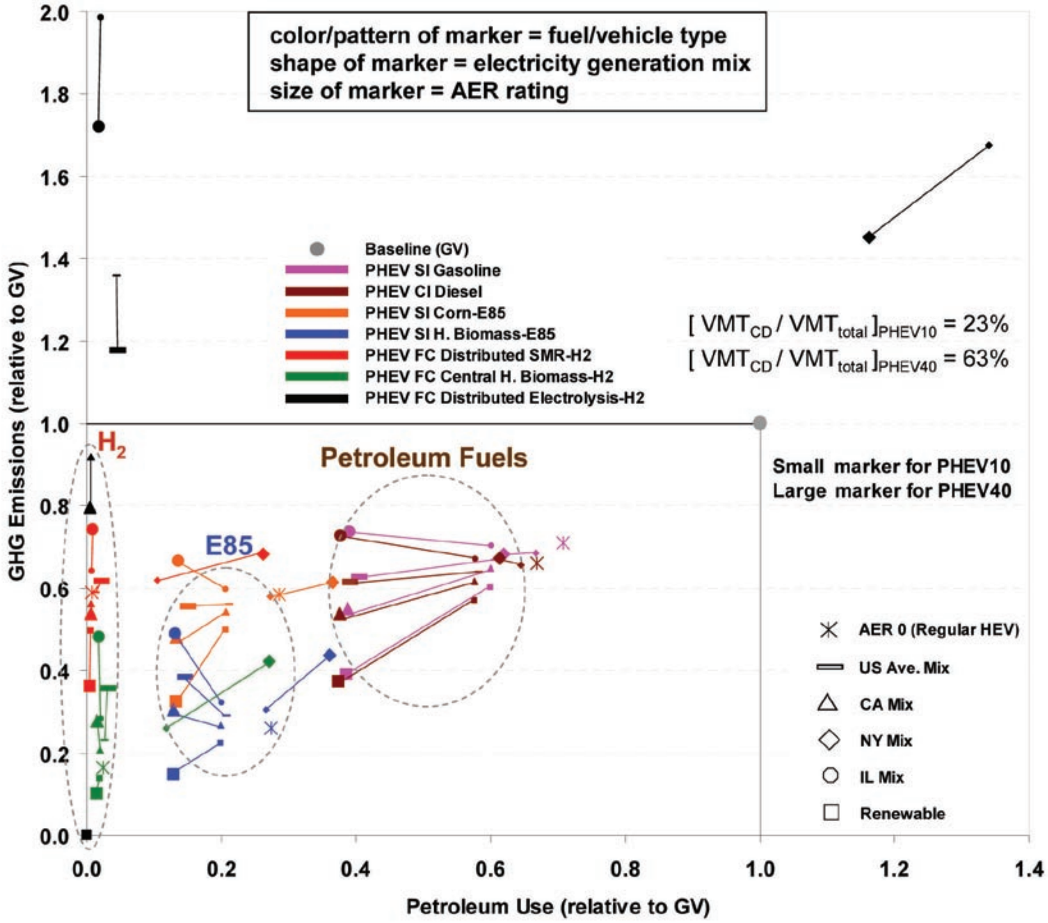

FIGURE 3. Summary of WTW Petroleum Energy Use and GHG Emissions for Combined Charge Depleting (CD) and Charge Sustaining (CS) Operations Relative to a Baseline ICE Gasoline Vehicle (GV)

5. Gaines, L., A. Elgowainy, and M. Wang, 2008, *Full Fuel-Cycle Comparison of Forklift Propulsion Systems*, ANL/ESD/08-3, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, October.