X.2 Fuel-Cycle Analysis of Hydrogen-Powered Fuel-Cell Systems with the GREET Model

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Objectives

- Expand and update Argonne's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model for hydrogen production pathways and for applications of fuel cell vehicles (FCVs) and other fuel cell (FC) systems.
- Conduct well-to-wheels (WTW) analysis of hydrogen FCVs with various hydrogen production pathways.
- Conduct life-cycle analysis of hydrogen-powered FC systems.
- Provide WTW results for Office of Hydrogen, Fuel Cells and Infrastructure Technologies efforts on the Hydrogen Posture Plan and the Multi-Year Program Plan.
- Engage in discussions and dissemination of 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 Analysis

Contribution to Achievement of DOE Systems Analysis Milestones

This project contributes to achievement of the following DOE milestones 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

- Examined potential energy and environmental implications of substituting fuel-cell propulsion technologies for existing technologies based on batteries and fossil fuels, in forklifts.
- Examined potential energy and environmental implications of substituting fuel-cell technologies for existing, combustion-based, distributed power generation technologies (e.g., internal combustion engines and gas turbines) as well as the various mixes of technologies associated with grid-electricity generation in different U.S. markets.
- Expanded GREET capabilities to compute compression energy use and efficiencies for natural gas (NG) and hydrogen based on thermodynamics principles.
- Added tube trailer delivery option for gaseous hydrogen from terminals to refueling stations.
- Updated the GREET model and released a new GREET version in May 2008.

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Introduction

Forklifts and distributed power generation have been identified as potential applications for early markets of fuel cells to help the development of hydrogen production and FC technologies. The GREET model has been expanded to examine fuel cycle energy use and greenhouse gases (GHGs) emissions associated with employing hydrogen fuel cells in forklifts and distributed electric power generation. The analysis compares fuel cells with conventional technologies, typically used in forklifts and distributed power generators, to explore the potential energy and environmental benefits of fuel cell technologies.

The GREET model has also been expanded to include algorithm for computing compression energy use and efficiencies associated with NG and hydrogen transportation to refueling stations as well as those associated with hydrogen compression at refueling stations for various storage and dispensing pressure requirements. The transportation and distribution options for different hydrogen pathways in GREET were expanded to include hydrogen delivery via tube-trailers. In May 2008, Argonne released version 1.8b of the GREET model. So far, more than 7,500 registered users have downloaded the GREET model.

Approach

GREET obtains data needed for simulating different hydrogen pathways from the open literature, simulation results from H2A production and delivery models, and from process engineering simulation models such as ASPEN. GREET uses simulation results from the PSAT (Powertrain System Analysis Toolkit) model to estimate fuel economy for hydrogen FCVs and for other advanced vehicle technologies. GREET researchers also interact with industry sources and users to obtain data on the characteristics and performance of systems and components associated with the different pathways of hydrogen as well as those associated with other fuels pathways. Then, the GREET model is expanded and updated to conduct WTW and fuel cycle simulations for the pathways of interest. GREET examines the fuel cycle energy use and emissions for the 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 fuel or feedstock (e.g., NG or biomass) to the production facility, the conversion of the primary fuel/feedstock in the production facility to the useable form of energy suitable for each technology, (e.g., NG-to-H_2 or -electricity), the conditioning of the fuels (e.g., hydrogen compression, direct to alternating current electricity inversion, etc), and the use of the conditioned fuels (e.g., hydrogen in forklifts or distributed power generators). Finally, the fuel cycle results are compared among competing fuel/technology options.

Results

ANL investigated the potential energy and environmental implications of substituting fuel cell technologies for existing forklift and distributed power generation technologies. Figure 1 summarizes the preliminary results of total energy use for different forklift technologies per kWh supplied to the forklift wheels. The full fuel-cycle impacts, as calculated with Argonne's GREET model, are shown, including initial recovery of the primary energy, conversion to the form used by the forklift (including compression and any transport required), and use at the forklift. Comparative results are independent of truck size. The fuel cell forklift with hydrogen from NG or coke oven gas uses slightly less energy than does the battery one, if powered

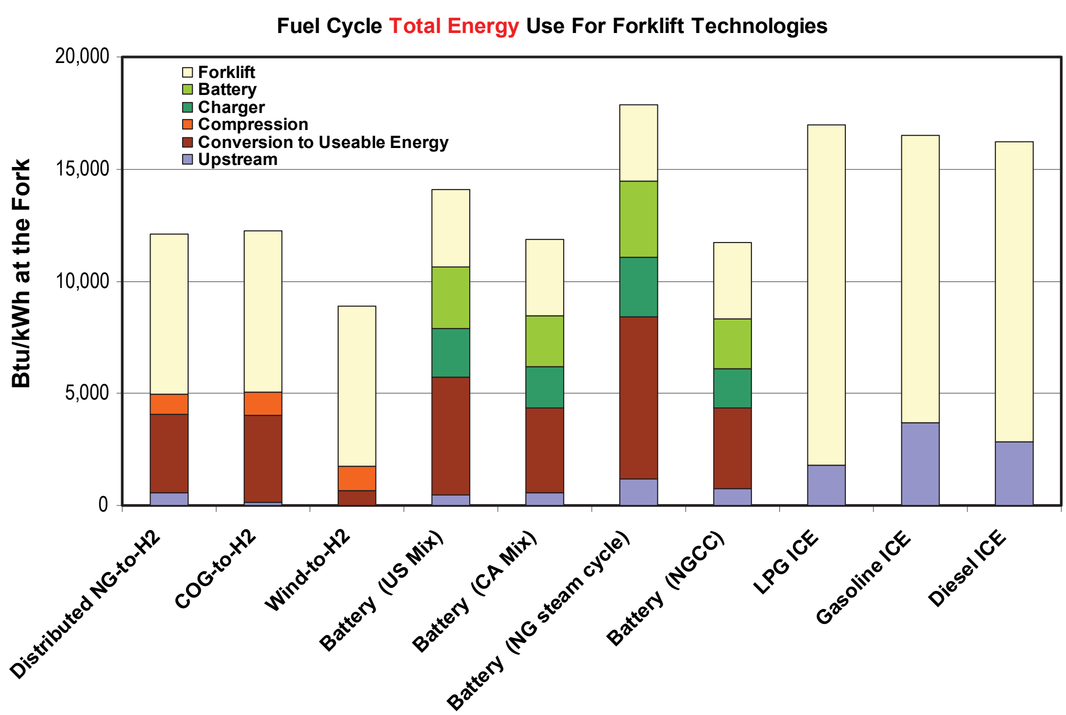

FIGURE 1. Comparison of Total Energy Use by Forklift Type, per kWh at the Forklift Wheels

by U.S.-average electricity, and slightly more energy if powered by the California mix, reflecting the use of renewable sources in that generation mix. Use of wind electricity to generate the hydrogen has a similar effect as shown in the figure. A comparison of options for powering a forklift with natural gas as the primary energy source shows that the fuel cell has a large total-energy advantage over battery power from natural gas-driven simple steam power cycle, and comes close to battery power supplied by the more efficient combined cycle. Note that the losses due to battery charging and discharging contribute significantly to the total energy use for the battery-powered forklifts. The coke oven gas-to-hydrogen pathway resembles the natural gas steam-reforming one for total energy use, but exhibits a significant greenhouse gas advantage due to the fact that coke oven gas is a by-product of steel mill operation. Figure 2 compares GHG emissions for the different forklift types. The internal combustion engine (ICE)-powered forklifts produce the highest fuel cycle GHG emissions, but the battery-powered trucks, charged from average U.S. electricity mix, produce almost as much. This is because the U.S. mix relies heavily on coal, which generates more GHG emissions per kWh. Use of wind, either to produce H_2 or as part of the California electricity generation mix minimizes emissions of GHGs. GHG emissions from the use of coke oven gas are low because coke oven gas contains approximately 55% hydrogen (dry basis). When comparing pathways starting with NG as the primary energy source, the one using the single-cycle power plants results in the highest GHG emissions, and the combined-cycle the lowest, with the path using steam reforming only slightly higher, but well below the pathways involving batteries charged with the average U.S. electricity generation mix.

The fuel cycle analysis of various power generation technologies starts by examining a unit of electric energy usage at the point of consumption, which is chosen to be 1 kWh or 3,412 Btu of electricity for this study, and then tracks the energy use and emission occurrences throughout the upstream processes up to the primary source of energy for each technology. The energy use and emission results are inherently dependent on the assumptions associated with each of the generation technologies. The key assumption for each technology is the generator's energy conversion efficiency. The literature data indicate that the efficiency of power generators varies by the generator's technology and capacity, with typically higher efficiencies for the higher capacity generators. The preliminary results for energy use and GHG emissions provided in Figures 3-4 are for technologies suited for power capacities much larger than 10 kW. The results for the U.S. average and California mixes of electricity, as well as for coal and natural gas grid generation technologies, are provided as cases for comparison with the results of different distributed power generation technologies. The energy use and GHG emissions associated with each stage of the power generation pathway for each generation technology are stacked together to provide the total fuel cycle result. Figure 3 shows that microturbines exhibit a higher use of energy than all other technologies, mainly

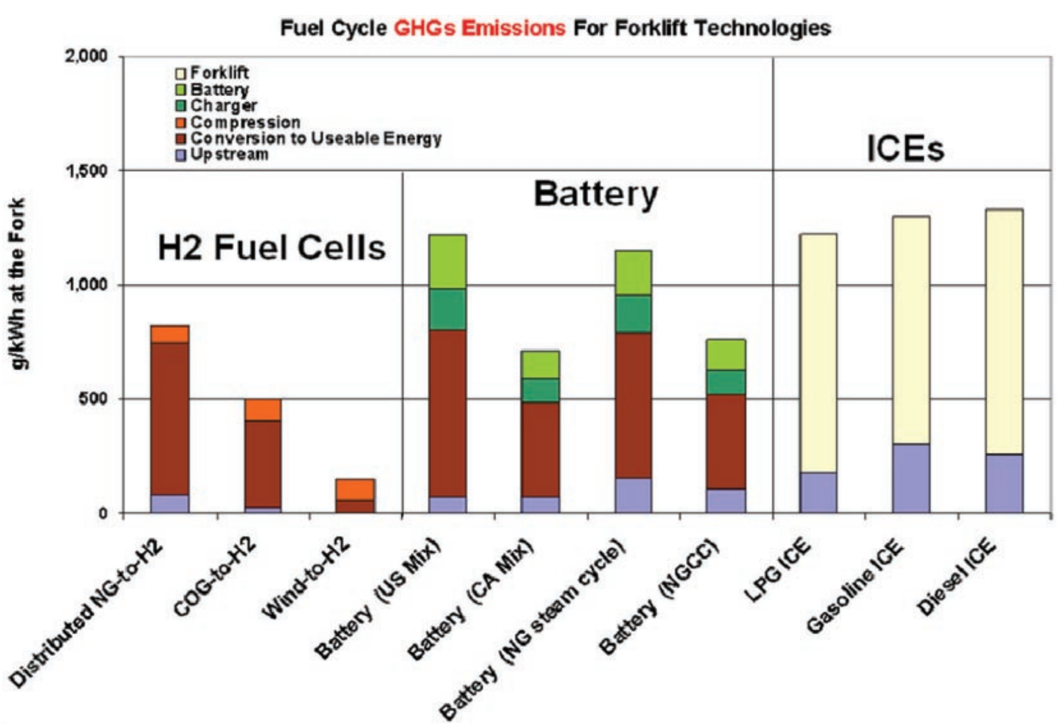

FIGURE 2. Comparison of GHG Emissions by Forklift Type, per kWh at the Forklift Wheels

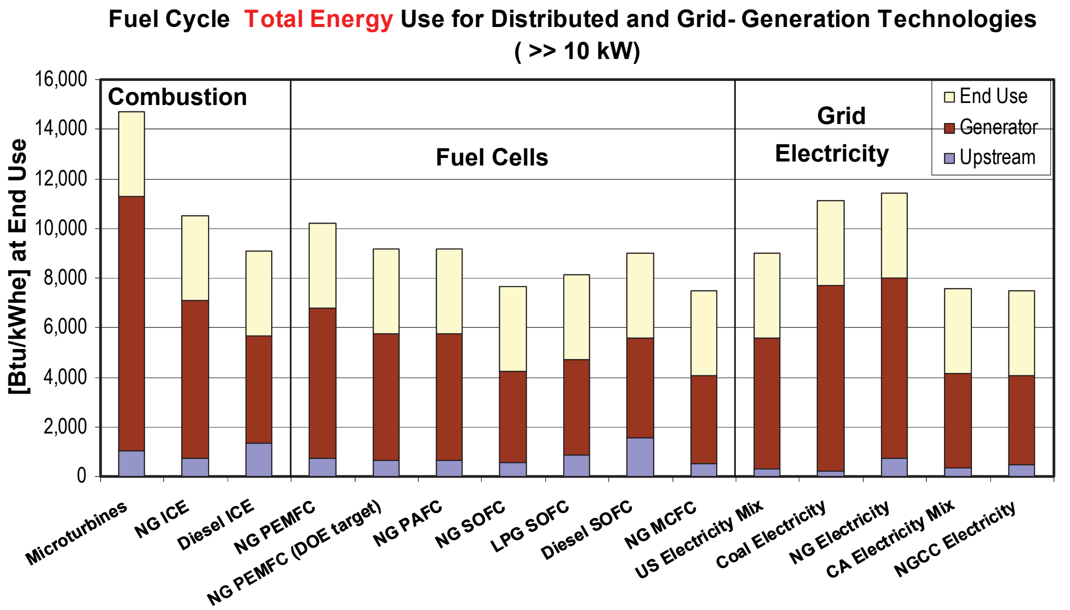

FIGURE 3. Comparison of Total Energy Use by Technology Type for Capacity >>10 kW, per kWh of Electricity Consumption

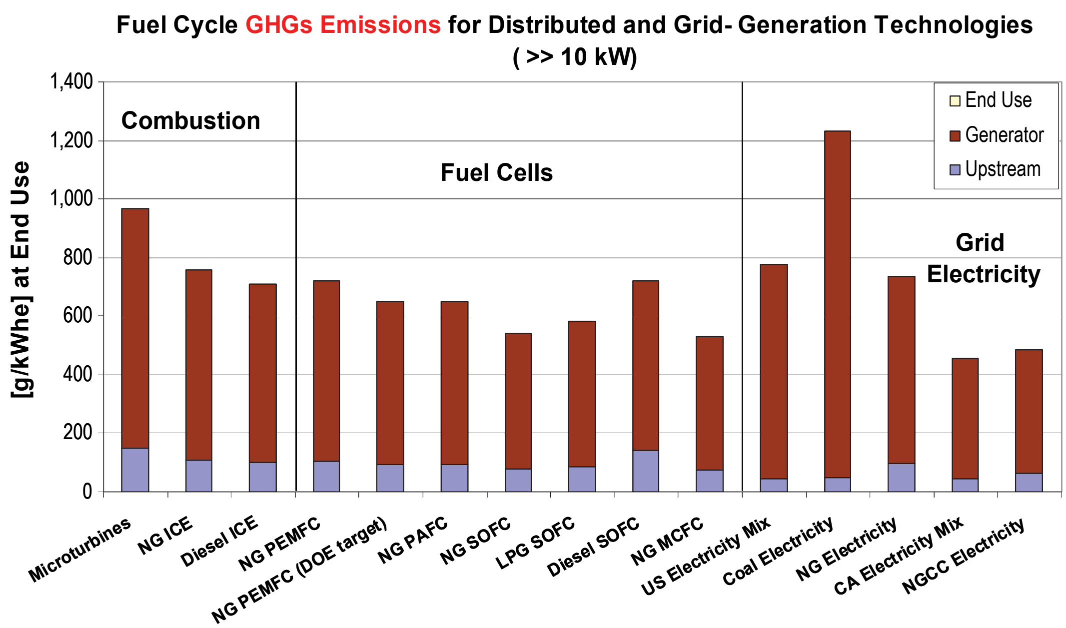

FIGURE 4. Figure 4 Comparison of GHG Emissions by Technology Type for Capacity >>10 kW, per kWh of Electricity Consumption

due to its relatively lower energy conversion efficiency. The NG-driven solid oxide fuel cell (SOFC), at 48% electrical efficiency, and the molten carbonate fuel cell (MCFC), at 49% electrical efficiency, exhibit energy use similar to that of the California grid mix, but lower than that of the U.S. grid mix and all other distributed generation technologies. Figure 4 shows the GHG emissions associated with the pathways of different distributed and grid generation technologies. The figure shows that fuel cell system efficiencies meeting or exceeding DOE efficiency target (40%) offer greenhouse gas emission benefits over all combustion technologies and the U.S. grid mix. Although diesel engines are much more efficient than NG ICEs, the higher carbon content of the diesel fuel per unit energy results in a small difference in the amount of GHG emissions compared to that of the NG ICE.

Conclusions and Future Directions

- Reductions in energy use and in GHG emissions can be accomplished by displacement of batteries (charged from U.S. mix sources) and fossil fuels in forklifts with fuel cells.
- FC systems for distributed power generation that meet or exceed DOE efficiency target (40%) offer energy and GHG emission benefits over all combustion-based technologies as well as the U.S. grid mix.

Future Work

- Examination of criteria pollutant emission benefits for both FC forklifts and FC distributed power generation in comparison with ICE-based forklifts and fossil fuel combustion-based technologies for distributed power generation.
- Examination of combined FC/gas turbine or combined heat and power applications for high-temperature FCs.
- Simulations of integrated stationary and mobile hydrogen FC system applications in central locations.
- Enhancement and expansion of GREET for additional hydrogen production, delivery, and storage options.
- Expansion of GREET to include FC plug-in hybrid vehicles.

Special Recognitions & Awards/Patents Issued

1. Michael Wang, 2008 DOE Hydrogen Program R&D Award in Recognition of Outstanding Hydrogen Well-to-Wheels Analysis and Contributions to Systems Analysis.

FY 2008 Publications/Presentations

1. Elgowainy, A. and M. Wang, 2008, Fuel Cycle Comparison of Distributed Power Generation Technologies, prepared for Office of Fuel Cell, Hydrogen, and Infrastructure Technologies, U.S. DOE, April 2008.

2. Gaines, L., A. Elgowainy, and M. Wang, 2008, Full Fuel Cycle Comparison of Forklift Propulsion Systems, prepared for Office of Fuel Cell, Hydrogen, and Infrastructure Technologies, U.S. DOE, April 2008.