XI.8 GREET Model Development and Life-Cycle Analysis Applications

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Project End Date: Project continuation is determined annually in consultation with DOE

Objectives

- Conduct fuel-cycle analysis of early market applications of fuel cell (FC) systems (to help development of hydrogen production and FC technologies).
- Evaluate environmental benefits of renewable hydrogen production pathways.
- Conduct well-to-wheels (WTW) analysis of hydrogen fuel cell vehicles (FCVs) with various hydrogen production pathways.
- Conduct vehicle-cycle analysis of hydrogen FCVs.
- Provide life-cycle results for DOE's Fuel Cell Technologies (FCT) Program activities such as the Multi-Year Research, Development, and Demonstration Plan.
- Engage in discussions and dissemination of energy and environmental benefits of FC systems and applications.

Technical Barriers

This project addresses the following technical barriers from section 4.5 of the Fuel Cell 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 milestone from the Systems Analysis section of the Fuel Cell 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. (2Q 2015)

Accomplishments

- Expanded the fuel-cycle analysis of renewable feedstock options for hydrogen production to include renewable natural gas (RNG) from landfill gas (LFG) and anaerobic digestion (AD) of animal waste.
- Conducted energy use and greenhouse gas (GHG) emissions analysis of FC systems for combined heat and power (CHP) and combined heat, hydrogen, and power (CHHP) generation using conventional natural gas (NG) and RNG.
- Evaluated the WTW energy and emissions benefits of FCVs powered by hydrogen from RNG.
- Conducted vehicle-cycle analysis of FCVs relative to conventional gasoline internal combustion engine (ICE) vehicles and gasoline hybrid electric vehicles (HEVs).
- Supported the collaborative effort of DOE's FCT Program and Vehicle Technologies Program (VTP) in updating DOE's WTW record for alternative fuel/vehicle systems, including FCVs and plug-in hybrid electric vehicles (PHEVs) [1].

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Introduction

The stages included in life-cycle analysis (LCA) are raw material acquisition, transportation and processing and product manufacturing, distribution, use and disposal or recycling. LCA of a fuel is called fuel-cycle analysis, while LCA of a vehicle is called vehicle-cycle analysis. A fuel cycle is also known as a WTW cycle when the fuel is used in transportation applications (vehicles). Combining WTW results with the vehicle-cycle energy use and emissions facilitates the comparison of alternative fuel/vehicle systems on a common (life-cycle) basis. Argonne examined fuel-cycle energy use and emissions associated with the use of RNG in stationary fuel cell applications. Argonne also conducted WTW analysis of hydrogen FCVs, including alternative feedstock sources for hydrogen production. To complete the LCA of hydrogen FCVs, Argonne evaluated the vehicle-cycle energy use and emissions associated with manufacturing FCVs and compared them to those of the manufacturing of gasoline ICEVs and HEVs.

Recovered methane (CH_4) gas from landfills or from AD originates from a renewable resource and is thus considered renewable energy. Because it is chemically identical to fossil natural gas yet produces far fewer GHG emissions, this RNG can power stationary fuel cells to produce heat and power with the option of co-producing hydrogen while providing significant GHG emissions benefits. According to Environmental Protection Agency, over 190 million metric tonnes (MMT) of CO_2-equivalent (CO_2e) emissions came from landfills, animal manure and wastewater treatment facilities in 2009, while another 98 MMT and 16 MMT were avoided by landfill gas-to-energy and manure biogas recovery projects, respectively [2,3]. By avoiding the release of methane and instead recovering and using it in stationary applications or to produce transportation fuels, large reductions in GHG emissions can be realized relative to petroleum gasoline. In the CHHP application, the excess hydrogen may be stored and used for the refueling of fuel cells powering material handling equipment (i.e., forklifts) or for the generation of supplemental electricity to satisfy the electric load during peak demand periods. The availability of a hydrogen co-product can also overcome one of the barriers to introducing hydrogen FCVs to some early FCV market places by facilitating a distributed source of hydrogen while effectively employing the primary energy source and the initial capital investment of the fuel cell to serve a facility's demand for electric and heat energy. In a mature FCV market, renewable hydrogen can be produced via steam methane reforming (SMR) of RNG to satisfy the demand for the hydrogen fuel in that market. This is especially important in places such as California where regulations require 33% of the hydrogen produced for use as fuel to come from renewable sources [4].

Approach

This study examines the fuel cycle of landfill gas and animal waste conversion to RNG, and the subsequent conversion of RNG to hydrogen fuel for FCVs. To assess the environmental benefits of RNG, we account for energy use and emissions in the reference case (or base case) and for those associated with the recovery and conversion of the renewable feed to RNG. Since the reference case consumes energy and generates emissions (in the absence of conversion to RNG), the net emissions associated with producing RNG are calculated by subtracting the reference case emissions from those emitted in the conversion process to RNG. The conversion processes of landfill gas and animal waste to RNG are described in details elsewhere [5,6].

The energy use and emissions associated with the use of RNG in stationary fuel cells for CHP and CHHP generation, and the slate of the co-products depend mainly on the efficiency of the integrated internal reformer. The individual conversion efficiencies to produce electricity, heat and hydrogen are extracted from the H2A power model developed by the National Renewable Energy Laboratory. We use the displacement approach to compare the generation of electricity and hydrogen among the different feedstock sources, and to calculate credits for the byproduct heat. The system boundary for this approach includes the fuel cell system and assumes full utilization of byproduct heat. The energy use and emissions for this approach are evaluated per one million Btu of net electricity and hydrogen generation. The credit of byproduct heat is calculated from the displacement of equivalent amount of heat from a typical standalone heating system. The displaced heat is assumed to be produced from a NG-fired heater with 90% efficiency. Hydrogen produced from RNG for FCV applications assumes 72% efficiency for the SMR conversion process. The WTW results of the alternative fuels and vehicle systems in this report are presented in per-mile basis as well as per-kg of hydrogen equivalent basis.

Results

The fuel-cycle GHG emissions for molten carbon fuel cell (MCFC) CHP and CHHP systems are shown in Figure 1. Employing RNG in CHP and CHHP fuel cell applications achieve 78-79% GHG emissions reduction relative to conventional NG-powered fuel cells. This large reduction in GHG emissions incorporates the impact of a 2% methane leakage rate assumed for the processing of RNG. Without accounting for such leakage, the reduction in GHG emissions for RNG pathways would be 96% relative to fuel cells powered with conventional NG. The GHG emissions credit due to the displacement of conventional heat with the byproduct heat is implied in Figure 1 for each of the investigated feedstock sources.

Figure 2 shows the WTW GHG emissions of various hydrogen production pathways, including the hydrogen use in FCVs. While hydrogen produced from renewable wind power sources for use in FCVs provides the largest reduction in GHG emissions (92%) relative to gasoline ICE vehicles, hydrogen produced from RNG provides the next largest reduction in GHG emissions (85%) relative to gasoline ICE vehicles. The corresponding reduction in GHG emissions for biomass, coal with carbon capture and sequestration (w/CCS), coal without carbon capture and sequestration (w/o CCS), coke oven gas, and conventional natural gas feedstock sources are 81%, 76%, 8%, 71%, and 45%, respectively. The conversion of gasoline consumption in an ICE vehicle to per-kg of hydrogen equivalent in Figure 2 employs an energy equivalency ratio (EER)[1] of 2.3 as adopted from California Air Resources Board's Low Carbon Fuel Standard [7]. The WTW GHG emissions per mile for the alternative feedstock sources for hydrogen production and use in FCVs are presented in Figure 3. The GHG emissions for hydrogen FCVs occur entirely in the well-to-pump (WTP) activities of hydrogen production, compression, and transportation, while the majority of GHG emissions for the baseline gasoline ICE vehicle occur in the pump-to-wheels (PTW) stage (i.e., during vehicle operation). To compare FCVs with baseline gasoline ICE vehicles on a life-cycle basis, we evaluated the vehicle cycle energy use and emissions associated with manufacturing FCVs and compared it to the manufacturing of gasoline ICEVs and

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[1] EER = miles per unit energy of hydrogen used in a FCV/miles per unit energy of gasoline used in an ICEV.

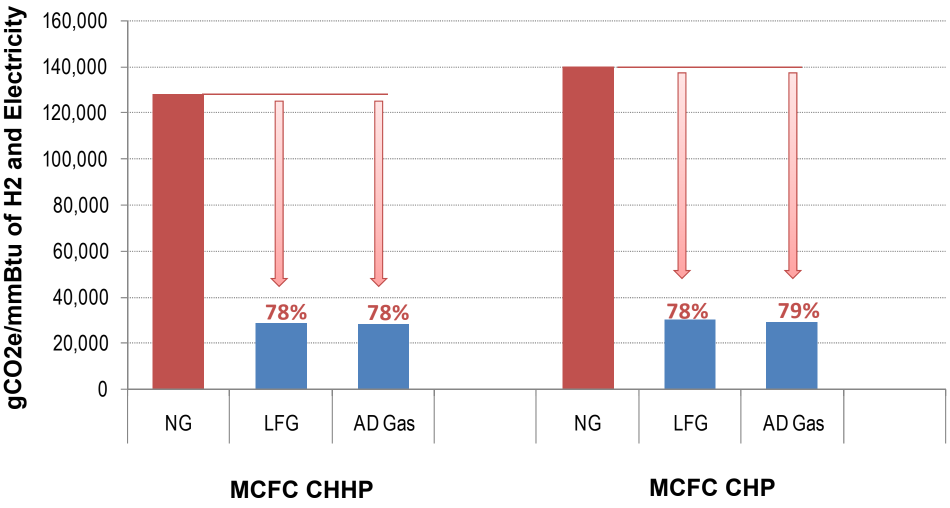
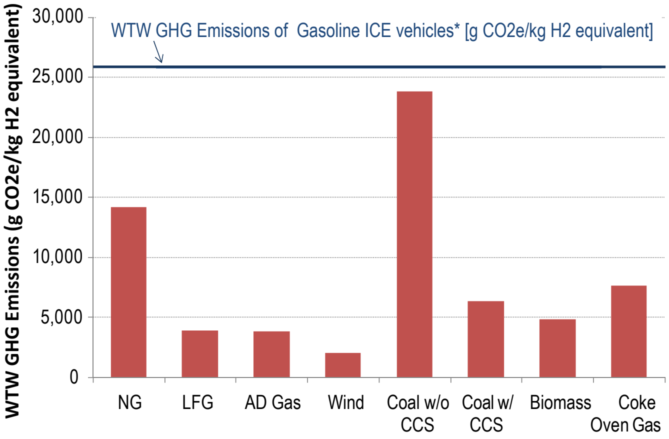


FIGURE 1. Fuel Cycle GHG Emissions from Conventional and Renewable Natural Gas Use in Stationary Fuel Cell Applications



*Assuming 2.3 fuel economy ratio between H2 FCV and gasoline ICEV
CCS - carbon capture system

FIGURE 2. WTW GHG Emissions from Alternative Feedstock Sources for Hydrogen Production and Use in FCV Applications (per-kg H2 equivalent)

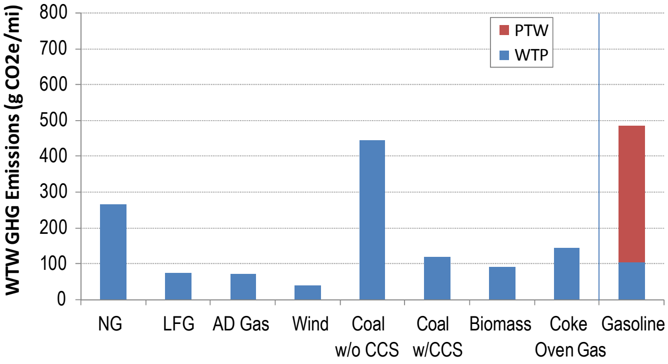


FIGURE 3. WTW GHG Emissions from Alternative Feedstock Sources for Hydrogen Production and Use in FCV Applications (per mile)

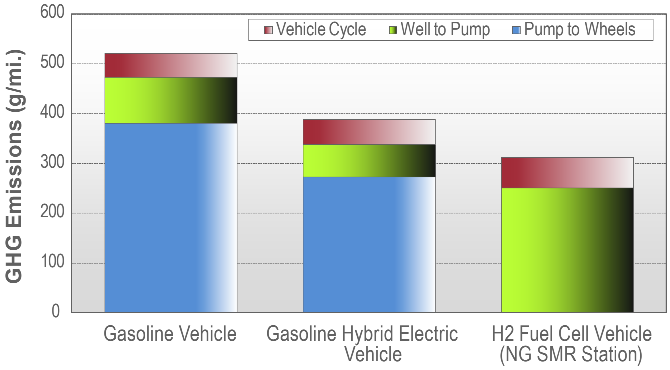


FIGURE 4. Comparison of Vehicle Cycle GHG Emissions of Hydrogen FCVs with Gasoline ICEVs and HEVs

HEVs. Figure 4 shows that while GHG emissions associated with the manufacturing of hydrogen FCVs are larger compared to gasoline ICEVs, the combined fuel cycle and vehicle cycle GHG emissions for FCVs (using hydrogen from SMR of natural gas) are 40% lower than gasoline ICEVs.

Conclusions

Hydrogen produced from RNG sources can achieve significant reductions in GHG emissions:

- CHHP and CHP FC systems powered by RNG achieve 78-79% GHG reduction relative to those powered by conventional NG.
- FCVs with hydrogen produced from RNG achieve WTW GHG reduction by:
    - 73% relative to FCVs with hydrogen produced from conventional NG.
    - 85% relative to gasoline ICEVs.

- On a vehicle-cycle basis, manufacturing FCVs require more energy and generate more GHG emissions compared to gasoline ICEVs, but FCVs reduce energy and emissions on a life-cycle basis (i.e., combined vehicle and fuel cycles).

Future Work

- Examine alternative feedstock sources for renewable hydrogen production such as waste water treatment plants.

FY 2011 Publications/Presentations

1. Nguyen, T. and Ward, J., 2010, "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles," Record # 10001, Offices of Vehicle Technologies & Fuel Cell Technologies, October 25.

2. Han, J., M. Mintz, M. Wang, 2011, "Life Cycle Analysis of Renewable Hydrogen from Waste", AIChE 2011 Spring Meeting, Chicago, IL, March 14–17.

3. Mintz, M., J. Han, M. Wang, C. Saricks, 2010, "Well-to-Wheels analysis of landfill gas-based pathways and their addition to the GREET model", ANL/ESD/10-3, Argonne National Laboratory, Argonne, IL.

4. Elgowainy, A, and Wang, M., 2011, "Well-To-Wheel Analysis of Sustainable Vehicle Fuels," Robert A. Meyers (ed.), Encyclopedia of Sustainability Science and Technology, DOI 10.1007/978-1-4419-0851-3.

5. Han, J., M. Mintz, M. Wang, 2011, "Life Cycle Analysis of Renewable Hydrogen from Waste", AIChE 2011 Spring Meeting, Chicago, IL, March 14-17.

6. Mintz, M., J. Han, M. Wang, C. Saricks, 2010, "Well-to-Wheels analysis of landfill gas-based pathways and their addition to the GREET model", ANL/ESD/10-3, Argonne National Laboratory, Argonne, IL.

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1. Nguyen, T. and Ward, J., 2010, "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles," Record # 10001, Offices of Vehicle Technologies & Fuel Cell Technologies, October 25.

2. U.S. EPA, 2011b. AgSTAR Program. http://www.epa.gov/agstar/. Accessed on July 1st, 2011.

3. U.S. EPA, 2011c. Landfill Methane Outreach Program. http://www.epa.gov/lmop/index.html. Accessed on July 1st, 2011.

4. California Senate Bill 1505: Environmental Performance Standards for Hydrogen Fuel.

5. Han, J., M. Mintz, M. Wang, 2011, "Life Cycle Analysis of Renewable Hydrogen from Waste", AIChE 2011 Spring Meeting, Chicago, IL, March 14-17.

6. Mintz, M., J. Han, M. Wang, C. Saricks, 2010, "Well-to-Wheels analysis of landfill gas-based pathways and their addition to the GREET model", ANL/ESD/10-3, Argonne National Laboratory, Argonne, IL.

7. California Air Resources Board (CARB), 2009, "Proposed Regulation to Implement the Low Carbon Fuel Standard," Volume I, Staff report: Initial Statement of Reasons. Sacramento, California.