XI.2 Life-Cycle Analysis of Vehicle and Fuel Systems with the GREET Model

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Project End Date: Project continuation and direction determined annually by DOE

Fiscal Year (FY) 2012 Objectives

- Evaluate environmental benefits of hydrogen fuel cell electric vehicles (FCEVs) with various renewable hydrogen production pathways relative to baseline gasoline pathways.
- Conduct vehicle-cycle analysis of hydrogen FCEVs.
- Conduct life-cycle analysis of hydrogen and petroleum infrastructure build up.
- 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 fuel cell systems and applications.

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:

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

Technical Targets

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 13: Complete environmental analysis of the technology environmental impacts for hydrogen and fuel cell scenarios and technology readiness. (4Q, 2015)

FY 2012 Accomplishments

- Updated conventional natural gas to hydrogen production pathway with the inclusion of shale gas (SG) pathway and updated methane (CH_4) emissions of natural gas to hydrogen pathways.
- Evaluated the well-to-wheels (WTW) energy use and emissions benefits of FCEVs powered by hydrogen from renewable sources such as biomass gasification and renewable natural gas (RNG) from sources such as landfill gas and animal manure.
- Evaluated vehicle-cycle energy use and emissions of baseline gasoline internal combustion engine vehicles (ICEVs), FCEVs with updated platinum loading of fuel cells, battery electric vehicles (BEVs) with updated battery manufacturing analysis, and light weighting materials for future vehicle designs.
- Evaluated the life-cycle energy use and emissions associated with the construction of petroleum refineries, hydrogen plants, and electric power plants.

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Introduction

The stages included in life-cycle analysis (LCA) are raw material acquisition, transportation and processing, as well as product manufacturing, distribution, use and disposal or recycling. LCA of a fuel is known as fuel-cycle analysis or WTW analysis (if the fuel is used for transportation applications), while LCA of vehicle manufacturing is known as vehicle-cycle analysis. Combining WTW with the vehicle-cycle facilitates the comparison of alternative fuel/vehicle systems on a common (life-cycle) basis. More recently, there has been significant interest in expanding the system boundary of life-cycle analysis of transportation fuels to include the impact of fuel infrastructure build up. Argonne examined fuel-cycle energy use and emissions associated with the production of shale gas for hydrogen production and updated the renewable pathways for hydrogen production. It also conducted vehicle cycle analysis of hydrogen FCEVs, including impacts of reduced platinum loading and vehicle light weighting for improved fuel economy. To complete the LCA of hydrogen FCEVs relative to baseline ICEVs and BEVs, Argonne evaluated the life-cycle energy use and emissions associated with the construction of steam methane reforming (SMR) plants for hydrogen production, the construction of petroleum refineries for gasoline production and of power plants for electricity generation.

Argonne updated the methane emissions associated with well field infrastructure and well completion for conventional natural gas (NG) pathway. Argonne also developed a new SG pathway in GREET. Currently, SG contributes to about 23% of the total U.S. natural gas supply, which is the main source for current hydrogen production. RNG from landfill gas or from anaerobic digestion of animal manure produces substantially less greenhouse gas (GHG) emissions than conventional NG and SG [1], and can be employed as feedstock sources to produce renewable hydrogen for FCEVs via SMR. This is especially important in places such as California where regulations require 33% of the hydrogen produced for use as a transportation fuel to come from renewable sources [2]. Vehicle manufacturing and recycling contribute fewer emissions compared to the fuel cycle but still constitute a significant portion of the total life-cycle GHG emissions. Argonne evaluated the impacts of critical materials on vehicle-cycle energy use and GHG emissions, including the platinum loading for FCEVs, battery manufacturing for BEVs, and light weight materials for future vehicle designs that target improved fuel economy. Energy use and GHG emissions associated with infrastructure and plant construction for baseline petroleum fuels and alternative fuels such as hydrogen for FCEVs and electricity for BEVs have long been expected to be much smaller compared to both fuel cycle and vehicle cycle. However, there have been recommendations from National Research Council [3] to quantify the impact of such infrastructure build up on the LCA of the baseline and alternative transportation fuels. Argonne examined in details the energy use and emissions associated with gasoline production in refineries, hydrogen production in SMR plants, and electricity production in various power plants. The energy use and GHG emissions associated with the construction of these plants were evaluated and added to the energy and emissions from the related fuel and vehicle cycles.

Approach

This analysis relied on GHG emissions data developed by the U.S. Environmental Protection Agency for different sectors to estimate the CH_4 emissions sources and amounts for conventional gas and SG [4]. These sectors include production, processing, transmission and distribution of natural gas. Within the production sector, the most important sources of CH_4 emissions are the well equipment, the liquid unloading, and the well completion and workover. Argonne examined in detail the key parameters affecting the life cycle energy use and emissions of conventional gas and SG and their implications on the current hydrogen production from the mix of these two NG sources.

Argonne also examined the parameters influencing the life cycle energy use and emissions associated with the production of RNG from landfill gas (LFG) and animal manure, and the subsequent conversion of RNG to hydrogen fuel for use in FCEVs. These parameters include the process efficiency and fuel yield, CH_4 leakage, and current practices with purging and flaring of LFG as well as the current manure management practices and anaerobic digestion residue applications. The net emissions associated with RNG production are calculated by subtracting emissions associated with current practices from those emitted in the conversion process to RNG. To assess the impact of the construction of fuel production plants, Argonne obtained data from a demolished refinery (that processed 120,000 BBL/day) and for a large SMR hydrogen plant (that produced 19 mmSCF/day). The refinery and SMR plant materials were compiled and then used as building blocks to estimate the environmental impacts of constructing gasoline and hydrogen production facilities. Vehicle component specifications and fuel economy are provided by the Autonomie modeling group at Argonne based on guidance from the DOE's FCT and Vehicle Technologies Programs. The fuel cell platinum loading reduction data is extracted from the DOE Hydrogen Program Record [5]. The material compositions by component for each vehicle are ported to the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET2) vehicle cycle model to evaluate the environmental impacts of vehicle manufacturing and recycling or disposal.

Results

The WTW GHG emissions for hydrogen production from conventional gas, SG, and the U.S. mix of NG are shown in Figure 1. The figure shows that CH_4 leakage is a major GHG emissions source for the hydrogen production pathway via SMR of NG. The major CH_4 emission source for conventional gas is the liquid unloading followed by the transmission and distribution of NG and the well equipment, while the major source for CH_4 emissions for SG is the transmission and distribution of NG, followed by the well equipment and the well completion and workover.

Figure 2 shows the WTW GHG emissions of various conventional and renewable hydrogen production pathways, including the hydrogen use by FCEV. The fuel economy values for the baseline gasoline ICEV and the alternative fuel/vehicle systems considered in this analysis are provided in Table 1. The figure shows that FCEVs with hydrogen produced from fossil NG reduce GHG emissions by over

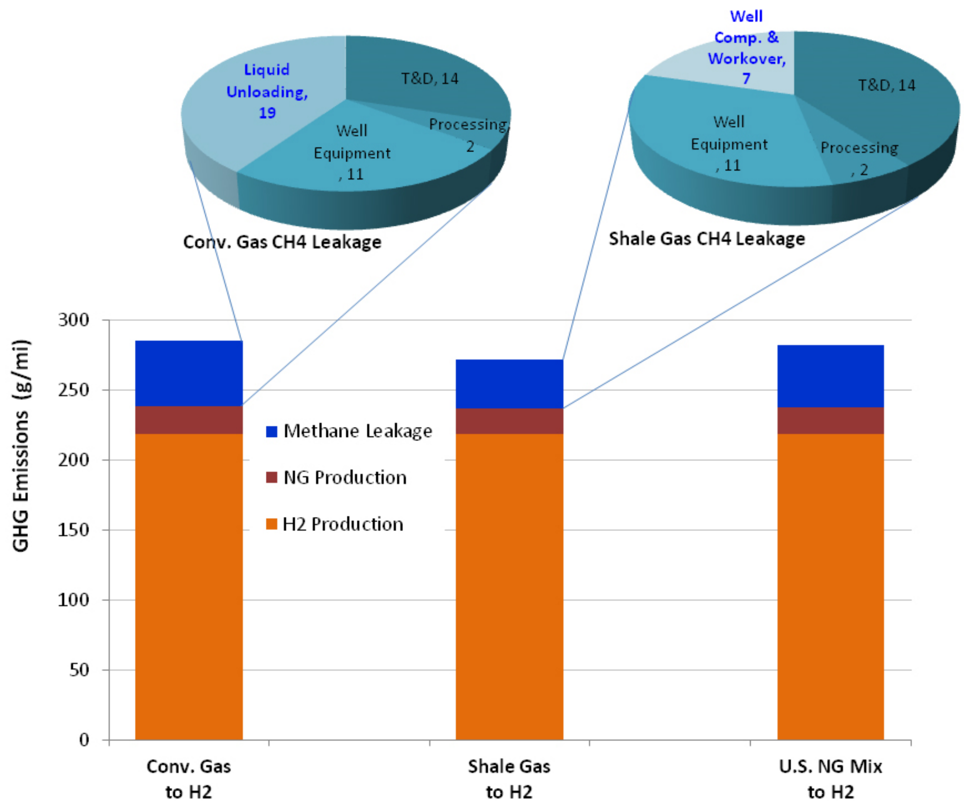
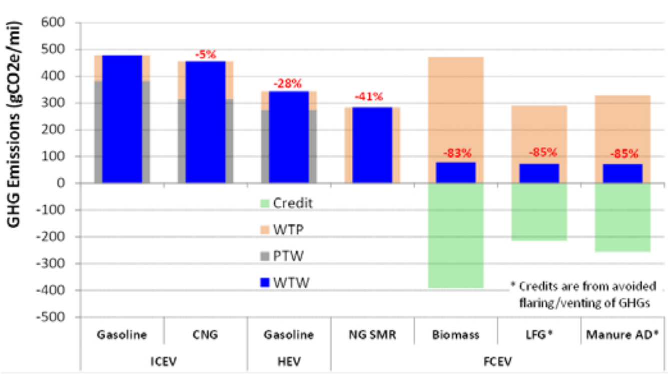


FIGURE 1. WTW GHG emissions of hydrogen production from conventional and shale gas for use in FCEVs



WTP - well to pump; PTW - pump to wheels; HEV - hybrid electric vehicle; LPG - liquefied petroleum gas; AD - anaerobic digestion

FIGURE 2. WTW GHG emissions of hydrogen FCEVs compared to conventional ICEVs and HEVs

40% relative to gasoline ICEVs, which compares to a 5% reduction if NG is used directly in compressed natural gas (CNG) vehicles. Hydrogen produced from renewable sources such as cellulosic biomass and RNG provides a substantial (83-85%) reduction in GHG emissions relative to gasoline ICEVs. To compare FCEVs with the baseline gasoline ICEVs and with BEVs on a life-cycle basis, we evaluated the vehicle cycle energy use and emissions associated with the manufacturing of these vehicles as well as the construction of their associated fuel production plants. Platinum loading is critical for the performance of fuel cell stacks in FCEVs. Each gram of platinum contributes approximately 12 kg of life-cycle GHG emissions. Based on a 70-kW fuel cell stack and platinum loading reduction from 1.1 g/kW in 2005 to 0.125 g/kW in 2015, GHG emissions of FCEVs are reduced by 5 g_{CO2e}/mi or 7% of the vehicle cycle GHG emissions. The GHG emissions per million Btu (mmBtu) of gasoline produced in a petroleum refinery are evaluated and compared with those of a SMR plant for hydrogen production, and NG combined cycle (NGCC) and coal power plants for electricity generated as shown in Figure 3. The figure shows that the emission profiles for refineries and hydrogen SMR plants are much smaller compared to NGCC and coal power plants.

TABLE 1. Fuel Economy Assumptions for Alternative Fuel/Vehicle Systems

Fuel/Vehicle System	Fuel Economy [mpgge*]
Conventional gasoline ICEV	23
CNG Vehicle	22
Gasoline HEV	33
Hydrogen FCEV	54
BEV	79**

* mpgge = miles per gallon of gasoline equivalent
** from wall outlet (assuming 85% charging efficiency)

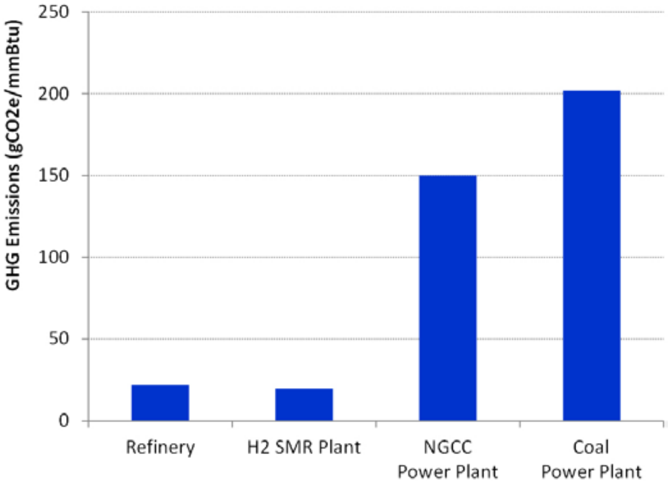


FIGURE 3. Plant construction GHG emissions for petroleum refineries, hydrogen SMR plants, and NGCC and coal power plants (per mmBtu of fuel produced)

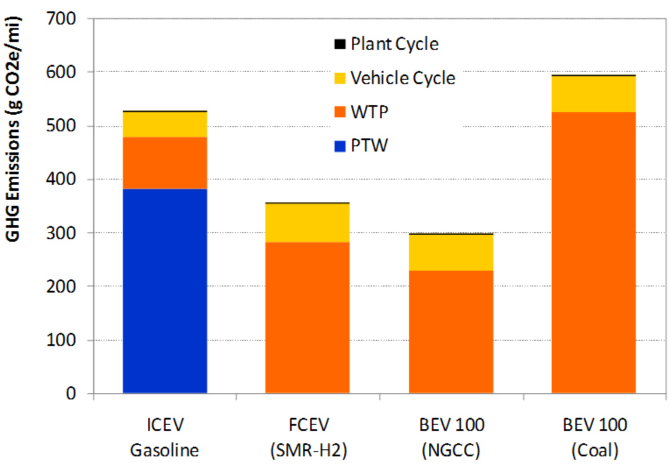


FIGURE 4. Comparison of life cycle GHG emissions of hydrogen FCEVs with gasoline ICEVs and BEVs

However, when these emissions are evaluated on a per-mile basis using fuel economies of the vehicles employing these fuels, the plant construction impact becomes negligible (<1% of the combined fuel and vehicle cycle emissions) compared to the fuel and vehicle cycles for all fuel/vehicle systems as shown in Figure 4.

Conclusions

- CH_4 leakage is a major GHG emissions source for production of hydrogen from conventional gas and shale gas.
- FCEVs with fossil and renewable hydrogen production pathways could have significant GHG reductions relative to gasoline ICEVs (by 41% when hydrogen is produced from fossil NG/SG and by 83-85% when hydrogen is produced from RNG or biomass).
- FCEV vehicle-cycle GHG emissions are reduced by 7% with platinum loading reduction.
- Emissions of fuel plant construction are negligible compared to fuel- and vehicle-cycle emissions.

Future Work

- WTW analysis of range extender FCVs.
- Complete and update upstream plant construction activities for the baseline petroleum-derived fuels and hydrogen plant construction.
- Expand the electricity module and develop stationary fuel cell systems in GREET.

Special Recognitions

1. DOE Fuel Cells Program R&D Award "In Recognition of Outstanding Contribution to Analysis and Modeling of Hydrogen Delivery." Awarded to Amgad Elgowainy at the DOE's Hydrogen Program Annual Merit Review (2012).

References

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

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4. Burnham, A., Han, J., Clark, C., Wang, M., Dunn, J., Palou-Rivera, I., 2012, "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal and Petroleum," Environ. Sci. Technol., 46 (2), pp 619–627.

5. DOE Hydrogen Program Record, June 1, 2010, Record # 9018.

FY 2012 Publications/Presentations

1. Burnham, A., Han, J., Clark, C., Wang, M., Dunn, J., Palou-Rivera, I., 2012, "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal and Petroleum," Environ. Sci. Technol., 46 (2), pp 619–627.

2. Han, J., Mintz, M., Wang, M., 2011, "Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model," Center for Transportation Research, Argonne National Laboratory, AN/ESD/11-06, Argonne, IL.