XI.5 Life-Cycle Analysis of Hydrogen Onboard Storage Options

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Project Start Date: October 2012
Project End Date: October 2013

Overall Objectives

Quantify environmental impacts of various physical and material-based hydrogen (H2) onboard storage technologies.

Fiscal Year (FY) 2013 Objectives

Quantify life-cycle greenhouse gas (GHG) emissions of the following physical and material-based H2 onboard storage technologies:

- 350-bar compressed gaseous storage system
- 700-bar compressed gaseous storage system
- Cryo-compressed hydrogen (CcH2) storage system
- Metal organic framework (MOF)-5 sorption storage system

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:

(C) Inconsistent Data, Assumptions and Guidelines

(D) Insufficient 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 Office Multi-Year Research, Development, and Demonstration Plan:

- Task 1.13: Complete environmental analysis of the technology environmental impacts for hydrogen and fuel cell scenarios and technology readiness. (4Q, 2015)

FY 2013 Accomplishments

- Quantified the energy use associated with the manufacturing and charging of four hydrogen onboard storage system technologies including the 350- and 700-bar compressed gaseous storage systems, CcH2 storage system, and gaseous storage in the MOF-5 sorption system.
- Quantified the GHG emissions associated with the manufacturing of fuel cell electric vehicles (FCEVs), including the manufacturing of the various onboard storage systems.
- Quantified the fuel cycle GHG emissions associated with hydrogen production, delivery, distribution, dispensing to the onboard storage system.

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INTRODUCTION

The stages included in the life-cycle of any product include its raw material acquisition, transportation and processing, as well as its manufacturing, distribution, use and disposal or recycling. Life-cycle analysis (LCA) of a fuel is known as fuel-cycle analysis or well-to-wheels (WTW) analysis, while LCA of vehicle manufacturing is known as vehicle-cycle analysis, Figure 1. Combining the environmental impacts of the fuel cycle with the vehicle cycle facilitates the comparison of alternative H2 fuel production, delivery, dispensing and onboard storage pathway options, including the manufacturing of FCEV components, on a common (i.e., life cycle) basis. The LCA of hydrogen FCEV systems depends on the vehicle's onboard storage technology. For example the CcH2 storage option requires the liquefaction of H2 and the manufacturing of super-insulated cryogenic vehicle's storage tank, while the 350- and 700-bar compressed gaseous storage options require compression, precooling and the manufacturing of high-pressure storage tanks. The MOF-5 storage option requires both precooling and compression to dispense an equivalent amount of hydrogen (5.8 kg) at a specified fill rate (1.67 kg/min). The manufacturing of the onboard storage system is part of the vehicle cycle which includes other FCEV components such as the fuel cell, transmission, chassis, traction motor, generator, electronic controller, fuel cell auxiliaries, body, tires, batteries, and fluids. The vehicle cycle also includes the vehicle's assembly process, and disposal or recycling at the end of the vehicle's life. The fuel cycle includes the production, compression/

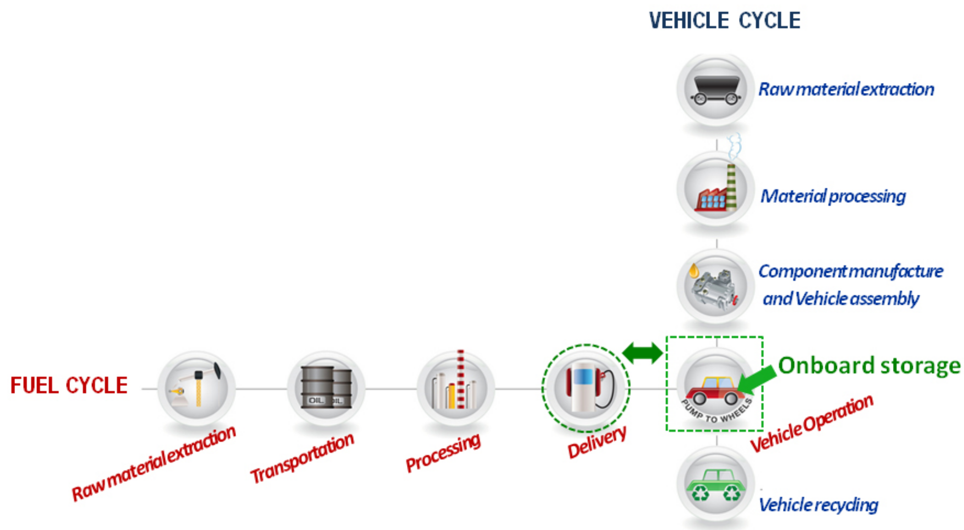

FIGURE 1. Fuel Cycle and Vehicle Cycle Stages in the GREET Model

precooling/liquefaction, delivery and consumption of hydrogen. The LCA of FCEVs combines the fuel cycle with the vehicle cycle to assess the environmental impacts associated with various hydrogen onboard storage options.

APPROACH

The material balance for the physical 350- and 700-bar compressed gas storage systems was obtained from the technical assessment of these systems conducted by Argonne National Laboratory and TIAX [1-2]. The material balance for the MOF-5 sorption storage system (200 liter, Type I tank) was obtained from the technical assessment done by the Hydrogen Storage Engineering Center of Excellence as shown in Table 1. The advanced materials in these storage systems, such as carbon fiber and MOF, were examined to determine the composition as well as the energy and carbon intensities of the basic materials used in the manufacturing process of these advanced materials. The carbon intensities of all vehicle components, including storage tank materials, e.g., aluminum and stainless steel, were obtained from the Greenhouse gases, Regulated Emissions, and Energy in Transportation (GREET) model for vehicle cycle evaluation. The GHG emissions associated with hydrogen production, liquefaction, compression, precooling, and delivery were obtained from the GREET fuel cycle model.

TABLE 1. Material Balance of MOF-5 Storage System

MOF-5 System Components	Weight (kg)	Material
Pressure vessel	62.2	Al
Vacuum shell	14.8	Al
Heat exchanger	4.3	Al
Insulation	7.7	PET
Adsorbent	24.4	MOF-5
Balance of plant	17.4	SS
Total	130.8	

Al – aluminum; PET – polyethylene terephthalate; SS – stainless steel

RESULTS

Table 2 lists the life cycle GHG emissions associated with the manufacturing of each H2 onboard storage system. Figure 2 shows vehicle cycle GHG emissions for various onboard storage options. As shown in the figure, it is assumed that the only difference in the vehicles' components is the onboard storage system. The total GHG emissions over the vehicle cycle range from 11.5 ton of carbon dioxide equivalent (CO_{2e}) for the cryo-compressed option to 12.8 ton of CO_{2e} for the 700 bar storage option. It should be noted that different onboard storage systems have different implications on the fuel cycle GHG emissions because of the different H2 packaging requirement for each system. For example, the 350-bar compressed gas system requires compression while the cryo-compressed system requires liquefaction. The 700-bar compressed gas requires additional precooling at 233 K to overcome the heat of compression while the MOF-5 system requires precooling at 80 K to overcome the heat of adsorption and reach the required energy density at 100 bar.

TABLE 2. Life-Cycle GHG Emissions of Various Hydrogen Onboard Storage Options

Onboard Storage Option	GHG Emissions
350-bar compressed gas storage	2,210 kg_{CO2e}
700-bar compressed gas storage	2,670 kg_{CO2e}
Cryo-compressed storage	1,490 kg_{CO2e}
MOF-5 storage	2,440 kg_{CO2e}

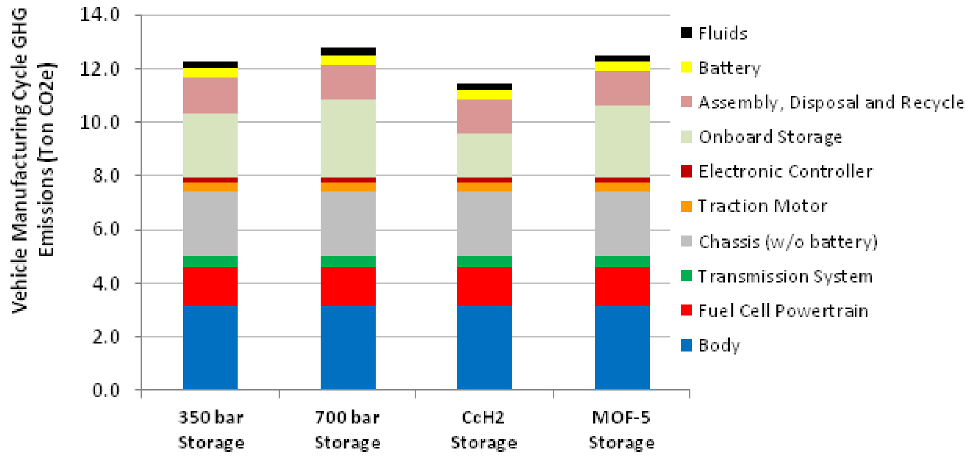

FIGURE 2. Vehicle Cycle GHG Emissions of Various Onboard Storage Systems

For the cryo-compressed storage option, the liquefaction GHG emissions from current plants in North America are estimated at 5 kg_{CO2e} per kg of H2 (instead of 8 kg_{CO2e} per kg of H2 when the U.S. average electricity generation mix is assumed as the source for liquefaction energy). The precooling to 80 K for the MOF-5 system requires approximately 10 kg of liquid nitrogen per kg of H2 and results in GHG emissions of 5.4 kg_{CO2e} per kg of precooled hydrogen. Table 3 shows the GHG emissions associated with the fuel cycle of hydrogen for various onboard storage systems, including the hydrogen production from steam methane reforming (SMR). In order to combine the vehicle cycle results in Table 2 with the fuel cycle results in Table 3, a common functional unit (e.g., vehicle's travelled mile) is required. A FCEV's fuel economy of 60 miles per kg of H2 is assumed to estimate the fuel cycle GHG emissions on a per mile basis. The vehicle's travelled distance over its lifetime is assumed to be 160,000 miles in order to estimate the vehicle cycle GHG emissions on a per mile basis. Table 4 shows per-mile combined fuel cycle and vehicle cycle GHG emissions associated with each onboard storage system. The hydrogen production via SMR is responsible for 200 g_{CO2e}/mi of the total life-cycle GHG emissions.

TABLE 3. Fuel Cycle GHG Emissions of H2 Associated with Various Onboard Storage Options (kg_{CO2e}/kg_{H2})

H2 Pathway (storage option)	Production (via SMR)	Transport (via trucks)	Compression/ liquefaction	Total
GH2 Pathway (350 bar)	12	0.7	2.0	14.7
GH2 Pathway (700 bar)	12	0.7	2.9	15.6
LH2 Pathway (CcH2)	12	0.1	5.2	17.3
GH2 Pathway (MOF-5)	12	0.7	5.4	18.1

GH2 – gaseous hydrogen; LH2 – liquefied hydrogen

TABLE 4. Combined Fuel Cycle and Vehicle Cycle GHG Emissions Associated with Various H2 Onboard Storage Systems (g_{CO2e}/mi)

H2 Pathway (storage option)	Onboard Storage	Balance of Vehicle Cycle	Fuel Cycle (WTW)	Total
GH2 Pathway (350 bar)	14	56	245	315
GH2 Pathway (700 bar)	17	56	257	330
LH2 Pathway (CcH2)	9	56	288	353
GH2 Pathway (MOF-5)	15	56	302	373

CONCLUSIONS AND FUTURE DIRECTIONS

Life-cycle GHG emissions associated with various hydrogen onboard storage systems were estimated between 315 and 373 g_{CO2e}/mi. Systems that require significant precooling (e.g., cryo-compressed and MOF-5) exhibited more GHG emissions compared with systems that require less precooling (i.e., 700-bar system) or no precooling (i.e., 350-bar system). The same methodology can be applied to evaluate the environmental impacts of new and emerging hydrogen onboard storage systems.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Amgad Elgowainy and Michael Wang received the DOE Joint Vehicle Technologies and Fuel Cell Technologies R&D Award in recognition for their outstanding contributions to life-cycle assessment of alternative fuel vehicles pathways, including fuel cell and battery electric vehicles (2013).

REFERENCES

1. Hua, T. and R. Ahluwalia et al., 2010, Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications, Argonne National Laboratory, Nuclear Engineering Division, Report No. ANL/10-24.

2. Ahluwalia, R. and T. Hua et al., 2009, Technical Assessment of Cryo-Compressed Hydrogen Storage Tank Systems for Automotive Applications, Argonne National Laboratory, Nuclear Engineering Division, Report No. ANL/09-33.