XI.7 Pathway Analysis: Projected Cost, Well-to-Wheels Energy Use and Emissions of Current Hydrogen Technologies

Todd Ramsden (Primary Contact), Mark Ruth
National Renewable Energy Laboratory
15013 Denver West Pkwy.
Golden, CO 80401
Phone: (303) 275-3704
Email: todd.ramsden@nrel.gov

DOE Manager
Fred Joseck
Phone: (202) 586-7932
Email: Fred.Joseck@ee.doe.gov

Project Start Date: January 1, 2012
Project End Date: August 30, 2013

Overall Objectives

- Conduct cost and life-cycle energy and emissions analyses of full current-technology hydrogen pathways to evaluate hydrogen cost, energy requirements and greenhouse gas (GHG) emissions.
- Provide detailed reporting of assumptions and data used to analyze hydrogen production, delivery, and dispensing technologies, enabling consistent and transparent understanding of results.
- Evaluate potential of current technologies to meet $2-$4/kg hydrogen cost target.
- Validate DOE's Fuel Cell Technologies Office (FCTO) Macro-System Model (MSM) and its underlying component models (in particular, the H2A Production model, the Hydrogen Delivery Scenario Analysis Model [HDSAM], and the Greenhouse gas, Regulated Emissions, and Energy use in Transportation [GREET] model) through industry review.

Fiscal Year (FY) 2013 Objectives

- Finalize and publish the current-technologies pathway analysis which began in FY 2012.
- Conduct detailed sensitivity analyses, including cost, energy use, and emissions analyses based on a fuel cell electric vehicle (FCEV) on-road fuel economy of 48 miles per gasoline gallon equivalent (gge) and 68 miles/gge.
- Complete technical report on the analysis, providing a detailed reporting of hydrogen cost and capital costs of the full hydrogen pathways to support FCEV's, upstream energy and feedstock usage and GHG emissions.
- Conduct a companion pathway analysis to consider future hydrogen technologies that are expected to be available in the 2020 to 2030 timeframe, assessing the impact technology improvements will have on hydrogen cost and well-to-wheels (WTW) energy use and emissions.

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:

(B) Stove-piped/Siloed Analytical Capability

(C) Inconsistent Data, Assumptions and Guidelines

(D) Insufficient Suite of Models and Tools

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE milestones from the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Milestone 1.12: Complete an analysis of the hydrogen infrastructure and technical target progress for technology readiness. (4Q, 2015)
- Milestone 1.13: Complete environmental analysis of the technology environmental impacts for hydrogen and fuel cell scenarios and technology readiness. (4Q, 2015)
- Milestone 1.15: Complete analysis of program milestones and technology readiness goals - including risk analysis, independent reviews, financial evaluations, and environmental analysis - to identify technology and risk mitigation strategies. (4Q, 2015)
- Milestone 1.18: Complete life cycle analysis of vehicle costs for fuel cell electric vehicles compared to other vehicle platforms. (4Q, 2019)
- Milestone 2.2: Annual model update and validation. (4Q, 2011 through 4Q, 2020)
- Milestone 3.4: Review Hydrogen Threshold Cost status. (4Q, 2014; 4Q, 2017; 4Q, 2020)

FY 2013 Accomplishments

- Estimated the total cost of fuel cell vehicle ownership for two hydrogen production, delivery and dispensing pathways, including the cost of hydrogen fuel and FCEV purchase and operating costs. Distributed hydrogen production from natural gas reformation pathway resulted in lowest costs, with costs of $0.10 per mile driven for hydrogen fuel and total vehicle ownership and operational cost of $0.66 per mile (in a mature market).

- Ten current-technology hydrogen production, delivery and dispensing pathways analyzed, providing evaluations of WTW costs, energy use and GHG emissions:
  - Estimated the cost of hydrogen in a mature market, with costs ranging from $4.60/kg-H2 for the distributed natural gas reformation pathway to $8.80/kg for the distributed ethanol reforming pathway.
  - Estimated the total lifecycle GHG emissions of all pathways, including upstream fuel- and feedstock-related emissions and vehicle production-related emissions. The distributed ethanol-reforming pathway had the lowest emissions, with 50 g CO_2-equivalent per mile at an assumed 68 miles/gge fuel economy (70 g CO_2-eq/mi at 48 miles/gge). The lowest cost distributed natural gas reforming pathway yielded 250 g CO_2/mi at 68 miles/gge fuel economy (350 g CO_2/mi at 48 miles/gge).
- Extensive industry review of overall results, modeling results, and input parameters provided external validation of the MSM and the related component models (H2A Production, HDSAM, and GREET).
- Conducted an initial assessment of future-technology hydrogen pathways expected to be available in the 2020 to 2030 timeframe.

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INTRODUCTION

DOE's FCTO had identified a need to understand the cost, energy use, and emissions tradeoffs of various hydrogen production, delivery, distribution, and use options under consideration for FCEVs. This study assesses 10 complete hydrogen production, delivery, and dispensing pathways to evaluate total dispensed hydrogen cost, total cost of ownership for a FCEV, and lifecycle assessments of total energy use and GHG emissions. The study considers the potential of current hydrogen technologies if they were brought to commercial scale in a mature fuel cell vehicle market; it is not an assessment of transition scenarios where equipment may not be fully utilized.

This study will help FCTO evaluate the potential of current technologies to meet the $2-$4/kg cost target for dispensed hydrogen. By providing a common framework for modeling using consistent data and assumptions, this study provides a detailed and transparent understanding of hydrogen technologies and will assist FCTO with goal setting and research and development decisions. Finally, this analysis will aid in understanding and assessing technology needs and progress, potential environmental impacts, and the energy-related economic benefits of various hydrogen pathways.

APPROACH

This study evaluated 10 hydrogen production, delivery, and dispensing pathways for hydrogen cost, energy requirements and GHG emissions (see Table 1). Considering plausible hydrogen production and delivery scenarios for mature hydrogen transportation-fuel markets combined with market penetration of hydrogen fuel cell vehicles, the study uses a common set of assumptions to provide a consistent assessment of all pathways. Major assumptions include:

- 2015 start-up year with 2015 FCEV purchase
- Currently available hydrogen technologies, projected to a commercial scale
- Costs reported in $2007
- 40-year analysis period for central production; 20-year analysis for distributed cases
- Feedstock and utility costs from the Annual Energy Outlook 2009, based on national averages
- On-road FCEV fuel economy of 48 miles/gge (with sensitivity analyses at 68 miles/gge)
- Urban demand area with a population of 1.25 million (nominally Indianapolis)
- 15% FCEV penetration
- Conventional, mid-sized FCEV (not light-weighted)
- 15,000 miles/year vehicle miles traveled per FCEV

TABLE 1. Hydrogen Pathways Evaluated

Path	Production Feedstock / Technology	Delivery Mode	Dispensing Mode
1	Natural Gas Reforming	Distributed Production	700 Bar, gaseous
2	Ethanol Reforming	Distributed Production	700 Bar, gaseous
3	Grid Electrolysis	Distributed Production	700 Bar, gaseous
4	Biomass Gasification	Gaseous H_2 in Pipelines	700 Bar, gaseous
5	Biomass Gasification	Gaseous H_2 Truck	700 Bar, gaseous
6	Biomass Gasification	Liquid H_2 Truck	700 Bar, gaseous
7	Biomass Gasification	Liquid H_2 Truck	Cryo-compressed
8	Natural Gas Reforming	Gaseous H_2 in Pipelines	700 Bar, gaseous
9	Wind Electrolysis	Gaseous H_2 in Pipelines	700 Bar, gaseous
10	Coal Gasification (with carbon capture)	Gaseous H_2 in Pipelines	700 Bar, gaseous

- Hydrogen dispensed for 700-bar, high-pressure storage (except cryo-compressed case)

The analysis was conducted using the MSM, which acts as a central transfer station, linking together the H2A Production model, HDSAM, GREET, and the Cost-Per-Mile tool. Making use of the discounted cash flow, rate of return features of H2A Production and HDSAM, the MSM provides cost results in terms of a levelized cost of hydrogen (incorporating a 10% real rate of return on investments) in a $/kg basis. The MSM also outputs well-to-pump, pump-to-wheels, and WTW efficiencies, GHG emissions, and energy use for each pathway. Emissions and energy use results include upstream energy use required for feedstock production, processing, and delivery. For all pathways evaluated, the key assumptions, modeling parameters, and analysis inputs were reviewed by industry partners through the U.S. DRIVE Fuel Pathways Integration Technical Team.

RESULTS

The MSM evaluation of the 10 current-technology hydrogen pathways presents the cost of hydrogen and the performance of the pathways in terms of total energy use, fossil energy use, and GHG emissions. Figure 1 shows the levelized cost of hydrogen from the 10 different pathways. DOE's FCTO has set a hydrogen cost target of $2-$4/gge dispensed at the pump. The distributed natural gas reformation pathway comes closest to this target, with a projected hydrogen cost of $4.60/gge. To achieve the $4/gge target, DOE has a hydrogen production target of $2/gge. The hydrogen pathways evaluation shows that four production pathways (distributed natural gas reformation, central biomass gasification, central natural gas reformation, and central coal gasification) achieve or approach this target, with production costs of $2.20/gge or less. Hydrogen station compression, storage, and dispensing costs for 700-bar dispensing (not including delivery) range from approximately $1.00/gge to $2.50/gge, showing that compression, storage, and dispensing is a critical area for research in order to meet overall hydrogen cost targets.

The study also evaluated the total cost of FCEV ownership including the costs of the hydrogen fuel and the costs of vehicle purchase and operation. The lowest cost of FCEV ownership resulted from hydrogen fuel produced and dispensed from the distributed natural gas reformation pathway. Assuming a 5-year ownership period and fuel economy of 48 miles/gge, the distributed natural gas pathway resulted in total ownership costs of $0.66 per mile. With fuel costs of $0.10/mi, the hydrogen fuel accounts for about 15% of ownership costs. The purchase of the FCEV (represented as finance and depreciation costs) account for about 50% of ownership costs.

Figure 2 illustrates that for a 48 miles/gge FCEV, all the pathways (except the distributed electrolysis pathway) result in GHG emissions (on a gram CO_2-equivalent per mile basis) lower than 350 g/mile, demonstrating a significant improvement over a conventional gasoline vehicle. Figure 2 also shows that when a higher fuel economy of 68 miles/gge is considered, all of the pathways except distributed

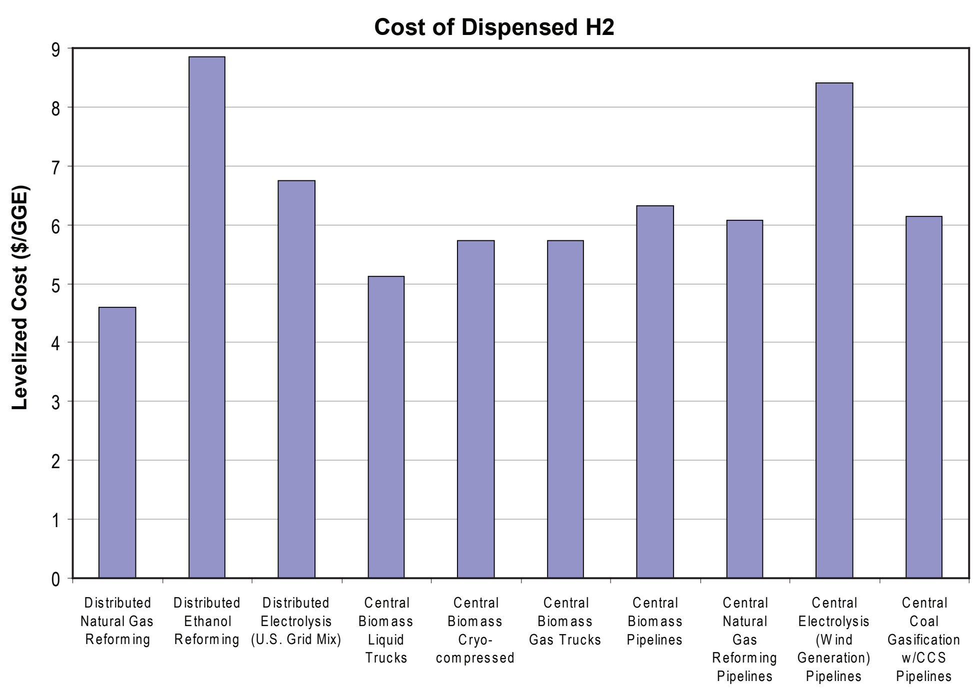

FIGURE 1. Cost of Dispensed Hydrogen from All Pathways

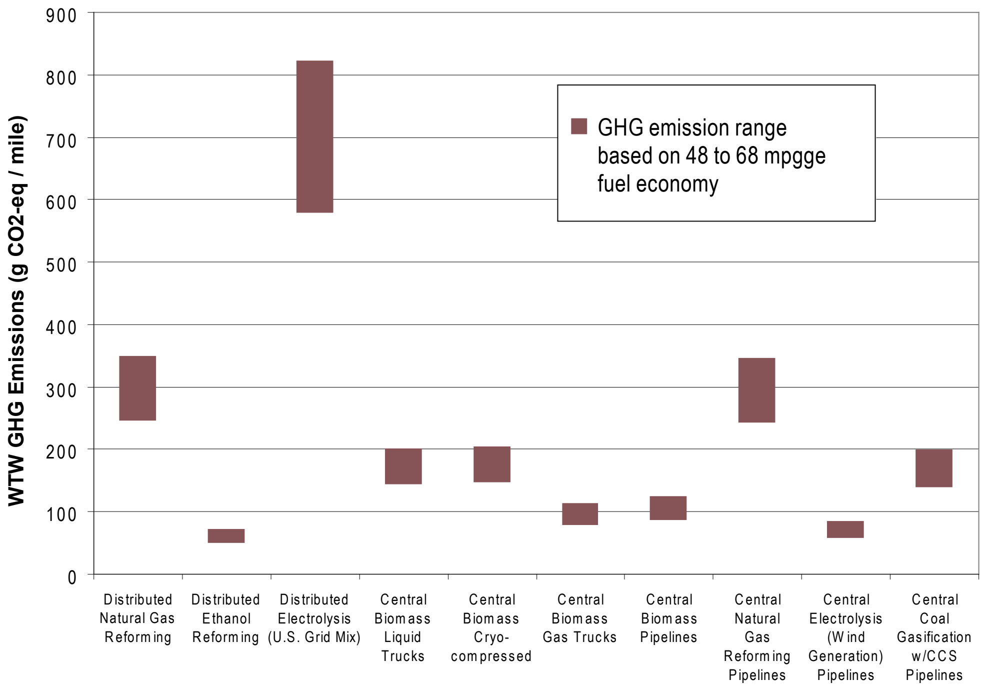

FIGURE 2. WTW GHG Emissions from All Pathways

electrolysis result in GHG emissions lower than 250 g/mile and four pathways have GHG emissions lower than 100 g/mile. Distributed electrolysis has high GHG emissions when compared to the other hydrogen pathways because of the assumed electricity grid mix (the U.S. average grid mix is assumed). The pathways that use natural gas as a feedstock use little petroleum but have high GHG emissions compared to most of the other pathways due to the GHGs released in producing hydrogen from natural gas. The coal pathway has slightly lower GHG emissions than the natural gas pathways because of the efficient sequestration system that is assumed. Of the four options for delivering hydrogen from a centralized production plant, pipeline delivery has the lowest GHG emissions and lowest petroleum use. The two liquid truck delivery options have higher GHG emissions because of the high electricity consumption of the liquefaction process (the U.S. average grid mix is assumed).

CONCLUSIONS AND FUTURE DIRECTIONS

The WTW analysis shows that based on current hydrogen production, delivery, and dispensing technologies, none of the pathways can achieve the $4/gge DOE target, even extrapolated out to full commercialization in a mature hydrogen market. However, almost all pathways demonstrate significant improvements in WTW GHG emissions compared to conventional gasoline vehicles.

In the latter part of FY 2013 and early FY 2014, the WTW pathways analysis will be extended to consider process and cost improvements that might be expected to be available in the 2020-2030 timeframe. This evaluation of future hydrogen technologies will project where hydrogen costs and associated energy and GHG emissions might be expected to fall based on continued research and development activities. This companion analysis should therefore provide a better picture of the potential of achieving DOE's $4/gge hydrogen cost target.

FY 2013 PUBLICATIONS/PRESENTATIONS

1. Todd Ramsden, "Pathway Analysis: Projected Cost, Well-to-Wheels Energy Use and Emissions of Current Hydrogen Technologies". Presentation at the 2013 DOE Hydrogen and Fuel Cell Technologies Program Annual Merit Review, Arlington, VA.