X.3 Pathway Analysis: Projected Cost, Life-Cycle Energy Use and Emissions of Future Hydrogen Technologies

Todd Ramsden (Primary Contact), Victor Diakov, Neil Popovich
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: June 1, 2013
Project End Date: September 30, 2014

Overall Objectives

- Conduct cost and lifecycle energy and emissions analyses of full future-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
- Report on upstream energy and feedstock usage and GHG emissions on a full lifecycle basis, including vehicle cycle and well-to-wheels fuel cycle
- Understand lifecycle costs, energy and emissions of hydrogen technologies to inform R&D decision-making process
- Evaluate potential of future hydrogen technologies to meet the hydrogen cost target of <$4/kg
- Validate the Fuel Cell Technologies Office's (FCTO's) Macro-System Model (MSM) and its underlying component models (in particular, the H2A Production model, the Hydrogen Delivery Scenario Analysis Model, and the Greenhouse gases, Regulated Emissions and Energy use in Transportation [GREET] model) through industry review

Fiscal Year (FY) 2014 Objectives

- Finalize an evaluation of nine complete hydrogen production, delivery, and dispensing pathways based on the cost and performance of future hydrogen technologies expected to be available in the 2020 to 2030 timeframe, assessing the impact technology improvements will have on lifecycle cost, energy use, and emissions
- Conduct detailed sensitivity analyses, including cost, energy use, and emissions analyses based on a fuel cell electric vehicle (FCEV) on-road fuel economy of 58 miles per gallon-equivalent (gge) and 68 miles/gge (mpgge)
- Complete technical report on the analysis, providing a detailed reporting of hydrogen cost and capital costs of the full hydrogen pathways to support FCEVs, upstream energy and feedstock usage and GHG emissions
- Initiate a companion pathway analysis to consider emerging renewable hydrogen production technologies

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 2014 Accomplishments

- Estimated the lifecycle costs, energy use, and emissions from nine future-technology hydrogen fuel pathways, including a total cost of fuel cell vehicle ownership that considers 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 $0.07 per mile driven for hydrogen fuel and total vehicle ownership and operational cost of $0.69 per mile (in a mature market).
- Nine future-technology hydrogen production, delivery and dispensing pathways analyzed, providing evaluations of well-to-wheels (WTW) costs, energy use and GHG emissions
  - Estimated the cost of hydrogen in a mature market, with costs ranging from \$3.80/kg-H_2 for the distributed natural gas reformation pathway to almost $7.50/kg for the distributed ethanol reforming pathway.
  - Estimated the total fuel-cycle (WTW) and lifecycle GHG emissions of all pathways, including upstream fuel- and feedstock-related emissions and vehicle production-related emissions. The central wind electrolysis pathway had the lowest WTW emissions, with emissions of about 40 g CO_2-equivalent per mile. The lowest cost pathway – distributed natural gas reforming – yielded 250 g CO_2/mi at 68 mpgge fuel economy (300 g CO_2/mi at 58 mpgge).
- Extensive industry review of overall results, modeling results, and input parameters, providing external validation of the MSM and the related component models.
- Conducted an initial assessment of emerging-technology renewable hydrogen production pathways.

✧ ✧ ✧ ✧ ✧

INTRODUCTION

DOE's FCTO had identified a need to understand the cost, energy use, and emissions tradeoffs of various hydrogen fuel infrastructure technologies under consideration for fuel cell vehicles. This study assesses nine complete hydrogen production, delivery, and dispensing scenarios based on the cost and performance of future hydrogen technologies expected to be available in the 2020 to 2030 timeframe, assessing the impact technology improvements will have on lifecycle cost, energy use, and emissions. The study considers the potential of future 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. The future-technology pathway analysis is a companion analysis of current-technology hydrogen pathways published in 2014 (publication 1).

This study will help FCTO evaluate the potential of future hydrogen technologies to meet the cost target of <$4/kg 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 R&D 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 nine hydrogen production, delivery, and dispensing pathways expected to be available in the 2020-2030 timeframe, assessing the impact technology improvements will have on 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:

- 2025 start-up year for hydrogen fuel infrastructure
- Future (2020-2030) 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 58 mpgge (with sensitivity analyses at 68 mpgge)
- Urban demand area with a population of 1.25 million (nominally Indianapolis)
- 15% FCEV penetration
- Mid-sized FCEV, chassis comparable to conventional vehicle
- 15,000 miles/year vehicle miles traveled per FCEV
- Hydrogen dispensed for 700 bar, high-pressure storage (except cryo-compressed case)

TABLE 1. Future-Technology 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	Natural Gas Reforming	Gaseous H_2 in Pipelines	700 bar, gaseous
5	Natural Gas Reforming	Gaseous H_2 Truck	700 bar, gaseous
6	Natural Gas Reforming	Liquid H_2 Truck	700 bar, gaseous
7	Natural Gas Reforming	Liquid H_2 Truck	Cryo-compressed
8	Natural Gas Reforming with CCS	Gaseous H_2 in Pipelines	700 bar, gaseous
9	Wind Electrolysis	Gaseous H_2 in Pipelines	700 bar, gaseous

CCS - carbon capture and storage

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 well-to-wheels 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.

RESULTS

The MSM evaluation of the nine future-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. For all pathways evaluated, the key assumptions, modeling parameters, and analysis inputs were reviewed by industry partners through the U.S. DRIVE Fuel Pathway Integration Technical Team. Figure 1 shows the levelized cost of hydrogen from the nine different pathways. DOE's FCTO has set a hydrogen cost target of <$4/gge. $4.00 per gge (approximately equivalent to 1 kg of hydrogen), dispensed at the pump. The distributed natural gas reformation pathway is expected to meet this target, with a projected hydrogen cost of $3.80/kg. To achieve the $4/gge target, DOE has a hydrogen production target of $2/kg. The hydrogen pathways evaluation shows that central natural gas production will achieve this target (production cost of $1.95/kg) and distributed natural gas reformation will approach this target with a production cost of $2.20/kg. Hydrogen station compression, storage, and dispensing costs for 700-bar dispensing (not including delivery) range from under $1.00/kg to about $1.60/kg.

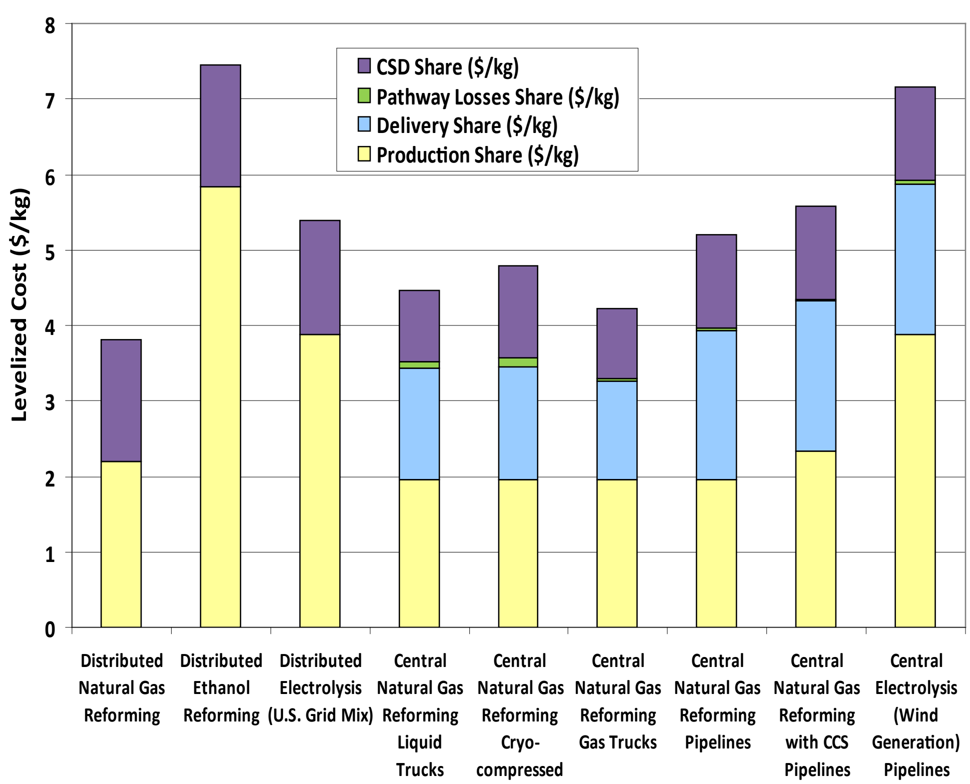

FIGURE 1. Cost of Dispensed Hydrogen from All Pathways

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 58 mpgge, the distributed natural gas pathway resulted in total ownership costs of $0.69 per mile. With fuel costs of $0.066/mi, the cost of hydrogen fuel represents 10% of ownership costs. The purchase of the FCEV (represented as finance and depreciation costs) accounts for about 50% of ownership costs.

Figure 2 illustrates that for a 58 mpgge FCEV, all the pathways (except the distributed electrolysis pathway) result in GHG emissions (on a gram CO_2-equivalent per mile basis) lower than 300 g/mile, demonstrating a significant improvement over a conventional gasoline vehicle. Figure 2 also shows that when a higher fuel economy of 68 mpgge is considered, all of the pathways except distributed electrolysis result in GHG emissions lower than 250 g/mile and three 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). Hydrogen production from the central natural gas with carbon sequestration case has increased production costs over the other natural gas production pathways, but the additional costs for sequestration yield a significant reduction in WTW GHG emissions. 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 lifecycle analysis shows that of the nine future-technology hydrogen production, delivery, and dispensing pathways investigated, only the distributed natural gas reformation pathway can achieve the $4/gge DOE target, although the central natural gas reformation with truck delivery cases approach the target. From an emissions perspective, almost all pathways demonstrate significant improvements in WTW GHG emissions compared to conventional gasoline vehicles.

In the latter part of FY 2014 and FY 2015, the hydrogen pathways analysis will be extended to consider emerging hydrogen production, delivery, and onboard vehicle storage technologies. This will include an assessment of high-

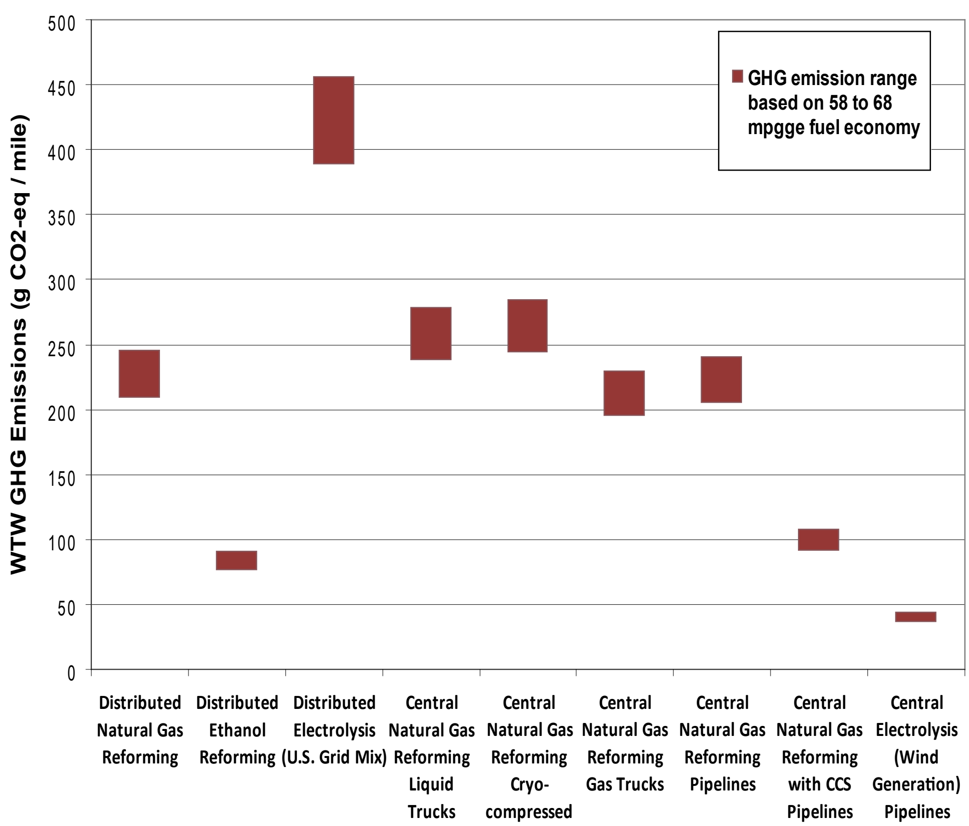

FIGURE 2. WTW Greenhouse Gas Emissions from All Pathways

pressure gaseous truck delivery and emerging renewable hydrogen production technologies such as photo-biological production, photo-electrochemical production, and solar thermo-chemical production. These evaluations of emerging hydrogen technologies will help to assess the potential of lowering hydrogen delivery costs and to evaluate the potential of a wider range of renewable hydrogen production pathways.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. Ramsden, T., Ruth, M., Diakov, V., Laffen, M., and Timbario, T., 2013. *Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios*, National Renewable Energy Laboratory, Technical Report NREL/TP-6A10-60528 (March), Golden, CO.

2. Todd Ramsden, 2013 [presentation]. *Pathways Analysis: Future Technology Hydrogen Production, Delivery & Dispensing Pathways.* U.S. DRIVE Fuel Pathway Integration Technical Team Meeting, Chevron, San Ramon, CA (October).

3. Todd Ramsden, 2014 [presentation]. *Hydrogen Pathway Analysis Project: Future Technologies.* U.S. DRIVE Production, Delivery and Fuel Pathway Integration Joint Technical Team Meeting, Argonne National Laboratory, Lemont, IL (April).

4. Todd Ramsden, 2014 [presentation]. *Pathway Analysis: Projected Cost, Lifecycle Energy Use and Emissions of Future Hydrogen Technologies.* 2014 DOE Hydrogen and Fuel Cell Technologies Program Annual Merit Review, Washington, D.C.