IX.3 Pathway Analysis: Projected Cost, Lifecycle Energy Use and Emissions of Emerging 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 Manger
Fred Joseck
Phone: (202) 586-7932
Email: Fred.Joseck@ee.doe.gov

Project Start Date: March 1, 2014
Project End Date: September 30, 2015

Overall Objectives

- Conduct cost and lifecycle energy and emissions analyses of complete future and emerging 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 research and development (R&D) decision-making process
- Evaluate potential of future hydrogen technologies to meet the $4/kg hydrogen cost target
- Validate the DOE Fuel Cell Technologies Office's (FCTO's) Macro-System Model (MSM) and its underlying component models (in particular, the Hydrogen Analysis [H2A] Production model, the Hydrogen Delivery Scenario Analysis Model [HDSAM], and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation [GREET] model) through industry review

Fiscal Year (FY) 2015 Objectives

- Conduct an evaluation of complete hydrogen production, delivery, and dispensing pathways based on the cost and performance of future and emerging technologies expected to be available in the 2020 to 2030 timeframe, assessing the impact technology improvements and developments will have on lifecycle cost, energy use, and emissions
  - FY 2015 evaluation focused on emerging, low-carbon hydrogen production paths
- 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 gasoline gallon equivalent (GGE) and 68 miles per GGE (mpgge)
- Conduct a detailed review of the evaluation framework, component models, input parameters, and results with DOE and industry stakeholders through the United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) partnership with a goal of assessing technology progress and remaining technology gaps where further R&D is needed

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the FCTO 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 FCTO 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 2015 Accomplishments

- Estimated the lifecycle costs, energy use, and emissions from four complete emerging 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
  – Of the emerging production technology pathways evaluated, hydrogen production from natural gas reformation with carbon capture and sequestration (CCS) resulted in the lowest total pathway cost, with a cost of $0.10 per mile driven for hydrogen fuel and a total vehicle ownership and operational cost of $0.72 per mile (in a mature market)
- Assessed the total pathway costs and well-to-wheels (WTW, or fuel-cycle) energy use and GHG emissions of the emerging-technology pathway scenarios
  – Estimated the cost of hydrogen in a mature market, with costs ranging from \$5.60/kg H_2 for the natural gas reformation with carbon sequestration pathway to over \$12/kg H_2 for the photo-biological production 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
  – Emerging carbon sequestration technologies are predicted to lower WTW emissions of the central natural gas reformation pathway from about 210 g carbon dioxide (CO_2)-equivalent per mile to 90 g CO_2-equivalent per mile at 68 mpgge fuel economy (110 g CO_2/mi at 58 mpgge)
- Completed 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, onboard hydrogen storage technologies

✧ ✧ ✧ ✧ ✧

INTRODUCTION

DOE's Fuel Cell Technologies Office 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 particular study is part of a broader assessment of complete hydrogen production, delivery, and dispensing scenarios. This evaluation considers the cost and performance of future and emerging hydrogen technologies expected to be available in the 2020 to 2030 timeframe, focusing particularly on the impact emerging, low-carbon hydrogen production technologies will have on lifecycle cost, energy use, and emissions. The study considers the potential of future and emerging 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 emerging technology pathway analysis is a companion analysis to the current and future technology hydrogen pathway assessments conducted previously in FY 2012–2014.

This study will help FCTO evaluate the potential of emerging, low-carbon hydrogen production technologies to meet the $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 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 four complete hydrogen production, delivery, and dispensing pathways with the potential to be available in the 2020-2030 timeframe, assessing the cost and performance of emerging, low-carbon production technologies coupled with future hydrogen delivery and dispensing technologies (see Table 1). The study assessed the impact technology developments and improvements will have on hydrogen cost, energy requirements, and GHG emissions. 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:

- A 2025 start-up year for hydrogen fuel infrastructure
- Future (2020-2030) hydrogen technologies, projected to a commercial scale
- Costs reported in 2007\$ (to be consistent with FCTO's cost target of \$4/kg in 2007\$)
- A 40-year analysis period for central production facilities
- Feedstock and utility costs from the DOE Energy Information Administration's Annual Energy Outlook (AEO) 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)
- A 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

TABLE 1. Emerging-Technology Hydrogen Pathways Evaluated

Path	Production Feedstock / Technology	Delivery Mode	Dispensing Mode
1	Natural Gas Reforming with CCS	Gaseous H_2 in Pipelines	700 bar, gaseous
2	Photo-biological	Gaseous H_2 in Pipelines	700 bar, gaseous
3	Photo-Electrochemical	Gaseous H_2 in Pipelines	700 bar, gaseous
4	Solar Thermo-Chemical	Gaseous H_2 in Pipelines	700 bar, gaseous

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 (CPM) 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 four emerging 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, analysis inputs, and results were reviewed by industry partners through the U.S. DRIVE Fuel Pathway Integration Technical Team (FPITT). Figure 1 shows the levelized cost of hydrogen from the emerging-technology pathways. DOE's Fuel Cell Technologies Office has set a hydrogen cost target of \$4.00 per GGE (approximately equivalent to 1 kg of hydrogen), dispensed at the pump. Of the low-carbon production pathways evaluated, the natural gas reformation with CCS pathway offers the lowest cost, with a dispensed hydrogen cost of \$5.60/kg. (Previous pathway analysis studies found that only the distributed natural gas reformation pathway is expected to meet the \$4/kg target,

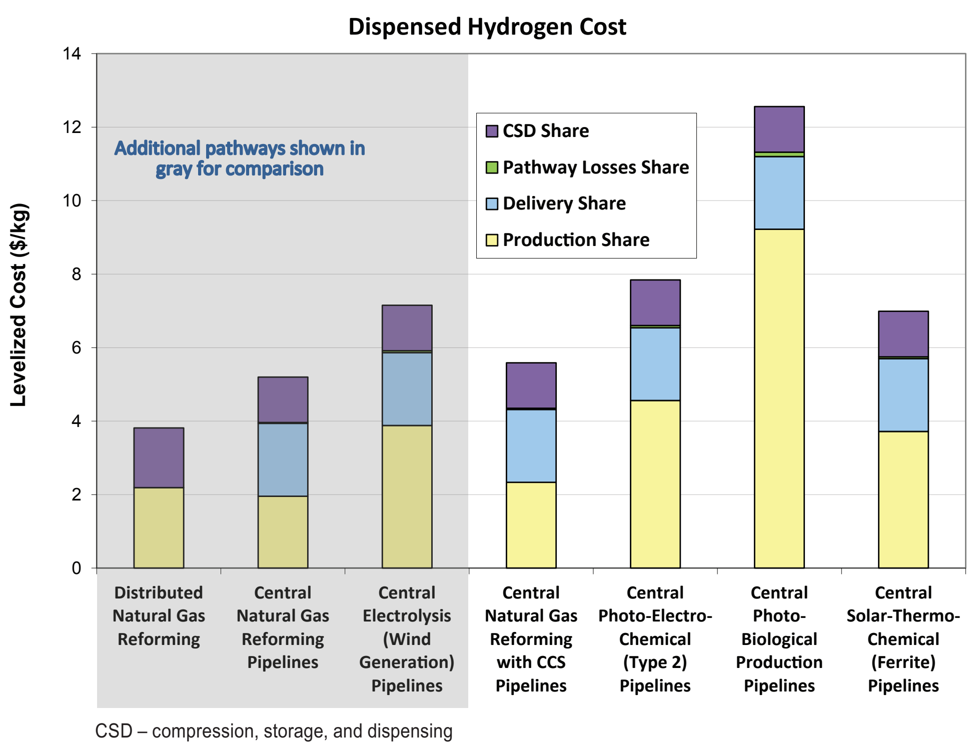

FIGURE 1. Cost of dispensed hydrogen from all pathways

with a projected dispensed hydrogen cost of $3.80/kg.) The renewable solar production pathways (photo-biological, solar-thermochemical, and photo-electrochemical hydrogen production) have higher dispensed hydrogen costs, ranging from $7/kg to over $12/kg, indicating the need for further R&D into these emerging technologies.

The pathway assessment evaluated the hydrogen cost contribution of capital costs, operations and maintenance (O&M) costs, and feedstock costs of the various pathways. As shown in Figure 2, the renewable solar production pathways have significant capital contribution costs, with costs of $3–5/kg attributable to production capital costs alone. This again points to the need for additional R&D to reduce these capital and O&M costs. It should be noted, however, that as low-technology-readiness-level pathways, renewable solar technologies are evolving rapidly and the latest research into these pathways is not necessarily reflected in the published H2A Production case studies used in this analysis.

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. Of the emerging technology pathways evaluated, the lowest cost of FCEV ownership resulted from hydrogen fuel produced from natural gas reformation coupled with carbon capture and sequestration. Assuming a 5-year ownership period and fuel economy of 58 mpgge, the natural gas reformation with CCS pathway resulted in total ownership costs of $0.72 per mile. With fuel costs of $0.10/mi, the cost of hydrogen fuel represents almost 15% of ownership costs. The purchase of the FCEV (represented as finance and depreciation costs) accounts for about 50% of ownership costs.

All of the emerging technology pathways were evaluated for lifecycle GHG emissions and energy use. Results of these investigations were discussed in depth with DOE and industry partners through the FPITT. The analysis shows that the addition of CCS to the central natural gas reformation pathway reduces fuel-cycle GHG emissions from about 210 g CO_2-equivalent/mi to 90 g CO_2-equivalent/mi at 68 mpgge fuel economy (110 g CO_2-equivalent/mi at 58 mpgge). This represents a significant improvement over the greater than 450 g CO_2-equivalent/mi emissions of a comparable conventional gasoline vehicle. The lifecycle emission results of the renewable solar hydrogen production pathways are expected to be lower than the natural gas with CCS pathway. (Preliminary results of these pathways have been developed and reviewed with DOE and industry, but are not being reported publicly as they are considered preliminary awaiting official published GREET cases for these pathways.)

CONCLUSIONS AND FUTURE DIRECTIONS

The lifecycle analysis shows that the emerging-technology hydrogen production, delivery, and dispensing

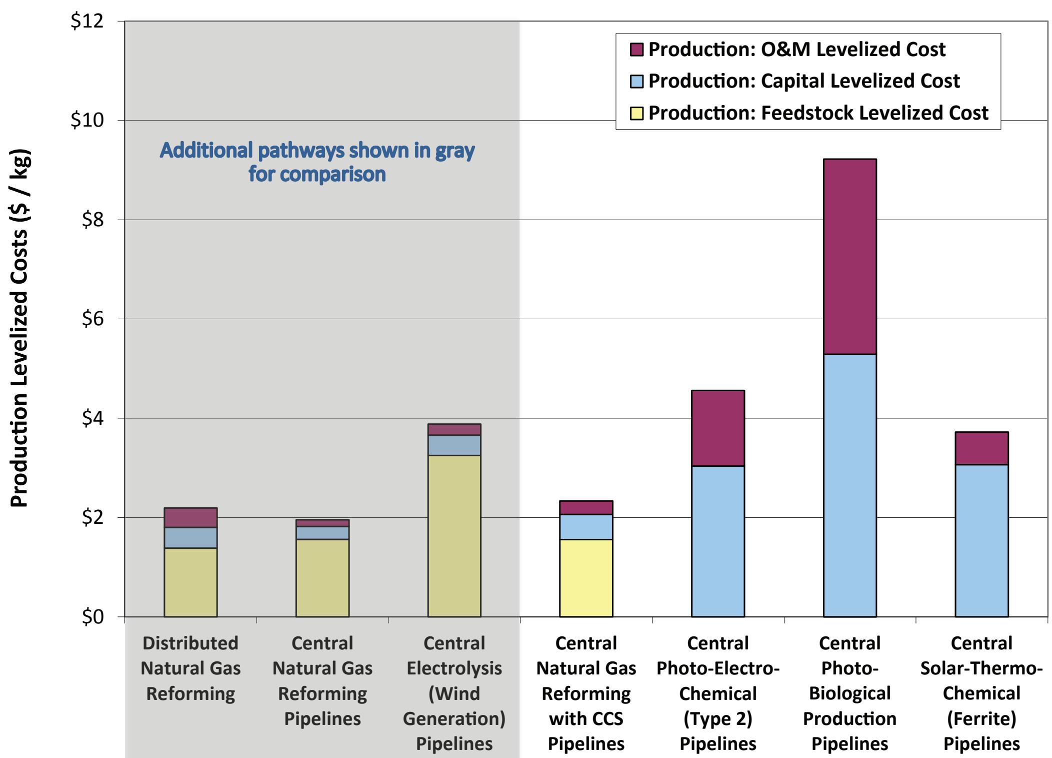

FIGURE 2. Hydrogen production cost contributions of capital, O&M, and feedstock for all pathways

pathways are expected to significantly reduce lifecycle GHG emissions, but all pathways are expected to result in costs above DOE's $4/kg target, indicating that further R&D into these emerging technologies is needed.

In the latter part of FY 2015 and in FY 2016, the hydrogen pathways analysis will be extended to consider emerging hydrogen delivery and onboard vehicle storage technologies. This will include an assessment of high-pressure gaseous truck delivery and emerging onboard hydrogen storage technologies such as cold hydrogen gas storage and sorbent storage.

FY 2015 PUBLICATIONS/PRESENTATIONS

1. Ramsden, T., Diakov, V., and Popovich, N., 2015 [expected]. *Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Future Technology Status of Nine Hydrogen Production, Delivery, and Distribution Scenarios*, National Renewable Energy Laboratory, Technical Report, Golden, CO (Draft report under DOE review).

2. Todd Ramsden, 2014. "Pathway Analysis: Emerging Hydrogen Production Pathways." U.S. DRIVE Fuel Pathway Integration Technical Team Meeting, Shell, Houston, TX (December).

3. Todd Ramsden, 2015. "Pathway Analysis: Emerging Hydrogen Production Pathways [Update]." U.S. DRIVE Fuel Pathway Integration Technical Team Meeting, Air Products, Allentown, PA (March).

4. Todd Ramsden, 2015. "Pathway Analysis: Initial Storage and Emerging Hydrogen Production Pathways." U.S. DRIVE Fuel Pathway Integration Technical Team Meeting, National Renewable Energy Laboratory, Golden, CO (July).