VII.15 Geo-Spatial Analysis of Hydrogen Infrastructure

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Objectives

- Develop a tool to allow users to compare hydrogen production pathways and policy options within a single common framework.
- Identify low-cost hydrogen production pathways at demand centers across the U.S.
- Perform scenario analysis to characterize the effect of factors such as the price of carbon, hydrogen demand, and feedstock costs on hydrogen price, resource utilization, and carbon dioxide (CO_2) emissions.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section (4.5) of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Future Market Behavior

(B) Stove-piped/Siloed Analytical Capability

(D) Suite of Models and Tools

Contribution to Achievement of DOE Systems Analysis Milestones

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

- **Milestone 5**: Complete analysis and studies of resource/feedstock, production/delivery and existing infrastructure for various hydrogen scenarios (4Q, 2009). The Hydrogen Logistics Model enables geographic analysis of hydrogen supply, demand, delivery and selling price.
- **Milestone 11**: Complete environmental analysis of the technology environmental impacts for the hydrogen scenarios and technology readiness (2Q 2015). The Hydrogen Logistics Model helps quantify the impact of hydrogen production pathways and carbon policy on greenhouse gas emissions from hydrogen production.

Accomplishments

- Developed a user-interactive tool to allow scenario analysis comparison between hydrogen production pathways and policy options within a single common framework.
- Identified the least-cost hydrogen production pathways at demand centers across the United States under a variety of demand, carbon tax, and resource price scenarios. Results indicate that coal, natural gas, and biomass-based production pathways dominate the supply over a robust set of input assumptions.
- Estimated hydrogen cost contributions, carbon mitigation cost, and resource utilization under several different scenarios. The average delivered cost of hydrogen was estimated to range from \$4.60/kg to \$5.45/kg depending on the level of demand, availability of carbon capture, and the cost of CO_2.

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Introduction

A number of hydrogen production, delivery, and storage options are being investigated that could eventually meet the demands of future hydrogen vehicles. Hydrogen production options include natural gas steam methane reforming, coal gasification, high-temperature nuclear electrolysis or thermochemical water splitting, and renewable options (e.g., biomass gasification, solar- and wind-based water electrolysis, solar thermochemical water splitting). The cost and availability of these resources varies widely based on the geographic location of demand and the size of the production facilties.

To help understand the economics of different hydrogen production pathways, TIAX developed a tool to estimate the price of delivered hydrogen to major demand centers across the U.S., as well as the associated resource utilization that is required to meet this demand. Hydrogen price and resource utilization were estimated by determining the location-specific combination of resources that minimizes the cost of delivering hydrogen. The present effort extends prior work [1] by incorporating additional conventional supply resources, carbon capture and sequestration (CC&S), and improving the compatibility between the Hydrogen Logistics Model inputs and outputs and other hydrogen crosscutting analysis models recently developed or currently under development for the DOE Hydrogen Program.

Approach

A hydrogen production and infrastructure modeling tool (the Hydrogen Logistics Model) was developed to investigate the resource constraints and fuel cost of a future hydrogen fueling infrastructure in the U.S. The Hydrogen Logistics Model is an interactive tool that uses geographic information system (GIS) data to optimally deploy hydrogen production resources. The inputs to the Logistics Model include location, quantity, and cost information for hydrogen production feedstocks, and the location and size of demand centers. Data was gathered from a variety of publically available sources, notably the National Renewable Energy Laboratory's (NREL's) GIS database [2], the DOE's Energy Information Administration [3], and H2A Production case studies [4]. A linear optimization algorithm uses these inputs to select the combination of hydrogen production resources that minimizes the average price for hydrogen at individual demand centers across the U.S. To account for the geographical variation in hydrogen resource feedstock supply and projected hydrogen demand, the model deconstructs the U.S. into a grid of discrete nodes, each with an associated resource supply and hydrogen demand. Using these inputs, the model projects the resources, infrastructure, and delivered price of hydrogen to each demand center. Ten different hydrogen production pathways were evaluated: coal gasification, natural gas, nuclear electrolysis, nuclear thermochemical hydrogen, biomass gasification, wind electrolysis, solar theromchemical, concentrating solar powered electrolysis, solar photovoltaic powered electrolysis, and landfill gas (LFG).

The Hydrogen Logistics Model was used to analyze a base case plus several sensitivity scenarios that vary factors such as demand, the price of CO_2, technology availability, and cost assumptions.

Results

The results of scenario analysis performed using the Hydrogen Logistics Model indicate that if CC&S is available, hydrogen is produced primarily from fossil-based production pathways – even with carbon taxes as high as $100 per ton – although biomass and LFG also make an important contribution. If CC&S is not available, biomass becomes the dominant production pathway. Other resources – notably wind, nuclear, or solar thermochemical hydrogen – become widely adopted only when CC&S is unavailable and using favorable cost assumptions. The average delivered price of hydrogen was estimated to vary from $4.60 per kg under a high demand scenario with no carbon tax to $5.40 per kg under a high demand scenario with $100 per ton carbon tax and no CC&S available.

In the base case scenario, which assumes a $25 per ton carbon tax and that CC&S is utilized and does not include LFG, hydrogen is produced primarily from fossil resources (~80% of supply), with biomass accounting for the remaining 20% at an average delivered price of approximately $4.90/kg H_2. A summary of these base case results is shown in Table 1.

The dominant contributor to the price of hydrogen is the delivery cost, which averages $3.25/kg H_2 (nearly 70% of the selling price), and does not vary appreciably with the production pathway (Figure 1). Analysis of the variable (per-mile) and fixed delivery costs showed a large price impact, but relatively minor shifts in resource utilization. Carbon mitigation costs (carbon taxes plus the cost of CC&S) account for less than 5% of the selling price in the base case, but reduce emissions by 93% compared to a scenario with no carbon constraints. An illustrative map of the geographical distribution of the delivered price of hydrogen to demand centers is

TABLE 1. Summary of Base Case Scenario Results

Type	Production (TPD)	Percent	Avg. Cost ($/kg)	# Plants	Avg. Plant Size (TPD)	Avg. Delivery Dist (mi)
Biomass	8,040	20%	$5.05	28	320	100
Coal	20,000	50%	$4.88	10	2,020	80
NG	11,800	30%	$4.86	13	915	70
Total	39,800	100%	$4.91	51	805	80

TPD = tons per day; NG = natural gas; Avg. = average

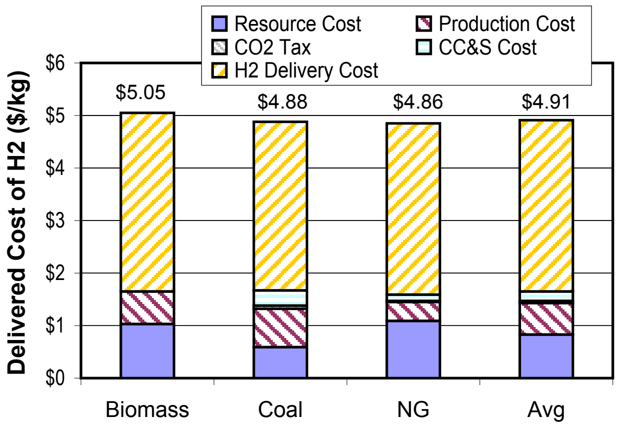

FIGURE 1. Hydrogen Price Breakdown for the Base Case Results

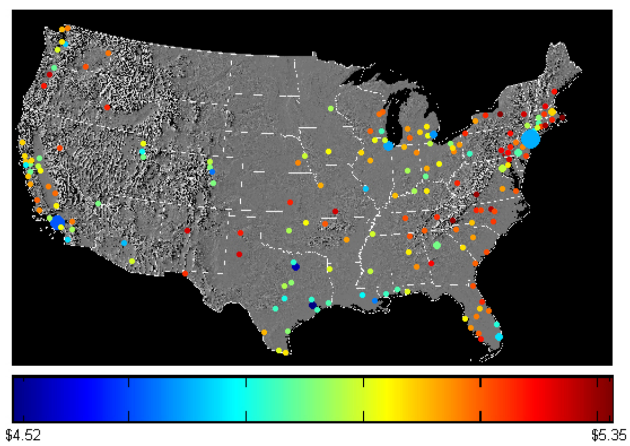

FIGURE 2. Geographic Distribution of Delivered Hydrogen Price

shown in Figure 2; alternative maps showing details such as the location and type of production plants and the delivery infrastructure may also be generated. As shown, hydrogen prices range from a low of $4.50 to a high of $5.95 per kg; a primary determinant of this price variation is the population density.

In addition to the base case, sensitivity scenarios that vary hydrogen demand (low, medium, and high); size of CO_2 tax ($0, $25, and $100 per ton); availability of CC&S technology; and the cost and availability for individual production pathways (favorable wind, favorable nuclear, favorable solar thermochemical, and including landfill gas) were evaluated. Figure 3 shows the resource utilization and average hydrogen selling price using four different sets of carbon constraints at three different levels of demand. This set of scenarios uses the same cost assumptions as those used in the base case. As shown, only coal, natural gas, and biomass resources are utilized, although the distribution between the three varies across the scenarios. In particular, increasing the cost of carbon causes a shift from coal to

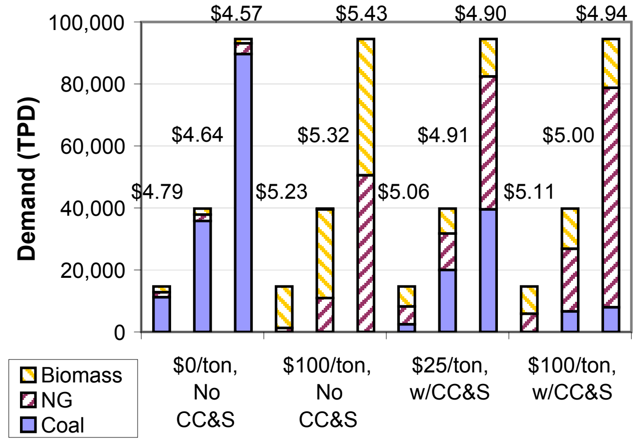

FIGURE 3. Resource Utilization and Hydrogen Price as a Function of Demand and Carbon Constraints

natural gas and biomass, while increasing demand tends to favor fossil resources over biomass. These scenarios do not include LFG-to-hydrogen pathway, which was included as a sensitivity scenario. If it is included, its market share ranges from 30% at low demand to 4% at high demand with a modest downward effect on the price of hydrogen.

Other hydrogen production pathways – wind electrolysis, nuclear electrolysis, nuclear thermochemical, and solar thermochemical – are adopted only when more favorable cost assumptions are included in combination with high carbon taxes ($100 per ton) and assuming that carbon capture is not available. Figure 4 shows the effect of these more favorable cost assumptions at three different demand levels.

Additional calculations were performed to estimate the CO_2 emissions impact and CO_2 mitigation cost (in dollars per ton of CO_2 avoided). These calculations show that if CC&S is available, CO_2 emissions can be reduced by upwards of 95% at a cost of $15 to $20 per ton of CO_2 avoided compared to a case with no carbon constraints. If CC&S is not available, CO_2 emissions reductions range from 80 to 100% with costs ranging from $20 to $50 per ton. The cost and efficacy of CO_2 mitigation is strongly influenced by demand if CC&S is not available, and weakly influenced if it is. These results suggest that at low demand, CO_2 emissions can be avoided at relatively low cost across a robust set of scenario, but that the feasibility and widespread deployment CC&S is a critical element to low-cost and efficacious CO_2 mitigation at high demand.

Conclusions and Future Directions

TIAX developed the Hydrogen Logistics Model to allow comparison between hydrogen production

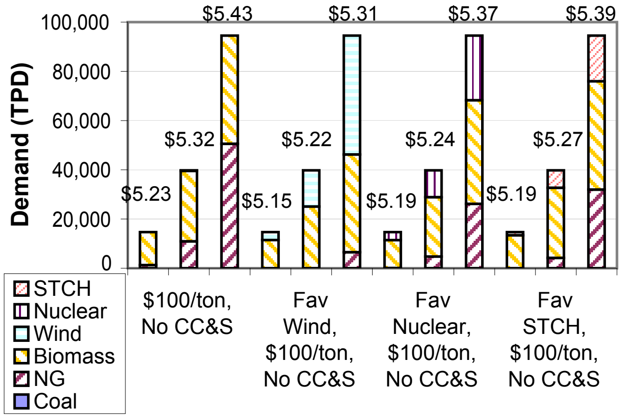

FIGURE 4. Resource Utilization and Hydrogen Price as a Function of Demand and Cost Assumptions

pathways and to perform scenario analysis on future hydrogen fueling infrastructure. Key conclusions from this scenario analysis include:

- If carbon capture and sequestration is available or if the price of carbon is low, hydrogen is produced primarily from fossil-based production pathways, although biomass and LFG also make an important contribution, accounting for up to 30% of supply.
- LFG and biomass are the most economic non-fossil production pathways, and are adopted under a robust set of input assumptions. Other low carbon pathways are only adopted when favorable cost assumptions are included in combination with high carbon taxes.
- The average delivered price of hydrogen ranges from \$4.60/kg to \$5.45/kg. The efficacy of carbon capture and the level of demand are the key factors influencing this price variation.
- Using base case assumptions, the average delivered price of hydrogen is \$4.90. This price varies geographically from \$4.50 to \$5.95 per kg. The dominant contribution to the hydrogen price is the delivery cost; population density is the primary determinant of the geographic variation in the price of hydrogen.
- The cost and efficacy of CO_2 mitigation is strongly influenced by demand if CC&S is not available and weakly influenced by demand if it is. Carbon mitigation costs range from \$15 to \$25 per ton of CO_2 avoided if carbon capture is available, but rise to as high as \$50 per ton under high demand scenarios without carbon capture. From a policy perspective, this suggests that at low demand, CO_2 emissions can be avoided at relatively low cost, regardless of the costs and availability of technologies such as CC&S, nuclear-to-hydrogen, or low cost wind. However, the feasibility and widespread deployment CC&S is a critical element to low-cost and efficacious CO_2 mitigation as demand rises.

The current project has been completed. However, several additional areas for further work are proposed:

- Include distributed production pathways in the analysis: allows comparison of centralized and distributed production within the same framework.
- Further integrate inputs and outputs with existing Hydrogen Program tools (HyDRA, Macro-System Model, etc) or GIS tools (e.g., ArcGIS).
- Use a design-of-experiments approach to model hydrogen infrastructure transition and evolution over time.
- Introduce additional policy constraints – e.g., renewable portfolio standards, low carbon fuel mandates, production tax credits.
- Model competition with alternative end-uses (e.g., electricity).
- Characterize high sensitivity parameters using Monte Carlo analysis.

FY 2010 Publications/Presentations

1. Kromer, M et al. “Geospatial Analysis of Hydrogen Infrastructure.” TIAX, LLC. Final Report to NREL, Subcontract AFT-9-88564-01. April, 2010.

2. Kromer, M et al. “Geospatial Analysis of Hydrogen Production Pathways.” TIAX, LLC. DOE Hydrogen Program Annual Merit Review, June 7–11, 2010, Washington, D.C.

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1. Lasher, S, et al. “Impact of Renewables on Hydrogen Infrastructure Analysis.” TIAX, LLC. Prepared for the National Renewable Energy Laboratory, Subcontract ACO-6-66414-01. July 2008.

2. National Renewable Energy Laboratory. “NREL: Dynamic Maps, GIS Data, and Analysis Tools Home Page”. Accessed August 2009. http://www.nrel.gov/gis/

3. Energy Information Administration (EIA). “Long Term Energy Outlook (Updated Reference Case Reflecting Provisions of the American Recovery and Reinvestment Act)”. U.S. Department of Energy. April, 2009. http://www.eia.doe.gov/oiaf/aeo/index.html

4. H2A Production Case Studies. DOE Hydrogen Program. http://www.hydrogen.energy.gov/h2a_prod_studies.html