III.6 Hydrogen Production in a Greenhouse Gas Constrained Situation

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Objectives

- To examine in a detailed quantitative manner plausible scenarios though 2050 for a transition to a hydrogen economy.
- To explicitly illustrate the sequencing of major phases of the transition scenarios and their implications.
- To quantify the greenhouse gas (GHG) reduction benefits of each of the transition scenarios, as well as the economic implications of the transition and energy savings.
- To explore the spatial characteristics of the transition scenarios based on geographic information system (GIS) analyses for four greater metropolitan areas of the USA: Boston, Denver, Houston, and Seattle.
- To account for relevant techno-economic and policy factors:
  – demographics, spatial characteristics, and refueling infrastructure
  – electric supply (including transmission and distribution) system characteristics/constraints
  – cost & performance of technologies (and future innovation) for hydrogen production, distribution, storage, and end-use (both transportation and stationary)
  – feedstocks for hydrogen production
  – regulatory contexts
  – timing and extent of transition pathways

Technical Barriers

This project is a cross-cutting analysis linked to the Systems Analysis Sub-Program. It contributes to decision-making by "providing greater understanding of the contribution of individual components to the hydrogen energy system as a whole, and the interaction of the components and their effects on the system" (page 4-1 of the Multi-Year Research, Development and Demonstration Plan). As a long-term scenario analysis, it moreover helps to "evaluate the alternatives for satisfying the functions and requirements of the future hydrogen system/economy and …. assess cross-cutting and overall hydrogen system issues, and to support the development of the production, delivery, storage, fuel cell and safety technologies" (page 4-1 of the Multi-Year Research, Development and Demonstration Plan). This project relates to the "Technical Analysis and

Evaluation" by focusing on the task of modeling potential technology pathways for wide-scale hydrogen implementation from the standpoints of application requirements, costs, risks, and environmental and societal impacts on a macro-system basis. The project relates to each of the following barriers:

- A. Lack of Prioritized List of Analyses for Appropriate and Timely Recommendations
- B. Lack of Consistent Data, Assumptions and Guidelines
- C. Lack of a Macro-System Model
- D. Stove-Piped/Siloed Analytical Capabilities
- E. Lack of Understanding of the Transition of a Hydrocarbon-Based Economy to a Hydrogen-Based Economy

Approach

This project examines the possible evolutionary paths of hydrogen technologies and a hydrogen infrastructure that meets the objectives laid out in the DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan to realize energy security, environmental, and economic benefits. This project's analysis:

- Takes an integrated approach, considering the entire chain of hydrogen from energy resource to production to distribution to end-use.
- Considers the use of hydrogen as an energy carrier to replace existing fuels.
- Takes a long-term perspective, constructing plausible scenarios by which hydrogen could expand in a gradual and orderly manner until it comprises the majority of transportation fuel use and a considerable portion of commercial and industrial cogeneration fuel use by 2050.
- Accounts for the important spatial aspect of infrastructure development, using GIS analysis to create realistic infrastructure development scenarios to 2050 for four cities: Denver, Houston, Boston, and Seattle. A total of 5 plausible scenarios per city have been examined.
- Accounts for the important national context for a transition to hydrogen, using paramaterization techniques to account for technology learning and fossil fuel price fluctuations. The same total of 5 plausible scenarios for the USA have been examined.
- Accounts for various feedstocks (biomass, coal, natural gas) and electricity (from central grid, from dedicated renewables) in hydrogen production facilities and various delivery options to refueling centers (pipeline and on-site production).
- Conducts sensitivity analysis for sequestration (with and without), fuel prices (low, mid, high), and light-duty vehicle fuel cell technology penetration rate (aggressive, very aggressive, most aggressive).
- Quantifies the greenhouse gas reduction benefits deriving from various integrated technological pathways for each city for each of the 5 scenarios, as well as for the USA for each of the 5 scenarios.
- Relies as much as possible on techno-economic assumptions of the DOE's hydrogen analysis community (i.e., the H2A group). Research literature and technology developer assumptions are used where H2A data is not available.
- Benchmarks the analysis to the Annual Energy Outlook 2003 (AEO2003), an energy and policy backdrop derived from the National Energy Modeling System (NEMS) of the DOE's Energy Information Administration.

Accomplishments

As indicated above, the key objective for this study has been to carry out an integrated analysis of a transition to a hydrogen economy in the four study areas. Because of the importance of understanding these transitions in light of national trends, resource constraints, technology learning impacts, and fuel price effects, we have also focused on the USA as a whole. Major accomplishments to date have focused on the topics outlined below. For each topic, a sample of typical outputs is presented for the purpose of illustrating results of the integrated analysis.

- Identification of techno-economic parameters underlying hydrogen production pathways based on primary literature and interaction with experts.
- Identification of techno-economic parameters for light-duty vehicles (cars, light-duty trucks), heavy-duty vehicles (buses, trucks), marine vessels (recreational boats, ships), rail (commuter and freight trains) and industrial/ commercial cogeneration. This involved the determination of a large number of parameters including vehicle sales trajectories, fuel economy, incremental costs of fuel cell vehicles over time, and others. See Figure 1 for national light-duty penetration rates together with corresponding incremental vehicle cost trajectories.
- Development of a computer model (called H_2M) for tracking the full fuel cycle impacts of growth in hydrogen demand on hydrogen production, fuel cell vehicle sales/stocks, energy use, costs, and greenhouse gas reductions. For each of the 5 regions considered (i.e., Boston, Denver, Houston, Seattle, and the USA) and for each scenario (i.e., business-as-usual, business-as-usual + H_2, greenhouse gas constrained, greenhouse gas constrained + H_2, and business-as-usual + H_2), the model provides outputs at two levels – detailed outputs for each of the 5 hydrogen-consuming end uses (i.e., light-duty vehicles, heavy-duty vehicles, marine vessels, trains, and industrial/commercial cogeneration) and summary outputs.
- Analysis of city-specific aspects of scenario development, including the types of hydrogen infrastructure required, locations of hydrogen refueling stations, regional feedstock supply zones, potential regional carbon dioxide sequestration zones, and others. The schedule of the emplacement of the elements of city-specific hydrogen infrastructure is costed to determine a breakdown of hydrogen delivery costs in both \$/mmbtu and \$/kg H_2 delivered. Figure 2 illustrates for the city of Boston the various components of hydrogen infrastructure projected to be in place by the end of the planning period.

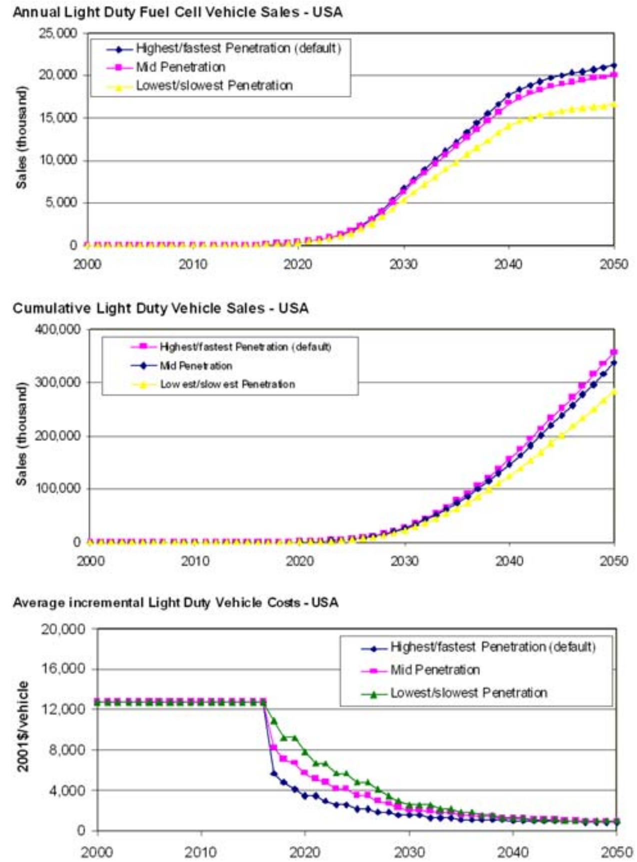

Figure 1. Light-Duty Vehicle Sales Trajectories and Corresponding Incremental Costs

- Construction of GIS maps for each city showing geocoded locations of existing private and fleet refueling stations. This information enables the determination of hydrogen demand density (in units of trills per square mile), which in turn provides the basis for a spatial and economic analysis of the transition from on-site to central production facilities with pipeline distribution to refueling centers. Figure 3 shows an example of the distribution of refueling station types for the city of Boston.

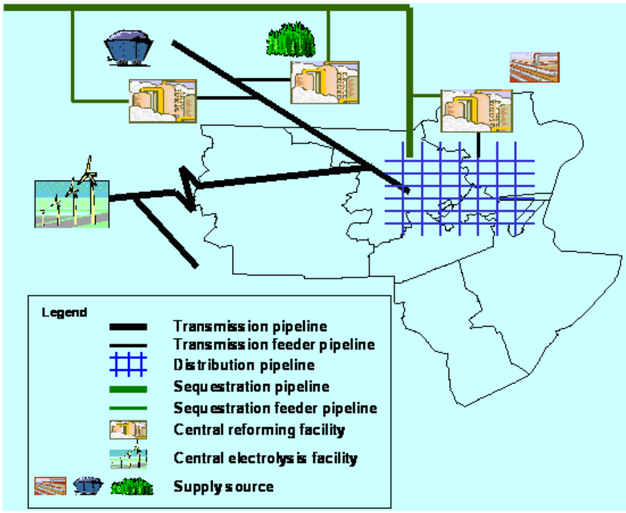

Figure 2. Types of Hydrogen Infrastructure Costed for the Boston Metropolitan Area

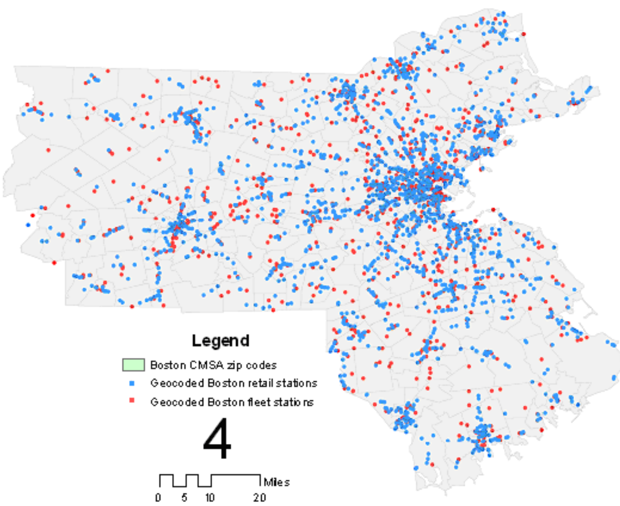

Figure 3. Refueling Stations in the Boston Metropolitan Area

- Analysis to determine how density and scale of demand influence the share of total hydrogen demand in each city that is met by hydrogen production from central facilities with pipeline distribution. This in turn influences the cost of delivery to end uses. The analysis involves running H_2M iteratively for hydrogen demand densities ranging from 0.002 to 3.2 trills per square mile to obtain the resulting central production share profiles in each year for each city. Figure 4 is a sample of the results for the Houston metropolitan area.

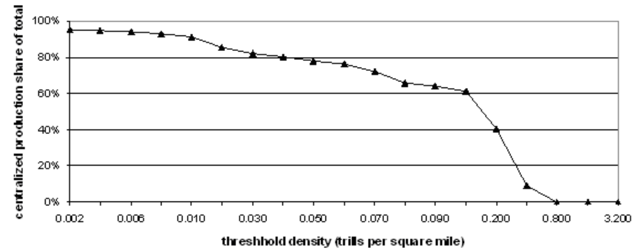

Figure 4. Central Production Shares for the Houston Metropolitan Area off the Business as Usual Counterfactual Scenario

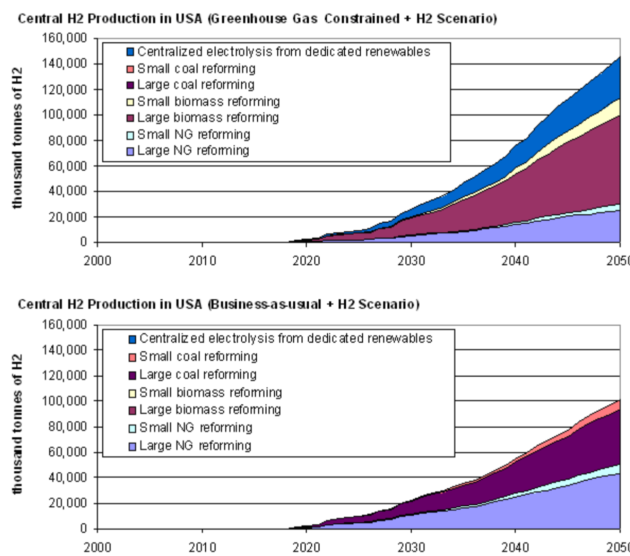

Figure 5. Central Hydrogen Production in the USA for Two Scenarios

- Determination of how spatial distribution of density of hydrogen demand for each city (as well as the USA) for each scenario affects the type, production, costs, and greenhouse reductions of the resulting hydrogen infrastructure emplaced. Figure 5 shows annual central hydrogen production in the USA in two scenarios, broken down by technology type.
- Analysis of feedstock supply constraints, which in turn affect feasible production and distribution pathways. Figure 6 shows annual levels of feedstock used for hydrogen production for the USA in two scenarios, broken down by feedstock type, corresponding to the two scenarios shown in Figure 5.
- Calculation of annual hydrogen production costs for each region and the USA broken out by

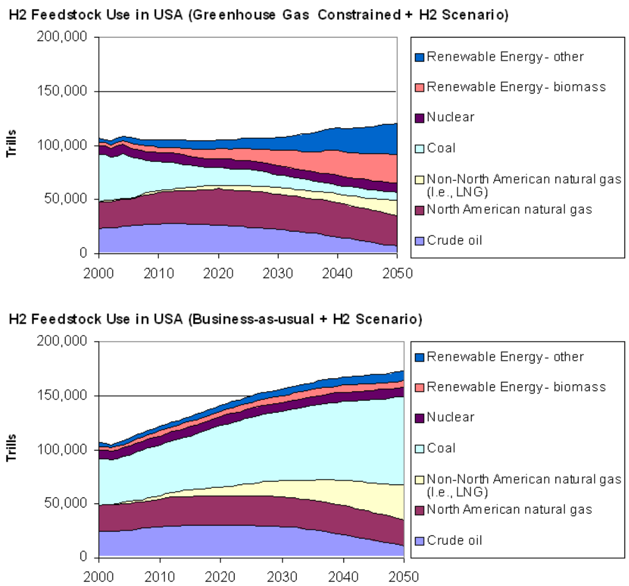

Figure 6. Feedstock Consumption in the USA for Hydrogen Production in Two Scenarios

hydrogen production technology and cost component [i.e., capital, fixed operation and maintenance (O&M), variable O&M, fuel] for each of the 5 scenarios. These results integrate the range of inputs and analyses for technology learning profiles, fuel price trajectories, feedstock constraints, hydrogen demand density characteristics, pipeline requirements, and sequestration options.

Future Directions

The integrated analysis described above has been completed, and we are currently in the process of finalizing a four-volume report, as outlined below, to be submitted as soon as possible.

- The first volume provides an expanded executive summary of the analytical framework, key supply/demand assumptions, major results, policy-relevant conclusions and recommendations.
- Volume 2 provides the technical details that underlie the analysis, including the methodological framework, city-based characteristics, cost and performance assumptions, and so forth. This volume has been designed to be useable to others in the H2A group.
- Volume 3 is a comprehensive set of results for each study city and the USA, including details of the hydrogen infrastructure, energy use impacts, carbon reductions, and overall costs.
- Volume 4 consists of source code for H_2M, the computer model developed in the visual basic programming language specifically to conduct the analysis in this study.

The study provides an analysis of how a hydrogen transition could plausibly unfold in the four metropolitan areas of Boston, Denver, Houston, and Seattle, as well as in the USA as a whole. While the analysis focuses on many aspects of the transition in these cities and the USA as a whole, it takes a full fuel cycle approach and seeks to answer three main questions for a transition to hydrogen in each of the five regions: what are the energy savings, what are the carbon dioxide emission reductions, and what are the costs?

Potential follow-up work for any future phase of this work in the coming months could focus on one or more of the following areas:

- Expand the city-based spatial GIS analysis to consider the USA as a whole. Currently, the USA analysis is based on a series of parameterization techniques rather than direct GIS-based modeling.
- Expand the city-based spatial GIS analysis to consider states (e.g., California) or regions (Southeastern USA) that did not have cities represented in the current analysis. The current GIS-built platform could be readily extended to these other areas.
- Expand the consideration of hydrogen production technologies to include more cutting-edge technologies such as biological processes, thermodynamic options, nuclear-based electrolysis, and other options.
- Include a macroeconomic modeling component in order to track the impact on state-level domestic product, local job creation, and market transformation. The outputs of H_2M could be readily linked to economic impact models to conduct such analyses.
- Assess the non-GHG related emission reduction benefits (e.g., criteria air pollutants, air toxics) associated with each of the city-scenario

combinations in the current study. Include this dimension in any expansion of the analytical framework to other states and/or regions.

- Introduce more detail into the carbon sequestration analysis as further information about carbon sequestration site stability and geographic distribution becomes available.
- Introduce a linear programming (or other) optimization algorithm for determining optimum pipeline routing for hydrogen delivery and carbon dioxide transport to sequestration sites.
- Introduce more analysis regarding risk management and hedging strategies in order to provide further policy-relevant information for addressing the competition between pathways toward hydrogen vehicles, electric vehicles, and biofuel vehicles.
- Analyze emerging small-scale, onsite technologies for co-producing hydrogen and electricity for synergies that would help establish a cost-effective hydrogen infrastructure.
- Extend the technology learning analysis in this study by exploring the impact of international technology investment and diffusion on hydrogen technology learning.

FY 2005 Publications/Presentations

1. DOE Hydrogen Program Contractors Meeting poster presentation (5/26/05).
2. Massachusetts Institute of Technology, Hydrogen Technology & Policy Discussion (4/5/05).
3. Harvard University Kennedy School of Government (11/11/04).