XI.3 Infrastructure Analysis of Early Market Transition of Fuel Cell Vehicles

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Project Start Date: May 1, 2005
Project End Date: Project continuation and direction determined annually by DOE

Fiscal Year (FY) 2011 Objectives

The Scenario Evaluation, Regionalization and Analysis (SERA) model is a geospatially and temporally oriented analysis model that determines the optimal production and delivery scenarios for hydrogen, given resource availability and technology cost. The objectives of the most recent phase of the project are:

- Interoperability
  - Add functions to SERA to work with new HyDRA (Hydrogen Demand and Resource Analysis) [1] tool features.
  - Import detailed H2A (hydrogen analysis) [2,3] cost models into SERA.
- Infrastructure Integration
  - Develop cost submodels representing a variety of alternative infrastructure development pathways.
- Scenario Analysis
  - Hydrogen production from biogas.
  - Niches for combined heat, hydrogen, and power (CHHP).
  - Minimizing delivery cost of renewable hydrogen.
  - Implications of stakeholder behavior and consumer preferences.
  - Price points between competing technologies.

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:

(B) Stove-piped/Siloed Analytical Capability
(D) Suite of Models and Tools
(E) Unplanned Studies and Analysis

Contribution to Achievement of DOE Systems Analysis Milestones

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

- **Milestone 3.** Begin a coordinated study of market transformation analysis with H2A and Delivery models.
- **Milestone 5.** Complete analysis and studies of resource/feedstock, production/delivery and existing infrastructure for various hydrogen scenarios.
- **Milestone 24.** Complete the linear optimization model (HyDS) to analyze the optimum production facilities and infrastructure for hydrogen demand scenarios.
- **Milestone 26.** Annual model update and validation.

FY 2011 Accomplishments

- Enhanced cost model:
  - Addition of biogas, CHHP, and wind cost models for hydrogen production.
  - Addition of rail and composite-tank truck delivery pathways.
  - New, advanced method for rapidly incorporating updates to H2A cost models into SERA.
- Added new submodels:
  - Vehicle choice
  - Vehicle stock
- Conducted first-of-kind studies:
  - Hydrogen production from biogas.
  - Niches for CHHP.
  - Minimizing delivery cost of renewable hydrogen.
  - Implications of stakeholder behavior and consumer preferences.
- Achieved significant enhancements in SERA usability:
  - Cleaner user interface.
  - Streamlined data storage mechanisms.

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Introduction

The SERA model fills a unique and important niche in the temporal and geospatial analysis of hydrogen infrastructure build-out for production and delivery. It nicely complements other hydrogen analysis tools and is well suited to contribute to scenario analysis involving the temporally specific geospatial deployment of hydrogen production and transmission infrastructure. Its key capabilities are (i) an optimization of the physical build-out of hydrogen infrastructure; (ii) the unified treatment of production, transmission, and distribution; (iii) the ease with which new technologies can be added to an analysis; (iv) the consistent physical and economic computations; (v) the ability to estimate costs and cash flows; (vi) the spatial and temporal resolution of hydrogen infrastructure networks; (vii) regional specificity; and (viii) the allowance for exogenously specified urban hydrogen demands. Its internal architecture is flexible, and it is compatible with geographic information systems (GIS) and the H2A models [2,3]. SERA is designed to answer questions such as: Which pathways will provide least-cost hydrogen for a specified demand? What network economies can be achieved by linking production facilities to multiple demand centers? How will particular technologies compete with one another?

Approach

In order to answer such questions, SERA supports analyses aimed at identifying optimal infrastructure to meet specified annual urban hydrogen demands, perhaps coupled to other multiple objectives and constraints. Cash flows are computed, detailed by infrastructure component, city, and region, and these provide insights into components of hydrogen costs, which are determined by year, volume, and locality. Four methods of long distance hydrogen transport are considered: pipeline, gaseous truck, liquid truck, and railroad. The major use of SERA is for studying potential turning points in infrastructure choice via sensitivity analysis on infrastructure, feedstock, and fuel cost inputs in the context of the complex transient and transitional interactions between increasing hydrogen demand and hydrogen infrastructure construction. With carefully constructed input data sets, SERA can also weigh tradeoffs between investments in various infrastructure types, given policy constraints (e.g., greenhouse gas). Figure 1 shows the interrelationship between the input data for SERA and the algorithms applied to them in order to compute the delivered cost of hydrogen. The infrastructure networks are optimized using a simulated-annealing algorithm that explores the large set of potential build-out plans that meet the input requirements for hydrogen delivery at cities over time. The hydrogen transport computations are based on graph-theoretic algorithms for determining optimal flows in networks. The cash flow computations rely on standard discounting approaches. Figure 2 shows sample SERA output in the form of an optimized hydrogen infrastructure network.

Results

We finalized a study that examines the relative cost-effectiveness of supplying hydrogen refueling stations via CHHP or on-site steam methane reforming (SMR) for a large urban area, under three fuel cell electric vehicle (FCEV) penetration scenarios. The major conclusions of this work are: (i) CHHP-based hydrogen production for use in nearby hydrogen refueling stations typically only has cost advantages over on-site SMR hydrogen production at some of those refueling stations, particularly for the early years of FCEV penetration scenarios where hydrogen demand and station sizes are initially small; (ii) variations in SMR or CHHP facility and energy-input costs can dramatically affect the overall cost of hydrogen, but they do not affect the mix of CHHP and SMR deployment as strongly; and (iii) for these scenarios and this study region, hydrogen costs typically drop from slightly above \$6/kilogram (kg) in early years to below \$5/kg in later years.

Furthermore, we finalized a study of the SERA biogas capability. This involved (i) provisionally incorporating the

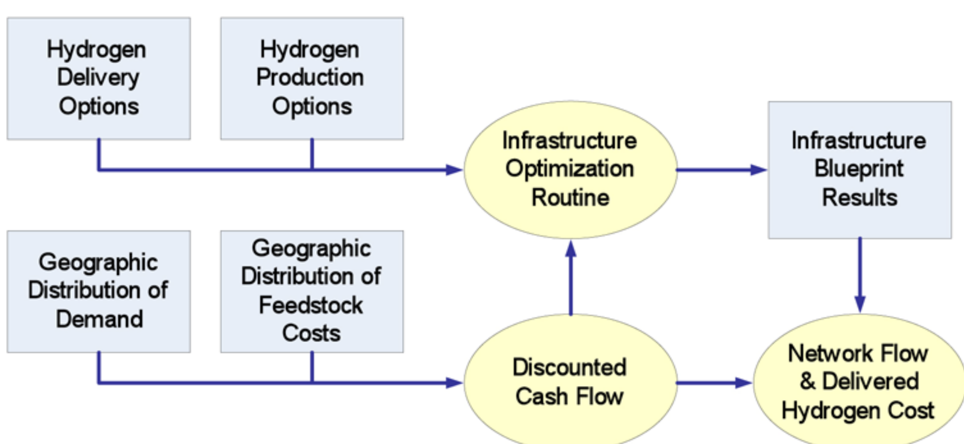

FIGURE 1. SERA Input and Output Data and Algorithms

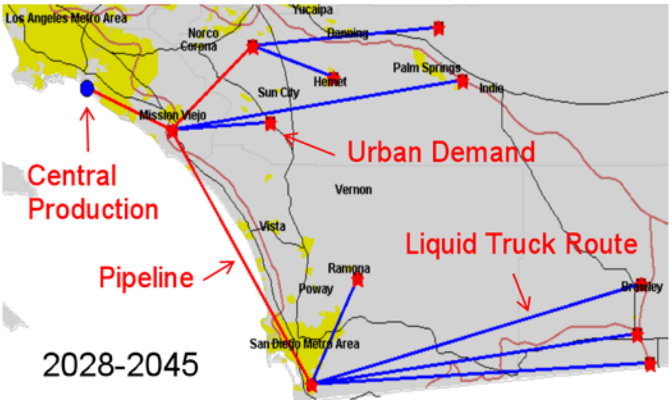

FIGURE 2. Illustrative Hydrogen Infrastructure Network Output from SERA

latest NREL biogas systems characterization into SERA, (ii) performing an illustrative analysis of infrastructure build-out highlighting the significance of biogas pathways, and (iii) developing insights for future in-depth studies involving biogas pathways. SERA uses cost estimates from the H2A biomethane systems model in conjunction with those from the H2A production model to evaluate the delivered cost of biogas-originated hydrogen. In the sample analysis that we performed (on a test case of Midwestern cities), the optimal choice of infrastructure often hinges upon the difference between biogas and natural gas prices: when the biogas price, plus the processing cost to biomethane, is less than the natural gas price, the biogas pathways have lower costs. In general, the most competitive biogas scenario is when a single large biogas plant supplies a dozen or more (typically small) on-site SMR plants.

We also explored three diverse avenues for the production of hydrogen from renewable resources in the context of substantial adoption of fuel cell vehicles and the large scale use of renewable for electricity production: (i) the production of hydrogen from wind-generated electricity that would have been curtailed by electric power grid congestion, (ii) the production of hydrogen directly from wind resources without the co-production of electricity, and (iii) co-production with a balance between electricity transmission and electrolysis. In this context, we varied the technological characteristics of the hydrogen production in considering current, future, and "breakthrough" situations. We found total delivered costs in the $4-$10/kg range (see Figure 3), along with a diverse use of infrastructure that highlights the niches where particular delivery pathways are most cost effective. The use of curtailed wind energy can lower the delivered cost of hydrogen dramatically, although sufficient curtailed resource is not available to allow wind-produced hydrogen to supply the majority of hydrogen in high penetration FCEV scenarios.

We completed the development of vehicle-choice and vehicle-stock capabilities for SERA. The objectives of this effort were to (i) incorporate the latest version of the Automotive Deployment Option Projection Tool (ADOPT) [4] vehicle choice model into SERA, (ii) verify that output from the SERA vehicle choice model matches that from ADOPT, (iii) integrate the new vehicle choice model with a existing vehicle stock model that tracks the ageing and energy use of vehicles, and (iv) develop insights for future studies involving vehicle choice and stock. This allows us to generate regional market shares for new vehicles over time. The new vehicle choice model can handle any user-defined set of vehicle makes and models, any user-defined set of vehicle types (e.g., internal combustion engines, FCEVs, electric vehicles), and any user-defined set of geographic regions (e.g., zip codes, counties, states, census regions, national). It aggregates the user-defined geographic regions into larger regions, generates annual market shares, estimates splits between fuel types, and provides output suitable for input into the SERA vehicle stock model. Furthermore, it supports the future inclusion of alternative algorithms for vehicle choice if those are deemed necessary for an analysis study. The current version of the SERA vehicle choice model exactly reproduces the output of the ADOPT model. The output of the SERA vehicle choice and stock models is used as input for SERA-based infrastructure optimization studies.

Finally, we made major progress automating the computations of hydrogen costs based on the H2A models, which are encoded as Excel spreadsheets. This capability is

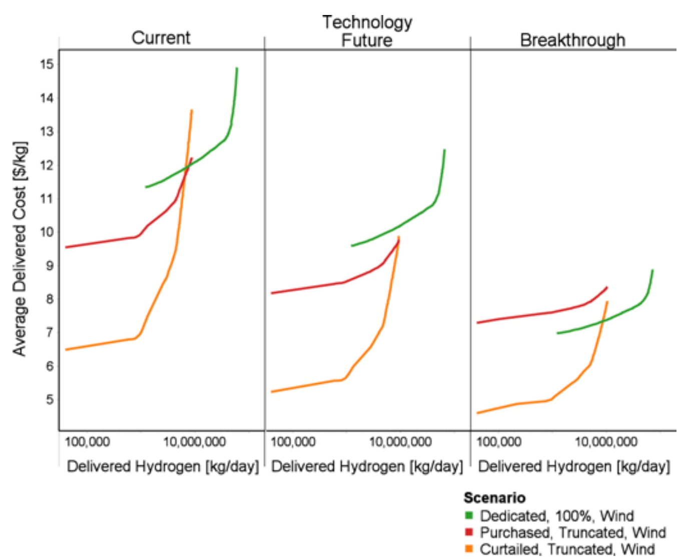

FIGURE 3. Effective-cost curves for wind-hydrogen scenarios. The "dedicated" cases are when the whole wind resource is used for hydrogen production; the "purchased" cases are when the curtailed wind resource is supplemented with additional electricity purchased from the wind farm; and the "curtailed" cases are when only the curtailed wind energy is used for electrolysis. The "current" and "future" technology cases roughly correspond to estimated 2010 and 2030 costs; the "breakthrough" technology case assumes costs substantially lower than the "future" case.

invaluable in keeping the cost inputs to SERA completely in synchronization with the latest H2A production and components models.

Conclusions and Future Direction

In summary, SERA is an effective, integrated, cross-cutting model for optimization-analysis studies of hydrogen infrastructure build-out compatible with the H2A models. It searches for optimal combinations of hydrogen production and transmission infrastructure to meet time-varying demand in urban areas over a region.

The SERA software is now essentially complete, but continued use of the tool in scenario studies requires regular updating of H2A and other cost inputs, software modifications to take advantage of new HyDRA features, and minor usability enhancements in response to analysts' requests. SERA will be applied to more complex deployment scenarios such as (i) identifying regional niches for production technologies and delivery infrastructure and (ii) assessing the influence of feedback from computed delivered costs of hydrogen to consumer and stakeholder decisions. We also plan collaborative exchange of data and scenarios assumptions with other models for the conduct of integrated multi-fuel studies, particularly when they involve scenarios with opportunities for addressing cost barriers in early years of FCEV transition.

FY 2011 Publications/Presentations

1. M. Melaina, *Optimal Production, Transport, and Delivery Infrastructure for Hydrogen Production from Renewable Resources*, Fuel Cell & Hydrogen Energy Conference, 13–16 February 2011. (conference presentation)

2. B. Bush, A. Jalalzadeh, M. Melaina, G. Saur, *SERA Biogas Capability Preview*, 30 June 2010. (management report)

3. B. Bush, A. Jalalzadeh, M. Melaina, G. Saur, *SERA Biogas Capability*, 31 July 2010. (management report)

4. B. Bush, M. Melaina, M. Penev, O. Sozinova, D. Steward, *CHHP Case Study and Cost Curves*, 27 September 2010. (management report)

5. B. Bush, M. Melaina, M. Penev, O. Sozinova, D. Steward, J. Svede, *Scenario Evaluation & Regionalization Analysis (SERA) Final Report for 2010*, 27 September 2010. (management report)

6. B. Bush, M. Melaina, K. Webster, A. Brooker, *SERA Vehicle Choice Capability*, 31 December 2010. (management report)

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2. "H2A Production Models and Case Studies." Version 2.1.2. *DOE H2A Production Analysis*. http://www.hydrogen.energy.gov/h2a_production.html. Accessed 17 Jan 2009.

3. "H2A Delivery Scenario Model." Version 2.0. *DOE H2A Delivery Analysis*. http://www.hydrogen.energy.gov/h2a_delivery.html. Accessed 17 Jan 2009.

4. National Renewable Energy Laboratory. Automotive Deployment Option Projection Tool (ADOPT). 2010.