VII.10 Macro System Model

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Objectives

- Develop a macro-system model (MSM):
  - Aimed at performing rapid cross-cutting analysis.
  - Utilizing and linking other models.
  - Improving consistency between models.
- Support decisions regarding programmatic investments through analyses and sensitivity runs.
- Support estimates of program outputs and outcomes.

Technical Barriers

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

(A) Future Market Behavior
(B) Stove-piped/Siloed Analytical Capability
(C) Inconsistent Data, Assumptions and Guidelines
(D) 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 System 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)
- Milestone 27: Complete the 2nd version of the Macro-System Model to include the analytical capabilities to evaluate the electrical infrastructure. (2Q, 2011)

Accomplishments

- Completed Version 1.0 of the MSM and used it for programmatic analysis.
- Linked H2A Production cases with the Hydrogen Delivery Scenario Analysis Model (HDSAM), the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, and physical property information from the Hydrogen Analysis Resource Center (HyARC) and validated the use of those models and the results generated using them.
- Developed a flexible, comprehensive Web-based user interface so that many members of the analysis community can use the MSM.
- Completed a user guide for the MSM.
- Added stochastic (Monte Carlo) capabilities to the MSM.
- Upgraded the MSM to the latest versions of H2A Production (V.2.1), HDSAM (V 2.0) and GREET (V 1.8c).
- Linked with geospatial model HyDRA to add the spatial dimension to the MSM.
- Integrated MSM with the temporal pathway evolution assessment tool HyPro.

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Introduction

At the DOE Hydrogen Program's behest, we are developing an MSM to analyze cross-cutting issues because no existing model sufficiently simulates the entire system, including feedstock, conversion, infrastructure, and vehicles, with the necessary level of technical detail. In addition, development of the

MSM exposes inconsistencies in methodologies and assumptions between different component models so that they can be identified and corrected when necessary.

Version 1.0 of the MSM has been developed and is available to the hydrogen analysis community. It links H2A Production, HDSAM, GREET, and physical property information from HyARC to estimate the economics, primary energy source requirements, and emissions of multiple hydrogen production/delivery pathways. A Web-based user interface has been developed so that many users have access to the MSM; stochastic capabilities have been added to it to provide uncertainty ranges around the results. The MSM has been used for several analyses to compare pathways and to understand the effects of varying parameters on pathway results.

Approach

The MSM is being developed as a tool that links or federates existing models across multiple platforms. This approach was chosen because the task of building a single monolithic model incorporating all of the relevant information in the existing models would have been overwhelming because the necessary expertise to do so was spread among half a dozen DOE laboratories and a dozen or more universities and private contractors. Linking models allows model users that depend on data from component models to continue using their models while retrieving data from component models in a less labor-intensive manner. In addition, it provides a common platform for data exchange necessary to update integrated models when the component models have been updated.

The MSM is being built on a framework inspired by an example of the federated object model (FOM). FOMs also link together models and are exemplified by the Department of Defense high level architecture [1]. The general MSM framework provides a common interlingua that is extensible (accommodates new models with a minimum of difficulty), distributable (can be used by multiple people in different areas of the country), and scalable (to large numbers of participating models). Version 1.0 of the MSM uses Ruby and Ruby interfaces to Microsoft Excel and other platforms to collect, transfer, and calculate data.

Results

Levelized hydrogen costs, primary energy requirements, and emissions have been estimated for multiple pathways using H2A 2.1 [2], HDSAM V2.0 [3], and GREET V1.8c [4]. Thus, Figure 1 [5] shows the levelized cost of the hydrogen pathways. The levelized cost of hydrogen is calculated directly in the H2A model for the distributed hydrogen production cases

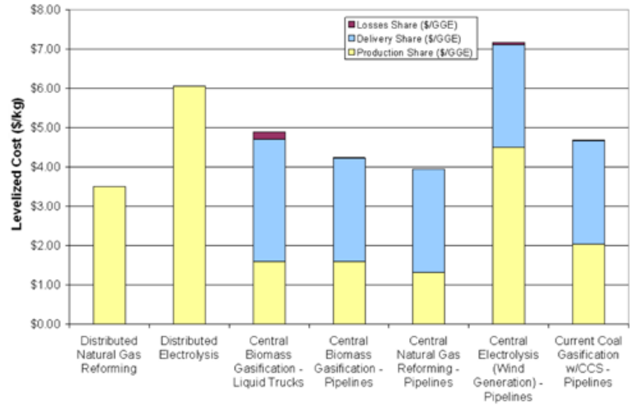

FIGURE 1. Levelized Cost of Hydrogen for Seven Production/Delivery/Dispensing Pathways

because the H2A distributed hydrogen production model includes the forecourt station capital and operating costs. For central production cases, the levelized cost of hydrogen is the sum of levelized production cost calculated in H2A, levelized delivery cost calculated in HDSAM, and the cost of excess production due to losses in delivery. For distributed production, the costs of compression, storage, and dispensing (CSD) are about $1.88/kg and are included in the production cost. For central production, the CSD costs are included in the delivery cost and depend upon the delivery technology (gas in pipelines vs. liquid from trucks). Note that the delivery costs are $2-$3/kg hydrogen; delivery costs may need to be reduced to make central production technologies competitive with distributed production technologies.

Connecting hydrogen production and other costs with associated emissions is one of the advantages that the MSM provides by linking together different models. Figure 2 shows the levelized hydrogen fuel cost per mile and the well-to-wheels (WTW) greenhouse gas (GHG) emissions for each of the seven pathways assessed based on U.S. average fuel costs and fuel cycle energy requirements. For comparison, it also shows the projected 2009 market price per mile (in 2005 dollars) and GHG emissions for gasoline-, diesel-, and E85-fueled vehicles. The levelized fuel cost was put onto a per-mile basis. The projected fuel cost per mile for most of the hydrogen pathways (based on projected, mature fuel cell electric vehicle markets) is similar to that for gasoline in a traditional vehicle and corn ethanol as E85 fuel in a flexible-fuel internal combustion engine (ICE) vehicle. The fuel costs per mile for gasoline in a hybrid electric vehicle (HEV) and diesel in a conventional diesel ICE vehicle are lower. The dotted green cloud in the figure represents the stochastic analysis results obtained based on input distributions for the forecourt steam methane reforming (SMR) production option [6]. The dispersion of the data points well surpasses the differences between the central (with pipeline delivery)

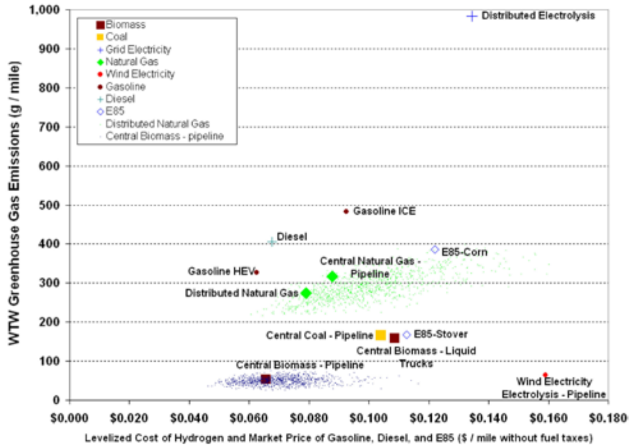

FIGURE 2. Pathways Levelized Costs and GHG Emissions

and distributed SMR production options. This relates to both the per-mile cost of hydrogen and the WTW GHG emissions. Similarly, the blue cloud shows the stochastic analysis result for the central biomass case. For the latter, as seen in the figure, the data point distribution is less significant when compared with the differences incurred by switching from pipeline to liquid truck delivery.

As key MSM inputs are sometimes region-specific, it is important to add the geospatial dimension into the range of the MSM features. Bilateral links with the online geospatial tool HyDRA [7] have been developed that allow the MSM user to easily apply regional electricity and natural gas (NG) feedstock data as MSM inputs and, conversely, update the HyDRA database and maps with the latest MSM version outputs. As an example, Figure 3 shows the results obtained for a selected (from HyDRA interface) region. For every county in the region, HyDRA supplies the MSM with the electricity grid mix and price data, and the MSM calculates hydrogen production (via electrolysis) costs and associated WTW GHG emissions. (The interaction between the models is implemented via internet.) As a result, regions with both lower hydrogen production cost and lower WTW GHG emissions can be easily selected.

The transition to high-market-penetration levels for hydrogen fuel cell vehicles will likely involve several hydrogen production/delivery/dispensing pathways. To facilitate this analysis and to involve the temporal dimension, the temporal pathway evolution assessment tool HyPro [8] is integrated with the MSM. As a result, HyPro inputs are updated via MSM (Figure 4) with latest current H2A Production and HDSAM models, and the MSM facilitates probing into the effect of any of the HyARC, HDSAM, or H2A Production model parameters on the potential evolution of hydrogen production/delivery/dispensing pathways.

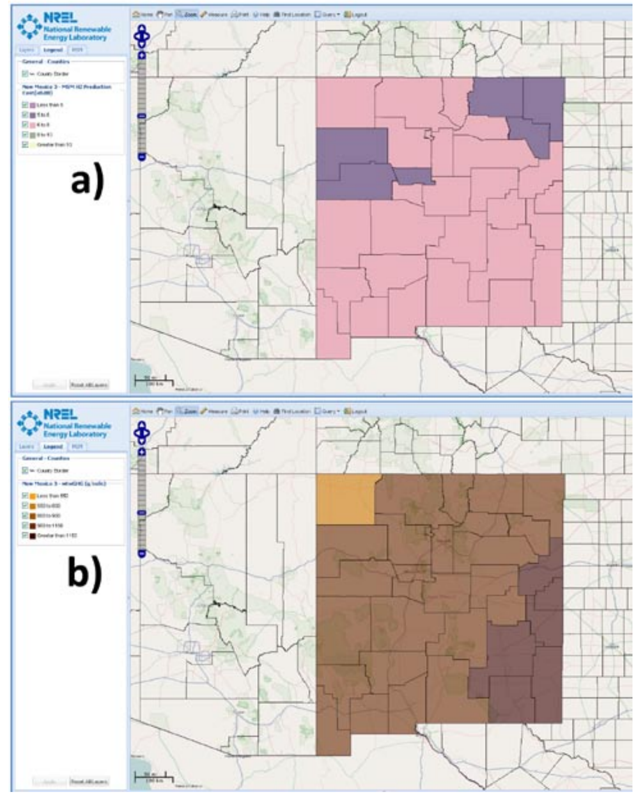

FIGURE 3. HyDRA Link with MSM on a County Level, Mapping a) H_2 Production Cost, and b) WTW GHG Emissions

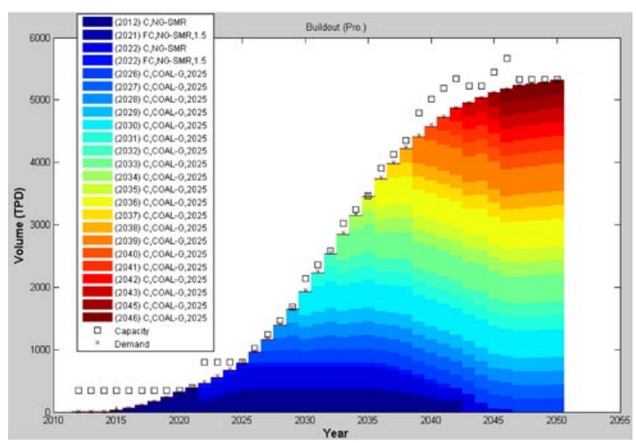

FIGURE 4. HyPro Predictions on the Production Technology Buildout

Conclusions and Future Directions

- By linking production/delivery/dispensing models, the MSM is a tool for rapid cross-cutting comparative analysis of various production/delivery pathways.
- The U.S. region-specific data are readily available as MSM inputs via live MSM/HyDRA links.

- As a result of linking HyPro with MSM, pathway evolution is examined in a manner consistent with latest versions of H2A and HDSAM.

Future directions:

- Include vehicle production and maintenance in the MSM analysis.
- Add combined heat and power as a production option.
- Expand delivery and distribution options to include the 700-bar storage, cryo-compressed and tube trailer delivery.
- Continue updating the MSM links to new model versions as they are released.

FY 2010 Publications/Presentations

1. Ruth, M., Laffen, M., and Timbario, T.A. (2009, September). Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios. Golden, CO: National Renewable Energy Laboratory.

2. Ruth, M., Diakov, V., Goldsby, M., Sa, T. (2009) Macro-System Model: a Federated Object Model for Cross-Cutting Analysis of Hydrogen Production, Delivery, Consumption and Associated Emissions. In Winter Simulation Conference, 2009.

3. Ruth, M., Laffen, M., Diakov, V., and Timbario, T.A. (2010) "Projected Cost, Energy Use, and Emissions of Hydrogen Technologies for Fuel Cell Vehicles." In ASME 2010 8th International Fuel Cell Science, Engineering & Technology Conference, 2010, Brooklyn, NY.

References

1. Judith S. Dahmann, Richard Fujimoto, and Richard M. Weatherly. "The Department of Defense high level architecture." In Winter Simulation Conference, pages 142–149, 1997.

2. Steward, D., Ramsden, T., and Zuboy, J. (2008, September). *H2A Production Model, Version 2 User Guide*. Golden, CO: National Renewable Energy Laboratory.

3. Mintz, M., Elgowainy, A., and Gillette, J. (2008, September). *H2A Delivery Scenario Analysis Model Version 2.0* (HDSAM 2.0) User's Manual*. Argonne, IL: Argonne National Laboratory.

4. Argonne National Laboratory. (2009, May). *How Does GREET Work?* Retrieved from http://www.transportation.anl.gov/modeling_simulation/GREET/index.html.

5. Ruth, M., Laffen, M., and Timbario, T.A. (2009, September). Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios. Golden, CO: National Renewable Energy Laboratory.

6. Duffy, M., Melaina, M., Penev, M., and Ruth, M. Management Report NREL/MP-150-43250, May 2008. Risk Analysis for Hydrogen, Fuel Cells and Infrastructure Program: Predecisional Report.

7. HyDRA: http://rpm.nrel.gov/.

8. James, B., Schmidt, P., and Perez, J. (2008, December). HyPro: A Financial Tool for Simulating Hydrogen Infrastructure Development (U.S. DOE Contract # DE-FG36-05G01519 Final Report).