VII.14 Potential Environmental Impacts of Hydrogen-Based Transportation and Power Systems

Thomas M. Grieb
Tetra Tech, Inc.
3746 Mt. Diablo Blvd., Suite 300
Lafayette, CA 94549
Phone: (925) 283-3771; Fax: (925) 283-0780
E-mail: tom.grieb@tetratech.com

DOE Technology Development Manager:
Fred Joseck
Phone: (202) 586-7932; Fax: (202) 586-9811
E-mail: Fred.Joseck@ee.doe.gov

DOE Project Officer: Katie Randolph
Phone: (303) 275-4901; Fax: (303) 275-4753
E-mail: Katie.Randolph@go.doe.gov

Contract Number: DE-FG36-07GO017108

Subcontractors:
- Stanford University, Palo Alto, CA
- Potomac-Hudson Engineering, Bethesda, MD

Project Start Date: September 26, 2007
Project End Date: September 25, 2009

Objectives

The overall goal of the project is to compare emissions of hydrogen, the six criteria pollutants (CO, SO_X, NO_2, particulate matter, ozone, and lead), and greenhouse gases from near- and long-term methods of generating hydrogen for vehicles and stationary power systems, and the effects of those emissions on climate, human health, the ecosystem, and structures. The specific objectives are as follows:

- Develop market penetration scenarios for hydrogen. Each scenario will include emission rates of hydrogen including leakage; emissions of the six criteria pollutants, volatile organic compounds (VOCs), and greenhouse gases for each technology used for production of hydrogen; and the timeframe for shifting vehicles and stationary power systems to hydrogen.
- Predict changes in atmospheric concentrations of hydrogen and other constituents in the troposphere and stratosphere.
- Quantify near and long-term effects on air quality, human health, ecosystems, and structures using model output and accepted health and ecosystem effect levels and ambient air criteria.
- Identify other more subtle effects of shifting to a hydrogen-based economy.

Technical Barriers

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

(A) Future Market Behavior
(C) Inconsistent Data, Assumptions and Guidelines
(E) Unplanned Studies and Analysis

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE milestone from the Systems Analysis section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 11:** Complete environmental analysis of the technology environmental impacts for the hydrogen scenarios and technology readiness. (2Q, 2015)

Accomplishments

The capabilities of the Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model (GATOR-GCMOM) soil routine have been extended to mechanistically represent hydrogen loss to soils. The total surface resistance term was generalized to include separate treatment of the vegetated and non-vegetated soil fractions. Resistance to soil uptake was parameterized in terms of deposition velocities appropriate for grasslands, forests, savannah, and agricultural lands (subdivided into two seasons). Soil moisture limitation and soil temperature corrections were included. For deserts, the uptake rates were scaled from uptake rates for forests by adjusting the soil organic carbon content as appropriate between the two biomes. Maximum uptake rates were based on laboratory experiments conducted under conditions that were non-limiting for either soil moisture, temperature, or organic carbon. The total soil uptake was then calculated by multiplying the maximum rate by each limiting factor.

- Using the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) Model, developed emissions for transportation in baseline years and for two scenarios in 2030 and 2050 using population, vehicle ownership rates, and other data consistent with the Intergovernmental Panel on Climate Change (IPCC) A1B cases for the U.S., Western Europe, Canada, Australia, China, Japan, New Zealand, and South Korea. The two scenarios included hydrogen fuel cell vehicles (HFCVs) produced using the range of methods specified below in the Results section. Sensitivity analyses were also conducted to compare alternative ways of producing hydrogen for the vehicles.

- Completed initial runs of the GATOR-GCMOM model for baseline 2000 and IPCC Scenario A1B with 90% HFCVs in developed countries and 45% HFCV penetration in other countries and where the hydrogen is produced by steam reforming of natural gas. These results were compared with recent simulation results in which the world's fossil-fuel onroad vehicles (FFOVs) are converted to HFCVs and where the hydrogen is produced by wind-powered electrolysis.

✧ ✧ ✧ ✧ ✧

Introduction

The goal of this project is to analyze the effects of emissions of hydrogen, the six criteria pollutants and greenhouse gases on climate, human health, ecosystems, and structures. Initial concerns with the adoption of a hydrogen economy have focused on possible effects of hydrogen releases to the atmosphere. Modeling results of Tromp et al. [1], predicted significant ozone (O_3) depletion and moisture increases in the stratosphere. The projected additional moisture was hypothesized to cause stratospheric cooling and increased formation of polar ice clouds that indirectly catalyze ozone destruction. Whereas O_3 is a problem in the troposphere causing medical, ecological, and material problems, in the stratosphere O_3 protectively absorbs ultraviolet radiation and protects the earth surface from bond breaking energy that can lead to health maladies such as skin cancer. However, numerous researchers were quick to note two major problems with the modeling and analysis presented in Tromp et al. [1]: 1) the projected H_2 leakage rates assumed were very high (i.e., 10 to 20 percent of production versus 1 to 3 percent projected by other investigators), and 2) the paper did not incorporate the decreases in CO_2 and priority pollutants that would accompany the shift to hydrogen. It is known that hydrogen can escape containment at rates about four times that of equally compressed air. Still, Tromp et al.'s assumed leakage rates were about a factor of ten times larger than those calculated by other investigators.

Approach

There are five elements associated with the overall technical approach:

- **Develop market penetration scenarios for hydrogen.** Each scenario includes emission rates of hydrogen, including leakage, emissions of the six criteria pollutants, VOCs, and greenhouse gases, for each technology used for production, the mix of technologies used, and the timeframe for shifting vehicles and stationary power systems to hydrogen.
- **Predict changes in atmospheric concentrations of hydrogen and other constituents.** The GATOR-GCMOM model developed by Mark Jacobson at Stanford University is being used to predict tropospheric and stratospheric concentrations of gases and aerosols.
- **Extend the GATOR-GCMOM soils module.** The dominant sink for H_2 in the troposphere is loss to soils. This accounts for about 80 percent of the total H_2 sink [2]. The capabilities of the GATOR-GCMOM soil routine have been extended to mechanistically represent hydrogen loss to soils.
- **Quantify near and long-term environmental effects.** The effects on air quality, human health, ecosystem, and building structures will be quantified using model output and accepted health and ecosystem effects levels, and ambient air quality criteria.
- **Identify other more subtle effects of shifting to a hydrogen-based economy.**

Results

The study team has identified two emission scenarios, for which we have quantified the emissions of hydrogen and six criteria pollutants, VOCs, and greenhouse gases. These scenarios are based on the U.S. hydrogen transportation scenarios per Greene et al. [3]. These scenarios are depicted in Figure 1. The emissions analysis used values derived from GREET 1.8 [4]:

- **Scenario 1:** (20% Fuel Cell Vehicles [FCVs] in 2030 and 90% FCVs in 2050). Assuming hydrogen production from steam reforming of natural gas in 2030 and from the no carbon policy source mix for 2050: Biomass without sequestration 5%; Coal gasification without sequestration 66%; Steam reforming using natural gas 28%; Renewable energy 1%.
- **Scenario 2:** (50% FCVs in 2030 and 95% FCVs in 2050). Assuming hydrogen production from steam reforming of natural gas in 2030 and from the carbon policy source mix for 2050: Biomass without sequestration 42%; Coal gasification with sequestration 45%; Steam reforming using natural gas 10%; Renewable energy 3%. The percent

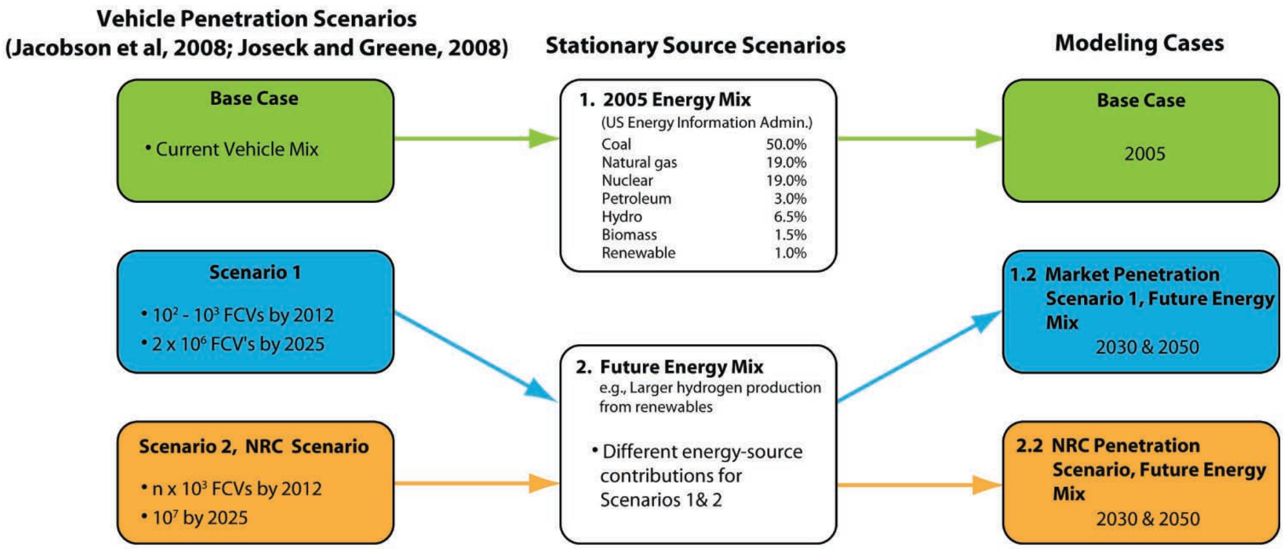

FIGURE 1. Vehicle Penetration and Stationary Source Scenario Options

using natural gas was reduced by 2 percent and added to renewables, given the large increase in wind capacity that occurred in 2007 and that is envisioned for 2030.

Emission estimates were also developed for Western Europe and six other countries.

Emission factors were developed using GREET for HFCVs for comparison to hybrids, gasoline, and diesel vehicles. The percent decrease in emissions with HFCVs was determined by the model for the 2030 and 2050 cases. The 2050 results showed that NOx, NO_2, CO, CO_2, and CH_4 would decrease, which is consistent with the preliminary results for GATOR-GCMOM. VOCs showed a decrease as a group based on the GREET results, although the specific results by chemical showed some increases in the GATOR-GCMOM results.

The GATOR-GCMOM model, which solves dynamical, gas, aerosol, cloud, transport, radiation and surface processes [5-7] was used to simulate the effects of converting the world's FFOVs to HFCVs, where the H_2 is produced by steam reforming of natural gas. Only the preliminary results after 1.5 years of the IPCC 2050 A1B simulation are available, but the results indicate that the conversion to 95% HFCVs in the developed countries and 45% HFCV penetration in other countries will result in reduced emissions of CO_2, CO, NO_x, aldehydes, and black carbon. A sample of the preliminary results for the atmospheric differences in ambient concentrations between the 2050 A1B base case and the conversion to HFCVs are in shown in Figure 2. Natural gas-HFCVs increased H_2 slightly, decreased CO_2 and CO, and increased ocean pH. These model simulations are still underway and will be extended to 10-year simulations to achieve study-state results.

These initial results are consistent with recent GATOR-GCMOM simulations of the conversion of the world's FFOVs to HFCVs, where the H_2 is produced by wind-powered electrolysis [8]. For the comparison of the same IPCC scenarios over 10 years, the conversion to HFCVs were calculated to reduce tropospheric CO ~5%, NO_x ~5-13%, most organic gases ~3-15%, OH ~4%, ozone ~6%, and peroxyacetyl nitrate ~13%, but to increase CH_4 ~4% due to the lower OH. Lower OH also increased upper tropospheric-lower stratospheric ozone, increasing its global column by ~0.25%. For the case of the wind-powered electrolysis production of H_2, the simulation results indicate that conversion to HFCVs will not adversely affect tropospheric pollution or the stratospheric ozone layer.

Conclusions and Future Directions

This project has been underway for almost two years and has made significant progress on the five primary objectives. In the final three months we will focus on the following efforts:

- Completion of the GATOR-GCMOM model simulations and the interpretation of the results.
- The quantification of the effects of implementing the selected market penetrations scenarios will examine potential effects in these five areas:
  - Climate: air temperature, cloud production, ozone levels, photochemical smog.
  - Human health: six criteria pollutants, lead, greenhouse gases compared to health-effect levels and national ambient air quality standards.

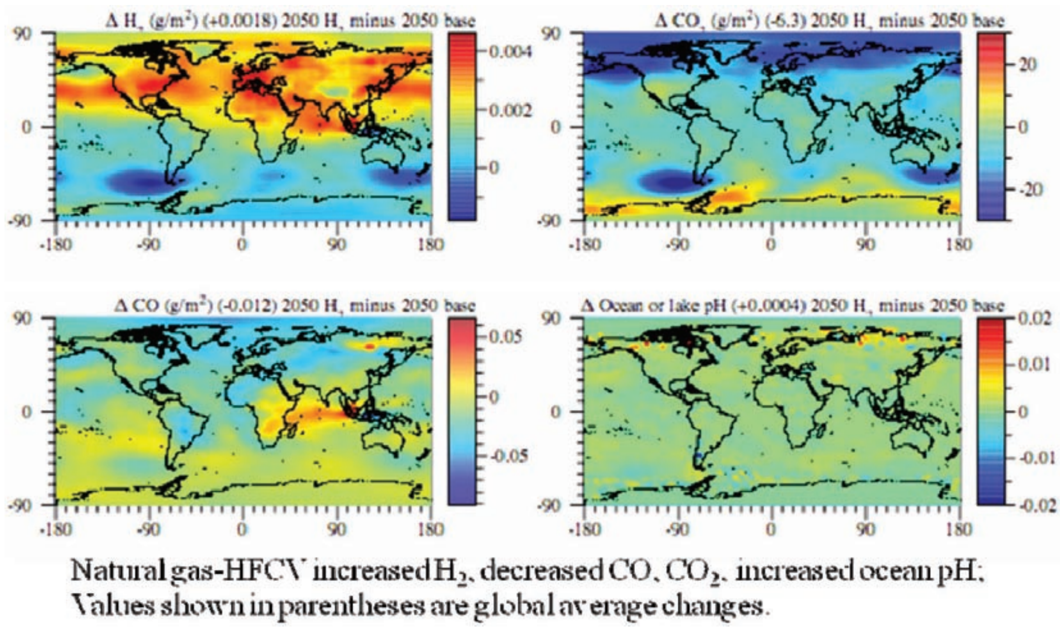

FIGURE 2. Preliminary results from GATOR-GCMOM simulation of the 2050 IPCC A1B. Scenario with 90% HFCVs in developed countries and 45% HFCV penetration in other countries.

- Ecosystems: use effects levels for criteria pollutants and greenhouse gases to evaluate impacts on aquatic and terrestrial biota.
- Structures: effects of acids, ozone, particulate matter, and greenhouse gases on materials, buildings, structures, historical sites, roadways.
- Other environmental effects: e.g. mining and processing of trace metals used as catalysts or in photovoltaic cells.

FY 2009 Publications/Presentations

1. Jacobson, M.Z. 2008. Effects of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate. Geophys. Res. Lett. 35, L19803, doi:10.1029/2008GL035102.

2. DOE 2009 Annual Merit Review & Peer Evaluation. Washington, D.C. May 19, 2009.

References

1. Tromp TK, Shia RL, Allen M, Eiler JM, Yung YL. 2003. Potential environmental impact of a hydrogen economy on the stratosphere. Science 300: 1740-1742.

2. Rhee TS, Brenninkmeijer CAM, Rockmann T. 2006. The overwhelming role of soils in the global atmospheric hydrogen cycle. Atmospheric Chemistry and Physics 6: 1611-1625.

3. Greene, D.L., P.N. Leiby, and D. Bowman. 2007. Integrated Analysis of Market Transformation Scenarios with HyTrans. Oak Ridge National Laboratory Report ORNL/TM-2007/094.

4. Argonne National Laboratory. 2008. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model 1.8b, May 2008. http://www.transportation.anl.gov/spftware/GREET/

5. Jacobson, M.Z. 2001. GATOR-GCMOM: 2. A study of daytime and night-time ozone layers aloft, ozone in national parks, and weather during the SARMAP field campaign. J. Geophys. Res., 106: 5403-5420.

6. Jacobson, M.Z. 2006. Effects of absorption by soot inclusions within clouds and precipitation on global climate. J. Phys. Chem. 110:6860-6873.

7. Jacobson, M.Z., Y.J. Kaufman, and Y. Rudich. 2007. Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions. J. Geophys. Res., 112, D24205, doi:10.1029/2005GL023187.

8. Jacobson, M.Z. 2008. Effects of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate. Geophys. Res. Lett. 35, L19803.