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

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Objectives

The overall goal of the project is to compare emissions of hydrogen, the six criteria pollutants (CO, SO_X, NO_2, particulate matter [PM], ozone, and lead), and greenhouse gases (GHGs) 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 GHGs 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

- Results of field and laboratory studies on hydrogen uptake by soils have been summarized for the period 1985-2008, where the studies expressed results as nmole/m^2/s. The sites were in the USA (AK, CA, HI), Germany, Japan, South Africa, and Finland. The results were compared to the global average estimate [3]. The global estimate fell between the ranges reported for 10 of the 14 studies.
- A summary of five studies that have developed global atmospheric hydrogen budgets has been completed. The sources are broken out to include fossil fuel combustion, biomass burning, photochemical production, biogenic nitrogen fixation, and oceans. The sinks are hydroxyl oxidation and soil uptake. The soil uptake rates are about three times higher than loss rates by hydroxyl oxidation, thus confirming the need for accurate estimates of soil uptake.
- A site-specific soil uptake module for hydrogen was completed based on lab data [5]. Uptake limitations

caused by soil temperature and soil moisture were simulated. Both temperature and soil moisture uncertainties were accommodated by using a Monte Carlo approach. A distribution of uptake rates was generated based on these uncertainties.

- Market penetration scenarios for producing hydrogen for vehicles and for stationary power generation from the present to a specified future date have been developed to serve as a basis for modeling the effects of emissions on climate, human health, the ecosystem, and structures.

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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 [6] 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) 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 Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model (GATOR-GCMOM) model developed by Mark Jacobson at Stanford University will be 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 [4]. The capabilities of the GATOR-GCMOM soil routine will be 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, and we are in the process of quantifying emissions of hydrogen and six criteria pollutants, VOCs, and greenhouse gases for them. These scenarios are based on the U.S. hydrogen transportation scenarios [2]. These scenarios are depicted in Figure 1. The emissions analysis will use values derived from GREET 1.8 [1]:

- **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 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.

The Team also developed similar scenarios for other countries:

- OECD Europe (Western Europe)
- Japan
- Canada

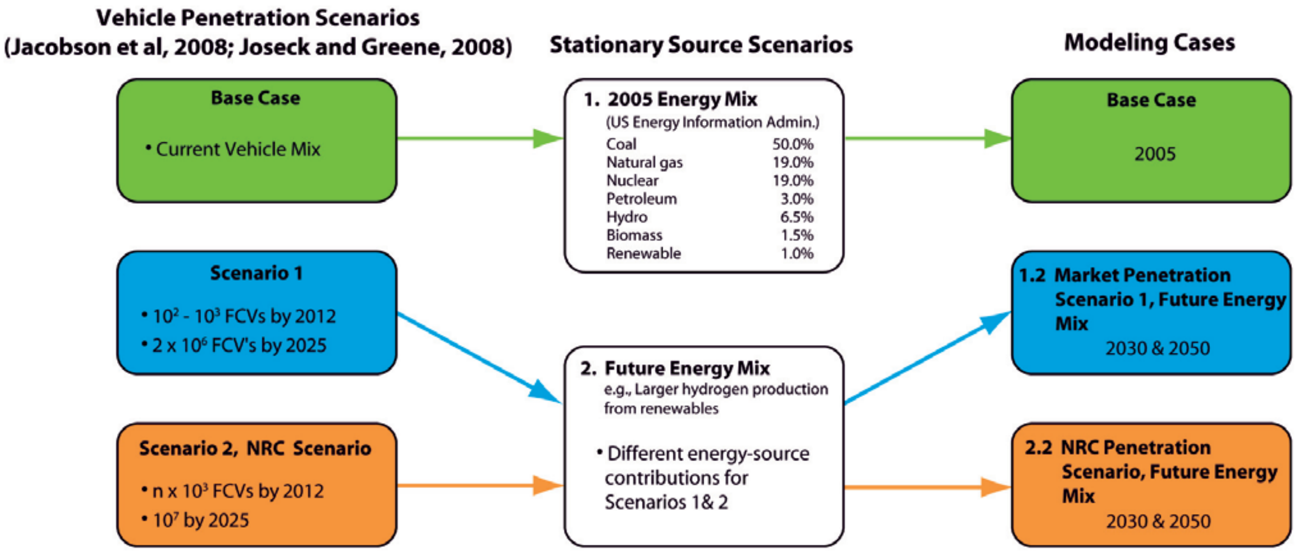

FIGURE 1. Vehicle Penetration and Stationary Source Scenario Options

- Australia
- New Zealand
- China
- South Korea

These countries were selected based on the strengths of their hydrogen research and development programs. FCV levels for each country for 2030 and 2050 will be based on the U.S. scenarios, with the exception of China at 50% of the U.S. rate.

For the development of the extension of the soil module for GATOR-GCMOM, we have completed the review of the results of field and laboratory studies on hydrogen uptake for the period 1985-2008. A subset of these results, where the studies expressed results as nmole/m^2/s, is presented in Figure 2. A site-specific soil uptake module for hydrogen was completed based on lab data [5]. Uptake limitations caused by soil temperature and soil moisture were simulated. Both temperature and soil moisture uncertainties were accommodated by using a Monte Carlo approach. A distribution of uptake rates was generated based on these uncertainties. The soil uptake approach [5] to scale-up globally from laboratory and field studies has been reviewed and evaluated. The approach assumes that diffusion is the primary mechanism for hydrogen to enter the soil, and then a first-order uptake process is assumed to continuously deplete the hydrogen in the soil over depth. The uptake rate is limited by temperature, soil moisture, and soil organic carbon content. The maximum uptake rate (when no limitation exists) is found from the limited number of laboratory studies where uptake limitations do not appear to exist. Diffusional limitations depend on snow cover and soil layer characteristics within the zone of diffusion. An analysis of the global uptake estimates predicted by this model showed the uptake rates are about 30 to 40 percent higher than estimates [3].

Conclusions and Future Directions

This project has been underway for less than one year and has made significant progress on the five primary objectives. In the upcoming months we will focus on the following efforts:

- The identification of the information and parameter values for hydrogen and criteria pollutants released from each technology used to generate hydrogen (fuel cells and electricity) for two market penetration scenarios that will be simulated using the GATOR-GCMOM model.
- The soil module update will be completed.
- Initiate the GATOR-GCMOM model simulations.
- The quantification of the effects of implementing the selected market penetrations scenarios will begin with the examination of effects in these five areas:
  - Climate: air temperature, cloud production, ozone levels, photochemical smog
  - Human health: six criteria pollutants, lead, GHGs compared to health-effect levels and national ambient air quality standards
  - Ecosystems: use effects levels for criteria pollutants and GHGs to evaluate impacts on aquatic and terrestrial biota
  - Structures: effects of acids, ozone, PM, and GHGs on materials, buildings, structures, historical sites, roadways

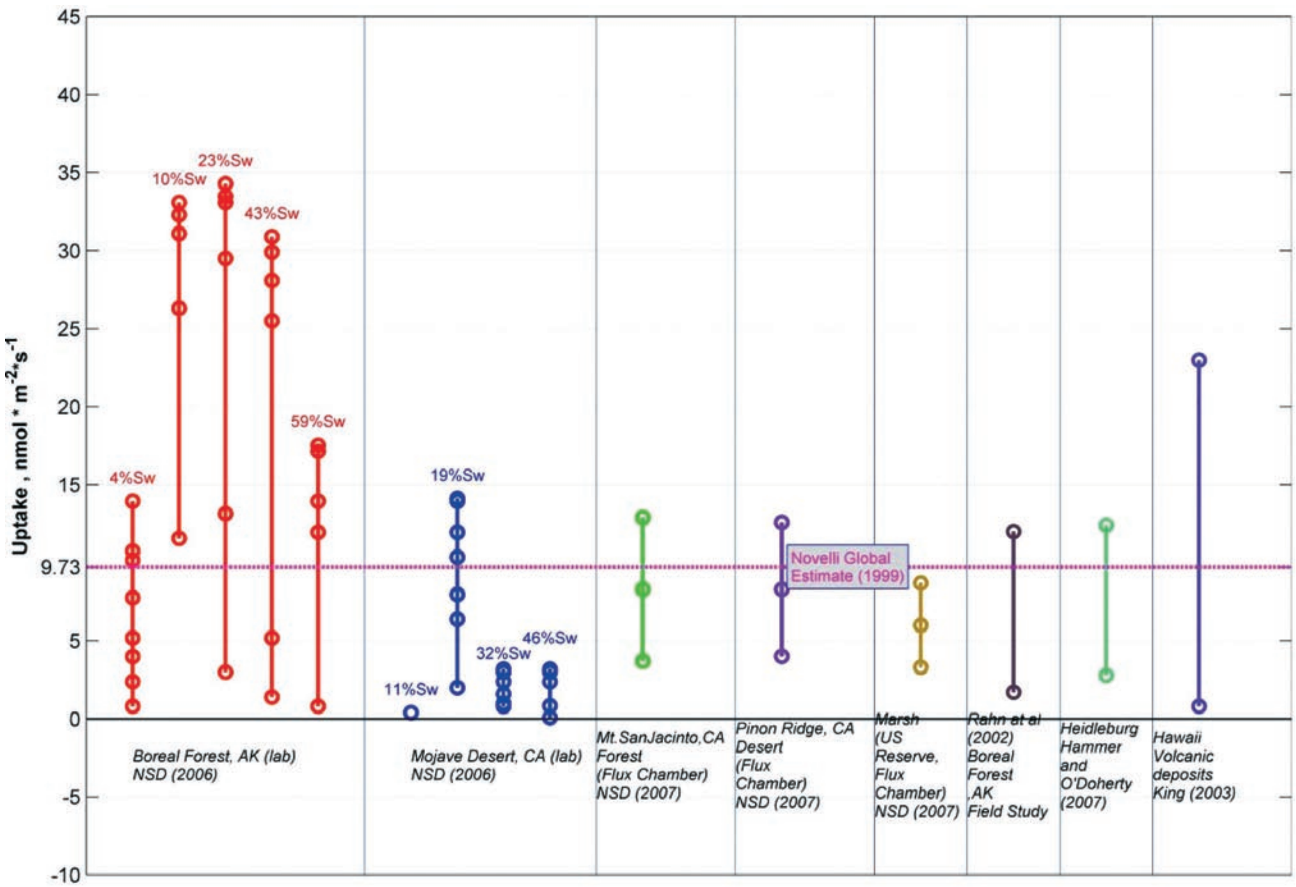

FIGURE 2. Results from Field and Laboratory Studies of Hydrogen Uptake

– Other environmental effects: e.g. mining and processing of trace metals used as catalysts or in photovoltaic cells

FY 2008 Publications/Presentations

1. DOE 2008 Annual Merit Review & Peer Evaluation. Washington D.C. June 13, 2008.

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