# Hydrogen Effects on Climate, Stratospheric Ozone, and Air Pollution

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## Introduction

The purpose of this project is to study the potential effects on air pollution, climate, and stratospheric ozone, of replacing fossil-fuel motor vehicles and electric power plants with hydrogen fuel cell vehicles and power plants, respectively, where the hydrogen is produced either from steam reforming of natural gas, coal gasification, or wind energy. The effects are being estimated with a three-dimensional numerical model of the atmosphere and ocean that is driven by emissions and that treats gases, aerosol particles, meteorology, clouds, radiation, oceans, soils, and other surfaces. An important part of the study is to develop emission scenarios for the atmospheric model simulations based on life cycle assessments of relevant power generation technologies.

## Background

During the last two years, a few papers have been published related to the effects of a hydrogen economy on the atmosphere. Tromp et al.[1] examined the potential impact of increasing atmospheric hydrogen on stratospheric ozone. They suggested that the addition of hydrogen would increase stratospheric water vapor and cool the stratosphere, a process that would delay recovery of the ozone layer. The paper did not look at the effect of simultaneously reducing fossil-fuel emission nor calculate the climate response of hydrogen itself.

Schultz et al.[2] examined the effects of a hydrogen economy on tropospheric air chemistry and direct radiative forcing of gases. Their scenarios assumed that a reduction in anthropogenic emission would accompany an increase in hydrogen use. They calculated that $NO_x$, CO, and OH would decrease and methane would increase in the global troposphere upon switching to hydrogen. Warwick et al.[3] similarly examined the effect of hydrogen leakage plus reduction in $NO_x$, CO, $CH_4$, and NMHC on tropospheric chemistry. Neither study (1) treated the effects of hydrogen on climate response (e.g., feedbacks to meteorology); (2) examined the effects of switching to hydrogen on local or regional pollution (they looked at large-scale effects); (4) treated aerosols or effects of a hydrogen economy on them; (5) treated specific emission scenarios, or (5) treated emissions resolved to the county level.

In addition, a few recent studies have examined the economic benefits and drawbacks of different methods of producing hydrogen[4,5] and the economic feasibility of a hydrogen economy[6,7,8,9]

## Results

Between January 2004 and May, 2005, six papers relating to this project have been written. Of these, four are published or in press and the other two have been reviewed and are pending publication.

Two papers examining the effects of converting all U.S. onroad vehicles to hydrogen fuel cell vehicles on air pollution have been submitted, reviewed, and revised for potential publication (Publications 1, 2). The abstracts of the papers are as follows:

### Switching to a U.S. Hydrogen Fuel Cell Vehicle Fleet: The Resultant Change in Emissions, Energy Use, and Greenhouse Gases

W.G. Colella, M.Z. Jacobson, and D.M. Golden.
Submitted to the *Journal of Power Sources*

This study examined the potential change in emissions and energy use from replacing fossil-fuel on-road vehicles (FFOV) with hybrid electric fossil fuel vehicles or hydrogen fuel cell vehicles (HFCV). The study analyzed the resultant emissions and energy usage from three different HFCV scenarios, with hydrogen produced from 1) steam reforming of natural gas, 2) electrolysis powered by wind energy, and 3) coal gasification. Using the US EPA's National Emission Inventory for a base case, other emission inventories were created using a Life Cycle Analysis of alternative fuel supply chains. For a range of reasonable HFCV efficiencies and methods of producing hydrogen, the replacement of FFOV with HFCV significantly reduces emissions associated with air pollution, even compared with a switch to hybrids. All HFCV scenarios decreased net air pollution emissions, including nitrogen oxides, volatile organic compounds, particulate matter, ammonia, and carbon monoxide. These reductions were achieved with hydrogen production relying on either a fossil fuel source such as natural gas or a renewable source such as wind. Furthermore, replacing FFOV with hybrids or HFCV with their fuel derived from natural gas, wing, or coal reduced the global warming impact of combined carbon dioxide and methane gases (measured in carbon dioxide equivalent emission) by 6%, 14%, 23%, and 2%, respectively. Finally, even if HFCV were fueled by a fossil fuel such as natural gas, no carbon was sequestered during hydrogen production, and 1% of methane in the feedstock gas was leaked to the environment, the natural gas HFCV scenario still achieved a significant reduction in greenhouse gases and air pollution over FFOV.

### Cleaning the Air and Improving Health With Hydrogen Fuel Cell Vehicles

M.Z.Jacobson, W.G. Colella, and D.M. Golden.
Submitted as a Report to *Science*

Converting all U.S. onroad vehicles to hydrogen fuel-cell vehicles (HFCV) may benefit air quality, health, and climate significantly, regardless of whether hydrogen is produced by steam-reforming of natural gas, wind-electrolysis, or even coal gasification. Most benefits result from eliminating current vehicle exhaust. Wind- and natural-gas-HFCV may improve health more than coal-HFCV or fossil-electric

> hybrid vehicles and save 3700-6400 U.S. lives annually. Wind-HFCV may benefit climate most. HFCV will hardly affect water vapor. Coal-HFCV may improve health but damage climate relative to hybrids. The near-term direct plus externality cost of hydrogen from wind-electrolysis may be below that of U.S. gasoline.

The first paper developed several scenarios for a hydrogen economy. A base-case emission scenario was first derived from U.S. EPA's National Emission Inventory (NEI), which treats all anthropogenic emissions from power plants, vehicles, industry, and other sources, by county and time of year in the United States. Alternative emission inventories were then prepared for three HFCV scenarios (where hydrogen was produced from steam reforming of natural gas, electrolysis powered by wind energy, or coal gasification), and one hybrid scenario, following a life cycle assessment (LCA) that accounted for energy inputs and pollution outputs during all stages of fuel production, distribution, processing, storage, and end-use.

For each scenario, we modified onroad, power-plant, and fugitive NEI emissions. In the HFCV cases, FFOV emission (including hydrogen and water) was removed, refinery volatile organic emission was reduced by half (the fraction of petroleum used for onroad vehicles), and leaked hydrogen and chemically-produced water vapor were added. Also, emission ($NO_x$, VOC, CO, $CO_2$) and leaks ($CH_4$) from steam reforming and emission ($NO_x$, CO, $CO_2$, $SO_2$) from coal gasification were added. Carbon dioxide sequestration was not considered. Emission due to power for compressing hydrogen in all HFCV cases and for gasifying coal in the coal case were added proportionally to the power plant emission mix in the inventory without changing the number of power plants or their control technologies. Energy required for the endothermic steam reforming of natural gas was also included. The fleet-averaged energy efficiency increase upon conversion of FFOV to hybrid vehicles was taken as 45%.

Three important results can be highlighted from this analysis. First, for a range of reasonable HFCV efficiencies and methods of producing hydrogen, replacing the current fossil fuel on-road vehicle fleet (FFOV) with a hydrogen fuel cell vehicle (HFCV) fleet may result in a significant reduction in air pollution emission, in comparison with a switch to hybrid-electric gasoline vehicles, due to the elimination of the combustion products at the internal combustion engine and the reduction of upstream petroleum processing emissions. In all HFCV scenarios, the net quantity of most types of emissions associated with air pollution would decrease, including nitrogen oxides ($NO_x$), volatile organic compounds (VOCs), particulate matter ($PM_{2.5}$ and $PM_{2.5-10}$), ammonia ($NH_3$), and carbon monoxide (CO). Similar reductions in air pollution emissions were achieved with a fossil fuel such as natural gas, as with a renewable source such as wind. Second, replacing FFOV with hybrid electric vehicles or with HFCV with their fuel derived from natural gas, wind or coal may reduce the global warming impact of combined $CO_2$ and $CH_4$ gases (measured in $CO_2$ equivalent emission) by 6%, 14%, 23%, and 2%, respectively. Assuming reliance on conventional power plants for electricity needed in hydrogen generation, this HFCV fleet would produce some additional $CO_2$ emission compared with the FFOV base case due to the electric power required for the compression of hydrogen, but less $CO_2$ emission on the road during vehicle operation.

Finally, if HFCV are fueled by hydrogen from natural gas, if no carbon is sequestered, and if 1% of methane in feedstock gas is leaked, equivalent greenhouse gas emission may decrease by 14% and air pollution emission may decrease significantly compared with the 1999 FFOV fleet. This result emanates from 1) the lower quantity of carbon in natural gas per unit of fuel energy as compared with gasoline or diesel fuel, 2) a high energy conversion efficiency in converting natural gas to hydrogen via the steam reforming reactions, 3) the higher efficiencies of electric drive trains over mechanical ones, and 4) the higher efficiency and lower emission profile of fuel cell systems over internal combustion engines. All proposed scenarios – either hybrid or fuel cell – significantly reduce air pollution and global warming compared with the current fleet.

The second paper is available at

www.stanford.edu/group/efmh/jacobson/fuelcellhybrid.html

so is not discussed here, except as follows. Two sets of figures from the two publications are shown for illustration. Figure 1 (from Publication 1) shows the estimated annual hydrogen fuel consumption by county in the United States resulting from the replacement of all on-road vehicles with hydrogen fuel-cell vehicles. Figure 2 (from Publication 2) shows the modeled effect on the monthly-averaged August mixing ratios of several pollutant gases due to converting the U.S. fleet of onroad vehicles to HFCV when the hydrogen is produced by steam reforming of natural gas. These figures are described in more detail below and in the respective papers.

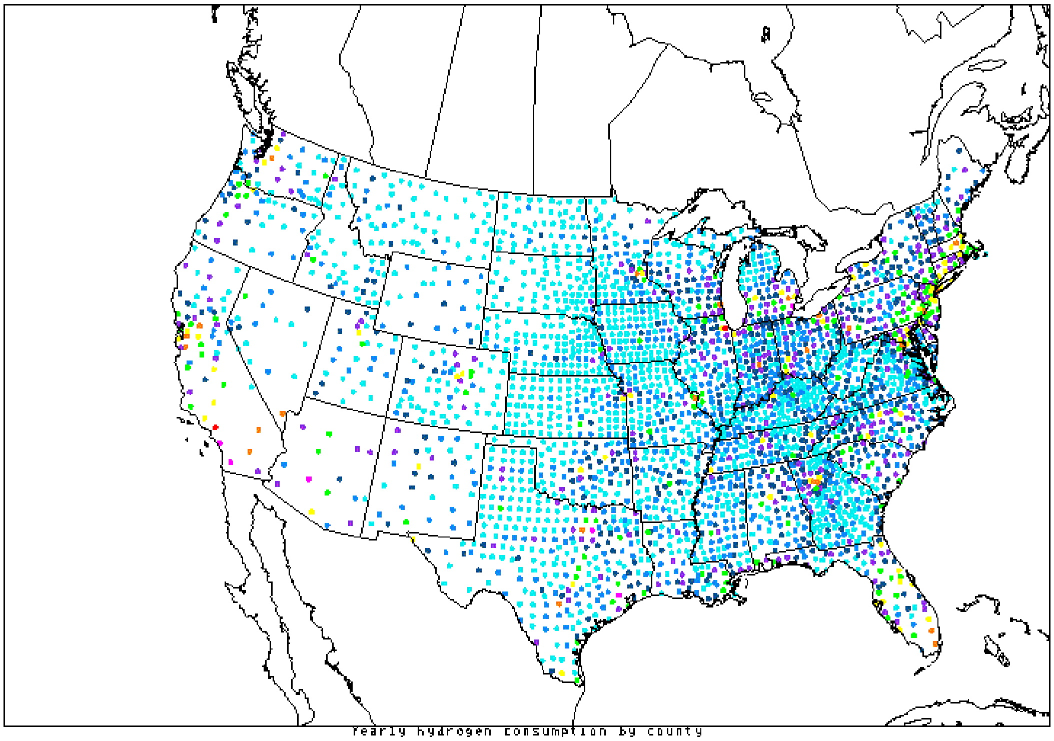
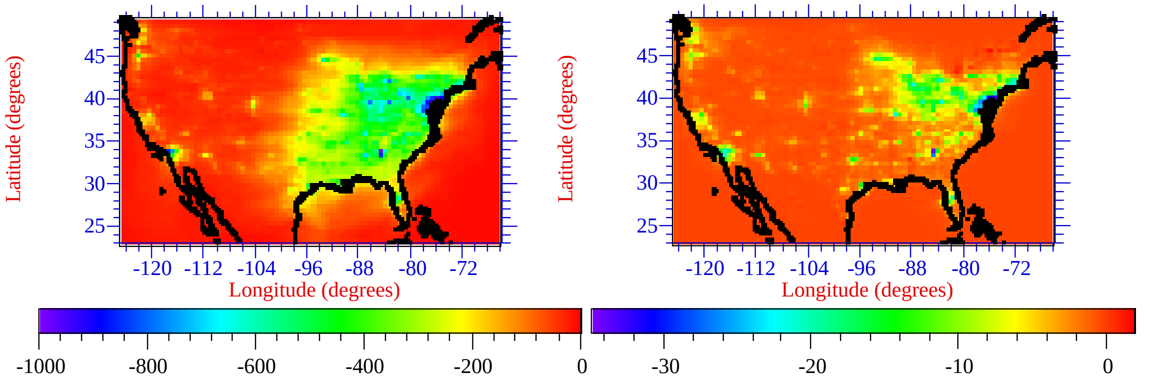
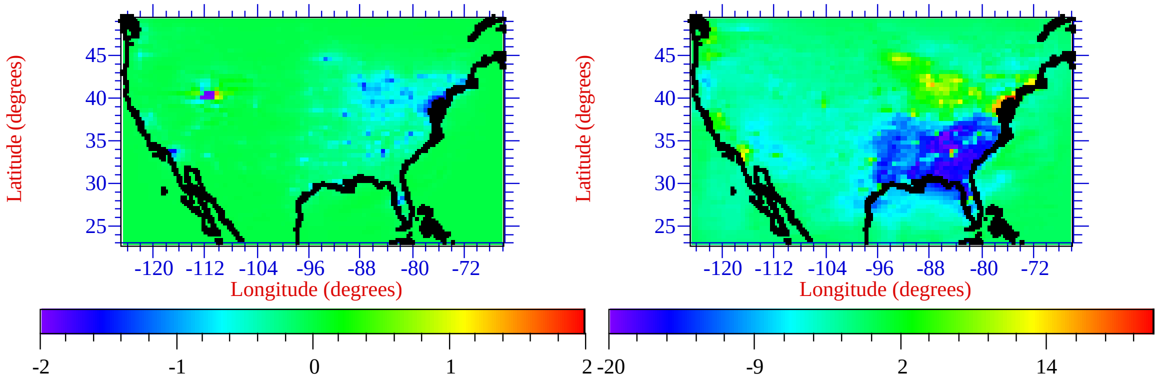


**Figure 1:** Map of estimated hydrogen consumption in the U.S. by county if all onroad vehicles were switched to hydrogen fuel-cell vehicles. Light blue=0-5; Medium blue=5-10; Dark blue=10-20; Purple=20-40; Green=40-80; Yellow=80-160; Orange=160-320; Magenta=320-640; Red>640 Gg/yr (1Gg=$10^9$g). See text for discussion. From Colella et al. (2005) (Publication 1). Each dot represents emission from an individual county and is located at the geographic center of the county.



(a) Near-surface carbon monoxide dif. (ppbv) nat. gas minus base

(b) Near-surface nitrogen dioxide dif. (ppbv) nat. gas minus base



(c) Near-surface toluene dif. (ppbv) nat. gas minus base

(d) Near-surface ozone dif. (ppbv) nat. gas minus base

**Figure 2**. Modeled differences, averaged over all day and night hours of the month of August 1999, of near-surface (a) carbon monoxide, (b) nitrogen dioxide, (c) toluene, and (d) ozone mixing ratio between a simulation in which the U.S. fleet of onroad vehicles is converted to hydrogen fuel cell vehicles, where the hydrogen is generated from steam-reforming of natural gas, and a baseline simulation (current fleet of onroad vehicles). From Jacobson et al. (2005) (Publication 2).

Two other areas of the project in which progress has been made include analyzing the feasibility of large-scale wind-electrolysis and improving the numerical model used for this study. With respect to the first goal, the world’s winds were mapped by continent and analyzed. The results were written up and accepted for publication (Publication 3 – please see web site listed with reference). Figure 3 shows a map of the winds in North America from that study.

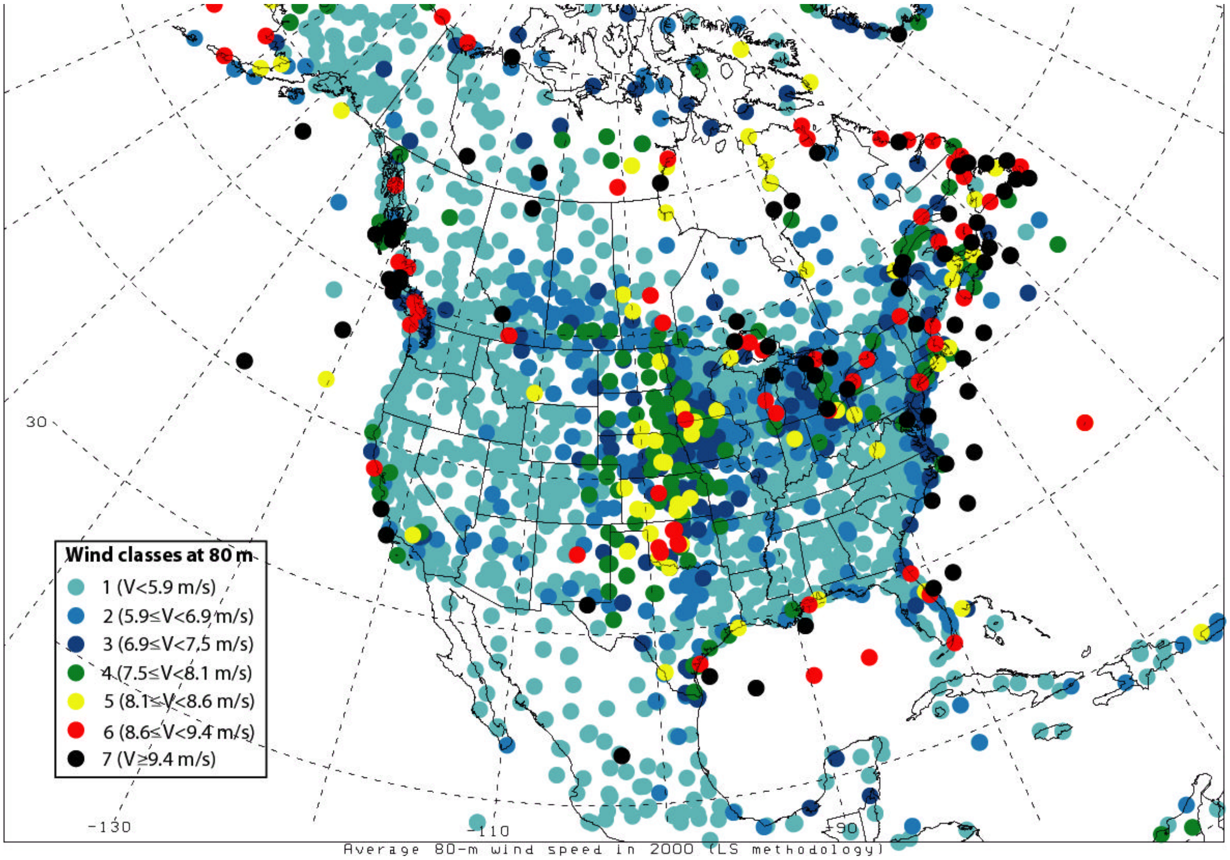


**Figure 2.** Map of 80-m winds in North America, derived from surface and sounding data. From Archer and Jacobson (2005) (Publication 3).

With respect to model improvements, a graduate student, Gerard Ketefian, improved the ocean and atmospheric dynamics modules for use by this project. He developed numerical algorithms that conserve several properties. He has now tested these algorithms extensively under a variety of flow conditions. He is currently writing up two papers describing the algorithms and their characteristics and has included much of the analysis in his PhD dissertation. The algorithms are being implemented into GATOR-GCMOM, the model used for this study.

Finally, three papers have been published (Publications 4-6) describing GATOR-GCMOM model improvements during the project period. The improvements were (a) a new method of solving nonequilibrium gas-aerosol transfer of acids and bases, (b) a new method of calculating absorption coefficients among multiple gases simultaneously, and (c) a new method of solving ocean-atmosphere exchange and ocean chemistry.

## Progress

The main progress to date toward determining technologies that would reduce greenhouse gases and air pollutants is described in Publications 1 and 2. These publications lay out scenarios examining the effects on air pollution, health, and climate of converting all U.S. vehicles to hydrogen fuel cell vehicles when the hydrogen is generated by one of three methods. The papers also examined the effects of converting to gasoline-electric hybrid vehicles. Several main conclusions are as follows:

1) Switching from the 1999 fossil-fuel onroad vehicle (FFOV) fleet to a hydrogen fuel cell vehicle (HFCV) or hybrid fleet may reduce air pollution, health, and climate problems and costs.
2) Although all three HFCV cases studied (wind, natural gas, coal) reduced health costs (since most air quality improvements resulted from eliminating FFOV exhaust), wind- and natural gas-HFCV reduced such costs the most and reduced ozone by up to 20 ppbv.
3) Wind-HFCV reduced climate costs the most, making it the most environmentally beneficial energy technology scenario.
4) Natural gas-HFCV increased $CH_4$ but reduced $CO_2$, making it the second-most-beneficial technology.
5) Hybrids reduced climate costs but increased health costs relative to coal-HFCV, suggesting a rough tie for third.
6) Hybrids and coal-HFCV reduced health and climate costs relative to FFOV.
7) HFCV had little impact on water vapor emission, either in terms of magnitude or location of the emission.

## Future Plans

The next stage of the project is to derive scenarios and run numerical simulations for examining the effects of converting traditional sources of electric power and heat generation to those from combined-heat-and-power (CHP) (cogeneration) fuel cell systems.[10-11] The simulations examined will include the following:

1) Current power plants and heat generation by conventional boilers and furnaces.
2) Converting coal, natural gas, and oil electric power plants, boilers, furnaces to
    a) advanced natural gas combined cycle gas turbines (CCGT).
    b) hydrogen CHP power plants, where the hydrogen is produced by
        (i) steam-reforming of natural gas (at low and/or high heat:power ratios)
        (ii) wind electrolysis
        (iii) coal gasification

The final stage of the project will be to run long-term simulations to examine the effects of converting FFOV and power plants to HFCV and CHP fuel cell systems on climate and stratospheric ozone.

## Publications

1. Colella, W.C., M.Z. Jacobson, and D.M. Golden, Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases, *J. Power Sources*, in review, 2005.

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11. Colella, W.G. "Design Options for Achieving a Rapidly Variable Heat-to-Power Ratio in a Combined Heat and Power (CHP) Fuel Cell System," *J. Power Sources*, 106, 388-396, 2001.

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