observed rates. Comparisons at regional to continental scales also show that mean snow accumulation from meteorological models is very low over most of the interior of the Antarctic continent. For example, basin-averaged, model-simulated, mean-annual snow accumulation compared with regional accumulation estimates compiled from in situ and passive microwave measurements (*19*) ranged from 25 to 50% for primarily interior basins (e.g., J″-K and B-C).

It is clear, therefore, that the ERA-40 reanalysis and ECMWF operational analyses used here capture much of the relative temporal variability in accumulation while underestimating the total amount, resulting in underestimation of the magnitude of modeled temporal trends in snowfall rate. Although some of the difference between observed elevation change and modeled snowfall-rate trends likely results from changes in snow densification in response to changing snow accumulation rate and temperature (*20*), most of the difference probably results from underestimation of the magnitude of annual-to-decadal changes in snowfall by the meteorological models.

Placing these results in perspective, a sea-level change of 1 mm/year corresponds to 360 billion metric tons of water per year (*21*). Using a near-surface snow density of 350 kg/m$^3$, an average elevation change of 1.8 ± 0.3 cm/year over an area of 7.1 million km$^2$ for the East Antarctic interior (table S1) corresponds to a mass gain of 45 ± 7 billion metric tons of water per year and a corresponding sea-level drop of 0.12 ± 0.02 mm/year. We believe that this is a conservative estimate. The spatially uniform and positive *dH/dt* values for the East Antarctic interior (Fig. 2) suggest that much of the area south of the East Antarctic ROC may also be thickening. These results are consistent with ice-core evidence, though sparse, for increasing accumulation in East Antarctica during the decades preceding our observational time period (*22*–*26*). Thus, we cannot rule out a longer-term mass imbalance due to increased precipitation, as predicted by earlier studies [e.g., (*27*, *28*)] and the most recent IPCC assessment (*6*).

The vast size of the East Antarctic ice sheet means that even a small imbalance has a large effect on sea-level change. For example, a 1.8 cm/year average *dH/dt* over the entire East Antarctic ice sheet (~10 million km$^2$) would correspond to a sea-level drop of 0.18 mm/year (assuming a recent change and snow density of 350 kg/m$^3$), nearly as large as the most recent estimate of 0.20 mm/year (*2*) for the Greenland ice sheet's contribution to sea-level rise, and larger than the most recent estimate for the West Antarctic ice sheet's contribution of 0.16 mm/year (*3*).

Our results show that the East Antarctic ice-sheet interior increased in overall thickness within the ROC from 1992 to 2003 and that this increase is probably the result of increased snowfall. Both of these observations are consistent with the latest IPCC prediction for Antarctica's likely response to a warming global climate (*6*). However, the IPCC prediction does not consider possible dynamic changes in coastal areas of the ice sheet. Moreover, these results have only sparse coverage of the coastal areas where recent dynamic changes may be occurring (*4*). Thus, the overall contribution of the Antarctic ice sheet to global sea-level change will depend on the balance between mass changes on the interior and those in coastal areas.

**References and Notes**


1. W. Krabill *et al.*, *Science* **289**, 428 (2000).
2. W. Krabill *et al.*, *Geophys. Res. Lett.* **31**, L24402 (2004).
3. E. Rignot, R. Thomas, *Science* **297**, 1502 (2002).
4. R. Thomas *et al.*, *Science* **306**, 255 (2004).
5. Intergovernmental Panel on Climate Change, *IPCC Third Assessment Report, Climate Change 2001: The Scientific Basis* (Cambridge Univ. Press, Cambridge, 2001).
6. J. A. Church *et al.*, in *Climate Change 2001: The Scientific Basis* (Cambridge Univ. Press, Cambridge, 2001), pp. 639–694.
7. J. R. McConnell *et al.*, *Nature* **406**, 877 (2000).
8. A. C. Ferguson, C. H. Davis, J. E. Cavanaugh, *IEEE Trans. Geosci. Remote Sens.* **42**, 2426 (2004).
9. C. H. Davis, A. C. Ferguson, *IEEE Trans. Geosci. Remote Sens.* **42**, 2437 (2004).
10. Y. Li, C. H. Davis, Proceedings of the 2005 International Geoscience and Remote Sensing Symposium, Seoul, South Korea (Institute of Electrical and Electronics Engineers, Piscataway, NJ), in press.
11. Materials and methods are available as supporting material on *Science* Online.
12. E. R. Ivins, X. Wu, C. A. Raymond, C. F. Yoder, T. S. James, *Int. Assoc. Geodesy Symp.* **123**, 361 (2001).
13. A. Shepherd, D. J. Wingham, J. A. D. Mansley, H. F. J. Corr, *Science* **291**, 862 (2001).
14. E. Rignot, S. Jacobs, *Science* **296**, 2020 (2002).
15. D. J. Wingham, A. J. Ridout, R. Scharroo, R. J. Arthern, C. K. Shum, *Science* **282**, 456 (1998).
16. E. Hanna, J. R. McConnell, S. Das, J. Cappelen, A. Stephens, *J. Clim.*, in press.
17. J. R. McConnell *et al.*, *J. Geophys. Res.* **40**, 605 (1998).
18. Q. S. Chen *et al.*, *J. Clim.* **10**, 839 (1997).
19. D. G. Vaughan, J. L. Bamber, M. Giovinetto, J. Russell, A. P. R. Cooper, *J. Clim.* **12**, 933 (1999).
20. R. J. Arthern, D. J. Wingham, *Clim. Change* **40**, 605 (1998).
21. S. S. Jacobs, *Nature* **360**, 29 (1992).
22. V. I. Morgan, I. D. Goodwin, D. M. Etheridge, C. W. Wookey, *Nature* **354**, 58 (1991).
23. E. Mosley-Thompson *et al.*, *Ann. Glaciol.* **21**, 131 (1995).
24. E. Mosley-Thompson, J. F. Paskievitch, A. J. Gow, L. G. Thompson, *J. Geophys. Res.* **104**, 3877 (1999).
25. J. Wen *et al.*, *Polar Meteorol. Glaciol.* **15**, 43 (2001).
26. I. Goodwin, M. de Angelis, M. Pook, N. W. Young, *J. Geophys. Res.* **108**, 4673 (2003).
27. J. Oerlemans, *J. Clim.* **2**, 1 (1982).
28. P. Huybrechts, J. Oerlemans, *Clim. Dyn.* **5**, 93 (1990).


29. ERA-40 and ECMWF operational analysis data were provided by A. Stephens (British Atmospheric Data Centre). This work was supported by NASA's Cryospheric Processes Program (C.H.D., Y.L., and J.R.M.) and the NSF Antarctic Glaciology Program (J.R.M. and M.M.F.). We thank the U.S. ITASE field team, R. Kreidberg for help with the manuscript, and two anonymous reviewers for comments that improved this manuscript.


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Materials and Methods
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# Cleaning the Air and Improving Health with Hydrogen Fuel-Cell Vehicles


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**Converting all U.S. onroad vehicles to hydrogen fuel-cell vehicles (HFCVs) may improve air quality, health, and climate significantly, whether the hydrogen is produced by steam reforming of natural gas, wind electrolysis, or coal gasification. Most benefits would result from eliminating current vehicle exhaust. Wind and natural gas HFCVs offer the greatest potential health benefits and could save 3700 to 6400 U.S. lives annually. Wind HFCVs should benefit climate most. An all-HFCV fleet would hardly affect tropospheric water vapor concentrations. Conversion to coal HFCVs may improve health but would damage climate more than fossil/electric hybrids. The real cost of hydrogen from wind electrolysis may be below that of U.S. gasoline.**


Switching from a fossil-fuel economy to a hydrogen economy would be subject to technological hurdles, the difficulty of creating a new energy infrastructure, and considerable conversion costs (*1*) but could provide health, environmental, climate, and economic benefits and reduce reliance on diminishing oil supplies. Although studies have modeled the effects of hydrogen leakage or reduced emission on global tropospheric and stratospheric chemistry (*2*–*4*), no study has examined the effect on urban pollution or health of establishing a hydrogen economy. Furthermore, no study has examined the likely effects of this switch on aerosol particles (which have a large impact on climate and are the deadliest components

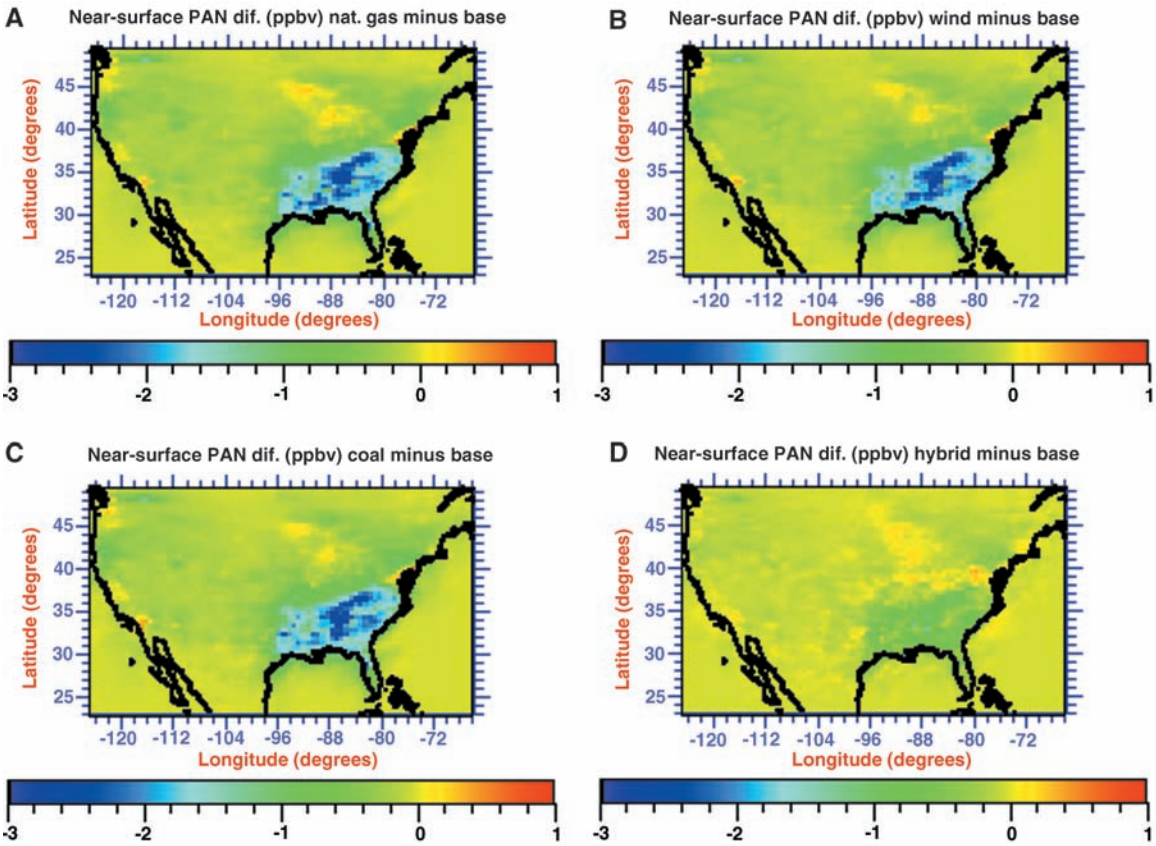


**Fig. 1.** Modeled differences, averaged over all day and night hours of the month of August 1999, of near-surface PAN. Each panel represents the difference between the (**A**) natural gas, (**B**) wind, (**C**) coal, and (**D**) hybrid cases and the baseline case, respectively. The maximum overall monthly-averaged reduction anywhere in the HFCV cases was 3 ppbv out of a baseline case maximum of 9 ppbv (Fig. S1h). The maximum difference in the hybrid case was 1.2 ppbv.

of air pollution), of generating hydrogen by any method aside from renewable energy, or of examining emission changes upstream of vehicles. Here we examine the possible effects on ambient gas and particle concentrations and on estimated health and climate costs of different methods of replacing all U.S. fossil-fuel onroad vehicles (FFOVs) with hydrogen fuel-cell vehicles (HFCVs).

For the study, we used GATOR-GCMOM, a parallel, global-through-urban nested gas, aerosol, transport, radiation, general circulation, mesoscale, and ocean computer model (*5–7*), together with the U.S. National Emission Inventory (NEI) (*8*), both described in (*9*). Emission inventories for HFCV and hybrid sensitivity experiments (summarized in table S1) were prepared for this study in (*10*) after a life-cycle assessment (LCA) that accounted for energy inputs, efficiencies, and pollution outputs during all stages of hydrogen and fossil-fuel production, distribution, storage, and end use. Model data comparisons with the baseline inventory are also given in (*10*).

Five global/regional nested simulations were run: one baseline scenario assuming August 1999 emissions, one where all FFOVs were instantly converted to fossil-fuel/electric hybrid vehicles, and three where FFOVs were switched to HFCVs in which the hydrogen was produced by (i) steam reforming of natural gas, (ii) wind electrolysis, or (iii) coal gasification. Although an instantaneous conversion of all FFOVs to hybrids or HFCVs will not occur, we assumed that it would in order to provide net (not time-dependent) differences in air pollution between current and future vehicle fleets. Because hybrids may represent advanced FFOVs, a comparison of HFCVs with FFOVs and hybrids may give a full range of HFCV benefits and disadvantages relative to current and more efficient FFOVs.

For each case, we modified onroad, power plant, and other NEI emissions. In the HFCV cases, FFOV emissions (including hydrogen and water) were 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 [nitrogen oxides ($NO_x$), volatile organic carbon (VOC), CO, and $CO_2$] and leaks ($CH_4$) from steam reforming and emission ($NO_x$, CO, $CO_2$, and $SO_2$) from coal gasification were added. Carbon sequestration was not included. Emissions produced by power use 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. Emissions from exploration, mining, storage, processing, and transport of fuels and infrastructure were assumed to be similar among cases.

The assumed hydrogen leakage rate was 10%, a probably unrealistic upper bound (*3*). A more realistic value may be 3%. The upper bound was used to ensure that the conclusions here, which were found to show net benefits of HFCVs, are conservative.

The fleet-averaged energy efficiency increase upon conversion of FFOVs to hybrid vehicles was taken as 45% (*11*), corresponding to a 31% emission decrease (1/1.45). Although some new FFOV vehicles will emit less, the fleet-averaged emission, which we are interested in, may not decrease so much, because not all new vehicles will be low emitters, and emission increases with vehicle age. HFCVs will emit only hydrogen and water at any age.

Figure 1 shows August-averaged (day and night) modeled differences in emission of peroxyacetyl nitrate (PAN), a potent eye irritant that also discolors plant leaves, between each case and the baseline case. Switching from current FFOVs reduced PAN in all cases in most locations, predominantly in the southeastern United States. The improvement was greater in the HFCV cases [up to 3 parts per billion by volume (ppbv) out of a baseline maximum of 9 ppbv] than in the hybrid case (up to 1.2 ppbv). Little difference occurred among the HFCV cases, because the emission increase in each

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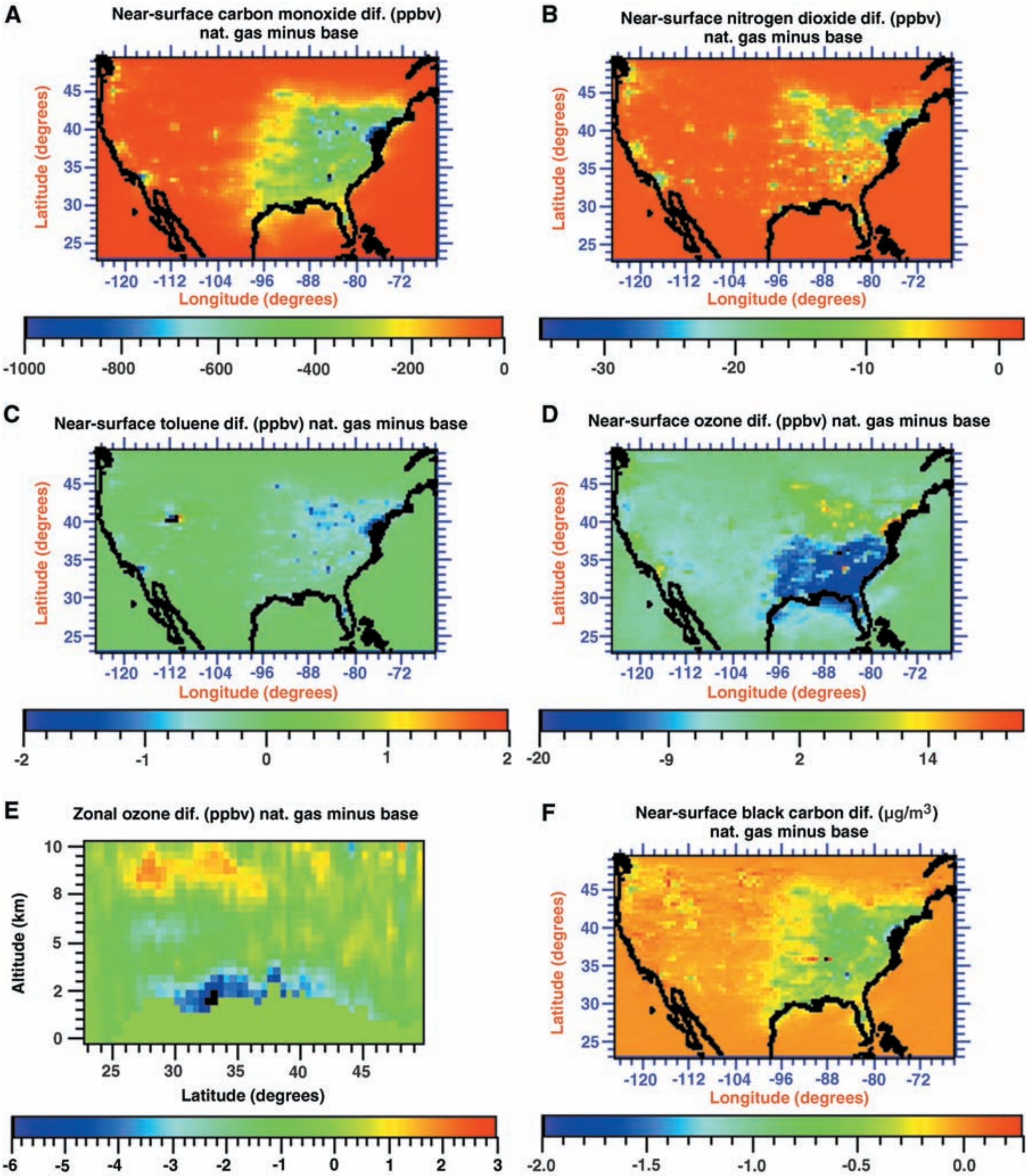


**Fig. 2.** Same as Fig. 1, but for (**A**) near-surface carbon monoxide (maximum reduction 1000 ppbv out of a baseline maximum of 1900 ppbv), (**B**) near-surface nitrogen dioxide (35 ppbv out of 63 ppbv), (**C**) near-surface toluene (2 ppbv out of 15 ppbv), (**D**) near-surface ozone (20 ppbv out of 103 ppbv), (**E**) zonally averaged (between –125 and –65.75 W) ozone (6 ppbv out of 46 ppbv), and (**F**) near-surface particulate black carbon (2 out of 12 μg/m$^3$). (E) shows zonally averaged orography as well, where ozone values are zero. Figure S1 shows the baseline cases and other difference cases.

HFCV case was smaller than the emission reduction from eliminating FFOVs. PAN declined most in the southeast, where reducing $NO_x$ had a big impact. PAN increased slightly in the northeast and Los Angeles, possibly because although $NO_x$ and organics decreased there, the decrease in NO and $CH_3O_2$, which destroy $CH_3CO_3$, increased $CH_3CO_3$, which then reacted with $NO_2$ to increase PAN.

Figure 2 shows August changes in several pollutants from the natural gas HFCV case. Changes were similar among other HFCV cases, as shown in (*9*), which also shows figures for other pollutants. Switching to HFCV reduced CO (Fig. 2A) over most of the United States by up to 1000 ppbv out of a baseline maximum of 1900 ppbv and reduced $NO_2$ (Fig. 2C) by up to 35 out of 63 ppbv. Toluene (Fig. 2B), a reactive ozone precursor, decreased over most of the United States by up to 2 out of 15 ppbv. Near-surface ozone decreased over most of the United States by up to 20 out of 103 ppbv. Ozone increased in regions of high $NO_x$ and low biogenic hydrocarbon emission, such as in Los Angeles and along the northeast corridor, because reducing $NO_x$ in those places reduced ozone titration by $NO + O_3 \rightarrow NO_2 + O_2$ and increased OH (fig. S1j) Fig. 2E, though, shows that zonally averaged near-surface ozone decreased over all latitudes by up to 6 ppbv.

HFCVs reduced near-surface particulate black carbon (BC) (Fig. 2F) by up to 2 out of 12 μg/m$^3$. Because particles are the most unhealthful components of air pollution, their reduction represents a benefit of switching to HFCVs (Table 1). Reducing BC, which enhances global warming, may also slightly reduce climate costs; reducing cooling particle components may unmask some global warming, slightly increasing such costs (Table 1).

The main differences among the three HFCV cases were their effects on greenhouse gases. Fig. S1o shows that hydrogen production from natural gas, under the assumption of a 1% natural gas leakage rate (*10*), increased methane by up to 40 ppbv during August out of a background of 1700 ppbv in 1999. Producing hydrogen from wind or coal decreased methane by up to 20 ppbv relative to FFOVs. The hybrid case resulted in

**Table 1.** Estimated health, climate, and total cost reductions (positive values) or increases (negative values) per year in 2004 dollars for each of the four cases discussed. The table does not reflect capital costs. Three significant digits are shown to illustrate small differences in some cases. The first species in the first column is the emitted pollutant. For health-effect agents, the species after the hyphen, if any, is an ambient pollutant causing a health hazard; otherwise, the emitted species also causes the health hazard. For climate agents, only emitted species are shown. Costs per year for a pollutant in a case were obtained by multiplying the cost per unit mass emission of the pollutant (second column of Table 1) by the change in mass emission per year of the pollutant for the case (table S1). VOC is assumed to be the same as total NMOC (nonmethane organic carbon) in table S1. Costs per unit mass emission were obtained for all species except for $CO_2$ and $CH_4$ from (*16*, *17*), adjusted from 1991 to 2004 dollars with the gross domestic product (GDP) deflator ratio (1.2721). $CO_2$ costs per unit mass emission were obtained from (*18*), adjusted from 1995 Euros to 2004 dollars assuming $1.25 per Euro in 1995 and the GDP deflator ratio from 1995 to 2004 (1.1634). $CH_4$ costs per unit mass emission were estimated as those of $CO_2$ multiplied by 23, the 100-year global warming potential (GWP) of $CH_4$. The BC+OM (sum of emitted sub–2.5-μm fossil-fuel particulate black carbon plus organic carbon) climate cost per unit mass was estimated as that of $CO_2$ multiplied by the 100-year temperature change per unit mass emission of BC+OM relative to that of $CO_2$, calculated here as 95 to 191 [section 5 of (*9*), using data from (*27*)]. $PM_{2.5}$-cooling components (PM, particulate matter) include emitted sub–2.5-μm sulfate, plus nitrate, plus 40% of $SO_x$, plus 10% of $NO_x$, plus 5% of VOC. Its climate cost per unit mass is estimated as that of $CO_2$ multiplied by the 100-year climate response ratio of $SO_x$, calculated here as 19 to 39 [calculated from section 5 of (*9*), using data from (*27*, *28*)]. Costs per displaced gallon of current fuel (last row of Table 1) were obtained by dividing the total cost of each case (second-to-last row) by the total gasoline plus diesel fuel used for onroad vehicles in the United States in 1999 ($1.57 \times 10^{11}$ gallons) (*10*). For consistency, this quantity was the same as that displaced to generate hydrogen for the cases herein.

| Species | $/kg of emission in 2004 | Hybrid (billion $/year) | Natural gas (billion $/year) | Wind (billion $/year) | Coal (billion $/year) |
|---|---|---|---|---|---|
| $SO_x$-sulfate PM | 8.78–83.3 | 0.76–7.23 | −3.25–(−30.8) | −3.25–(−30.8) | −8.51–(−80.8) |
| $NO_x$-nitrate PM | 1.30–21.1 | 3.05–49.5 | 9.43–153 | 9.45–153 | 9.24–150 |
| $NO_x$-$NO_2$ | 0.19–0.93 | 0.45–2.18 | 1.39–6.75 | 1.39–6.76 | 1.36–6.61 |
| VOC-organic PM | 0.13–1.46 | 0.19–2.23 | 0.70–8.01 | 0.70–8.01 | 0.70–8.01 |
| $PM_{2.5}$ | 13.3–202.5 | 0.69–10.6 | 1.98–30.3 | 1.98–30.3 | 1.89–28.9 |
| $PM_{2.5\text{-}10}$ | 8.52–22.4 | 0.12–0.32 | 0.30–0.79 | 0.30–0.79 | 0.24–0.64 |
| VOC+$NO_x$-$O_3$ | 0.13–1.46 | 0.49–5.67 | 1.62–18.7 | 1.62–18.7 | 1.60–18.4 |
| $NH_3$-ammonia PM | 1.30–21.1 | 0.10–1.56 | 0.31–5.01 | 0.31–5.01 | 0.31–5.01 |
| CO | 0.0127–0.11 | 0.24–2.20 | 0.79–7.07 | 0.79–7.07 | 0.74–6.67 |
| Subtotal health | | 6.10–81.5 | 13.2–197 | 13.3–199 | 7.56–143 |
| $CO_2$ | 0.026–0.067 | 8.27–21.1 | 20.8–53.2 | 32.6–83.2 | 1.62–4.15 |
| $CH_4$ | 0.60–1.54 | 0.14–0.38 | −0.79–(−2.03) | 0.49–1.24 | 0.48–1.24 |
| BC+OM | 2.49–12.8 | 0.11–0.56 | 0.34–1.74 | 0.34–1.74 | 0.34–1.72 |
| Cooling $PM_{2.5}$ | 0.51–2.62 | −0.18–(−0.91) | −0.44–(−2.23) | −0.44–(−2.24) | −0.31–(−1.57) |
| Subtotal climate | | 8.35–21.2 | 19.9–50.7 | 33.0–84.0 | 2.14–5.54 |
| Total | | 14.5–103 | 33.1–248 | 46.2–283 | 9.70–149 |
| Total $/gallon | | 0.09–0.65 | 0.21–1.58 | 0.29–1.80 | 0.06–0.95 |

a lesser reduction in methane than did the coal or wind case. Because of its long lifetime (8 to 10 years) and the long-term effect by $NO_x$ and OH on it, ambient methane would change further over a longer simulation.

Table S1 shows that the coal HFCV case resulted in the lowest reduction of $CO_2$ emission, followed by the hybrid case. The wind HFCV case resulted in the greatest $CO_2$ emission reduction.

HFCVs increased $H_2$ by up to 1000 ppbv above the global background of 530 ppbv (*12*) in some locations during August (fig. S1q). The U.S.-averaged increase in the natural gas case was 100 ppbv. The increase in hydrogen had little effect on short-term smog, because hydrogen's chemical lifetime is about 4.5 to 10 years, too long to affect smog except in the background. The overall $H_2$ lifetime is 2 to 3 years because of its microbial loss in soil (*12*–*14*). The hybrid case reduced $H_2$, a fossil-fuel combustion product.

Switching to HFCVs caused virtually no change in water vapor emission. Complete combustion of gasoline, represented by $C_nH_{1.87n}$ (*15*), produces 925 mol of $H_2O$ per 1000 mol of $CO_2$. With 1371 metric tons of $CO_2$/year emitted in 1999 from primarily gasoline FFOVs in 1999 (*10*), the U.S. FFOV water vapor emission rate was about 519 tons of $H_2O$/year. A fuel cell emits 1 mol of $H_2O$ per mol of $H_2$; thus, an equivalent 1999 fleet of HFCVs that uses 56.8 tons/year of $H_2$ (*10*) emits about 508 tons of $H_2O$/year. Additional power to compress hydrogen increased the total HFCV water vapor emission to only 2% above that of current FFOVs. Because HFCVs and FFOVs will be co-located, HFCVs should have virtually no impact on urban-scale water vapor emission. Switching to hybrids reduced water vapor emission. Water vapor emission from U.S. HFCVs, hybrids, and FFOVs paled in comparison with that from natural sources globally, which is $5 \times 10^8$ tons of $H_2O$/year.

Table 1 estimates changes in yearly health and climate costs from switching to HFCVs or hybrids, calculated from the yearly emission change from each case (table S1) and health and climate cost estimates per yearly emission change (Table 1). Neither infrastructure costs due to converting to hydrogen nor our calculated monthly ambient pollutant differences (Figs. 1 and 2) were used in the health/climate cost calculation. The health costs per unit of emission, however, were obtained from studies (*16*, *17*) that first modeled changes in ambient concentrations of U.S. vehicle-derived pollution per unit of emission and then applied estimated health costs per unit change in ambient concentration. Although costs per pollutant in Table 1 accounted for seasonality and location of emission (*16*, *17*), they are conservative because particle health impact estimates and rural exposure to pollutants due to urban sprawl are now higher than at the time of the studies. Health cost uncertainties include exposures and health effects per unit of exposure. Climate costs per unit of emission were estimated from (*18*). Uncertainties include future effects of pollutants on climate and feedbacks effects of climate change on health, environment, coastlines, etc.

Table 1 shows that all four future cases reduced costs as compared with current FFOVs. Benefits from wind HFCVs slightly exceeded those from natural gas HFCVs, primarily because of the climate benefit of wind. Health and climate benefits from wind and natural gas exceeded those from coal and hybrids. Coal HFCVs reduced health problems (Table 2) but worsened climate costs (Table 1) relative to hybrids.

Previous studies (*19*, *20*) suggested that HFCVs may reduce emission and energy efficiency only modestly over hybrids. However, we find that wind HFCVs may save 2300 to 4000 lives/year and $32 billion to $180 billion/year in the United States relative to hybrids (Tables 1 and 2), and that wind or natural gas HFCVs may save 3700 to 6400 lives/year and reduce asthma by 1 million to 3 million cases/year relative to current FFOVs.

**Table 2.** Avoided health and mortality cases due to each of the four cases discussed. The table was obtained by scaling the number of cases per year in 1990 for each ambient pollutant from [table 2 of (*16*)] by the ratio of the change in emission of the pollutant's precursor(s) for each 1999 case (*10*) to the total U.S. anthropogenic emission of the precursor(s) from 1999 (*29*). The precursors were as follows: CO for ambient CO; $NO_x$ for ambient $NO_2$, VOC + $NO_x$ for ambient $O_3$; $PM_{2.5}$ + 0.1 $PM_{10\text{-}2.5}$ + 0.4 $SO_x$ + 0.1 $NO_x$ + 0.05 VOC for ambient PM [predominantly from (*16*)]. The "% mortality reduction" is the change in mortality from reducing primary and secondary PM by implementing HFCV, divided by the total number of deaths from all primary and secondary anthropogenic PM {80,000 or 137,000 deaths per year for the low or high cases, respectively [table 2 of (*16*)]}. This table does not account for global-warming health effects, which is why the wind and natural gas cases differ only in digits not shown. ARD2, any other symptom; RRAD, respiratory restricted activity days.

| Ambient pollutant | Health effect | Hybrid (cases/year) | Natural gas (cases/year) | Wind (cases/year) | Coal (cases/year) |
|---|---|---|---|---|---|
| CO | Headache | $2.34–2.78 \times 10^7$ | $7.52–8.94 \times 10^7$ | $7.52–8.94 \times 10^7$ | $7.09–8.43 \times 10^7$ |
| | Hospitalization | 1,100–3160 | 3,530–10,200 | 3,530–10,200 | 3,330–9,570 |
| | Mortality | 70–206 | 220–660 | 220–660 | 208–620 |
| $NO_2$ | Sore throat | $2.7–8.3 \times 10^7$ | $8.34–8.46 \times 10^7$ | $8.35–8.47 \times 10^7$ | $8.2–8.3 \times 10^7$ |
| | Excess phlegm | $1.24–1.26 \times 10^7$ | $3.82–3.88 \times 10^7$ | $3.83–3.89 \times 10^7$ | $3.74–3.80 \times 10^7$ |
| | Eye irritation | $1.11–1.13 \times 10^7$ | $3.44–3.49 \times 10^7$ | $3.45–3.50 \times 10^7$ | $3.37–3.42 \times 10^7$ |
| $O_3$ | Asthma attacks | $2.74–8.62 \times 10^5$ | $1.03–3.25 \times 10^6$ | $1.04–3.25 \times 10^6$ | $1.02–3.21 \times 10^6$ |
| | Eye irritation | $2.54–2.80 \times 10^6$ | $9.59–10.6 \times 10^6$ | $9.59–10.6 \times 10^6$ | $9.48–10.5 \times 10^6$ |
| | Lower respiratory illness | $3.65–6.09 \times 10^6$ | $1.38–2.30 \times 10^7$ | $1.38–2.30 \times 10^7$ | $1.36–2.27 \times 10^7$ |
| | Upper respiratory illness | $1.11–1.85 \times 10^6$ | $4.19–6.99 \times 10^6$ | $4.19–6.99 \times 10^6$ | $4.14–6.91 \times 10^6$ |
| | ARD2 | $0–2.07 \times 10^7$ | $0–7.82 \times 10^7$ | $0–7.82 \times 10^7$ | $0–7.73 \times 10^7$ |
| PM | Asthma attacks | $5.19–5.48 \times 10^4$ | $1.39–1.47 \times 10^5$ | $1.39–1.47 \times 10^5$ | $1.03–1.08 \times 10^5$ |
| | RRAD | $1.53–2.07 \times 10^6$ | $4.11–5.57 \times 10^6$ | $4.11–5.57 \times 10^6$ | $3.03–4.10 \times 10^6$ |
| | Chronic illness | 673–1610 | 1,800–4,300 | 1,800–4,300 | 1,330–3,180 |
| | Mortality | 1,380–2,370 | 3,710–6,350 | 3,710–6,350 | 2,730–4,680 |
| | % mortality reduction | 1.7 | 4.6 | 4.6 | 3.4 |

Because wind HFCVs resulted in the greatest health-plus-climate benefit among all cases, examining the cost to the U.S. economy of producing hydrogen from wind is warranted. This analysis does not consider political issues, such as zoning and larger subsidies for conventional electricity sources, affecting wind's competitiveness.

The unsubsidized near-term (<10 years) cost of producing hydrogen from wind is estimated as follows (table S2) [direct electricity from modern wind turbines in the presence of annual winds at speeds of >6.9 m/s, present over >20% of the United States (*21*)]: cost, \$0.03 to \$0.05 per kilowatt-hour (kWh) (*22*, *23*); transmission cost, $\$3.45 \times 10^{-6}$ to $\$1.38 \times 10^{-5}$ per kWh/km (*22*); transmission distances, 20 to 1500 km; internal combustion engine efficiency, 0.16 (*10*); HFCV efficiency, 0.43 to 0.46 (*10*); electrolyzer cost, \$400 to \$1000/kW (*11*); interest rate, 6 to 8%; electrolyzer energy requirement, 53.4 kWh/kg of $H_2$ (*24*); fraction of time wind is available to electrolyzer, 0.5 to 0.95 (*9*); compressor cost, \$0.7 to \$1.34/kg of $H_2$ (*25*, *26*); and storage cost, \$0.31/kg of $H_2$ (*26*). The total is \$3.0 to \$7.4/kg of $H_2$, or \$1.12 to \$3.20/gallon of displaced gasoline/diesel, which compares with the actual costs of U.S. gasoline and diesel in mid-March 2005 of \$2.06 and \$2.19, respectively. Adding the reduction in health and mortality costs from wind HFCVs of \$0.29 to \$1.80/gallon (Table 1), which is the externality cost of gasoline, gives a direct cost plus externality cost of U.S. gasoline/diesel of \$2.35 to \$3.99/gallon, which exceeds the mean cost of hydrogen from wind (\$2.16/gallon) even if retail hydrogen is marked up.

This model sensitivity experiment concludes that switching from the 1999 FFOV fleet to an HFCV or hybrid fleet may reduce air pollution, health, and climate problems and costs. Although the three HFCV cases all reduced health costs (because most improvements in air quality resulted from eliminating FFOV exhaust), wind and natural gas HFCVs reduced such costs the most and reduced ozone by up to 20 ppbv. Wind HFCVs reduced climate costs the most, making it the most beneficial environmental technology. Natural gas HFCVs increased $CH_4$ but reduced $CO_2$, making them second. Hybrids reduced climate costs but increased health costs relative to coal HFCVs, suggesting a rough tie for third. Both HFCVs and hybrids reduced health and climate costs relative to FFOVs. HFCVs had little impact on water vapor emission. Some uncertainties are the health and climate (to a greater extent) costs per unit of emission, how emission changes outside the United States over the next few decades might affect U.S. background pollution, and how climate change may affect biogenic emission.

**References and Notes**


1. R. F. Service, *Science* **305**, 958 (2004).
2. T. K. Tromp, R.-L. Shia, M. Allen, J. M. Eiler, Y. L. Yung, *Science* **300**, 1740 (2003).
3. M. G. Schultz, T. Diehl, G. P. Brasseur, W. Zittel, *Science* **302**, 624 (2003).
4. N. J. Warwick, S. Bekki, E. G. Nisbet, J. A. Pyle, *Geophys. Res. Lett.* **31**, L05107 (2004).
5. M. Z. Jacobson, *J. Geophys. Res.* **106**, 5403 (2001).
6. M. Z. Jacobson, *J. Geophys. Res.* **106**, 5385 (2001).
7. M. Z. Jacobson, J. H. Seinfeld, G. R. Carmichael, D. G. Streets, *Geophys. Res. Lett.* **31**, L02116 (2004).
8. U.S. Environmental Protection Agency (EPA), Clearinghouse for Inventories and Emission Factors (2003) (www.epa.gov/ttn/chief/).
9. Supporting materials are available on *Science* Online.
10. W. C. Colella, M. Z. Jacobson, D. M. Golden, *J. Power Sources*, in press.
11. National Academy of Sciences, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (National Academies Press, Washington, DC, 2004).
12. P. C. Novelli *et al.*, *J. Geophys. Res.* **104**, 30427 (1999).
13. T. Rahn *et al.*, *Nature* **424**, 918 (2003).
14. R. G. Derwent, W. J. Collins, C. E. Johnson, D. S. Stevenson, *Clim. Change* **49**, 463 (2001).
15. J. B. Heywood, *Internal Combustion Engine Fundamentals* (McGraw-Hill, New York, 1988).
16. D. R. McCubbin, M. A. Delucchi, *J. Transp. Econ. Policy* **33**, 253 (1999).
17. M. A. Delucchi, *J. Transp. Econ. Policy* **34**, 135 (2000).
18. ExternE—Externalities of Energy, Vol. 7: Methodology 1998 (1998) (www.externe.info/reports.html).
19. J. A. Turner, *Science* **305**, 972 (2004).
20. N. Demirdoven, J. Deutch, *Science* **305**, 974 (2004).
21. C. L. Archer, M. Z. Jacobson, *J. Geophys. Res.* **108**, 4289 (2003).
22. M. Z. Jacobson, G. M. Masters, *Science* **293**, 1438 (2001) and E-Letter response (www.sciencemag.org/cgi/eletters/294/5544/1000).
23. M. Bolinger, R. Wiser, "Summary of Power Authority Letters of Intent for Renewable Energy" (memorandum, Lawrence Berkeley National Laboratory, 30 October 2001).
24. National Renewable Energy Laboratory (NREL), *Technology Brief: Analysis of Current-Day Commercial Electrolyzers* (NREL report FS-560-36705, NREL, Golden, CO, September 2004).
25. D. B. Myers, G. D. Ariff, R. C. Kuhn, B. D. James, Hydrogen from renewable energy sources: Pathway to 10 quads for transportation uses in 2030 to 2050, FY 2003 Progress Report (2003) (www.eere.energy.gov/hydrogenandfuelcells/pdfs/iia11_myers.pdf).
26. K. Lee, *Economic Feasibility of Producing Hydrogen Using Excess Electricity from Wind Turbines on the Big Island of Hawaii* (World Renewable Energy Congress VIII, Denver, CO, 3 September 2004), www.sentech.org/Lee,%20K_Economic%20Feasibility%20Hawaii.pdf.
27. M. Z. Jacobson, *J. Geophys. Res.* **109**, D21201 (2004).
28. M. Z. Jacobson, *J. Geophys. Res.* **107** (D19), 4410 (2002).
29. U.S. Environmental Protection Agency, Clearinghouse for Inventories and Emission Factors (www.epa.gov/ttn/chief).


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