The effects on air pollution and health of converting all U.S. vehicles to hydrogen fuel cell or hybrid vehicles

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Hydrogen Scenarios Considered

• Baseline case (1999 fleet of onroad vehicles)
• Hybrid case
• Hydrogen fuel-cell vehicles (HFCV), where H₂ from
  – Steam-reforming of natural gas
  – Wind-electrolysis
  – Coal gasification
U.S. National Emission Inventory (1999)

- 370,000 stack and fugitive sources
- 250,000 area sources
- 1700 vehicle classifications
Assumptions Taken From Literature

- Current overall vehicle energy efficiency: 16%
- Energy efficiency of HFCV: 46%
- Efficiency of hybrid over current vehicles: 45%
- Natural gas leak rate: 1%
- H₂ leak rate (high value to ensure conservative result): 10%
- Reduction in refinery VOCs upon switching to HFCVs: 50%
- Emission of NOₓ, VOC, CO, CO₂, CH₄ during steam reforming
- Emission of NOₓ, CO, CO₂, SO₂ during coal gasification
- Exploration, mining, storage, processing, transport same all cases
Baseline hourly comparisons of predicted (solid) with paired-in-time-and-space observed (dashed) parameters for August 1999

Air pressure (hPa)

Wind speed (m/s)

Air temperature (°C)

Wind direction (deg.)

Solar radiation (W/m²)

UV radiation (W/m²)
GATOR-GCMOM

Comparisons of predicted (solid) with paired-in-time-and-space observed (dashed) parameters (hourly for month of August 1999)

Nitrogen dioxide (ppmv)  Isoprene (ppmv)

Nonmethane organic carbon (ppmv)  Carbon monoxide (ppmv)

Propane  PM$_{10}$ ($\mu$g/m$^2$)
GATOR-GCMOM

Comparisons of predicted (solid) with paired-in-time-and-space observed (dashed) ozone (hourly for month of August 1999)

Ozone (ppmv)
### Percent Reduction in Total U.S. Anthropogenic Emission Upon Switching Onroad Vehicles to Hydrogen from Steam-Reforming of Natural Gas

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Percent Reduction</th>
<th>Pollutant</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>-15</td>
<td>Ethene</td>
<td>-25</td>
</tr>
<tr>
<td>CH₄</td>
<td>+21</td>
<td>Formald.</td>
<td>-20</td>
</tr>
<tr>
<td>CO</td>
<td>-55</td>
<td>Higher ald.</td>
<td>-52</td>
</tr>
<tr>
<td>NOₓ</td>
<td>-33</td>
<td>Toluene</td>
<td>-17</td>
</tr>
<tr>
<td>SO₂</td>
<td>+2</td>
<td>Xylene</td>
<td>-28</td>
</tr>
<tr>
<td>NH₃</td>
<td>-5.3</td>
<td>BC₂.₅</td>
<td>-15</td>
</tr>
<tr>
<td>Paraffins</td>
<td>-27</td>
<td>OM₂.₅</td>
<td>-2</td>
</tr>
</tbody>
</table>
Near-Surface NO$_2$ Diff. (ppbv)

Natural gas-HFCV minus base

Wind-HFCV minus base

Coal-HFCV minus base

Hybrid minus base
Near-Surface Toluene Diff. (ppbv)

- Natural gas-HFCV minus base
- Wind-HFCV minus base
- Coal-HFCV minus base
- Hybrid minus base
Near-Surface PAN Diff. (ppbv)

Natural gas-HFCV minus base

Wind-HFCV minus base

Coal-HFCV minus base

Hybrid minus base
Near-Surface O$_3$ Difference (ppbv)

- Natural gas-HFCV minus base
- Wind-HFCV minus base
- Coal-HFCV minus base
- Hybrid minus base
Zonal O$_3$ Difference (ppbv)

Natural gas-HFCV minus base

Wind-HFCV minus base

Coal-HFCV minus base

Hybrid minus base
Near-Surf. Black Carbon Diff. (µg/m³)

Natural gas-HFCV minus base

Wind-HFCV minus base

Coal-HFCV minus base

Hybrid minus base
Near-Surface Nitrate Diff. ($\mu$g/m$^3$)

Natural gas-HFCV minus base  Wind-HFCV minus base

Coal-HFCV minus base  Hybrid minus base
Near-Surface CH₄ Difference (ppbv)

- **Natural gas-HFCV minus base**
- **Wind-HFCV minus base**
- **Coal-HFCV minus base**
- **Hybrid minus base**
Near-Surface CO$_2$ Difference (ppbv)

- Natural gas-HFCV minus base
- Wind-HFCV minus base
- Coal-HFCV minus base
- Hybrid minus base
Near-Surface \( \text{H}_2 \) Difference (ppbv)

- Natural gas-HFCV minus base
- Wind-HFCV minus base
- Coal-HFCV minus base
- Hybrid minus base
## Annual Reduction in Illness/Mortality

<table>
<thead>
<tr>
<th></th>
<th>Hybrid</th>
<th>Nat. gas</th>
<th>Wind</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asthma (millions)</td>
<td>0.3-0.9</td>
<td>1.2-3.4</td>
<td>1.2-3.4</td>
<td>1.1-3.3</td>
</tr>
<tr>
<td>Resp. Illness (millions)</td>
<td>5-8</td>
<td>18-30</td>
<td>18-30</td>
<td>17-29</td>
</tr>
<tr>
<td>Death</td>
<td>1400-2400</td>
<td>3700-6400</td>
<td>3700-6400</td>
<td>2700-4700</td>
</tr>
<tr>
<td></td>
<td>Hybrid</td>
<td>Nat. gas</td>
<td>Wind</td>
<td>Coal</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Billion $/yr</td>
<td>15-103</td>
<td>33-248</td>
<td>46-283</td>
<td>10-149</td>
</tr>
<tr>
<td>$/gallon Gas/diesel displaced</td>
<td>0.09-0.65</td>
<td>0.21-1.58</td>
<td>0.29-1.80</td>
<td>0.06-0.95</td>
</tr>
</tbody>
</table>
Annual 80-m Wind Speeds at Soundings

Wind classes at 80 m
1 (V<5.9 m/s)
2 (5.9≤V<6.9 m/s)
3 (6.9≤V<7.5 m/s)
4 (7.5≤V<8.1 m/s)
5 (8.1≤V<8.6 m/s)
6 (8.6≤V<9.4 m/s)
7 (V≥9.4 m/s)

Mean 80-m Wind Speed in North America

www.stanford.edu/group/efmh/winds/
Mean 80-m Wind Speed in Europe

www.stanford.edu/group/efmh/winds/
## Global 80-m Wind Speed Distribution

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>No of Stations</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5.9</td>
<td>6222</td>
<td>75.9</td>
</tr>
<tr>
<td>5.9-6.9</td>
<td>939</td>
<td>11.5</td>
</tr>
<tr>
<td>6.9-7.5</td>
<td>337</td>
<td>4.1</td>
</tr>
<tr>
<td>7.5-8.1</td>
<td>233</td>
<td>2.8</td>
</tr>
<tr>
<td>8.1-8.6</td>
<td>132</td>
<td>1.6</td>
</tr>
<tr>
<td>8.6-9.4</td>
<td>131</td>
<td>1.6</td>
</tr>
<tr>
<td>&gt;9.4</td>
<td>205</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8199</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td><strong>Total &gt;6.9</strong></td>
<td><strong>1038</strong></td>
<td><strong>12.7</strong></td>
</tr>
</tbody>
</table>
## Global 80-m Wind Speeds (m/s)

<table>
<thead>
<tr>
<th></th>
<th>All stations</th>
<th>At stations &gt; 6.9 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>8.6</td>
<td>9.3</td>
</tr>
<tr>
<td>Land</td>
<td>4.5-4.8</td>
<td>8-8.4</td>
</tr>
</tbody>
</table>

- Wind power at land stations > 6.9 m/s: 72 TW
- Global electric power demand: 1.6-1.8 TW
- Global overall power demand: 9.4-13.6 TW
Summary

- Switching vehicles in the U.S. may reduce NO_x, CO, CO_2, BC, NO_3^-, HCHO, Toluene, PAN, O_3, (although some increases locally), increase H_2, and SO_2 (slightly).

- All HFCV scenarios resulted in lower health/climate costs and mortality than current vehicles:
  - Wind-HFCV $0.29-$1.80/gal. 3700-6400 deaths/yr
  - Nat. gas-HFCV $0.21-$1.58 3700-6400
  - Coal HFCV $0.06-$0.95 2700-4700
  - Hybrids $0.09-$0.65 1400-2400

- Wind-HFCV better for climate than natural gas-HFCV
- Hybrids better for climate but worse for air quality than coal-HFCV
Summary

U.S. ($/gal)

- Gas cost May. ‘05: 2.16
- Gas+externality: 2.45-4.09

Near-term cost of hydrogen from wind-electrolysis

- Electricity ($0.03-$0.05/kWh+transmiss) $1.18-2.78/kg-H\textsubscript{2}
- Electrolyzer (50-95% occupied) $0.39-2.00/kg-H\textsubscript{2}
- Water $0.005-0.009/kg-H\textsubscript{2}
- Compressor $0.70-1.34/kg-H\textsubscript{2}
- Storage $0.30-0.31/kg-H\textsubscript{2}

Total $2.59-6.44/kg-H\textsubscript{2}

Total per gallon of gasoline displaced: $0.97-2.77/gallon

Near-term cost of H\textsubscript{2} from wind may be \leq real cost of gasoline

Sufficient winds available to produce hydrogen and electricity globally

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