Wind Versus Biofuels for Addressing Climate, Health, and Energy

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Causes of Global Warming

Temperature Change Since 1750 (°C)

- Greenhouse gases
- Fossil-fuel soot particles
- Urban heat island
- Cooling particles
- Net observed global warming

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Effects of Global Warming from 2000 to 2030 on Ozone

A1B: +36,000 to 106,000 deaths/yr
B1: +24,000 to +71,000 deaths/yr
## Global Power Demand and Clean Renewable Supply

<table>
<thead>
<tr>
<th>Resource</th>
<th>Potential Availability (TW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global overall power demand</td>
<td>9.4-13.6</td>
</tr>
<tr>
<td>Solar over land</td>
<td>1700</td>
</tr>
<tr>
<td>Land-wind at 80 m and &gt; 6.9 m/s</td>
<td>72\textsuperscript{a}, 80\textsuperscript{b}</td>
</tr>
<tr>
<td>Geothermal</td>
<td>9.5\textsuperscript{b}</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>6.5\textsuperscript{b}</td>
</tr>
<tr>
<td>Wave</td>
<td>5\textsuperscript{b}</td>
</tr>
<tr>
<td>Tidal</td>
<td>3.7\textsuperscript{b}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Archer and Jacobson, 2005; \textsuperscript{b} Stacey and Davis, 2006
## Installed Wind Capacity Worldwide

<table>
<thead>
<tr>
<th>Country</th>
<th>2005 (MW)</th>
<th>2006 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>18,428</td>
<td>20,261</td>
</tr>
<tr>
<td>Spain</td>
<td>10,027</td>
<td>11,615</td>
</tr>
<tr>
<td>U.S.</td>
<td>9,149</td>
<td>11,603</td>
</tr>
<tr>
<td>India</td>
<td>4,430</td>
<td>6,270</td>
</tr>
<tr>
<td>Denmark</td>
<td>3,122</td>
<td>3,136</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td>59,084</td>
<td>74,223</td>
</tr>
<tr>
<td></td>
<td>(900 offshore)</td>
<td></td>
</tr>
</tbody>
</table>

Individual turbine $\approx 0.4$ MW
\[\Rightarrow \approx 150,000\text{ turbines}\]
## 2006 New U.S. Installations

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>10,000</td>
</tr>
<tr>
<td>Wind</td>
<td>2454</td>
</tr>
<tr>
<td>Coal+oil</td>
<td>400</td>
</tr>
</tbody>
</table>
## Wind For Battery-Electric Vehicles

### 5 MW 126-m diameter turbine

<table>
<thead>
<tr>
<th>Description</th>
<th>Low Case</th>
<th>High Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual wind speed</td>
<td>8.5 m/s</td>
<td>7.5 m/s</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>0.425</td>
<td>0.338</td>
</tr>
<tr>
<td>Transmission/conversion/array losses</td>
<td>10%</td>
<td>15%</td>
</tr>
<tr>
<td>Turbine energy output with losses (kWh/yr)</td>
<td>$1.67 \times 10^7$</td>
<td>$1.26 \times 10^7$</td>
</tr>
<tr>
<td>2006 U.S. onroad miles traveled (mi/yr)</td>
<td>$3.16 \times 10^{12}$</td>
<td>$3.16 \times 10^{12}$</td>
</tr>
<tr>
<td>Energy to power vehicles (kWh/yr)</td>
<td>$1.03 \times 10^{12}$</td>
<td>$1.15 \times 10^{12}$</td>
</tr>
<tr>
<td>Battery efficiency</td>
<td>0.86</td>
<td>0.75</td>
</tr>
<tr>
<td>Energy to power battery vehicles (kWh/yr)</td>
<td>$1.19 \times 10^{12}$</td>
<td>$1.54 \times 10^{12}$</td>
</tr>
<tr>
<td>Number of turbines to power BEV</td>
<td>71,000</td>
<td>122,000</td>
</tr>
<tr>
<td>Fraction of U.S. land area required</td>
<td>0.0035</td>
<td>0.0059</td>
</tr>
<tr>
<td>Turbine area touching ground (km²)</td>
<td>1.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Wind For Electricity and Vehicles

5 MW 126-m diameter turbine with 8.5-7.5 m/s annual wind speed

<table>
<thead>
<tr>
<th>U.S. Energy Source 2005-6</th>
<th>Number of turbines to displace</th>
<th>MT-CO$_2$/yr Reduction</th>
<th>Death Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal (elec.)</td>
<td>120,000-160,000</td>
<td>1910</td>
<td>26,000</td>
</tr>
<tr>
<td>Gas (elec.)</td>
<td>45,000-60,000</td>
<td>455</td>
<td>3000</td>
</tr>
<tr>
<td>Oil (elec.)</td>
<td>7450-10,000</td>
<td>110</td>
<td>1000</td>
</tr>
<tr>
<td>Oil (onroad veh.)</td>
<td>(a) 71,000-122,000</td>
<td>1620</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>(b) 224,000-364,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>130,000-187,000</td>
<td>2175</td>
<td>10,000</td>
</tr>
<tr>
<td>U.S. total</td>
<td>375,000 - 540,000</td>
<td>6270</td>
<td>50,000</td>
</tr>
<tr>
<td>World total</td>
<td>1.7-2.5 million</td>
<td>28,970</td>
<td>800,000</td>
</tr>
</tbody>
</table>

Wind for (a) battery-electric (b) hydrogen fuel cell vehicles
Sources of U.S. CO₂

- Coal electricity (30.4%)
- Oil electricity (1.8%)
- Natural gas electricity (7.3%)
- Other (34.7%)
- Onroad vehicles (25.8%)

2005 total CO₂: 6270 MT-CO₂

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Thousands of 5 MW Wind Turbines Needed to Displace 100% U.S. CO$_2$

- Onroad vehicles (battery) (71-122)
- Other (131-188)
- Natural gas electricity (45-60)
- Oil electricity (7-10)
- Coal electricity (120-160)

Total (2005) 374-540

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Mean 80-m Wind Speed in Europe

Mean 80-m Wind Speed in North America

U.S. Offshore Wind

June 20, 2003 - CNC
“A study by Stanford University reported that…the greatest reservoir of previously uncharted wind power in the continental U.S. may be offshore and onshore along the southeastern and southern coasts. Ever since it was released, Texas’s General Land Office has been fielding calls from developers.”

October 24, 2005 - USA Today
“Texas has sold a lease for an 11,000-acre tract in the Gulf of Mexico that backers believe could become the first wind energy farm along the U.S. coast, state officials announced Monday.”

May 11, 2006 - USA Today
“The nation’s largest offshore wind farm will be built off the Padre Island seashore in South Texas…” (500 MW)
Water Depths and Transmission Near California’s Coast

Dvorak et al. (2006)

25 km from coast

10 km from coast

Dark blue: depth ≤ 20 m
Light blue: depth ≤ 40 m
Floating Wind Turbine Concepts

Floating Turbines 30-200 m Depth

MIT/NREL
Aggregate Wind Power (MW) From 81% of Spain’s Grid Versus Time of Day, Oct. 26, 2005
Birds and Wind

U.S. bird deaths from current wind turbines 10,000-40,000/yr (!)
U.S. bird deaths from communication towers: 50 million/yr (!)
Worldwide bird deaths from avian flu: 200 million/yr (%)

Est. bird deaths with 2,300,000 turbines worldwide: 2-10 million/yr

Premature U.S. deaths fossil-/biofuel pollution: 50,000/yr (*)

The effect of wind turbines on birds will be small relative to the benefit of reducing fossil-biofuels on human and animal illness.

(!) Bird Conservancy (April 2006);  (%) San Jose Mercury News (April 2006)
(*) McCubbin and Delucchi (1999)
Ethanol CO$_2$-Equivalent Emissions

Delucchi (2006)  
U.S. corn ethanol $\sim$2.4% less CO$_2$-eq. emis. than light-duty gasoline  
(China +17%; India +11%; Japan +1%, Chile -6%)

Switchgrass ethanol projected 52.5% less CO$_2$-eq. emis. than LDG -  
DOE: large-scale cellulosic technology 15 years from fruition

Soy biodiesel $\sim$50% more CO$_2$-eq. emis. than heavy-duty diesel  
Mostly due to fuel, feedstock, fertilizer production/cultivation

Corn ethanol $\sim$6% more CO$_2$-eq. emis. than heavy-duty diesel

Patzek (2006) Corn ethanol $\sim$20% more CO$_2$-eq. emis. than gasoline

Farrell et al. (2006) Corn ethanol $\sim$10-15% less CO$_2$-eq. emis. than gas
Is Ethanol Good For Your Health?

American Lung Association:
“E85 is cleaner. E85 reduces ozone-forming pollution by 20%. Ethanol is less toxic. Gasoline contains compounds like benzene, toluene, and xylene. Use of E85 reduces the release of these chemicals…”

Clean Fuels Network
“E85 burns cleaner compared to conventional gasoline by reducing ozone-forming volatile compounds…”

Wikipedia
“Ethanol…can be blended with gasoline…to reduce air pollution”

Statements based on back-of-the-envelope estimates.
Let’s look at 3-D physical/chemical/radiative/dynamical computation with spatial emissions, population, health-effects data
# Emission Differences E85: Gas From Field/Laboratory Data

<table>
<thead>
<tr>
<th>Component</th>
<th>Percent change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxides of nitrogen</td>
<td>-30 (-59 to +33)</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>+5 (-33 to +320)</td>
</tr>
<tr>
<td>Total organic gas</td>
<td>+22 (+38 to +95)</td>
</tr>
<tr>
<td>Methane</td>
<td>+43 (+43 to +340)</td>
</tr>
<tr>
<td>Nonmethane organic gas</td>
<td>+43 (0 to +63)</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>+60 (+7 to +240)</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>+2000 (+1250 to +4340)</td>
</tr>
<tr>
<td>1,3-butadiene</td>
<td>-10 (0 to -13)</td>
</tr>
<tr>
<td>Benzene</td>
<td>-79 (-62 to -85)</td>
</tr>
<tr>
<td>PM number</td>
<td>0 (+100)</td>
</tr>
<tr>
<td>PM mass</td>
<td>0 (+31)</td>
</tr>
</tbody>
</table>
Los Angeles / U.S. Population Distributions
Effect in 2020 of E85 vs. Gasoline on Ethanol and Acetaldehyde
Effect in 2020 of E85 vs. Gasoline on Formaldehyde and Methane
Effect in 2020 of E85 vs. Gasoline on Nitrogen Dioxide and Toluene
Effect in 2020 of E85 vs. Gasoline on 1,3-Butadiene and Benzene
Effect in 2020 of E85 vs. Gasoline on PAN
Ozone isopleth

\[ 0.08 = O_3 \text{ (g), ppmv} \]

\[ \text{NO}_x \text{ (g), ppmv} \]

\[ \text{ROG (ppmC)} \]
Effect in 2020 of E85 vs. Gasoline on Ozone and Health

Δ Pop-weighted ozone ≥ 35 ppbv E85 minus gas: +1.33 ppbv
Δ Ozone deaths/yr: +120 (+9%)
Δ Ozone hospitalizations/yr respiratory illness: +650
Δ Ozone-emergency-room visits/yr for asthma: +770
Δ Cancer/yr USEPA CUREs - for carcinogens: +0.3
Δ Cancer/yr OEHHA CUREs - for carcinogens: -3.5
U.S. Onroad Vehicles Can Run With

220-390 million acres corn (9.6-17.2% of U.S. land or 2.2-3.9 Californias) for E85.
Eliminates 30 MT-CO$_2$/yr (0.6% US total) and adds 200 deaths/yr
or
104-360 million acres of switchgrass (4.6-16% of U.S. land or 1-3.6 Californias) producing same amount of ethanol as corn.
Eliminates 620 MT-CO$_2$/yr (13.6% US total) and adds 200 deaths/yr.
Benefits eliminated in 15 years with 13.6% population increase
or
71,000-122,000 5 MW wind turbines in 8.5-7.5 m/s winds producing electricity for BEVs or 224,000-364,000 turbines for H$_2$ for HFCVs.
Requires 0.35%-0.59% of land (or 0% if all water) for BEVs or 1.1%-1.8% of U.S. land for HFCVs (1 turbine per 0.44 km$^2$).
Eliminates 1620 MT-CO$_2$/yr (26% US total) and 10,000 deaths/yr
Future U.S. Deaths Per Year From Onroad Vehicle Emissions

- Gas/diesel: 10,000
- Corn ethanol: 10,200
- Cellulosic ethanol: 10,200

U.S. Deaths per Year

- Wind for batteries: 0
- Wind for hydrogen fuel cells: 0
- Solar for batteries: 0

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Area to Power 100% of U.S. Onroad Vehicles

Map: www.fotw.net
Precent Decrease in Total U.S. Carbon Dioxide Upon Replacing 100% of Onroad Vehicles

- Ignoring land constraints
- With land constraints

-0.62 Corn ethanol
-0.19
-13.6 Cellulosic ethanol
-25.5 Wind for batteries
-25.5 Wind for hydrogen fuel cells
-23.4 Solar for batteries

Replacing 30% of vehicles
Pathway to Future U.S. Energy Mix
With 80% Reduction in CO$_2$

- Onshore & offshore wind (50%)
- Solar PV & thermal (15%)
- Efficiency (10%)
- Existing fossil, biofuels (20%)
- Hydroelectric, geothermal, wave, tidal, existing nuclear (5%)

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Land Area For 50% of US Energy From Wind

Map: www.fotw.net
Alternatively, Water Area For 50% of US Energy From Wind
Summary

• Sufficient wind and solar are available worldwide to supply all electric and nonelectric energy and to solve air pollution/climate problems simultaneously.

• One-third of wind can be smoothed by interconnecting wind farms. Additional wind can be smoothed with or added to solar, hydro, geothermal, or others. Remaining intermittent wind can be used for HFCVs and electric vehicles.

• Ethanol enhances ozone over current vehicles. Long lifetime of unburned ethanol may result in a global source of acetaldehyde.
Summary

• Other studies suggest corn ethanol has near-zero climate benefit. Cellulosic ethanol does not exist at the commercial scale and could reduce U.S. CO$_2$ at most 4% due to land constraints, a benefit lost in 5 years by a population increase. Soy biodiesel produces more equivalent CO$_2$ than regular diesel for heavy-duty vehicles.

• CO$_2$ emissions must decrease by 80% to stabilize ambient CO$_2$, accounting for growth. Immediate conversion to near-zero emission renewables needed.

• Diversion of resources to biofuels, which have no discernable air quality or climate benefit today based on current scientific understanding, at the expense of true renewables, which have immediate benefit, will cause certain climate and health damage as CO$_2$, population, and energy use rise further.

• More info: www.stanford.edu/group/efmh/jacobson/E85vWindSol