Comparing Wind With Other Energy Sources for Addressing Climate and Air Pollution

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From Local to Global: The Rhode Island Model for Harnessing Wind Power Worldwide

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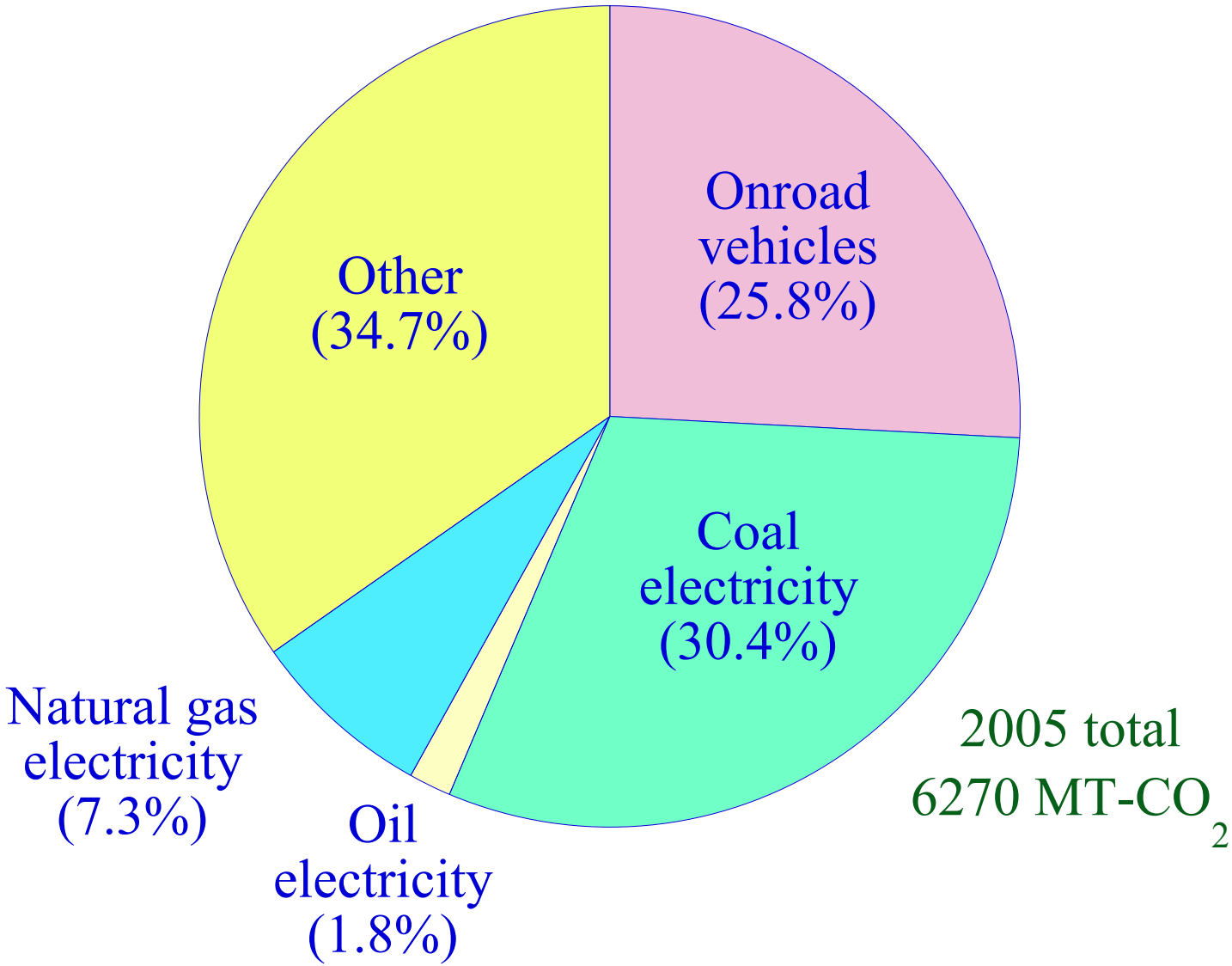
Sources of U.S. CO_2



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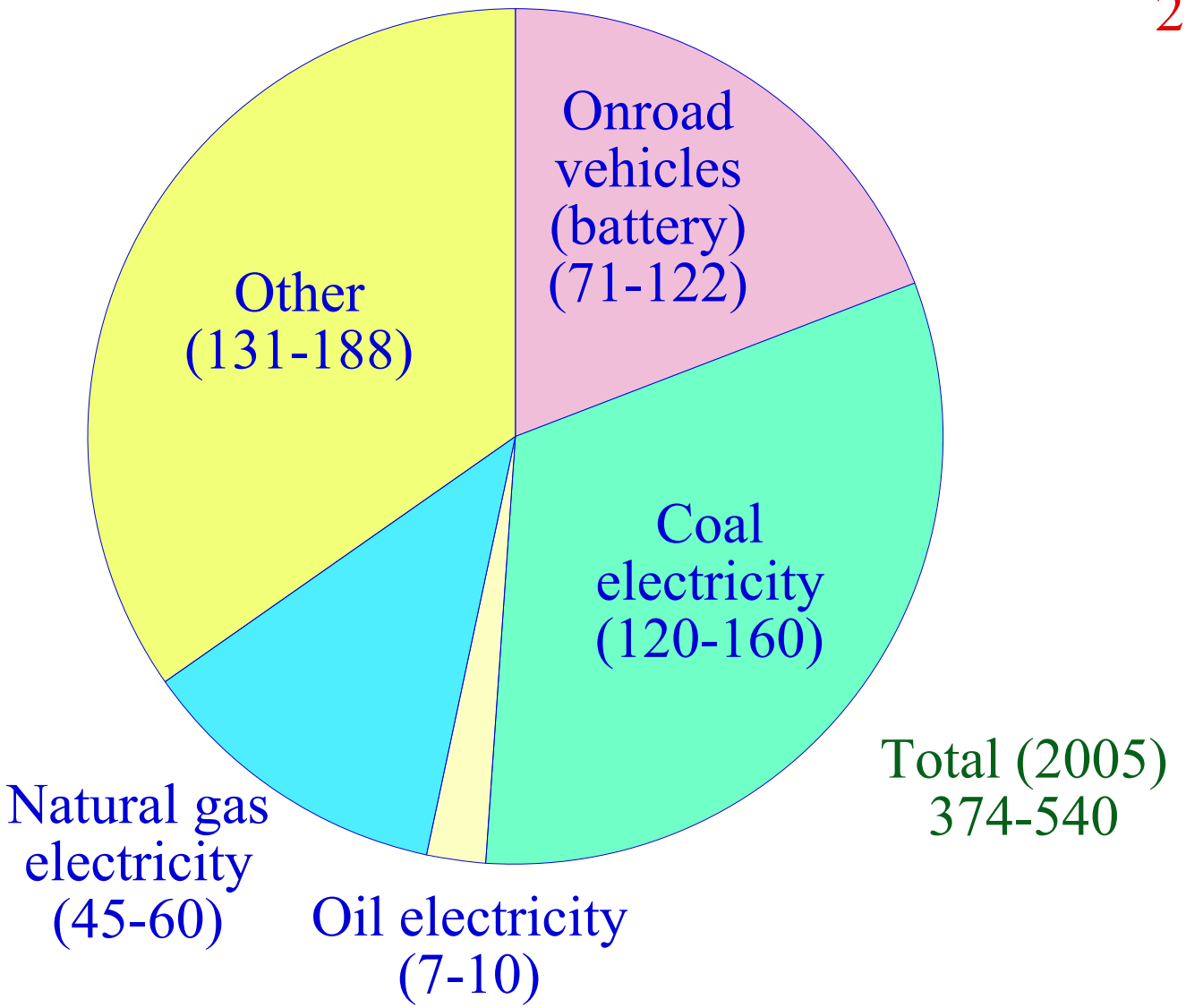
Wind For Battery-Electric Vehicles

5 MW 126-m diameter turbine

	Low Case	High Case
Mean annual wind speed	8.5 m/s	7.5 m/s
Capacity factor	0.425	0.338
Transmission/conversion/array losses	10%	15%
Turbine energy output with losses (kWh/yr)	1.67×10^7	1.26×10^7
2006 U.S. onroad miles traveled (mi/yr)	3.16×10^{12}	3.16×10^{12}
Energy to power vehicles (kWh/yr)	1.03×10^{12}	1.15×10^{12}
Battery efficiency	0.86	0.75
Energy to power battery vehicles (kWh/yr)	1.19×10^{12}	1.54×10^{12}
Number of turbines to power BEV	71,000	122,000
Fraction of U.S. land area required	0.0035	0.0059
Turbine area touching ground (km^2)	1.1	1.9

Thousands of 5 MW Wind Turbines Needed to Displace 100% U.S. CO_2



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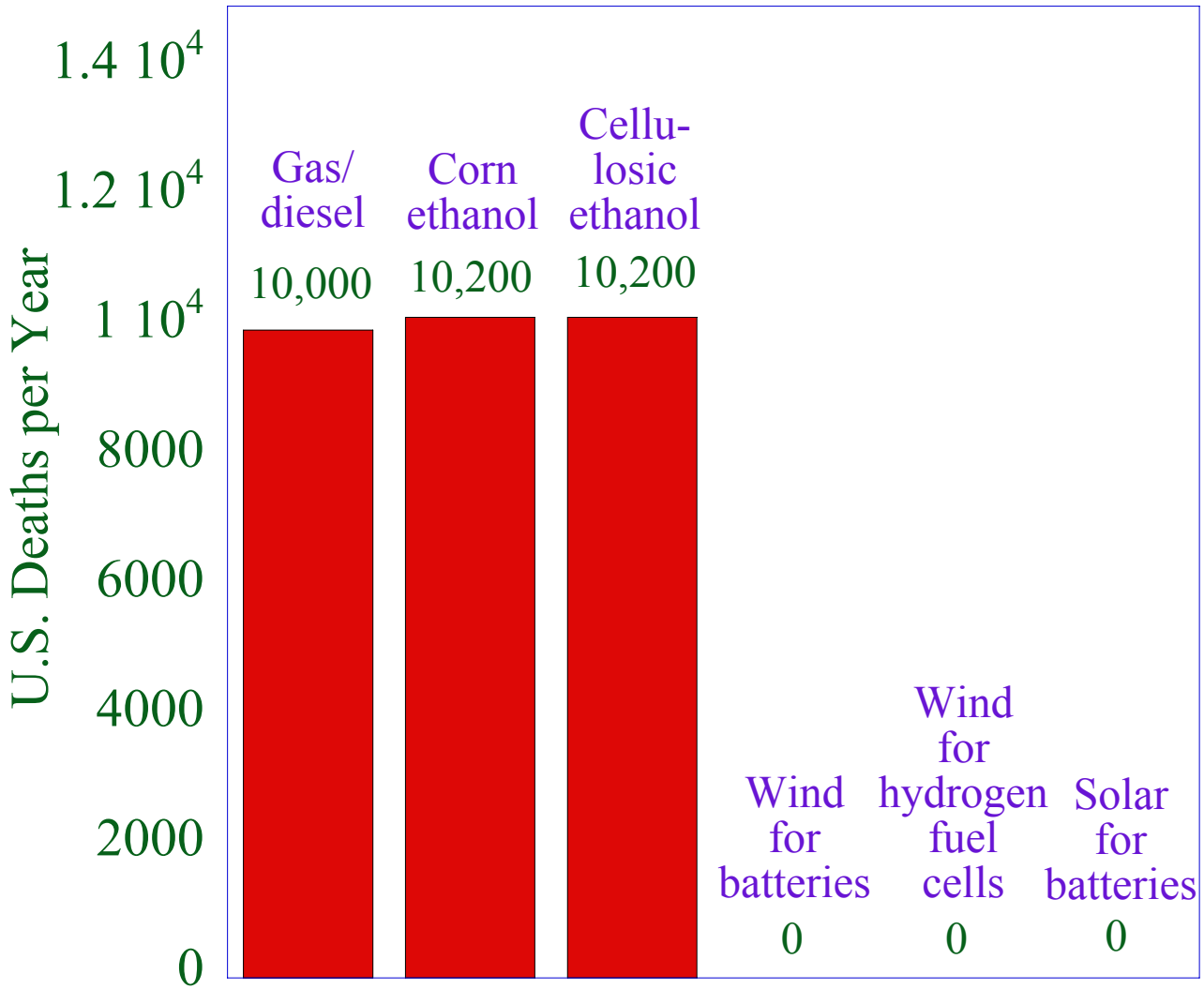
Wind For Electricity and Vehicles

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

U.S. Energy Source 2005-6	Number of turbines to displace	MT-CO_2/yr Reduction	Death Reduction
Coal (elec.)	120,000-160,000	1910	26,000
Gas (elec.)	45,000-60,000	455	3000
Oil (elec.)	7450-10,000	110	1000
Oil (onroad veh.)	(a) 71,000-122,000 (b) 224,000-364,000	1620	10,000
Other	130,000-187,000	2175	10,000
U.S. total	374,000 - 540,000	6270	50,000
World total	1.7-2.5 million	28,970	800,000

Wind for (a) battery-electric (b) hydrogen fuel cell vehicles

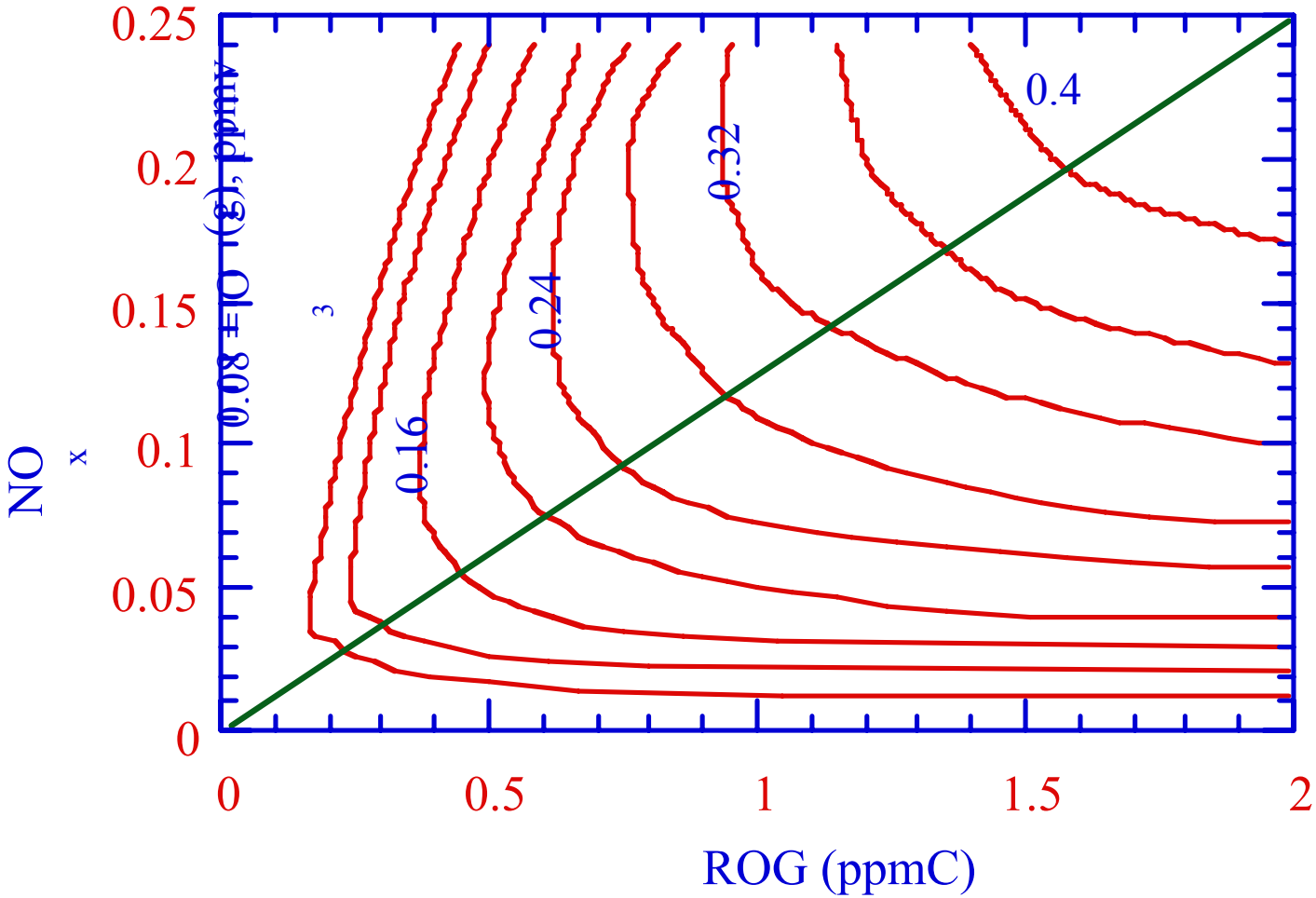
Future U.S. Deaths Per Year From Onroad Vehicle Emissions



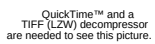
Emission Differences E85:Gas From Field/Laboratory Data

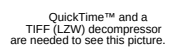
	Percent change
Oxides of nitrogen	-30 (-59 to +33)
Carbon monoxide	+5 (-33 to +320)
Total organic gas	+22 (+38 to +95)
Methane	+43 (+43 to +340)
Nonmethane organic gas	+43 (0 to +63)
Formaldehyde	+60 (+7 to +240)
Acetaldehyde	+2000 (+1250 to +4340)
1,3-butadiene	-10 (0 to -13)
Benzene	-79 (-62 to -85)
PM number	0 (+100)
PM mass	0 (+31)

Ozone isopleth



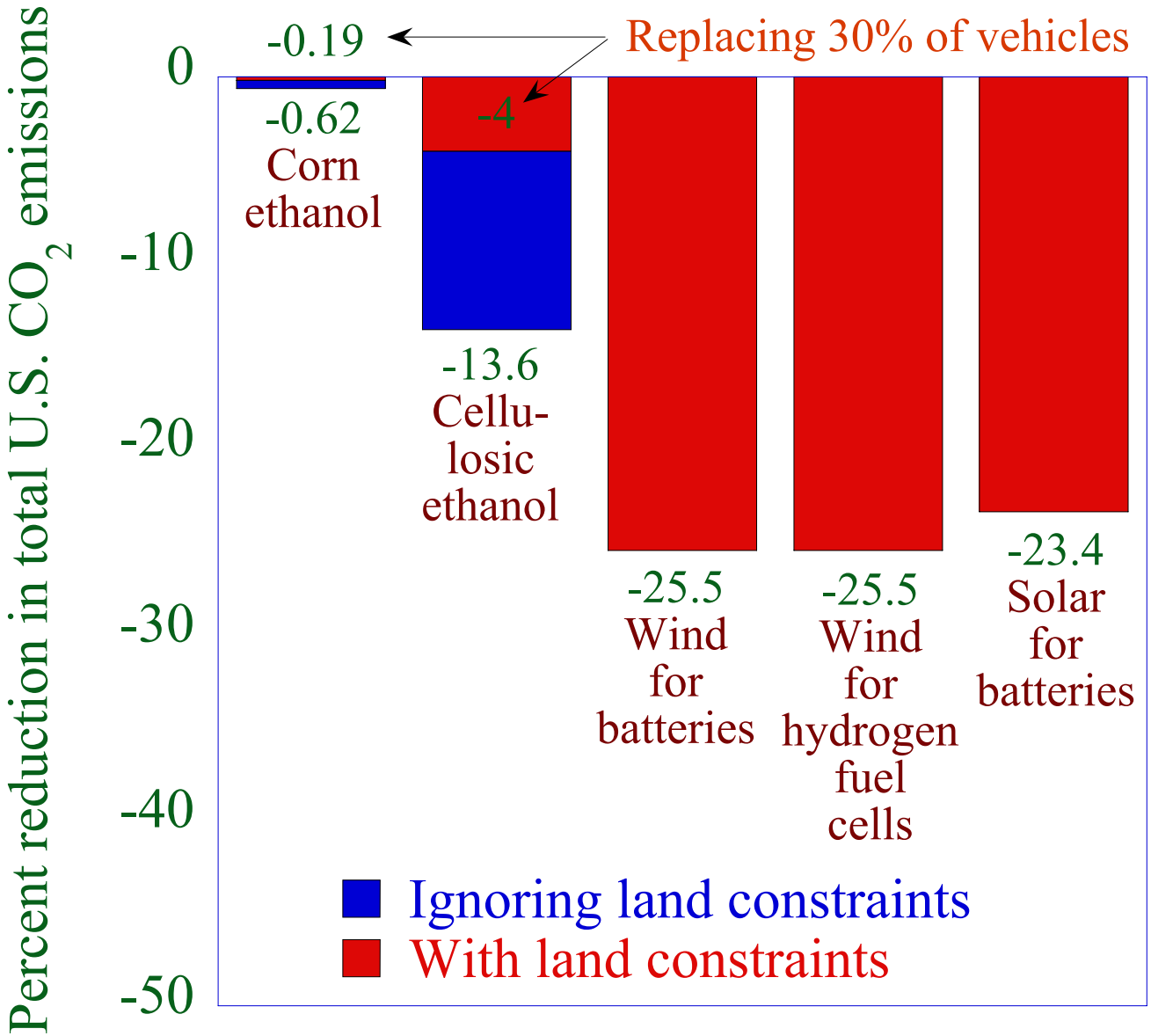
Effect in 2020 of E85 vs. Gasoline on Ozone and Health





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 Cancer/yr :	-3.5 to +0.3

Percent Decrease in Total U.S. Carbon Dioxide Upon Replacing 100% of Onroad Vehicles



Ethanol CO_2-Equivalent Emissions

Delucchi (2006)

U.S. corn ethanol ~2.4% less CO_2-eq. emis. than light-duty gasoline
(China +17%; India +11%; Japan +1%, Chile -6%)

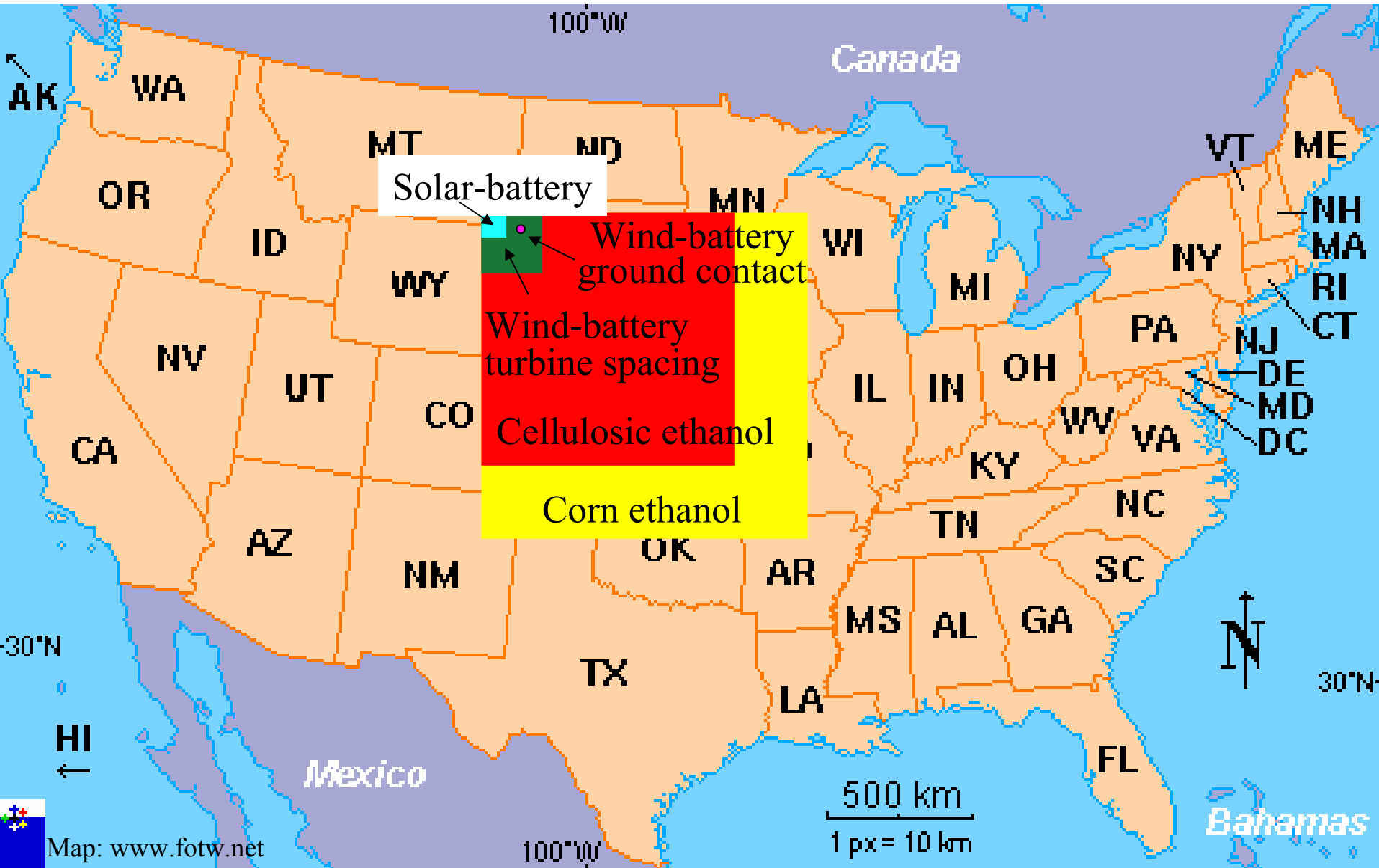
Switchgrass ethanol projected 52.5% less CO_2-eq. emis. than LDG -
DOE: large-scale cellulosic technology 15 years from fruition

Soy biodiesel ~50% more CO_2-eq. emis. than heavy-duty diesel
Mostly due to fuel, feedstock, fertilizer production/cultivation

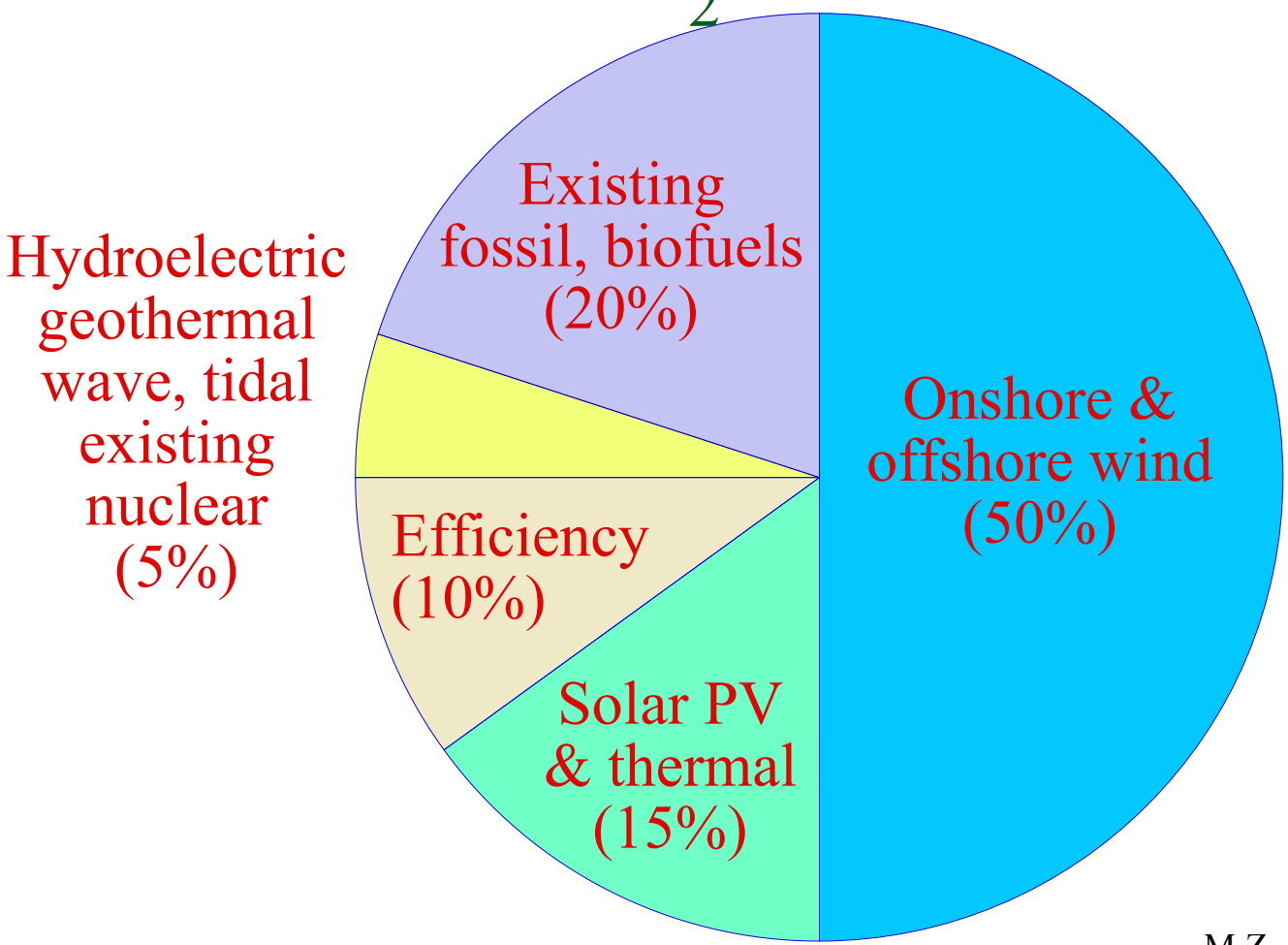
Patzek (2006) Corn ethanol ~20% more CO_2-eq. emis. than gasoline

Farrell et al. (2006) Corn ethanol ~10-15% less CO_2-eq. emis. than gas

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



Path to Satisfy All U.S. Energy Needs and Reduce CO_2 and BC by 80%



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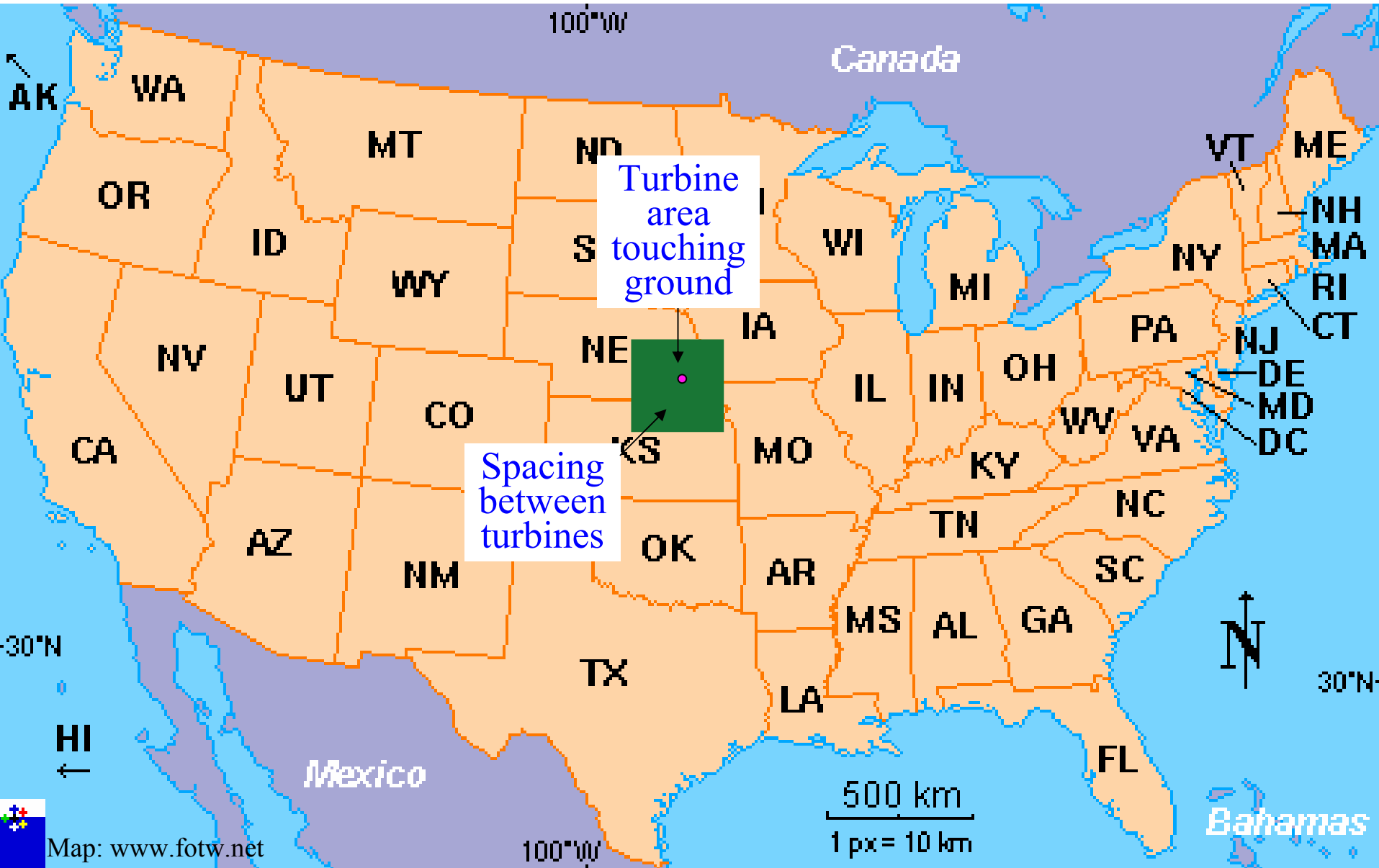
Land Area For 50% of US Energy From Wind



Alternatively, Water Area For 50% of US Energy From Wind

Health/climate cost reduction due to replacing gasoline/diesel with hybrids or hydrogen from three sources

	Hybrid	Nat. gas	Wind	Coal
$/gallon Gas/diesel displaced	0.09-0.65	0.21-1.58	0.29-1.80	0.06-0.95

This is the health cost of gasoline (Jacobson et al., Science, 2005)

Estimated Cost of Hydrogen from Wind

	U.S. ($/gal)
Gas cost April 9, '07:	2.80
Gas+externality:	3.09-4.60

Near-term cost of hydrogen from wind-electrolysis

Electricity ($0.03-$0.05/kWh+transmiss)	$1.60-3.77/kg-$H_2$
Electrolyzer (50-95% occupied)	$0.39-2.00/kg-$H_2$
Water	$0.005-0.009/kg-$H_2$
Compressor	$0.70-1.34/kg-$H_2$
Storage	$0.31-0.31/kg-$H_2$
Total	$3.01-7.43/kg-$H_2$
Total per gallon of gasoline displaced:	$1.12-3.20/gallon

Near-term cost of H_2 from wind may be $\leq$ real cost of gasoline

Direct and Externality Costs of Three Energy Sources

	Direct cost (¢/kWh)	Global warming cost (¢/kWh)	Particle health cost (¢/kWh)	Other environ. cost (¢/kWh)	Total cost (¢/kWh)
New coal	3.5-4	0.4-1	3-8	1.6-3.3	8.5-16
New nat gas	3.3-3.6	0.7-1.1	0.4-2	0.5-1.1	4.9-7.8
New wind	2.9-4.7	<0.1	<0.1	<0.1	2.9-5.0

Sources:

DOE Office of Fossil Energy (2001)

Derived From UNEP (2001)

Atmos. Environ. 35, 4763 (2001)

Science 293, 1438 (2001)

European Commission (1995)

Summary

- Wind energy addresses climate, air-pollution health, and energy supply with minimal land use requirements compared with corn or cellulosic ethanol.

- Wind for battery-electric vehicles is about 2.5-3 times more efficient than that for hydrogen fuel cell vehicles although the climate and air pollution benefits are similar.

- Ethanol enhances ozone and mortality over current vehicles. Long lifetime of unburned ethanol may result in a global source of acetaldehyde.

Summary

- The most complete lifecycle study to date suggests corn ethanol has near-zero climate benefit. Cellulosic ethanol could reduce total U.S. CO_2 at most 4% due to land constraints, a benefit lost in 5 years by a population increase.

- Emissions must decrease by 80% to stabilize ambient CO_2, accounting for growth. Immediate conversion to near-zero emission renewables is needed.

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

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