Review of Solutions to Global Warming, Air Pollution, and Energy Security

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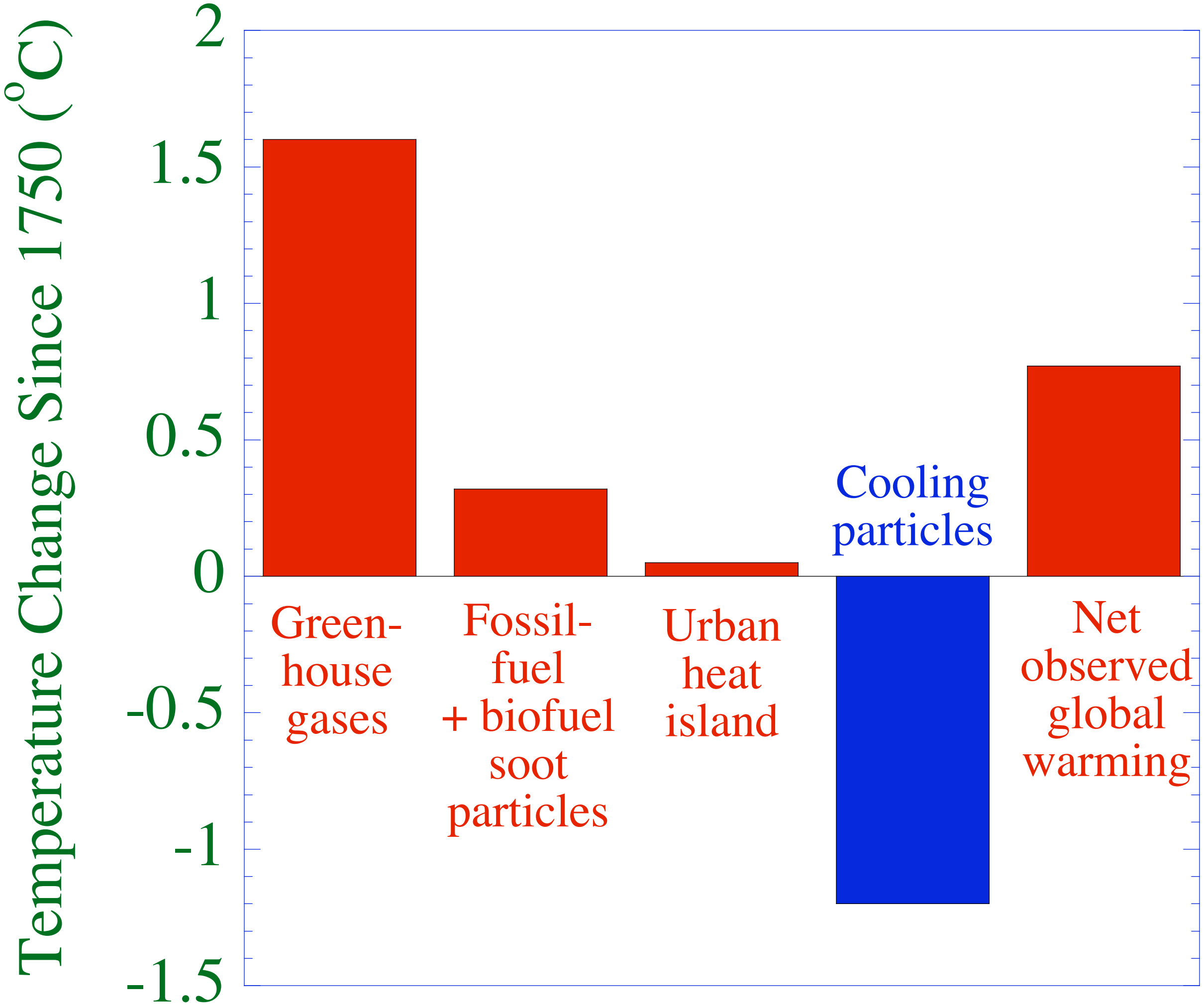
Causes of Global Warming



M.Z. Jacobson

Comparison of Energy Solutions to Global Warming

Electricity Sources
- Wind turbines
- Solar photovoltaics (PV)
- Geothermal power plants
- Tidal turbines
- Wave devices
- Concentrated solar power (CSP)
- Hydroelectric power plants
- Nuclear power plants
- Coal with carbon capture and sequestration (CCS)

Vehicle Technologies
- Battery-electric vehicles (BEVs)
- Hydrogen fuel cell vehicles (HFCVs)

Liquid Fuel Sources
- Corn ethanol (E85)
- Cellulosic ethanol (E85)

Flex-fuel vehicles (FFVs)

Effects Examined

Resource abundance
Carbon-dioxide equivalent emissions
- Lifecycle
- Opportunity cost emissions from planning-to-operation delays
- Leakage from carbon sequestration
- Nuclear war / terrorism emission risk from nuclear-energy

Air pollution mortality
Water consumption
Footprint on the ground
Spacing required
Effects on wildlife
Thermal pollution
Water chemical pollution / radioactive waste
Energy supply disruption
Normal operating reliability

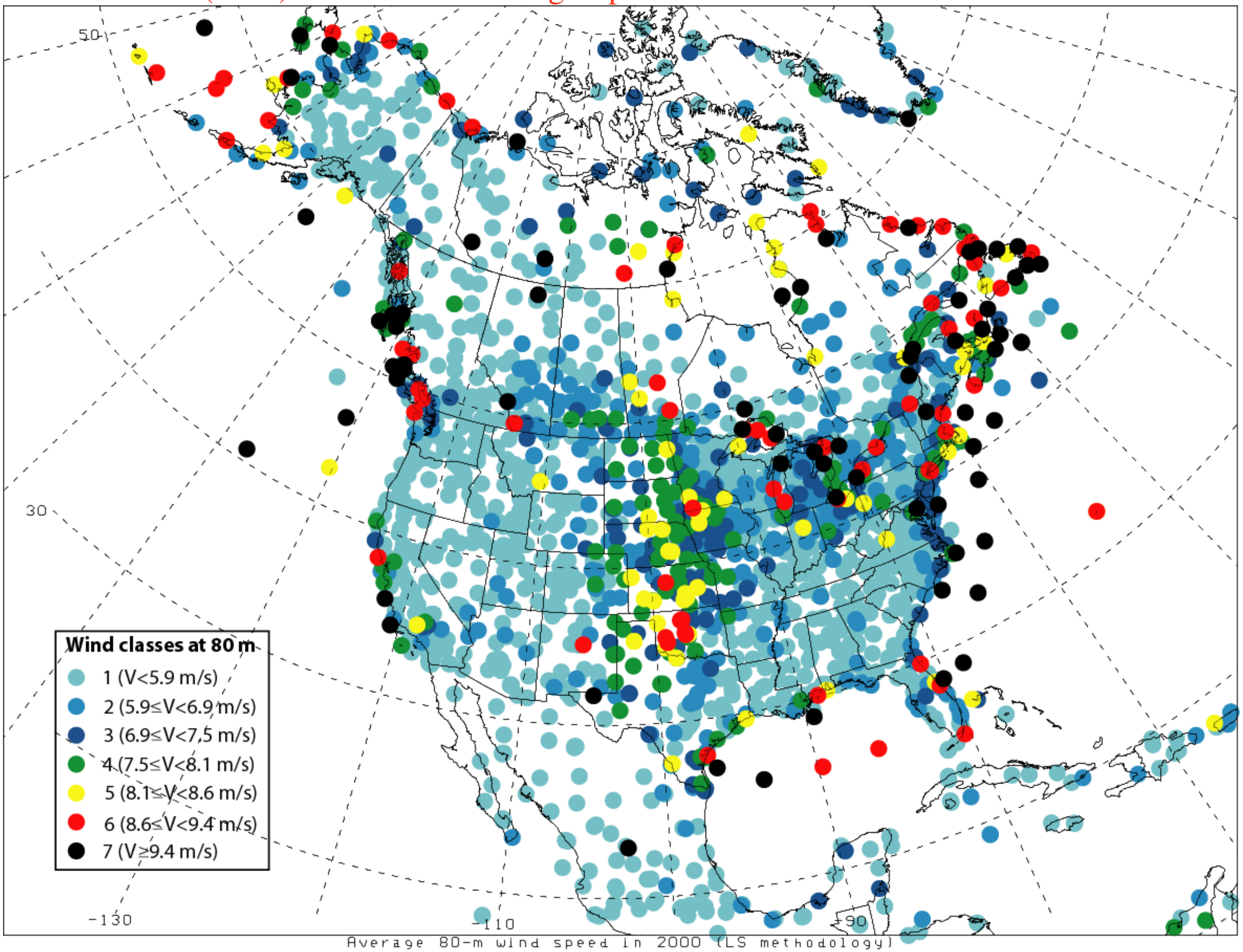
Global Renewable Energy Resources

	Max	Potential	Current
Wind over land > 6.9 m/s (TW)	72	47	0.02
Solar over land (TW)	1700	340	0.001
Geothermal (TW)	160	0.15	0.007
Hydroelectric (TW)	1.9	<1.9	0.32
Wave+tidal (TW)	3.5	0.5	0.00006

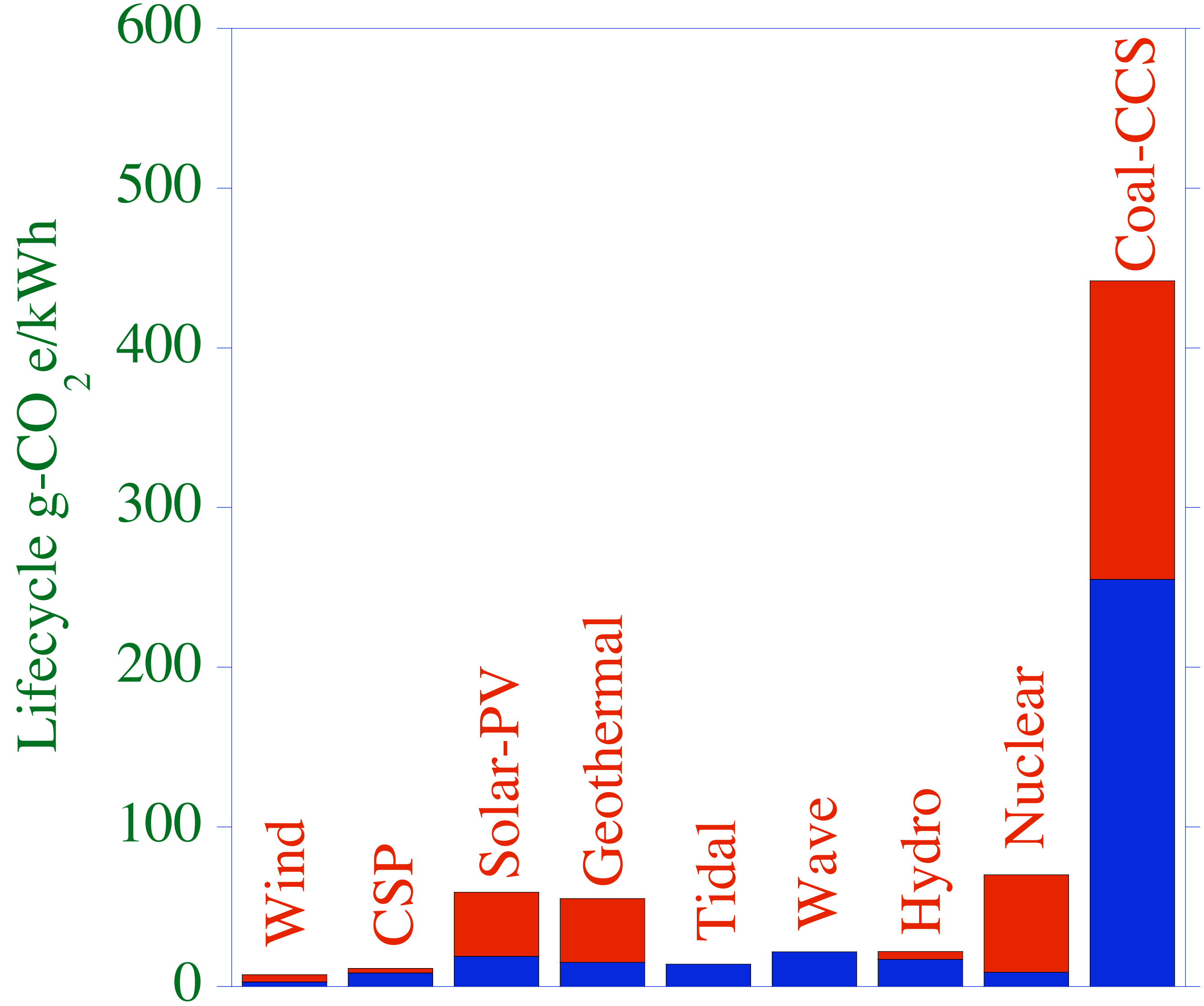
Global electric power demand (TW)	1.6-1.8
Global overall power demand (TW)	9.4-13.6

Mean 80-m Wind Speed in North America

Archer and Jacobson (2005) www.stanford.edu/group/efmh/winds/



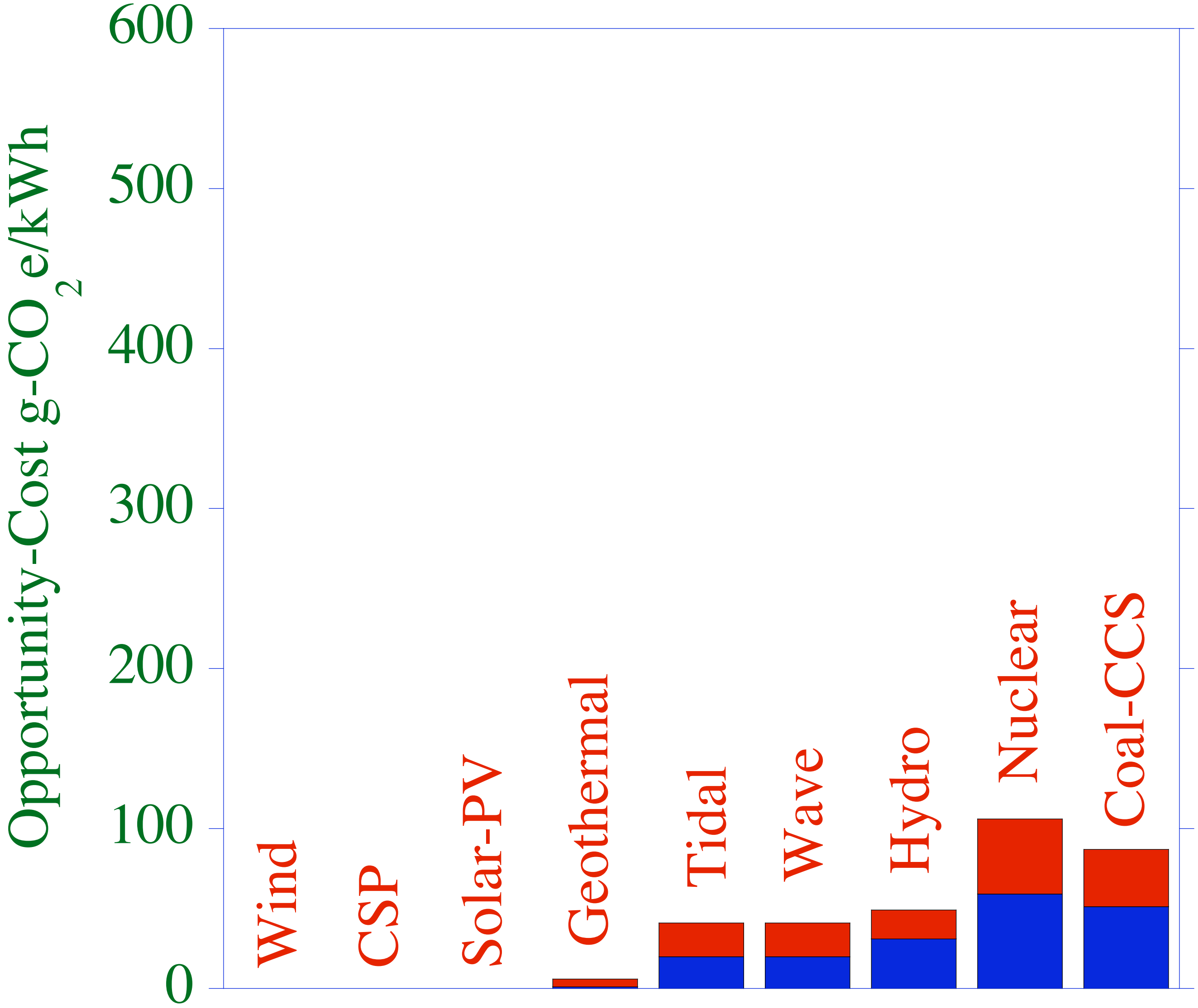
Lifecycle CO_2e of Electricity Sources



Time Between Planning & Operation

Nuclear:	10-19 y (lifetime 40 y)
Site permit (NRC): 3.5 y minimum with new regs. – 6 y	
Construction permit approval and issue 2.5-4 y	
Construction time 4-9 years (Low value Europe/Japan)	
Hydroelectric:	8-16 y (lifetime 80 y)
Coal-CCS:	6-11 y (lifetime 35 y)
Geothermal:	3-6 y (lifetime 35 y)
Ethanol:	2-5 y (lifetime 40 y)
CSP:	2-5 y (lifetime 30 y)
Solar-PV:	2-5 y (lifetime 30 y)
Wave:	2-5 y (lifetime 15 y)
Tidal:	2-5 y (lifetime 15 y)
Wind:	2-5 y (lifetime 30 y)

Opportunity-Cost CO_2e of Electricity Sources



Nuclear Energy/Weapons Risks

"There is no technical demarcation between the military and civilian reactor and there never was one" (Los Alam. Rept. LA8969MS,UC-16)

42 countries have fissionable material to produce weapons.

9 have nuclear weapons stockpiles
(US, Russia, UK, France, China, India, Pakistan, Israel, N. Korea)

22 of 42 countries with fissionable material have facilities in nuclear energy plants to produce enriched uranium or to separate plutonium

13 of the 42 countries are active in producing enriched uranium or separating plutonium.

→Spread of nuclear weapons material is caused by the spread of nuclear energy.

Nuclear weapons treaties safeguard only 1% of the world's highly -enriched uranium and 35% of the plutonium.

Toon et al. (2007)

Leakage From Carbon Sequestration

Leakage rate (Tg/yr)

L = I - S(t) / t where

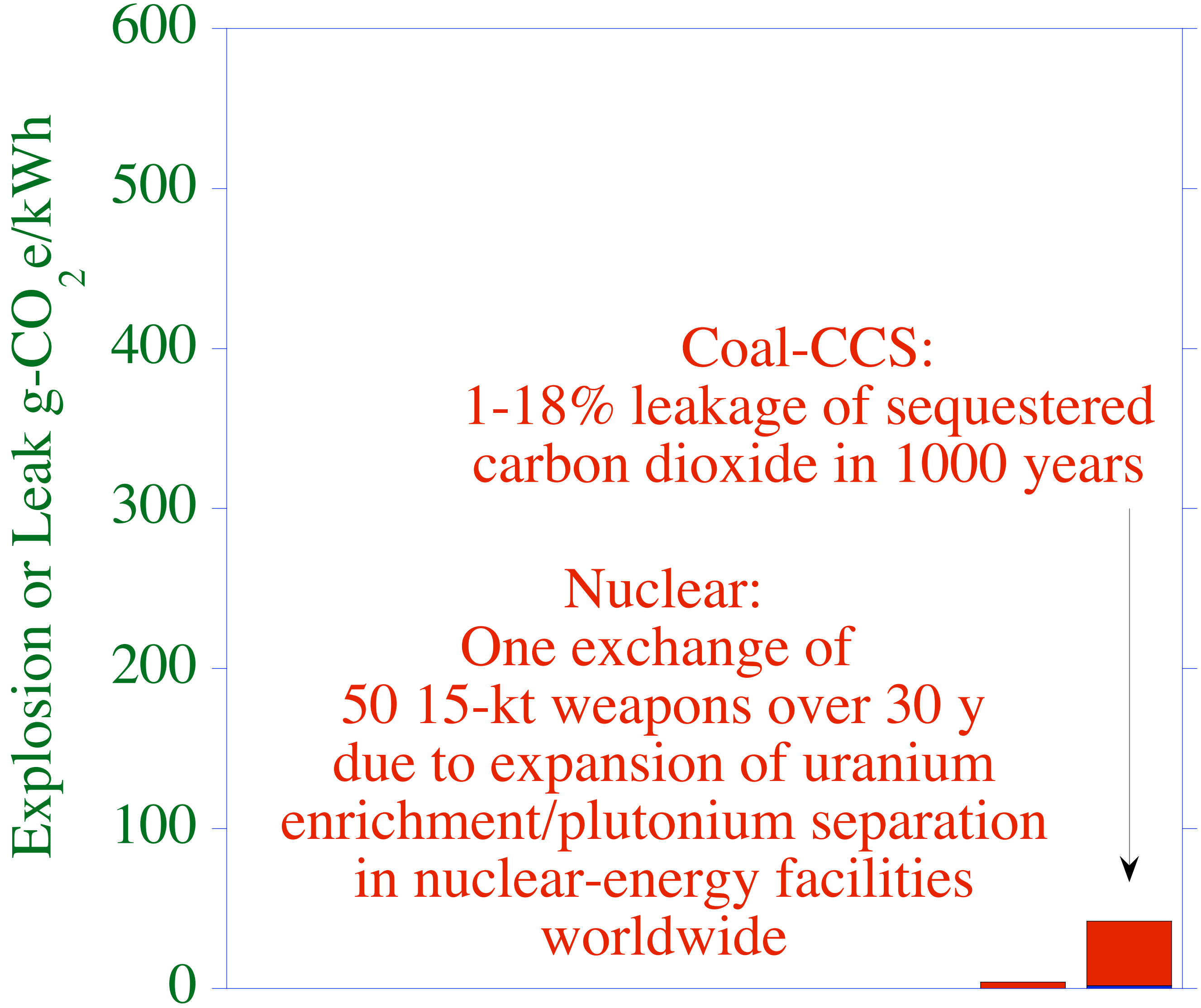
I = injection rate
t = time (years)
S = stored mass (Tg)

$$S(t) = S(0)e^{-t/t} + tI(1-e^{-t/t})$$

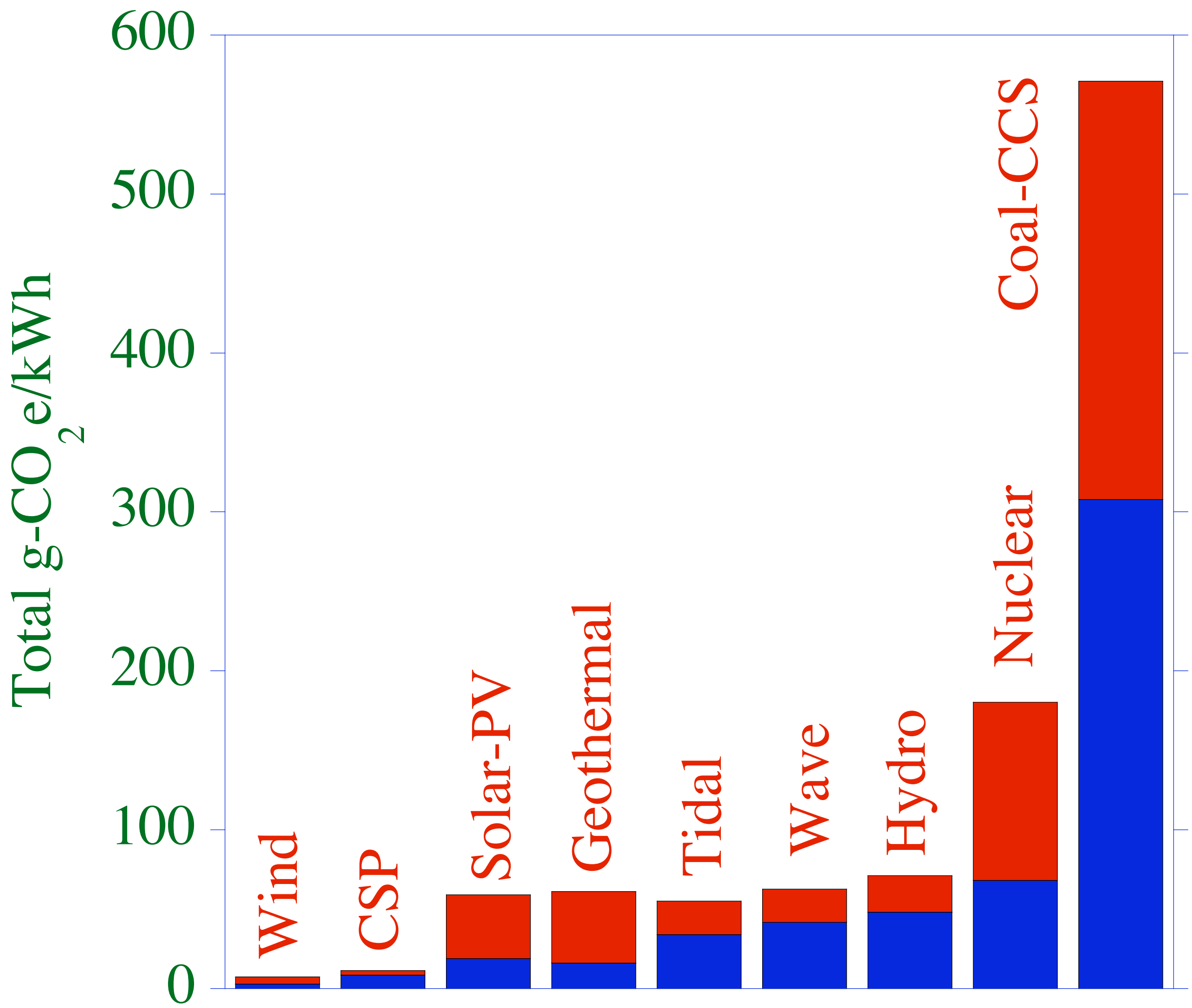
t = e-folding lifetime of stored material against leakage (years)

High est. t=100,000 (1% leakage over 1000 years, IPCC, 2005
Low est. t=5000 years (18% over 1000 years – Natural gas storage has leaked up to 10% over 1000 years, IPCC, 2005)

War/Leakage CO_2e of Nuclear, Coal



Total CO_2e of Electricity Sources



Lifecycle CO_2-Equivalent Emissions Corn and Cellulosic Ethanol

Delucchi (2006)* Accounts for

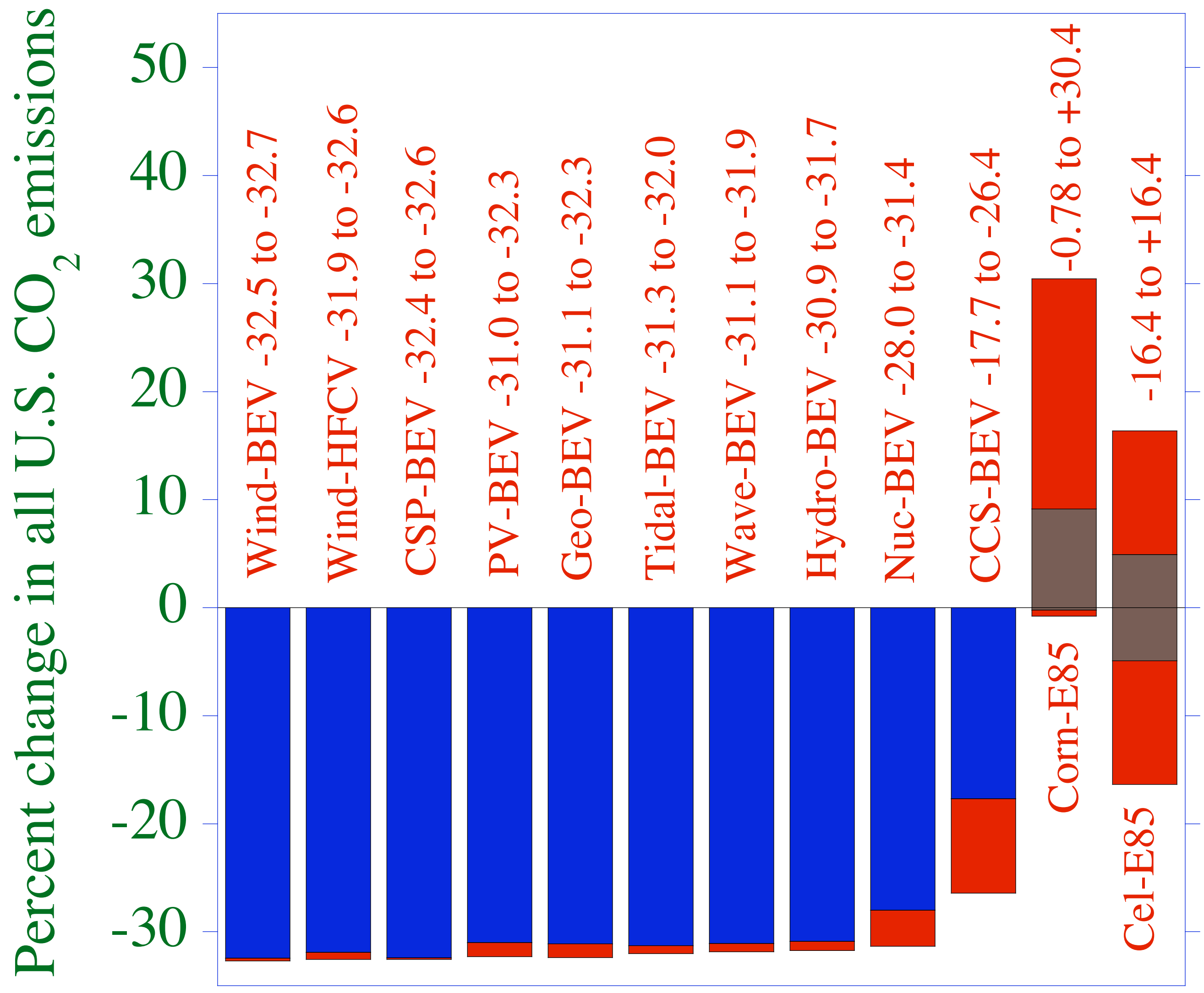
- seeding, fertilization, irrigation, cultivation, crop transport, refining, distribution, combustion.
- climate impacts of BC, other PM, NO, CO
- detailed nitrogen cycle, basic landuse/price impacts

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 ~52.5% less CO_2-eq. emis. than LDG -

Searchinger et al. (2008)# Adds gridded global landuse/price impacts
U.S. corn ethanol ~90% more CO_2-eq. than gasoline
Switchgrass ethanol ~50% more CO_2-eq. than LDG

*www.its.ucdavis.edu/publications/2006/UCD-ITS-RR-06-08.pdf
#Science 319, 1238 (2008)

Percent Change in U.S. CO_2 From Converting to BEVs, HFCVs, or E85



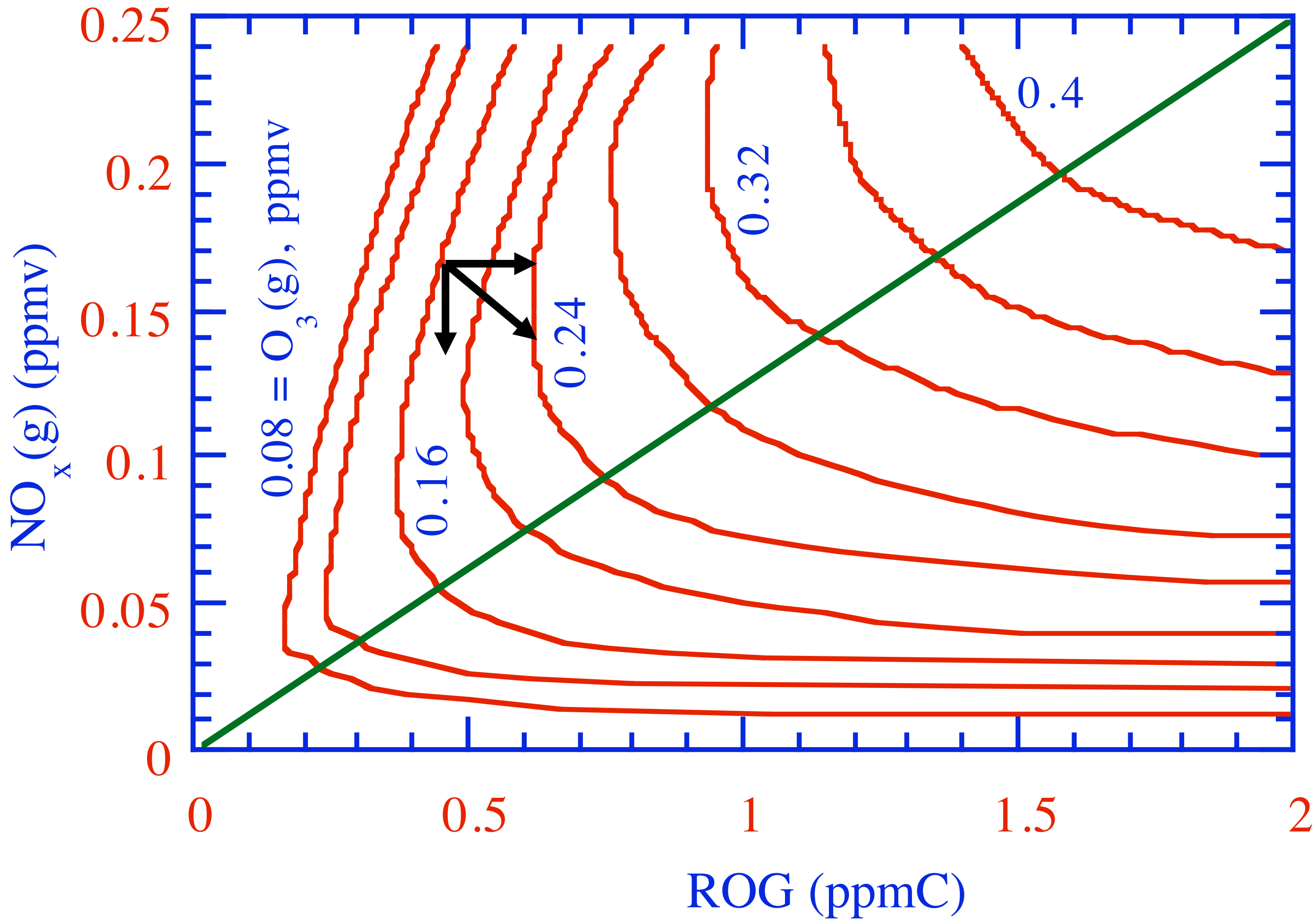
Comparison of Emission Assumptions With Recent CARB and Other Data

Percent change E85 minus gas

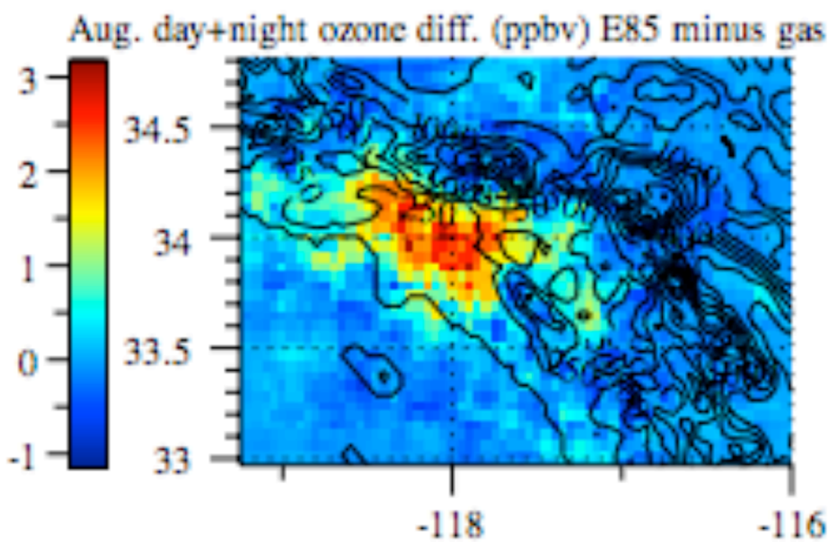
	Cert data (2006)	Jacobson (2007)
NMOG	+45%	+19.6%
NO_x	-29.7%	-30%

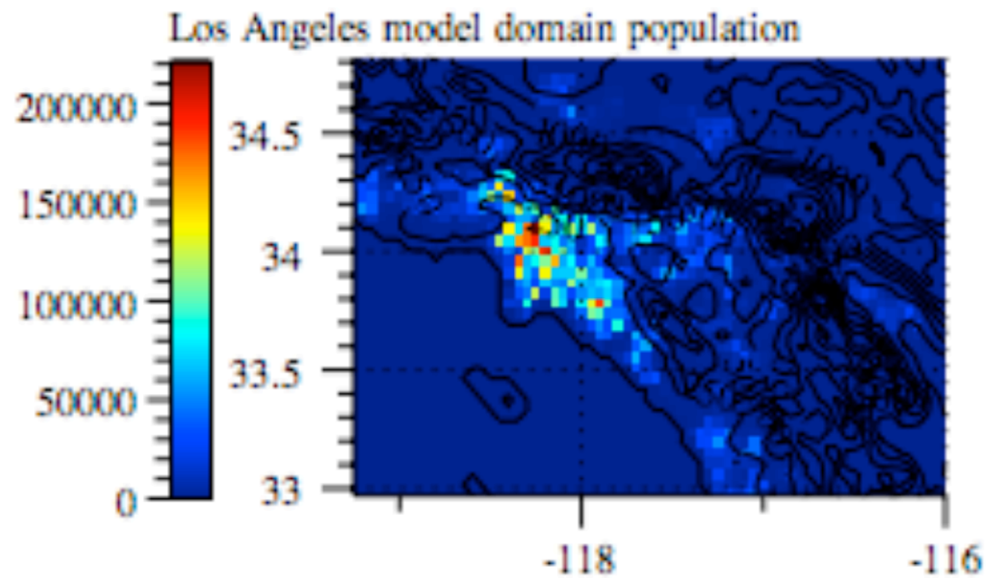
	Whitney (2007)	Jacobson (2007)
Benzene	-64%	-79%
1,3-butadiene	-66%	-10%
Acetaldehyde	+4500%	+2000%
Formaldehyde	+200%	+60%

Ozone isopleth



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

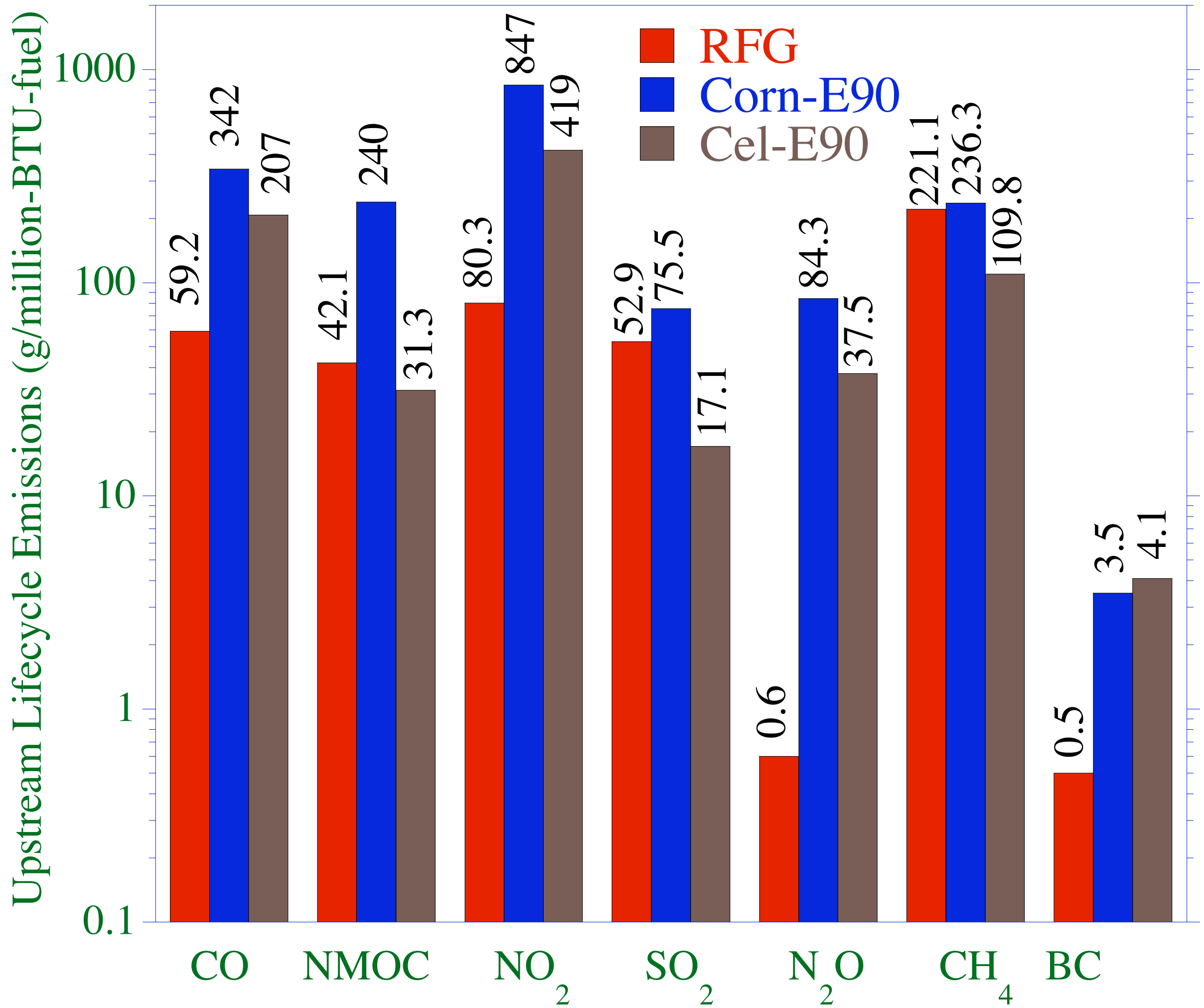




Change in ozone deaths/yr due to E85: +120 (+9%) (47-140)

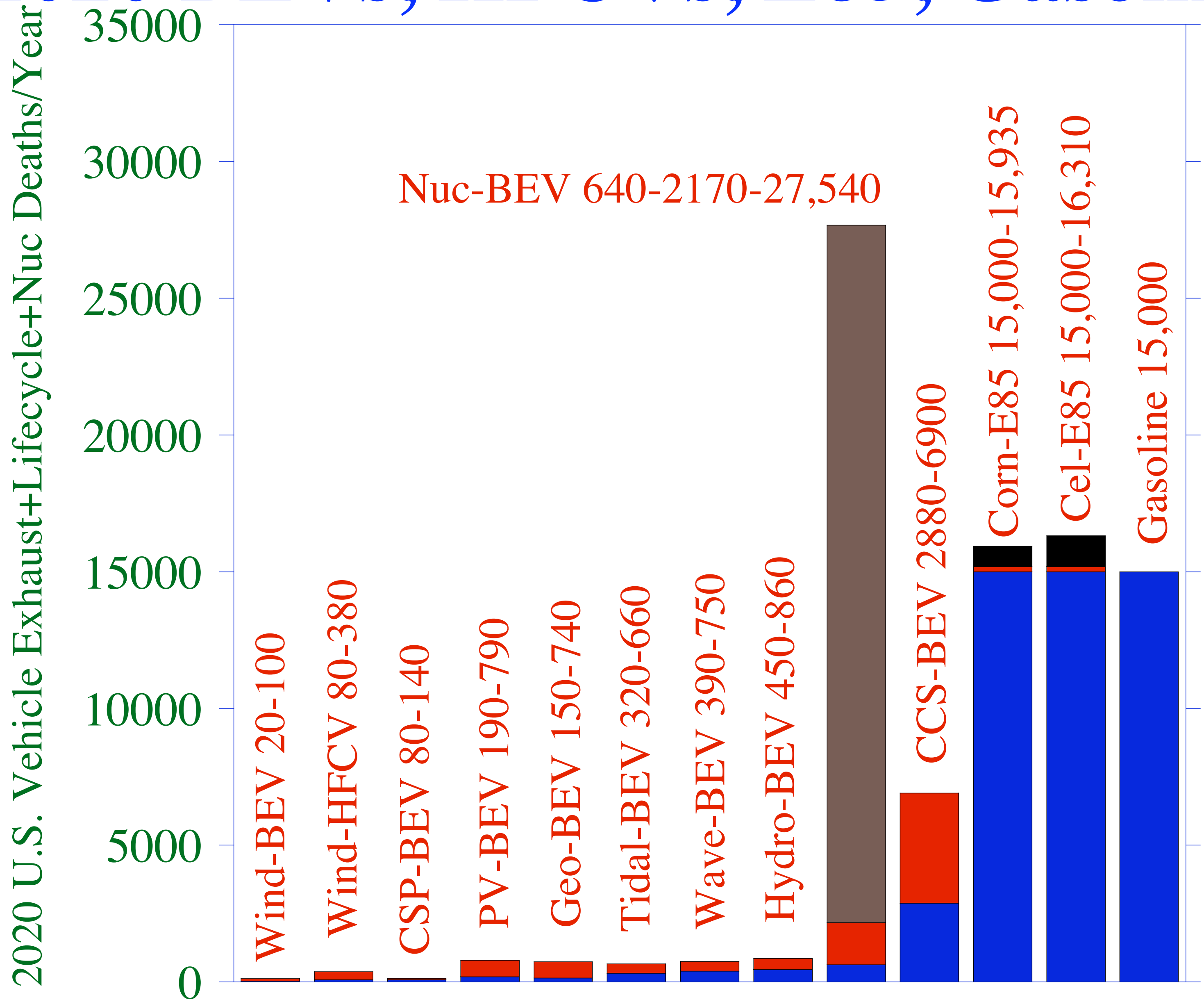
Changes in cancer/yr due to E85: -3.5 to +0.3

Upstream Lifecycle Emissions Gasoline, Corn-E90, Cellulosic-E90



DeLucchi, 2006

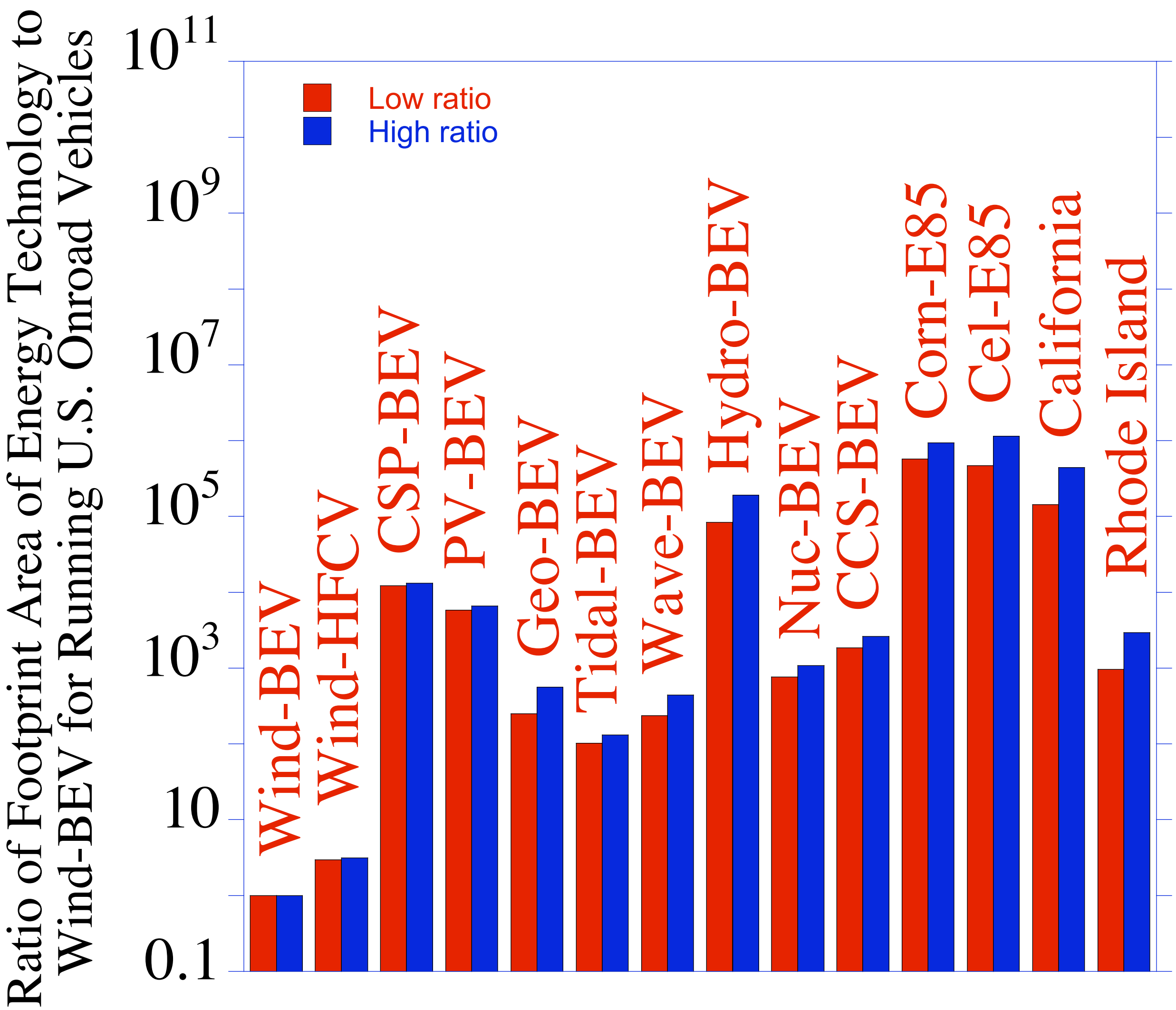
Low/High U.S. Air Pollution Deaths For 2020 BEVs, HFCVs, E85, Gasoline



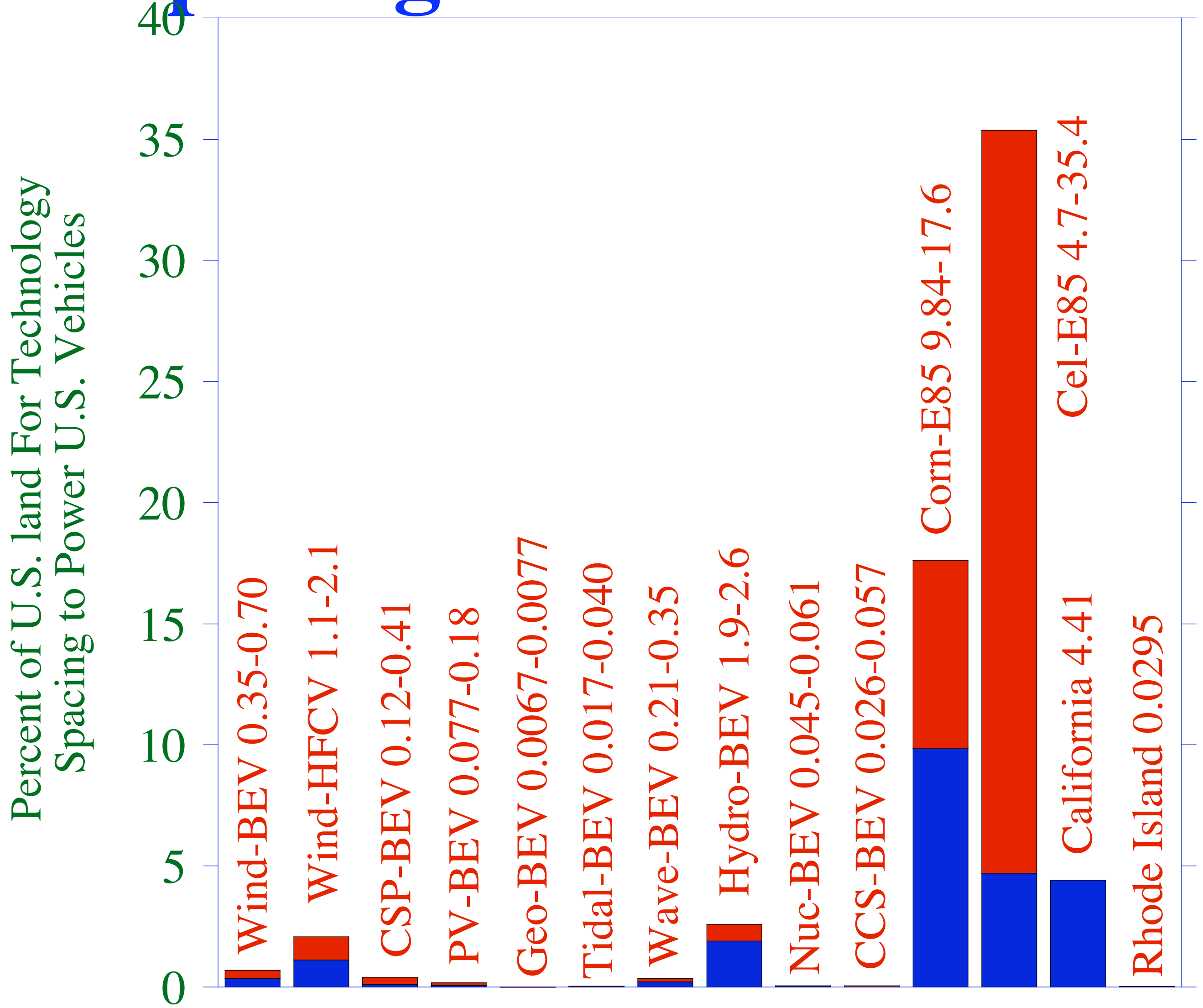
Number of Plants to Run All U.S. Vehicles as Battery-Electric

Nuclear:	202-275	850 MW plants
Hydroelectric:	270-365	1300 MW plants
Coal-CCS:	460-1010	425 MW plants
Geothermal:	1500-2250	100 MW plants
CSP:	5900-15,400	100 MW plants
Solar-PV:	4.6-12.5 billion	160 W panels
Wave:	770,000-1,275,000	0.75 MW devices
Tidal:	419,000-1,000,000	1 MW turbines
Wind:	73,000-144,000	5 MW turbines

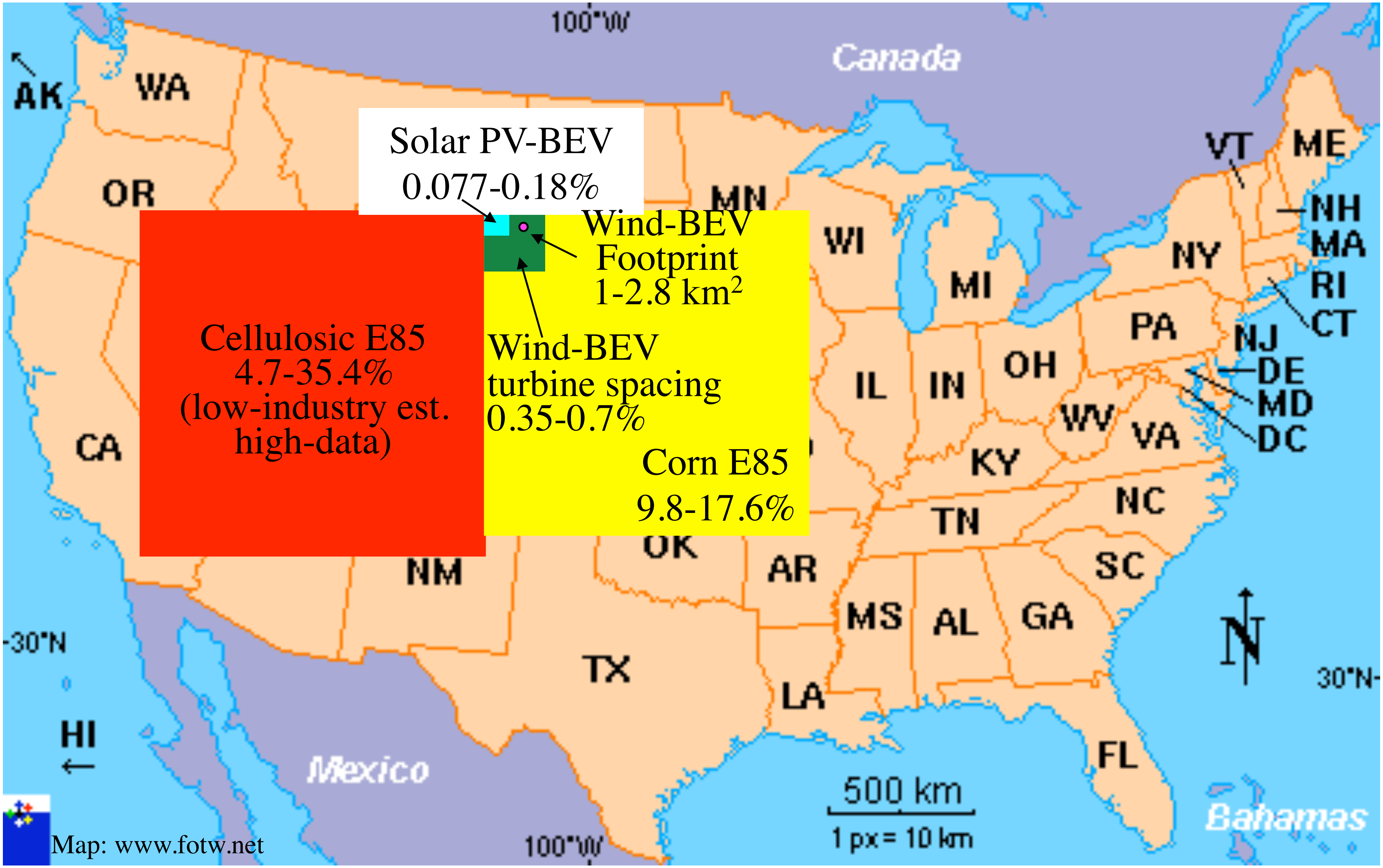
Ratio of Footprint Area of Technology to Wind-BEVs for Running U.S. Vehicles



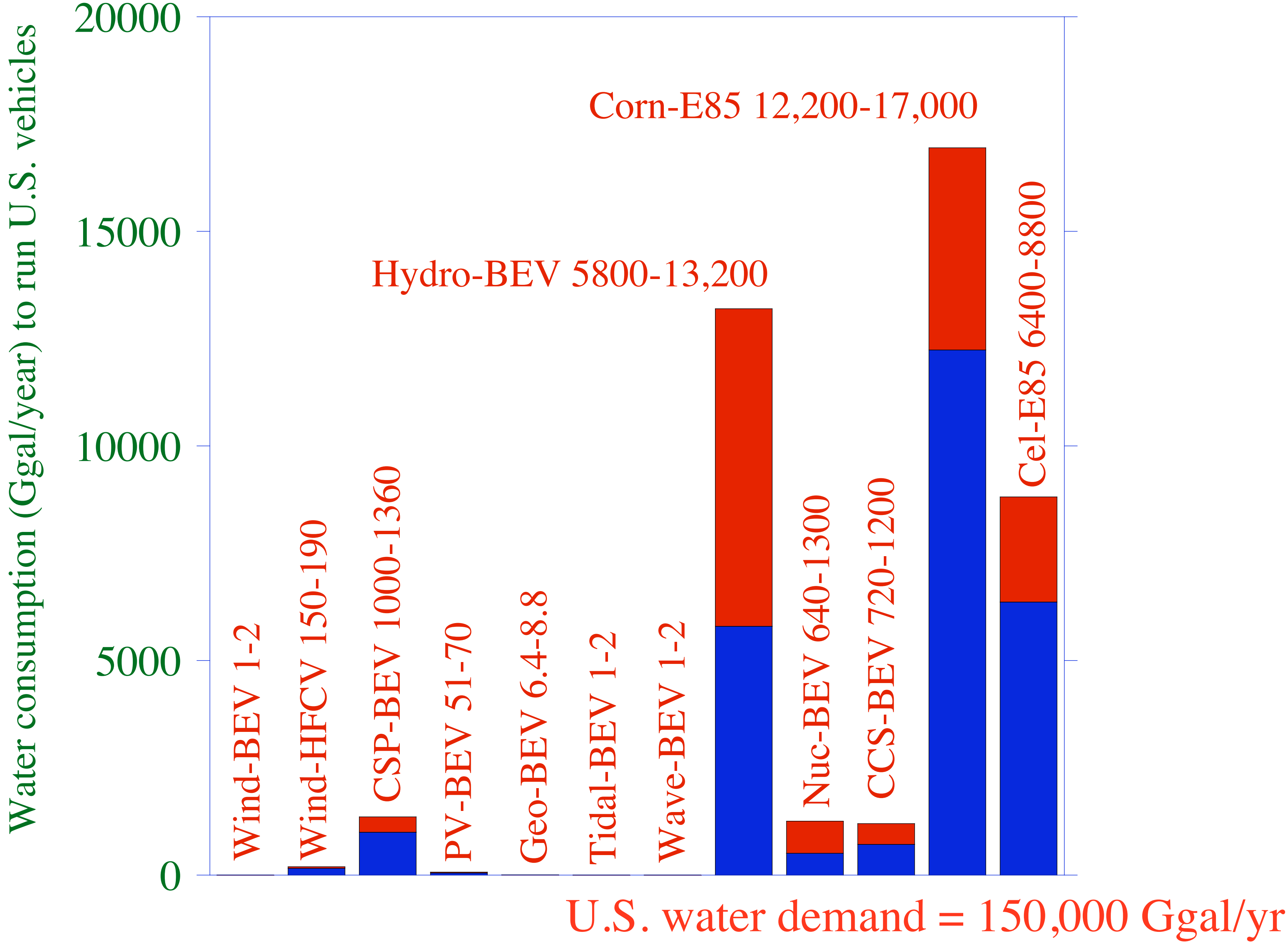
Percent of U.S. (50 states) for Footprint + Spacing to Run U.S. Vehicles



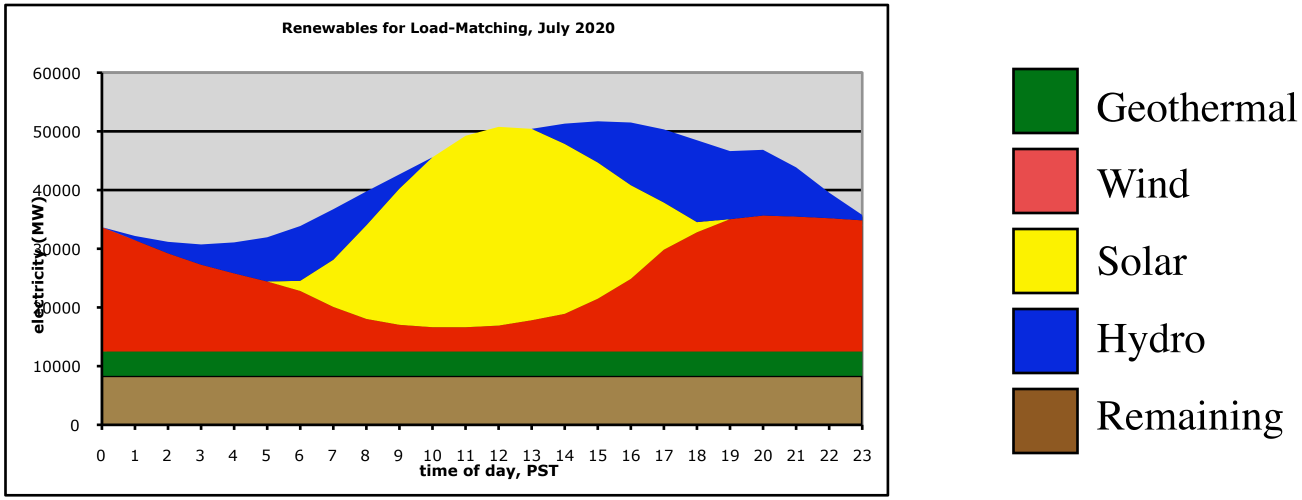
Area to Power 100% of U.S. Onroad Vehicles



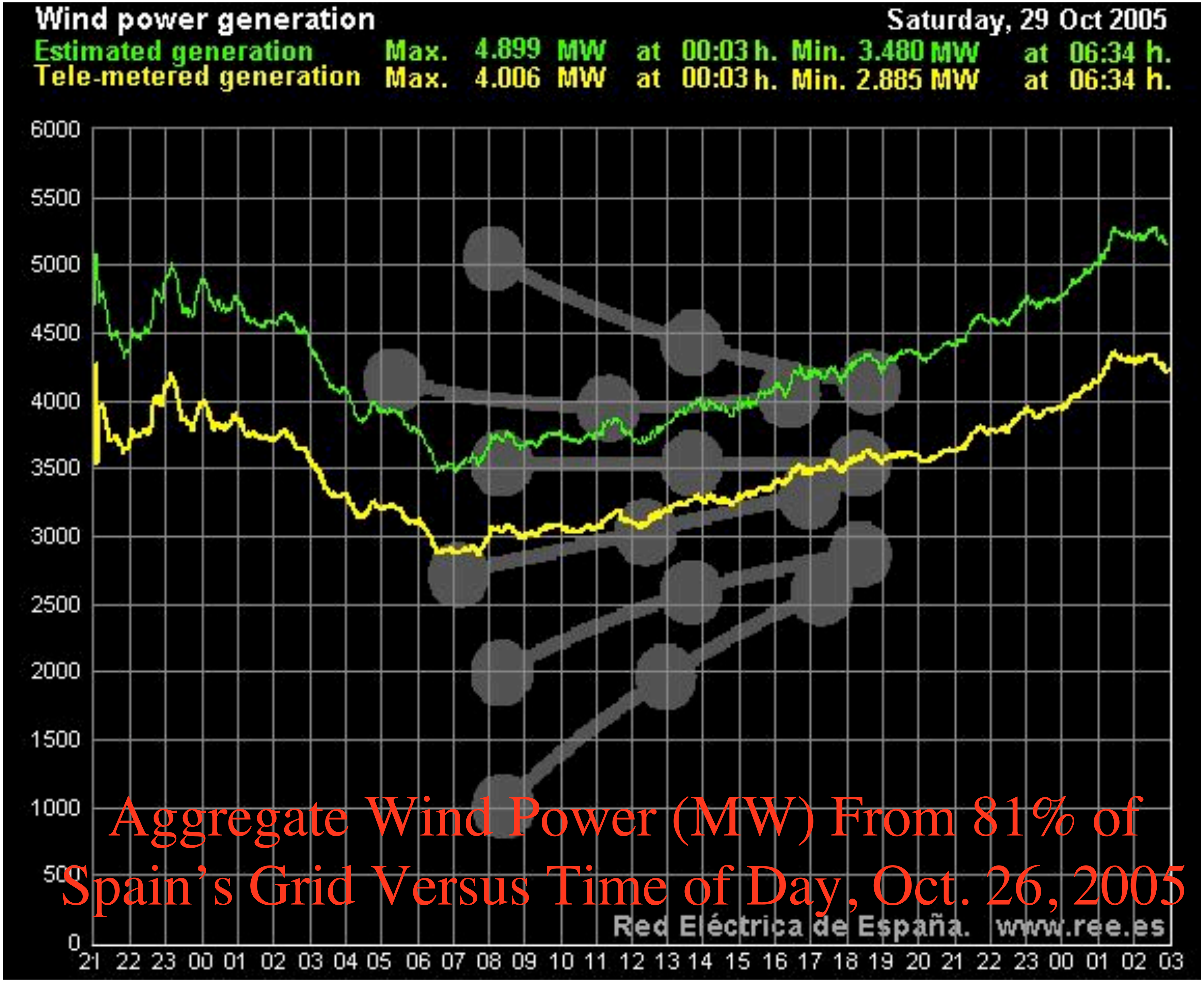
Water Consumed to Run U.S. Vehicles



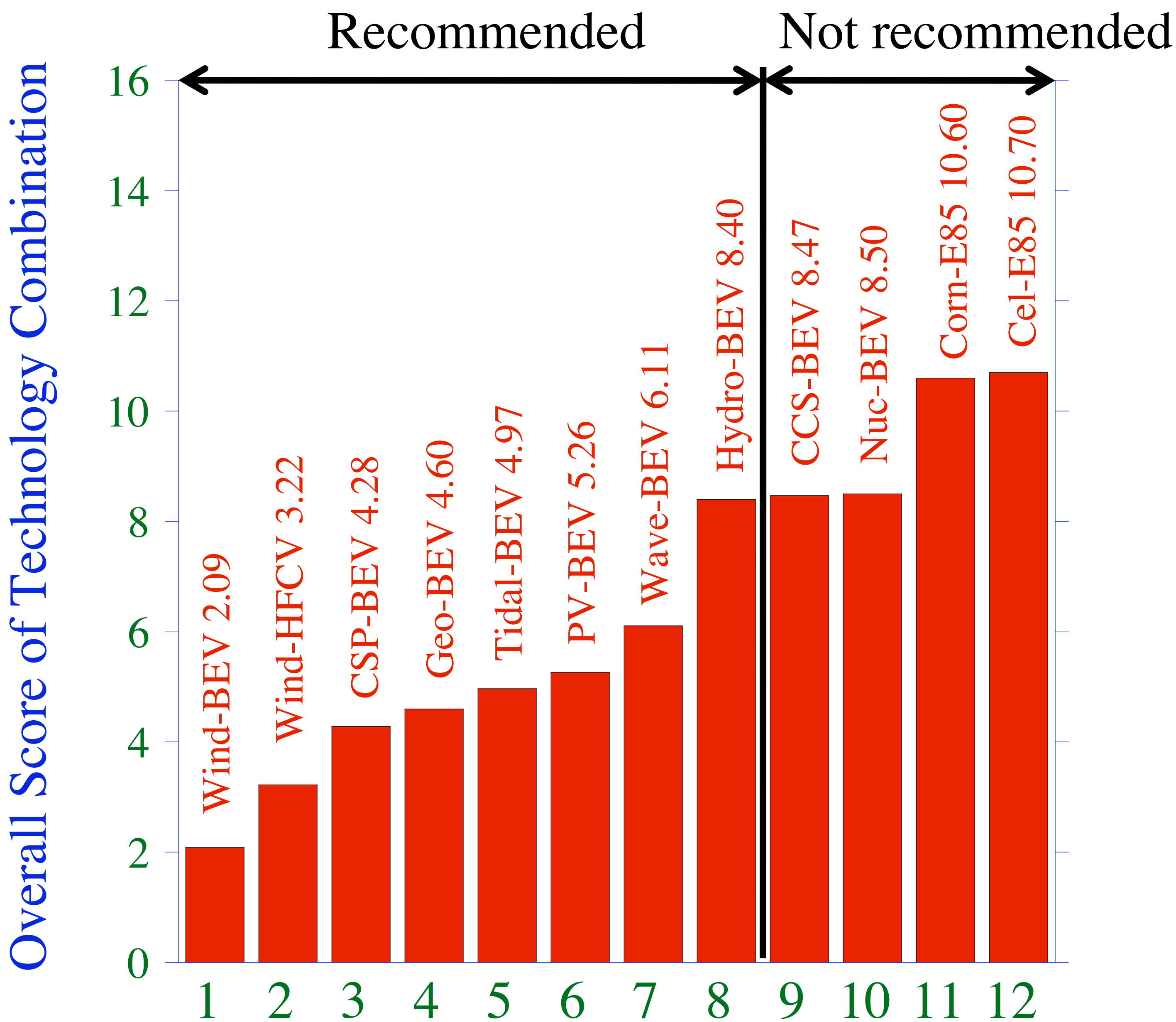
Matching Hourly Electricity Demand in 2020 With 80% Renewables



Hoste et al. (2007)


Wind power generation
Saturday, 29 Oct 2005
Estimated generation Max. 4.899 MW at 00:03 h. Min. 3.480 MW at 06:34 h.
Tele-metered generation Max. 4.006 MW at 00:03 h. Min. 2.885 MW at 06:34 h.
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
21 22 23 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00 01 02 03
Red Eléctrica de España. www.ree.es
Aggregate Wind Power (MW) From 81% of Spain's Grid Versus Time of Day, Oct. 26, 2005

Overall Scores/Rankings (Lowest is Best)



Summary

Among many vehicle options, wind-BEVs and wind-HFCVs have the greatest benefit and least impact in terms of solving climate, pollution, landuse, water supply problems. Wind requires 2-6 orders of magnitude less land footprint than any other option.

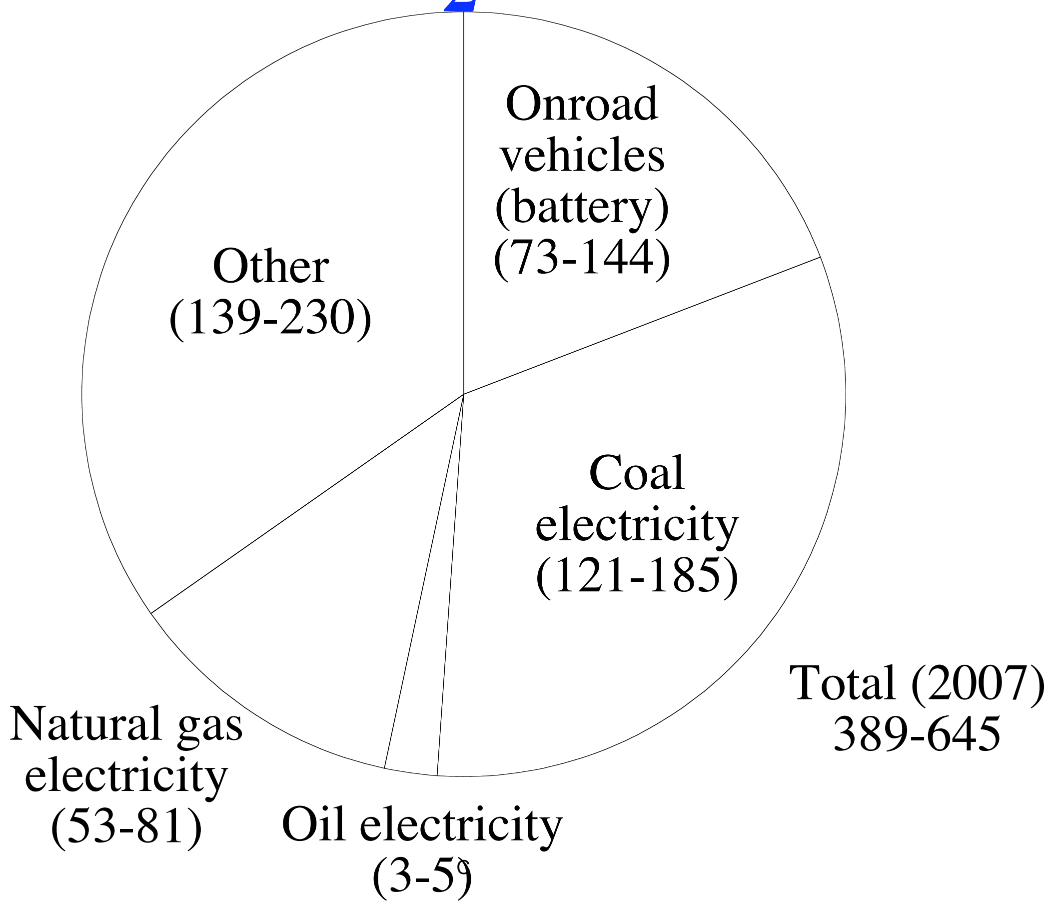
CSP-, hydro-, geothermal-, PV-, tidal-, wave-BEVs also extremely beneficial. Hydro-BEVs recommended due to load balancing ability.

Nuclear-BEVs, coal-CCS-BEVs are less beneficial options for addressing climate/air pollution and should not be favored at expense of other options.

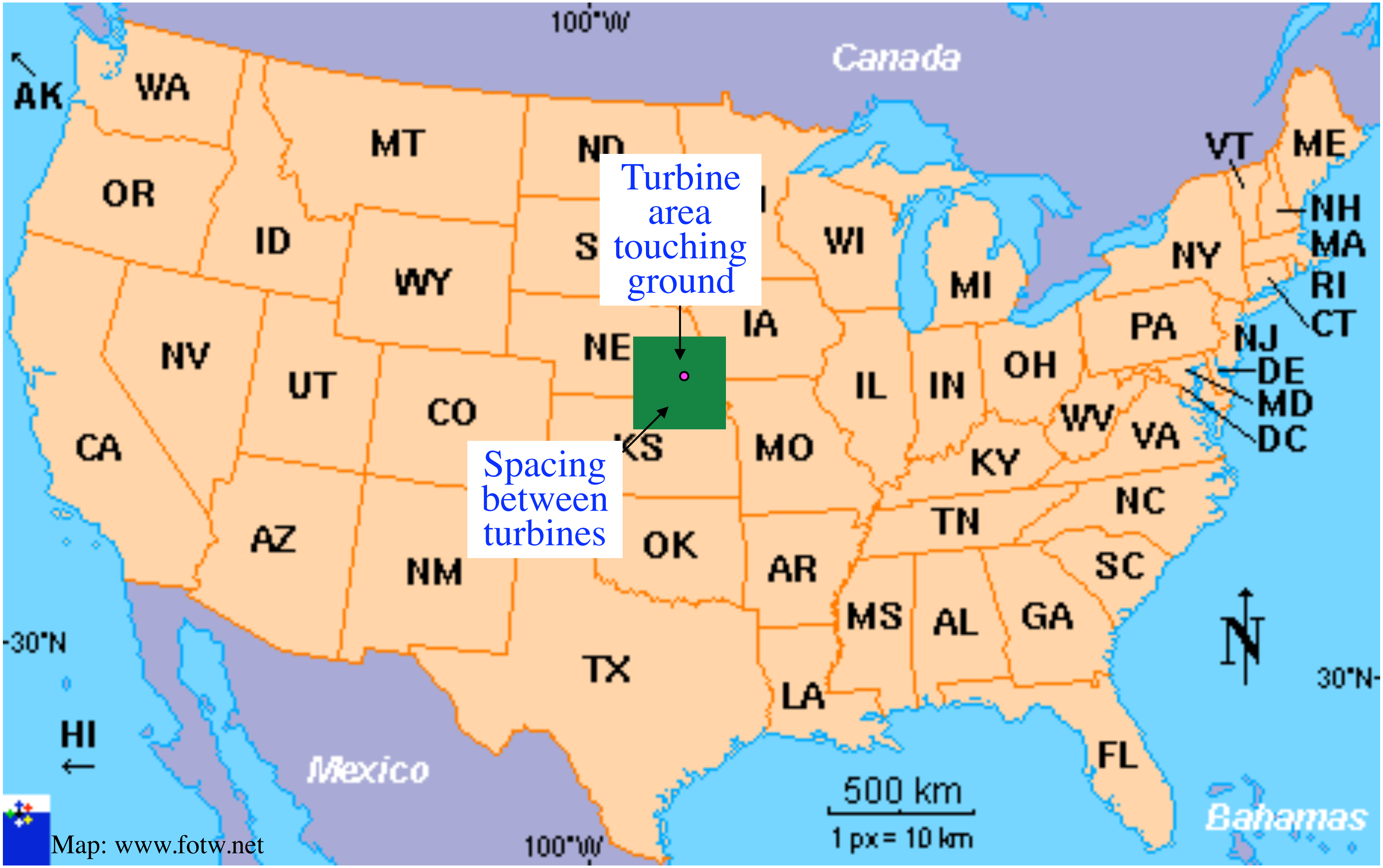
Corn-E85, cellulosic-E85 detrimental to climate, air quality, land, water, undernutrition compared with other technologies. Should not be included in policy options to address climate or air pollution.

More at
www.stanford.edu/group/efmh/jacobson/revsolglobwarmairpol.htm

Number of 5 MW Wind Turbines in 7-8.5 m/s winds to Eliminate All U.S. CO_2 2007



Land Area For 50% of US Energy From Wind



Map: www.fotw.net

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