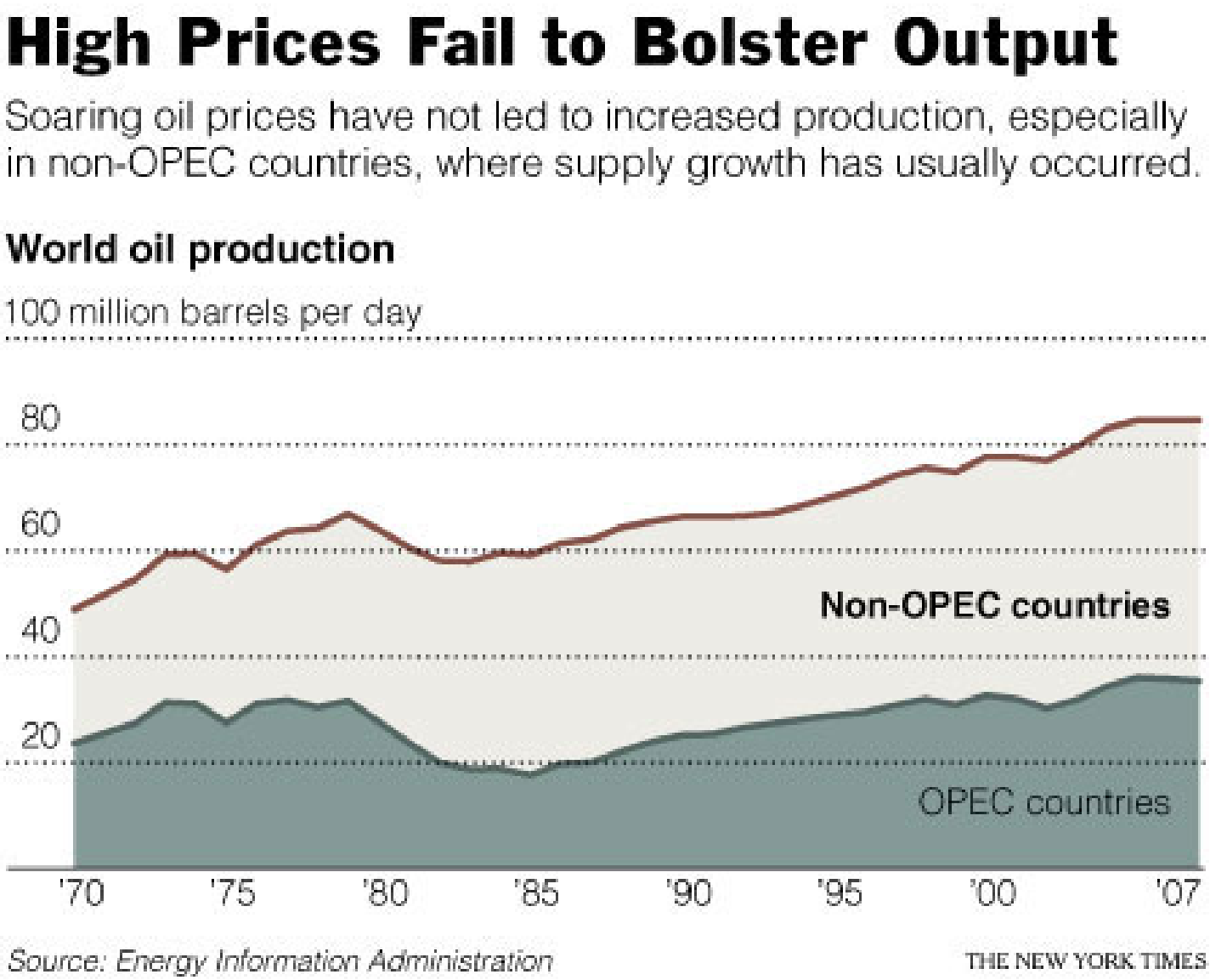
TeraWatts of Wind Power
Global calming: a new role for meteorologists

May 1, 2008

Prof. Brian H. Fiedler

School of Meteorology, University of Oklahoma

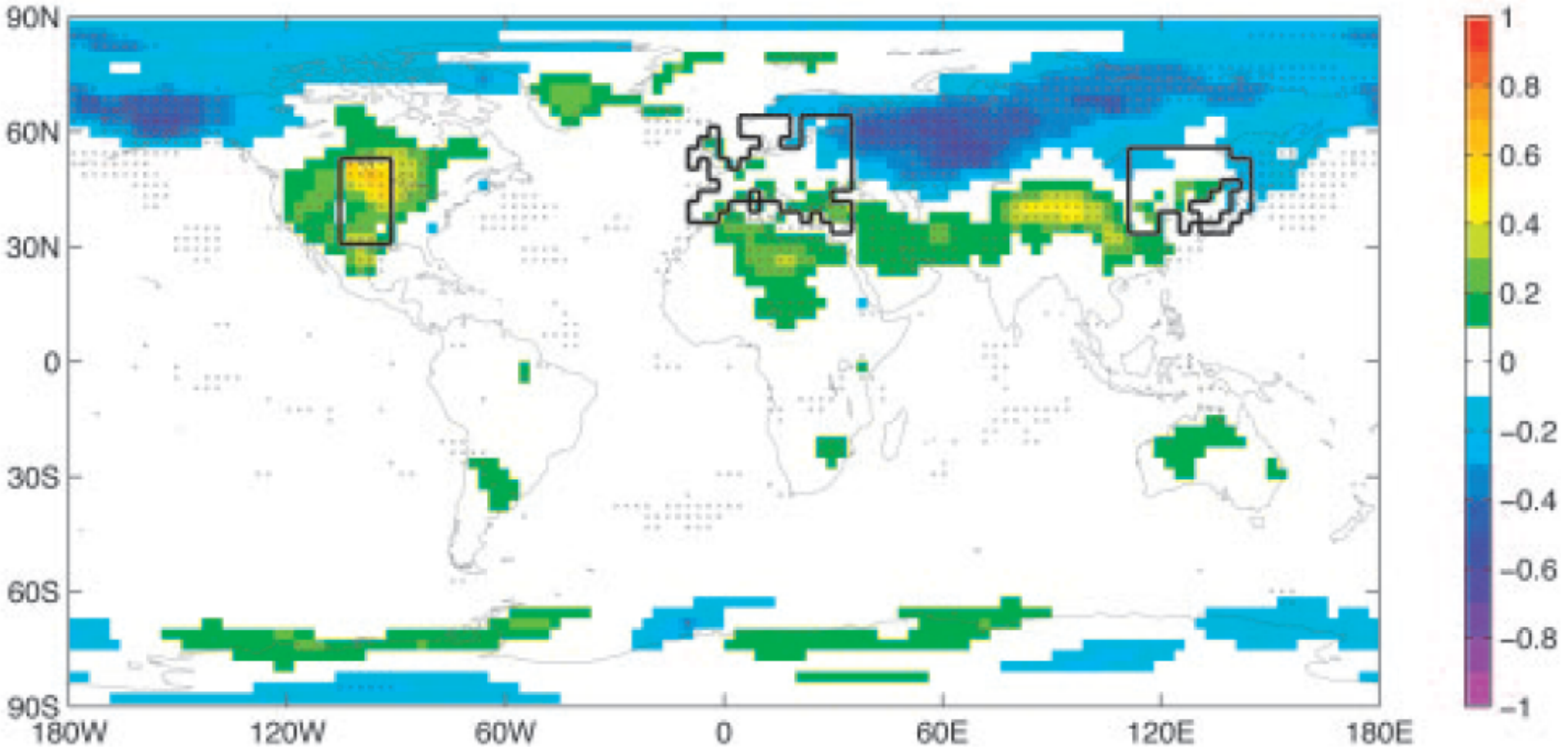


NYT 4/29/2008: "Experts expect prices above \$4 a gallon this summer, and one analyst recently predicted that gasoline could reach \$7 in the next four years."

NYT 4/23/2008: "Over the next five years, Italy will increase its reliance on coal to 33 percent from 14 percent..."

"...Driven by rising demand, record high oil and natural gas prices, concerns over energy security and an aversion to nuclear energy, European countries are expected to put into operation about 50 coal-fired plants over the next five years, plants that will be in use for the next five decades."

"In the United States, fewer new coal plants are likely to begin operations, in part because it is becoming harder to get regulatory permits and in part because nuclear power remains an alternative. Of 151 proposals in early 2007, more than 60 had been dropped by the years end, many blocked by state governments. Dozens of other are stuck in court challenges."



Keith *et al.* PNAS, 2004. NCAR GCM surface air temperature. Experiment with an extra 21 TW of power dissipation in the boundary layer, minus control.

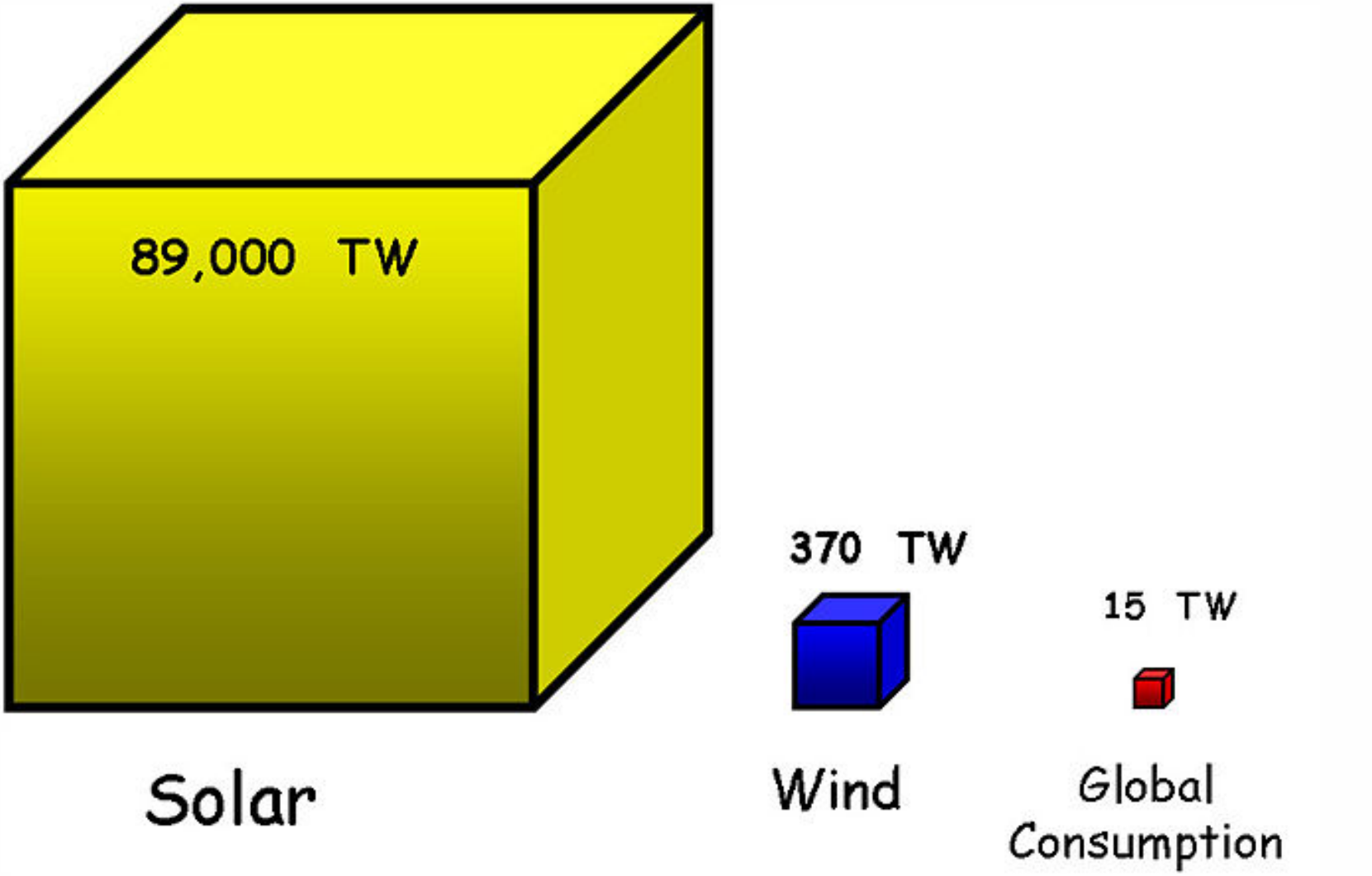
Global Energy Consumption in 2004:
15 TW = 15 x 10^{12} W

Global Human Population in 2006 was 6.5 x 10^{9},
projected to be 10^{10} in 2050

Americans consume 10^{4} W

Humans eat 10^{2} W

Humans produce work at a rate of 10 W



(175 W m^{-2}) (0.72 W m^{-2}) (0.029 W m^{-2})

- Holton gives a tropospheric wind scale of $U = 10$ m s^{-1}.
- The rate of kinetic energy production, per volume, by horizontal wind is $\vec{V} \cdot \vec{F}$, or $-\vec{V} \cdot \nabla p$
- Let's estimate the cross-isobaric flow in the boundary layer to be 1 m s^{-1}.
- $$1 \text{ m s}^{-1} \frac{1000 \text{ Pa}}{10^6 \text{ m}} = 10^{-3} \text{ J m}^{-3} \text{ s}^{-1}$$
- In a boundary layer of depth 1000 m, the production of kinetic energy by cross-isobaric flow is $1 \text{ J m}^{-2} \text{ s}^{-1} = 1 \text{ W m}^{-2}$

Harvesting 16×10^{12} W at 1 W m^{-2} requires a wind farm of 4000 km by 4000 km.

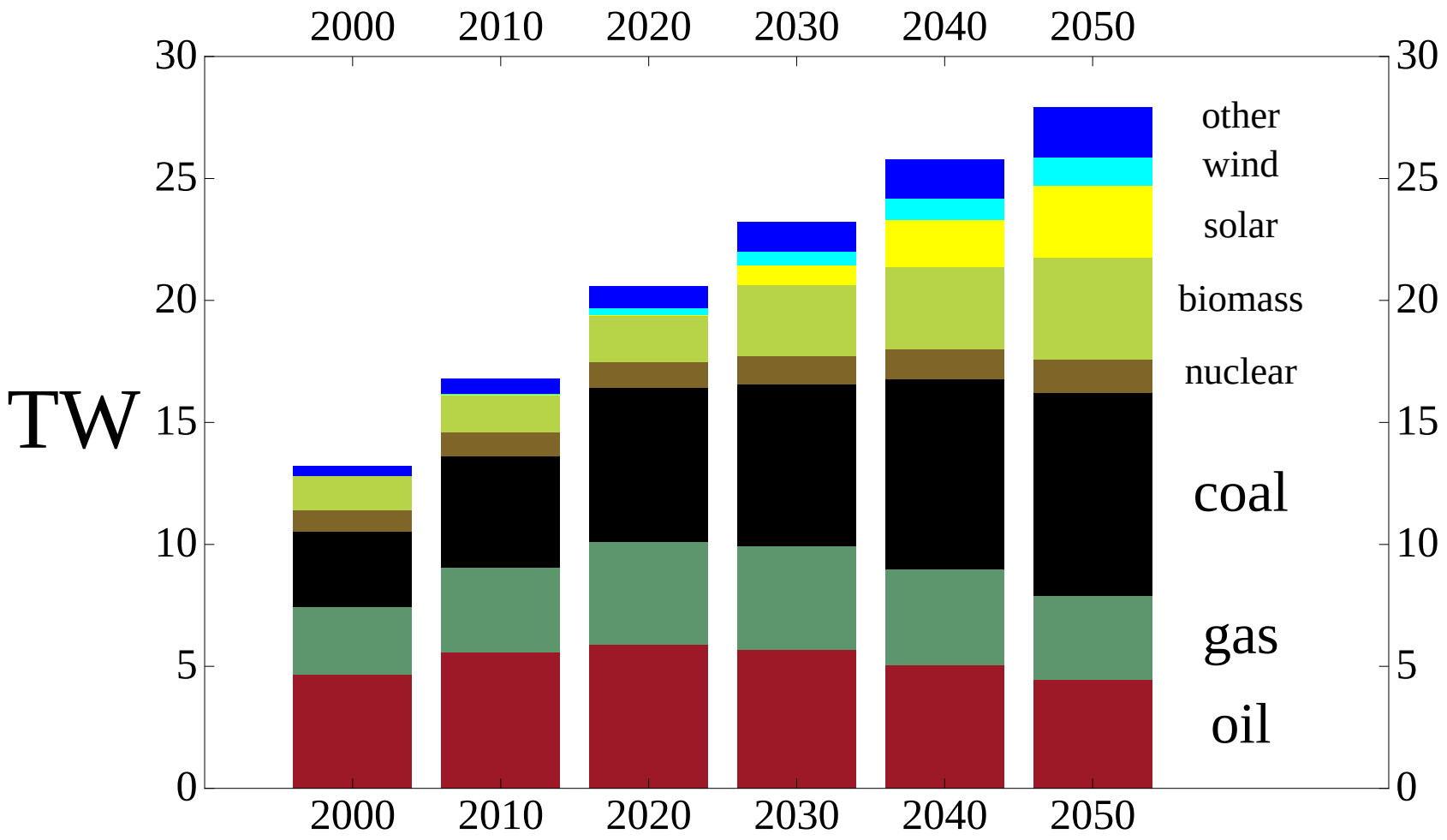
Harvesting the deep atmosphere:

The atmosphere has a column density of 10^4 kg m^{-2}.

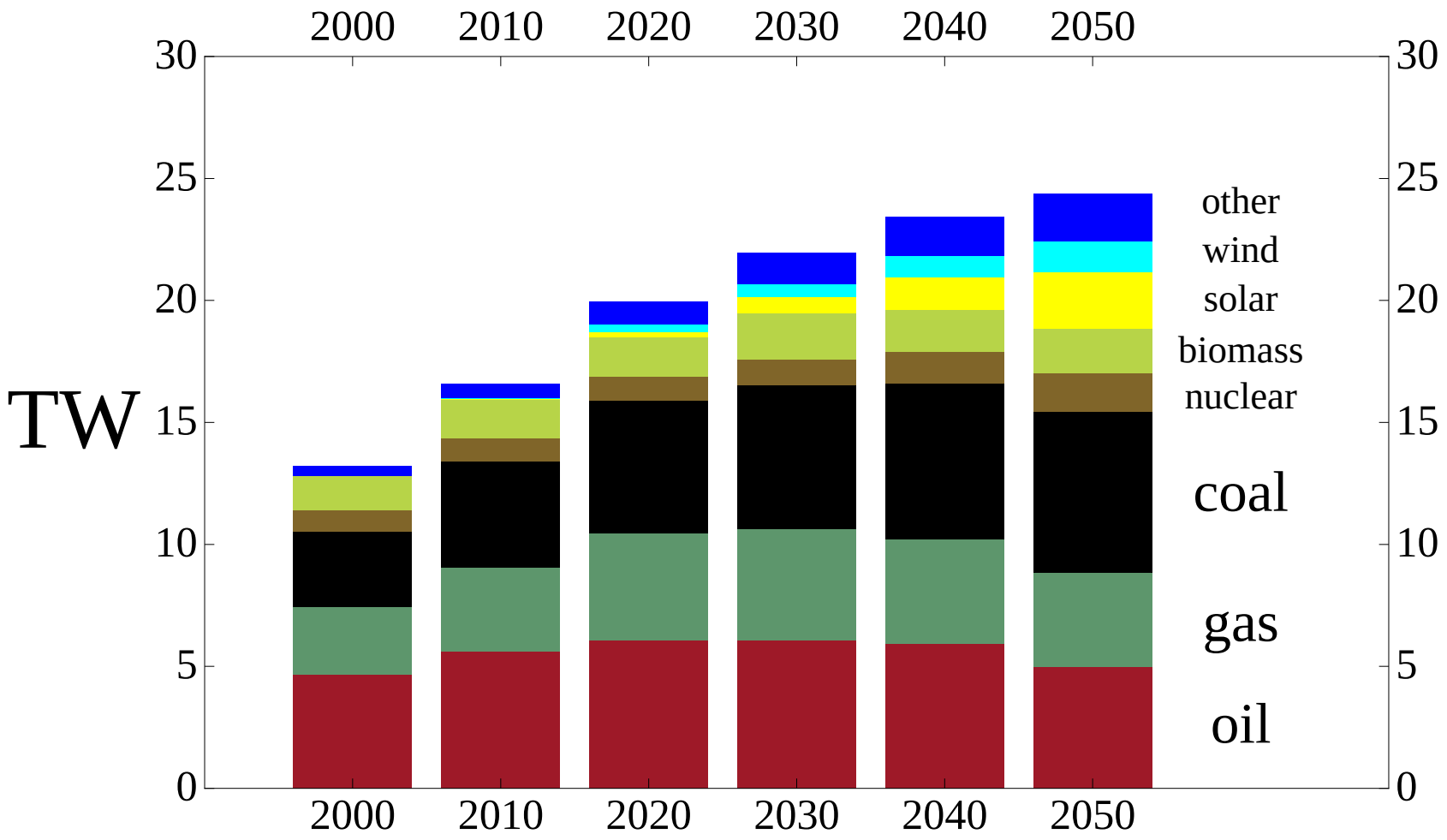
Using the Holton scale for wind of $U = 10$ m s^{-1} gives a column energy density of 5×10^5 J m^{-2}. In one day, or 10^5 seconds, humans consume 15×10^{17} J.

We can obtain this energy by extracting, in one day, the entire kinetic energy of the entire depth of atmosphere in an area of 3×10^{12} m^{-2}, or 1732 km by 1732 km.

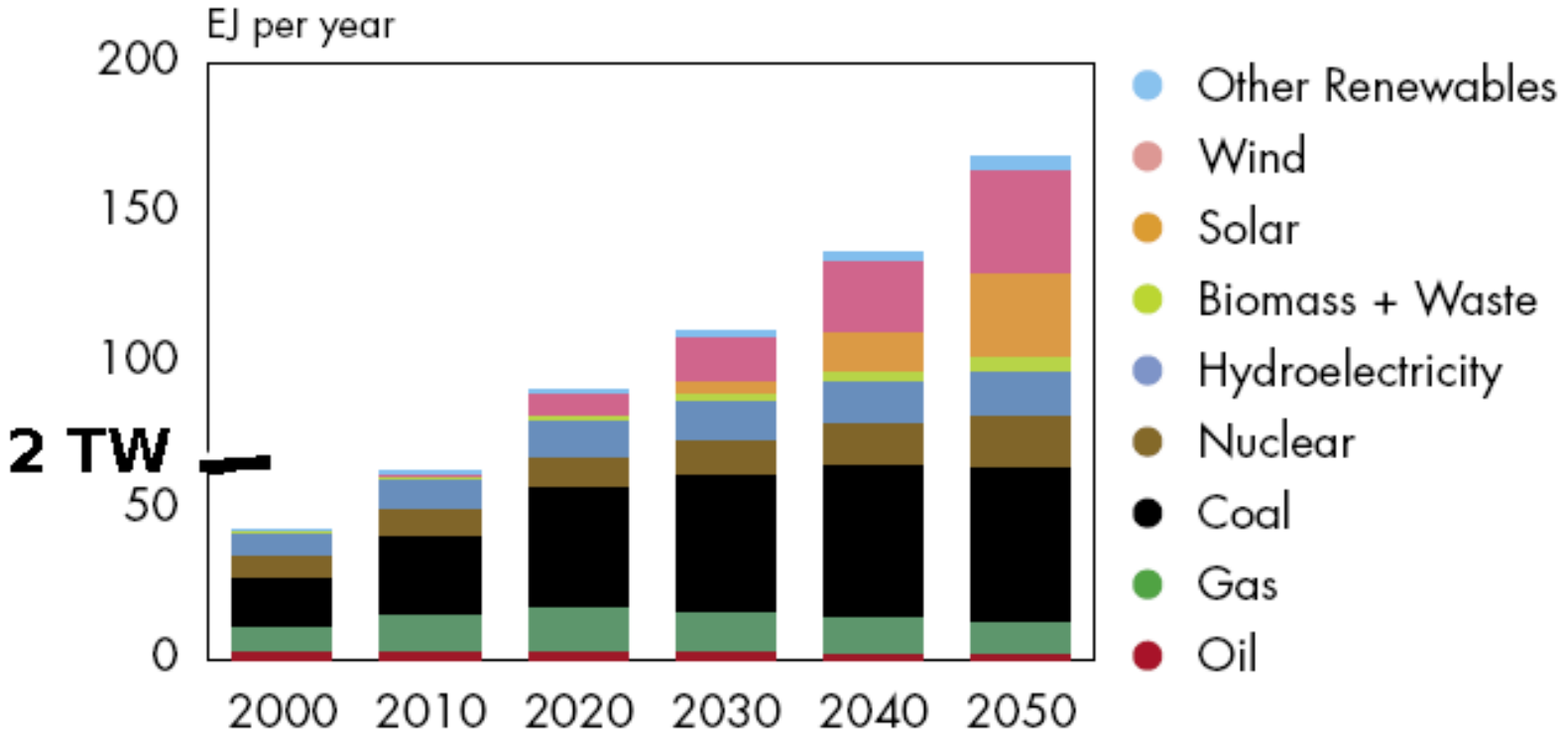
Shell Oil *Scramble Scenario:*

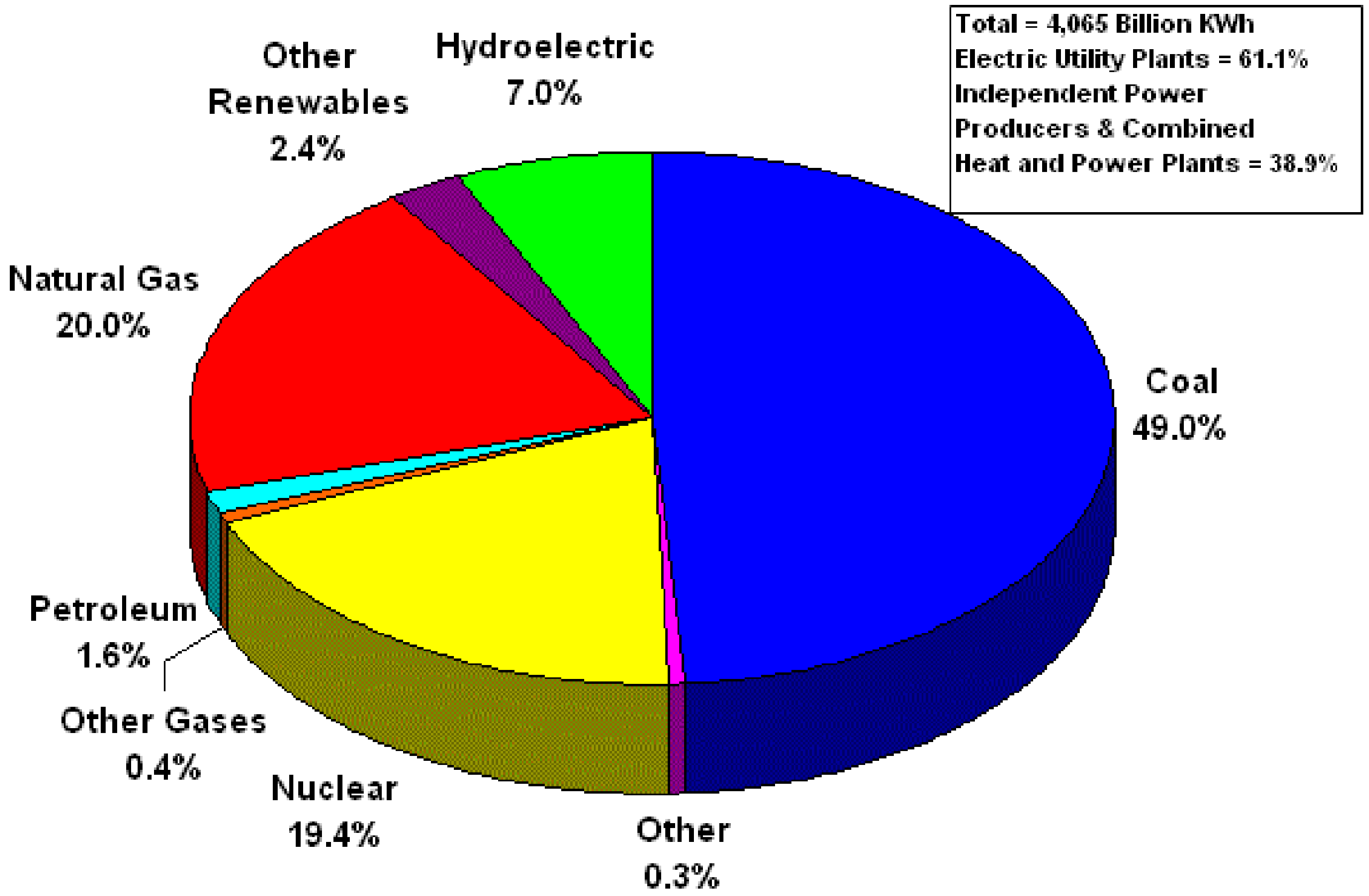


Shell Oil *Blueprint Scenario:*



Final energy consumption of electricity



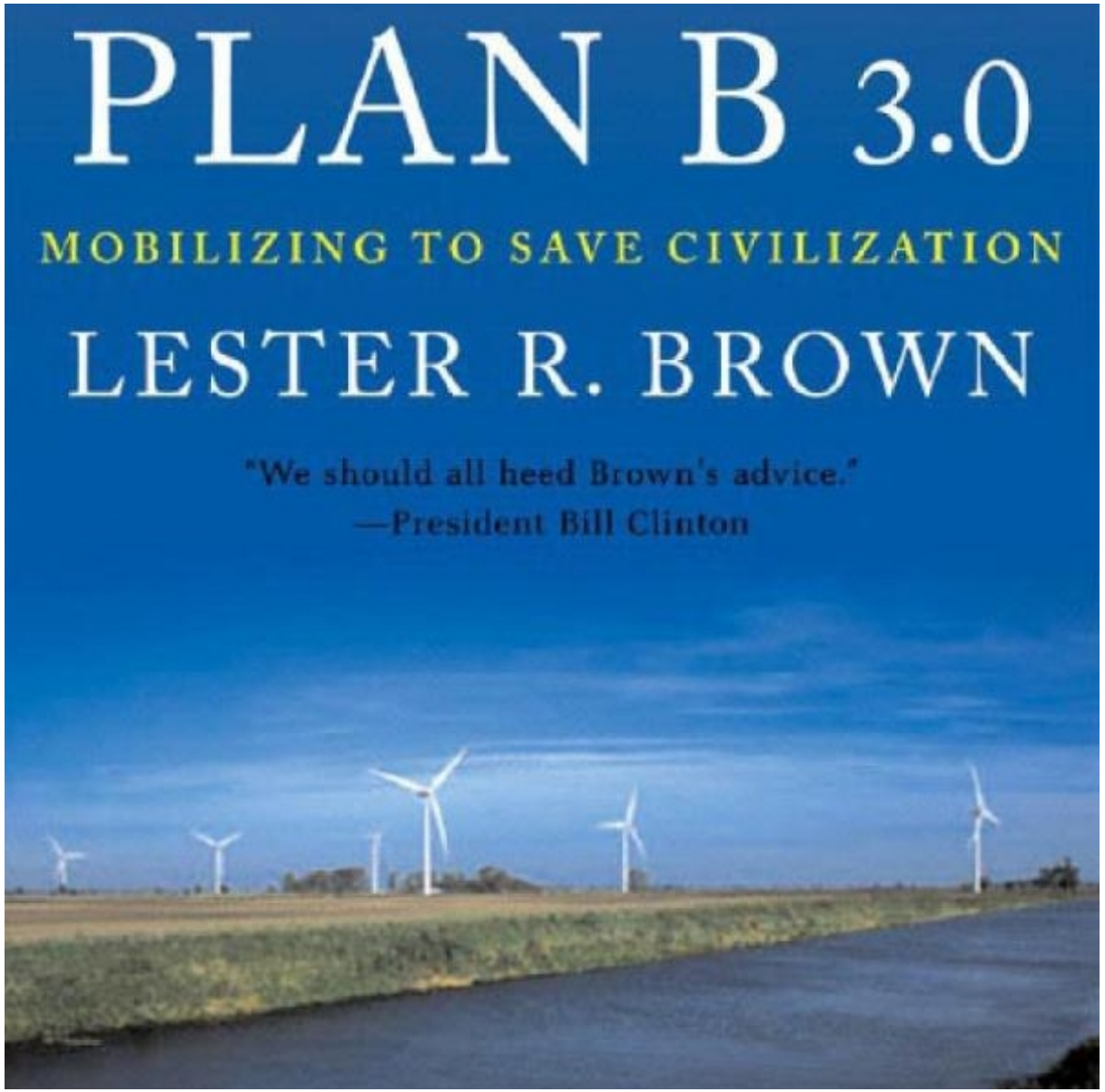


US Electric Power Generation is 0.46 TW

Reuters June 5, 2007:

The U.S. wind power industry will see half a trillion dollars of investment by 2030 to take the renewable source up to 20 percent of U.S. electricity generation, an industry conference heard on Monday.

That would mean by 2030 there will have to be 325 gigawatts of installed wind turbines in the United States, said Michael Robinson of the National Renewable Energy Laboratory.


PLAN B 3.0
MOBILIZING TO SAVE CIVILIZATION
LESTER R. BROWN
"We should all heed Brown's advice."
—President Bill Clinton

Source	Installed Capacity 2006	Installed Capacity 2020
Electricity Generating Capacity	Electrical	Gigawatts
Wind	74	3,000
Rooftop Solar Electric Systems	9	1,090
Solar Electric Power Plants	0	100
Solar Thermal Power Plants	0	200
Geothermal	9	200
Biomass	45	200
Hydropower	850	1,350
Total	987	6,140

Altamont Pass Wind Farm produces 125 MW or .00012 TW with 4900 turbines

NYT 2/1/2008: Many of the California companies are start-ups exploring exotic materials like copper indium gallium selenide, or CIGS, an alternative to the conventional crystalline silicon that is now the dominant technology.

The newcomers hope that CIGS, while less efficient than silicon, can be made far more cheaply than silicon-based cells. Indeed, the Nanosolar factory looks more like a newspaper plant than a chip-making factory. The CIGS material is sprayed onto giant rolls of aluminum foil and then cut into pieces the size of solar panels.

livescience.com 19 February 2008:

He predicted the fall of the Soviet Union. He predicted the explosive spread of the Internet and wireless access.

Now futurist and inventor Ray Kurzweil is part of distinguished panel of engineers that says solar power will scale up to produce all the energy needs of Earth's people in 20 years.

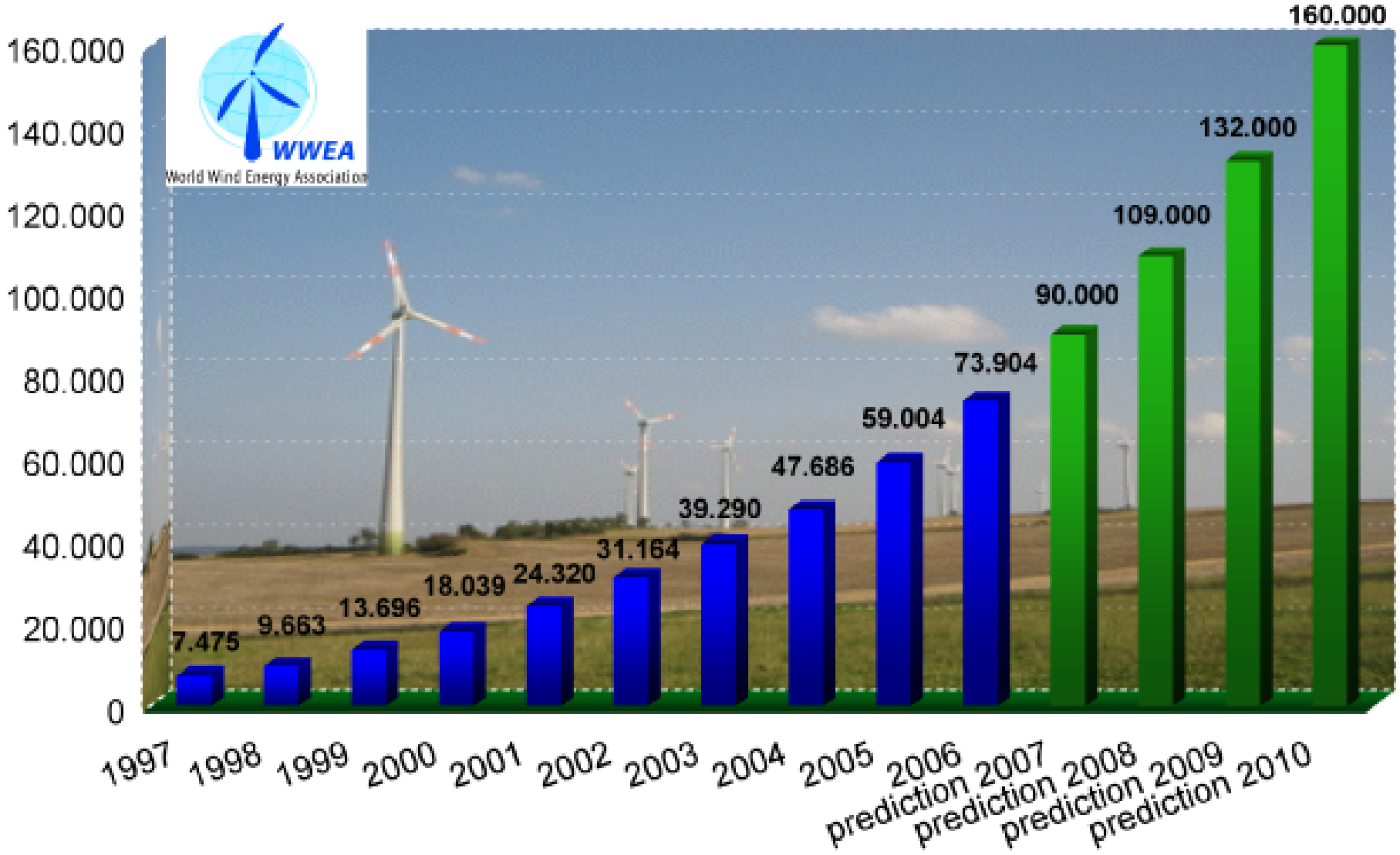
NOVEMBER 27, 2006

Ray Kurzweil: Why humans will soon live forever

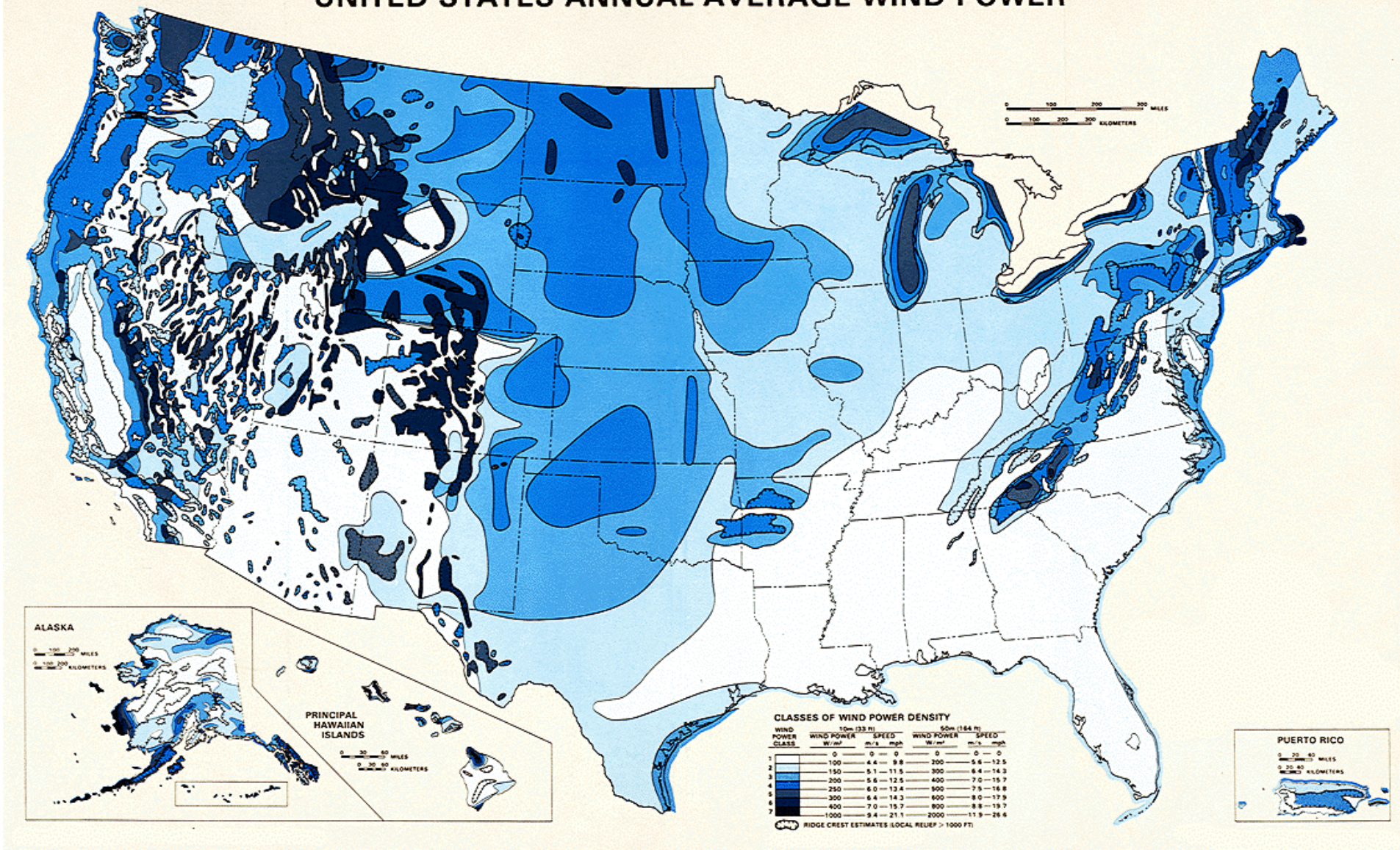
Expanding on some of the themes found in his new book The Singularity is Near, futurist and innovation guru Ray Kurzweil explains that we are almost at the point where hyper-powerful computers will enable people to live forever:

Vertigro... would therefore deliver approximately 33,000 gallons of algae oil per acre per year. $40\ \mathrm{W\ m^{-2}}$! Compare with $1\ \mathrm{W\ m^{-2}}$ from photosynthesis in crops.

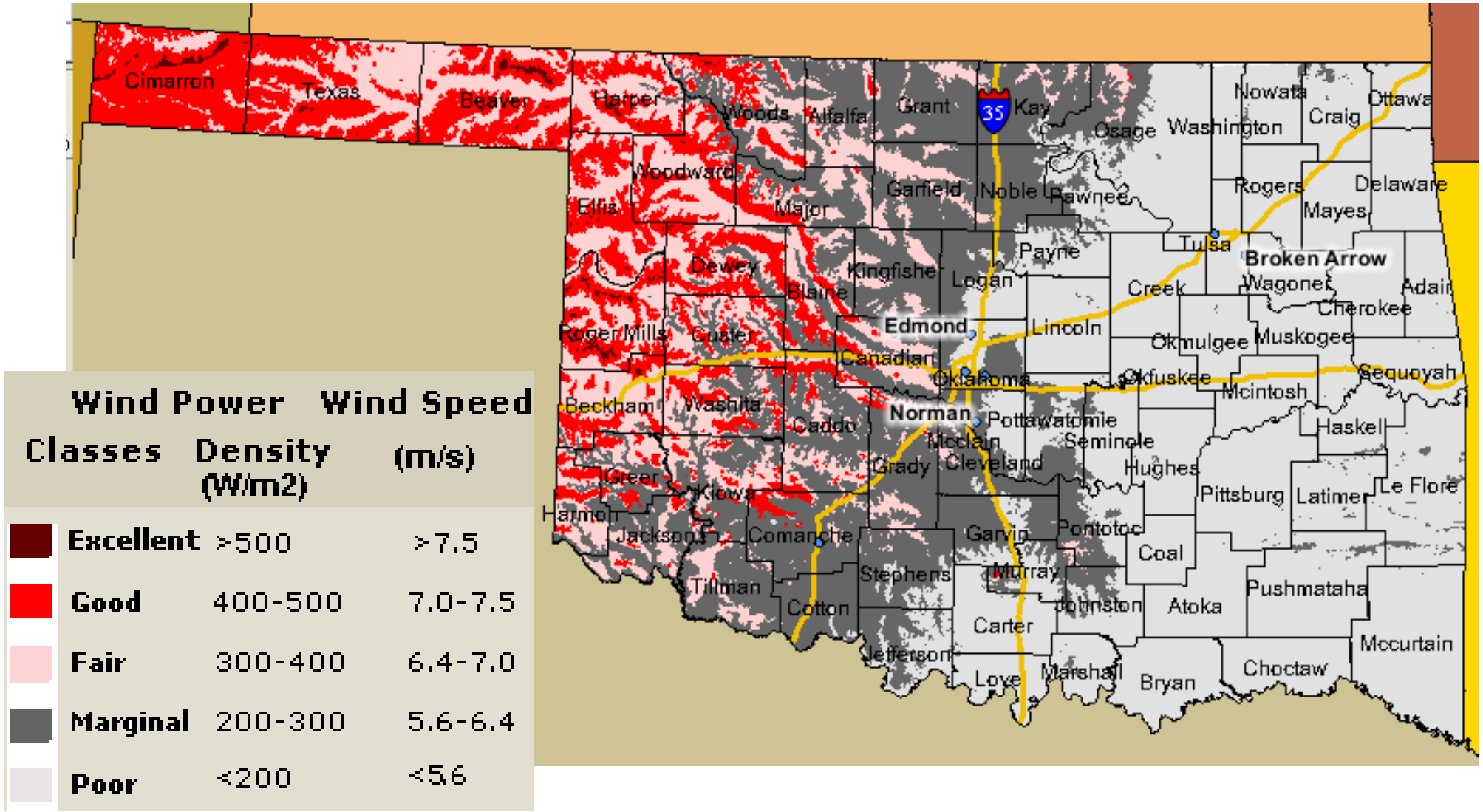
World Wind Energy - Total Installed Capacity (MW) and Prediction 1997-2010



UNITED STATES ANNUAL AVERAGE WIND POWER



$$\text{Power/Area} = V \times \tfrac{1}{2}\rho V^2$$



Wind Power Classes	Density (W/m2)	Wind Speed (m/s)
Excellent	>500	>7.5
Good	400-500	7.0-7.5
Fair	300-400	6.4-7.0
Marginal	200-300	5.6-6.4
Poor	<200	<5.6

"The Bear Creek Wind Power Project ... is a 24 MW wind energy facility ...is expected to produce over 75 million kilowatt-hours of wind energy annually (8.5 MW)."

Table 3. Percentage of Materials Used in Current Wind Turbine Component

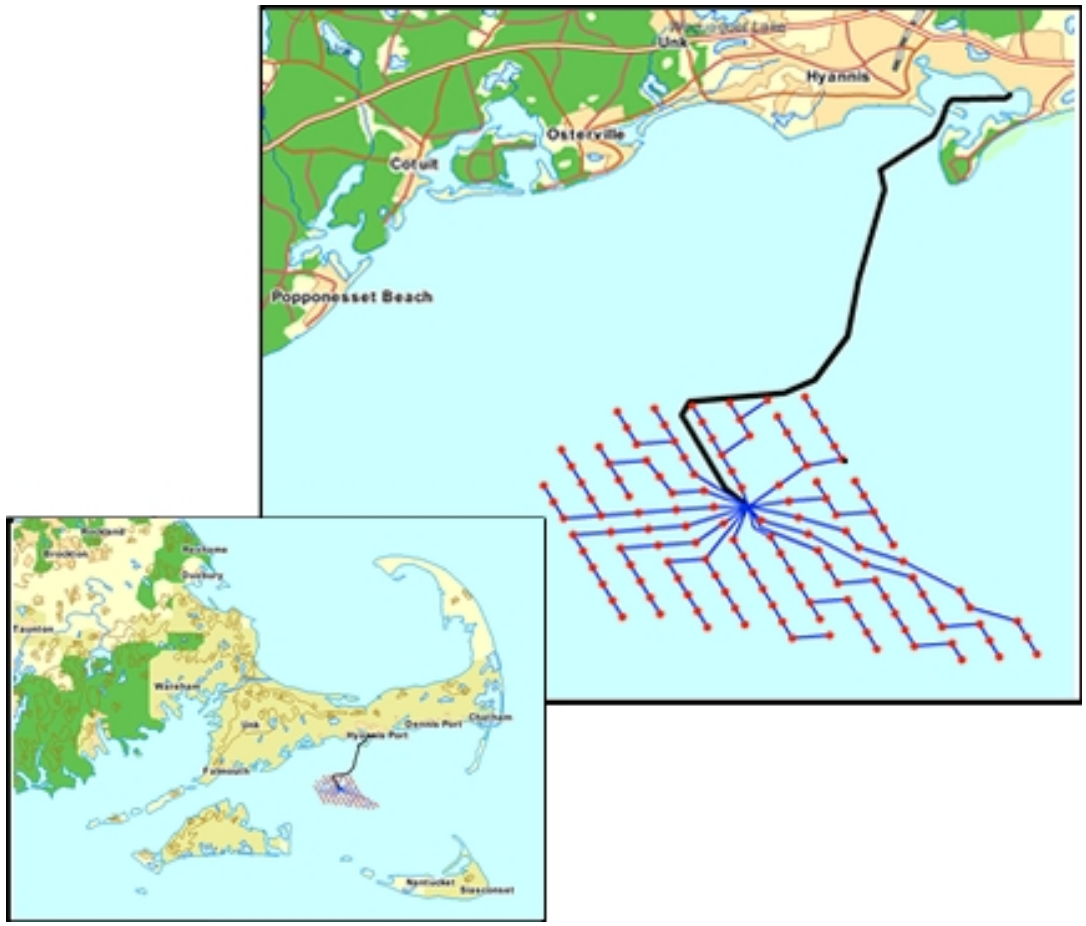
	Large Turbines and *(Small Turbines*[1])							
Component/ Material (% by weight)	**Permanent Magnetic Materials**	**Pre-stressed Concrete**	**Steel**	**Aluminum**	**Copper**	**Glass Reinforced Plastic** [4]	**Wood Epoxy** [4]	**Carbon Filament Reinforced Plastic** [4]
Rotor								
Hub			*(95)* - 100	*(5)*				
Blades			5			95	*(95)*	*(95)*
Nacelle [2]	*(17)*		*(65)* - 80	3 - 4	14	1 - *(2)*		
Gearbox [3]			98 -*(100)*	*(0)* - 2	*(<1)* - 2			
Generator	*(50)*		*(20)* - 65		*(30)* - 35			
Frame, Machinery & Shell			85 - *(74)*	9 - *(50)*	4 - *(12)*	3 - *(5)*		
Tower		2	98	*(2)*				

Notes:
1. Small turbines with rated power less than 100 kW- (listed in italics where different)
2. Assumes nacelle is 1/3 gearbox, 1/3 generator and 1/3 frame & machinery
3. Approximately half of the small turbine market (measured in MW) is direct drive with no gearbox
4. Rotor blades are either glass reinforced plastic, wood-epoxy or injection molded plastic with carbon fibers

Material fatigue properties are an important consideration in wind turbine design and materials selection. During the expected 30 year life of a wind turbine, many of the components will need to be able to endure 4×10^8 fatigue stress cycles. This high cycle fatigue resistance is even more severe than aircraft, automotive engines, bridges and most other man-made structures.

- “100 tons of steel for a 1 MW capacity tower ”
- 1 MW capacity produces .3 MW, or satisfies 30 Americans total energy needs
- 3 tons per American = 1 Hummer-equivalent per American
- 1 TW construction per year = 1,000,000 tower per year = 100 million tons
- Annual global steel production is currently 800 millions tons (requiring .5 TW).

- Making a ton of steel requires 2×10^{10} J.
- Making steel for a 1 MW wind turbine requires 2×10^{12} J.
- Producing 0.3 MW for a year produces 10^{13} J.



from Kempton et al.: A private company, Cape Wind Associates, proposes to install 130 wind turbines in 62 km^2 (24 square miles) of Nantucket Sound. ... These machines are 128 meters from sea level to top blade tip (420 feet, or about 40 stories) and their nameplate electrical output is 3.6 MW.

This development is projected to generate a peak power of 420 MW, adding up to 1,491,384 MW hours of electricity per year (170 MW), which is about 3/4 the electrical needs of Cape Cod, or 1/10 of the demand of the entire state of Massachusetts...

From the Draft EIS: The Cape Wind Energy Project developer, Cape Wind Associates, LLC (the applicant), proposes to build, operate, and eventually decommission an electric generation facility with a maximum electric output of 468 megawatts and an average output of 182.6 megawatts, in Nantucket Sound off the coast of Massachusetts (proposed action). The proposed action would generate electricity from wind energy resources on the Outer Continental Shelf. The applicant seeks to commence construction in 2009 and begin operation in 2010.

Investigate the claim of 1/10 of MA electricity:

- Massachusetts consumes 6 GWe. Cape Wind is 2.8% of MA electricity.
- 6 million Massachusettians consume 10,000 W each of total energy, or 60 GW. Cape Wind is 0.28% of MA energy.

Calculate the flux density:

- 6.7 W m^{-2} peak. 2.7 W m^{-2} average.

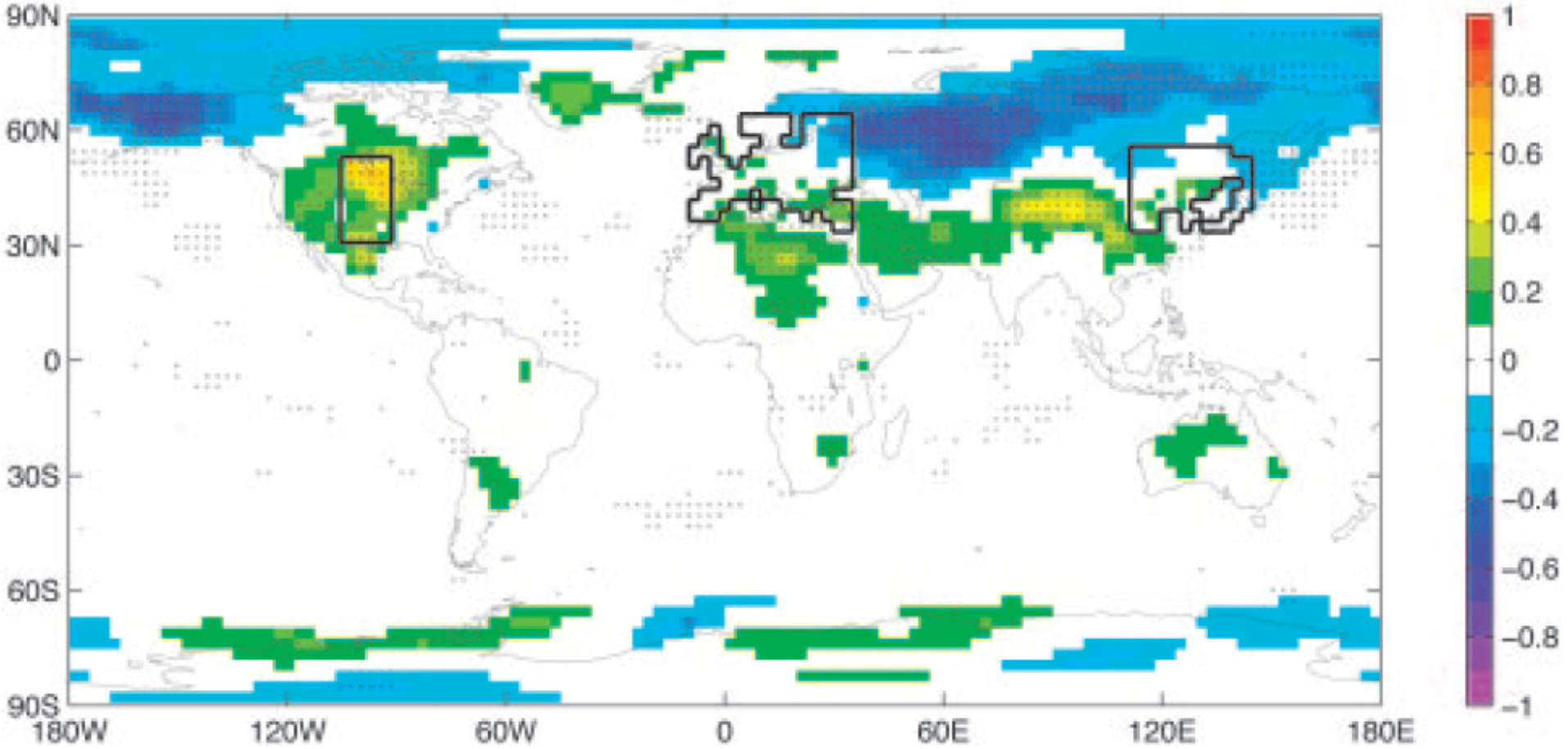
from Kempton et al.: Geographically, the developer states that Nantucket Sound is a highly favorable site for wind development, arguably the best on the east coast (strong steady winds, close to power lines on shore, shallow water, protected from high waves, and minimal conflicts with transportation systems). Financially, private investors are supplying about $750M capital; about $12M has been spent to date on environmental impact studies, erecting a wind measuring tower on-site, and an extensive public relations campaign.

- $4.40 per Watt of production
- 7.5% return on investment requires selling for $0.038 per kWh.

NY Times, February 23, 2008:

Not to be outdone, Mr. Pickens is planning his own 150,000-acre Panhandle wind farm of 4,000 megawatts that would be even larger and cost him $10 billion.

- 234 square miles (42% of Cleveland County)
- 6.6 W m^{-2} (Peak or Average??)
- 0.004 TW
- \$2.50 per Watt of capacity



Keith *et al.* PNAS, 2004. NCAR GCM surface air temperature. Experiment with an extra 21 TW of power dissipation in the boundary layer, minus control.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, D19101, doi:10.1029/2004J

Can large wind farms affect local meteorology?

S. Baidya Roy and S. W. Pacala

Department of Ecology and Evolutionary Biology, Princeton University, Princeton, New Jersey, USA

R. L. Walko

Department of Civil Engineering, Duke University, Durham, North Carolina, USA

Received 11 March 2004; revised 9 July 2004; accepted 20 July 2004; published 1 October 2004.

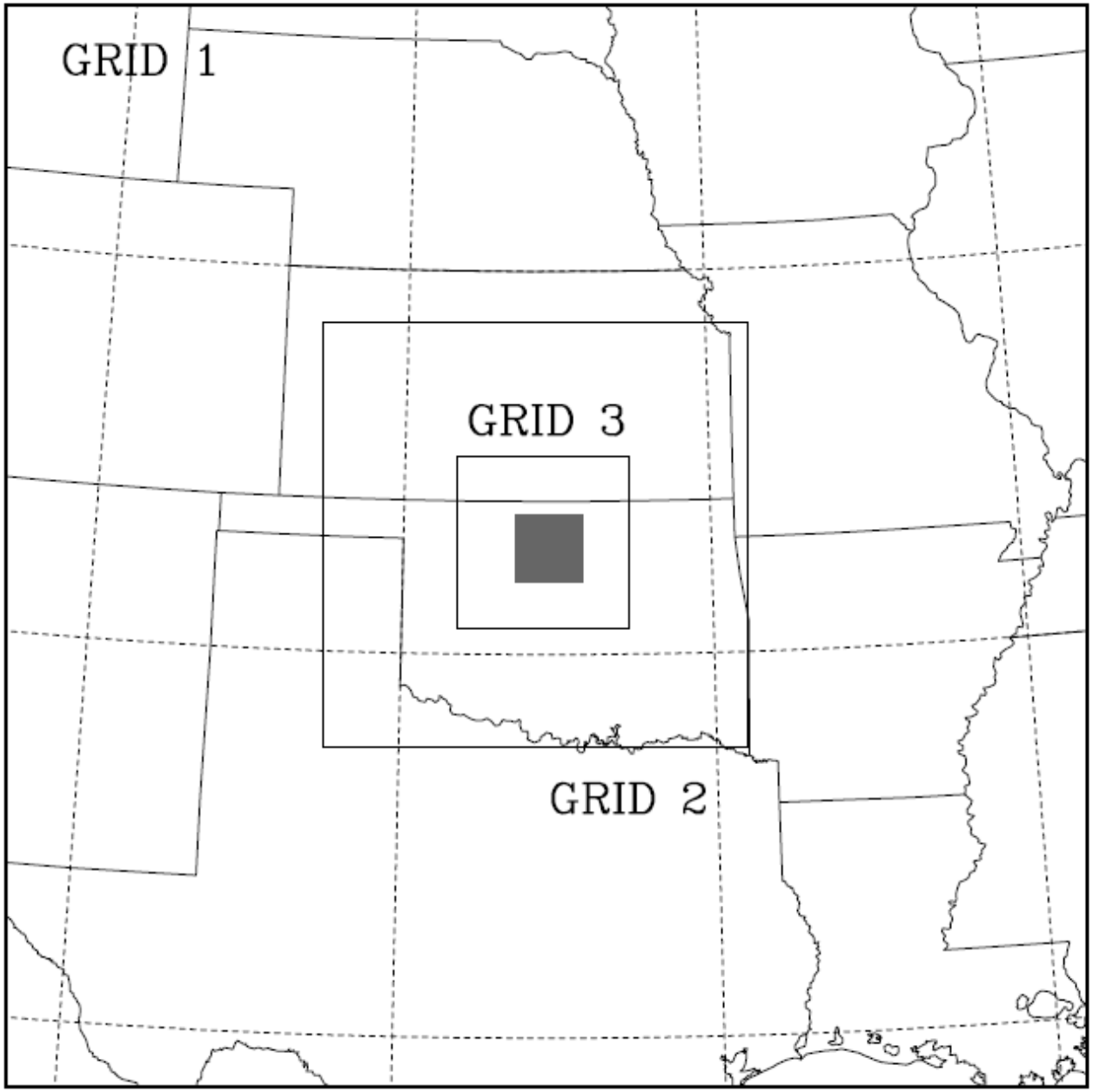


Figure 1. Model domain showing the three grids. The shaded area in the center of grid 3 denotes the wind farm.

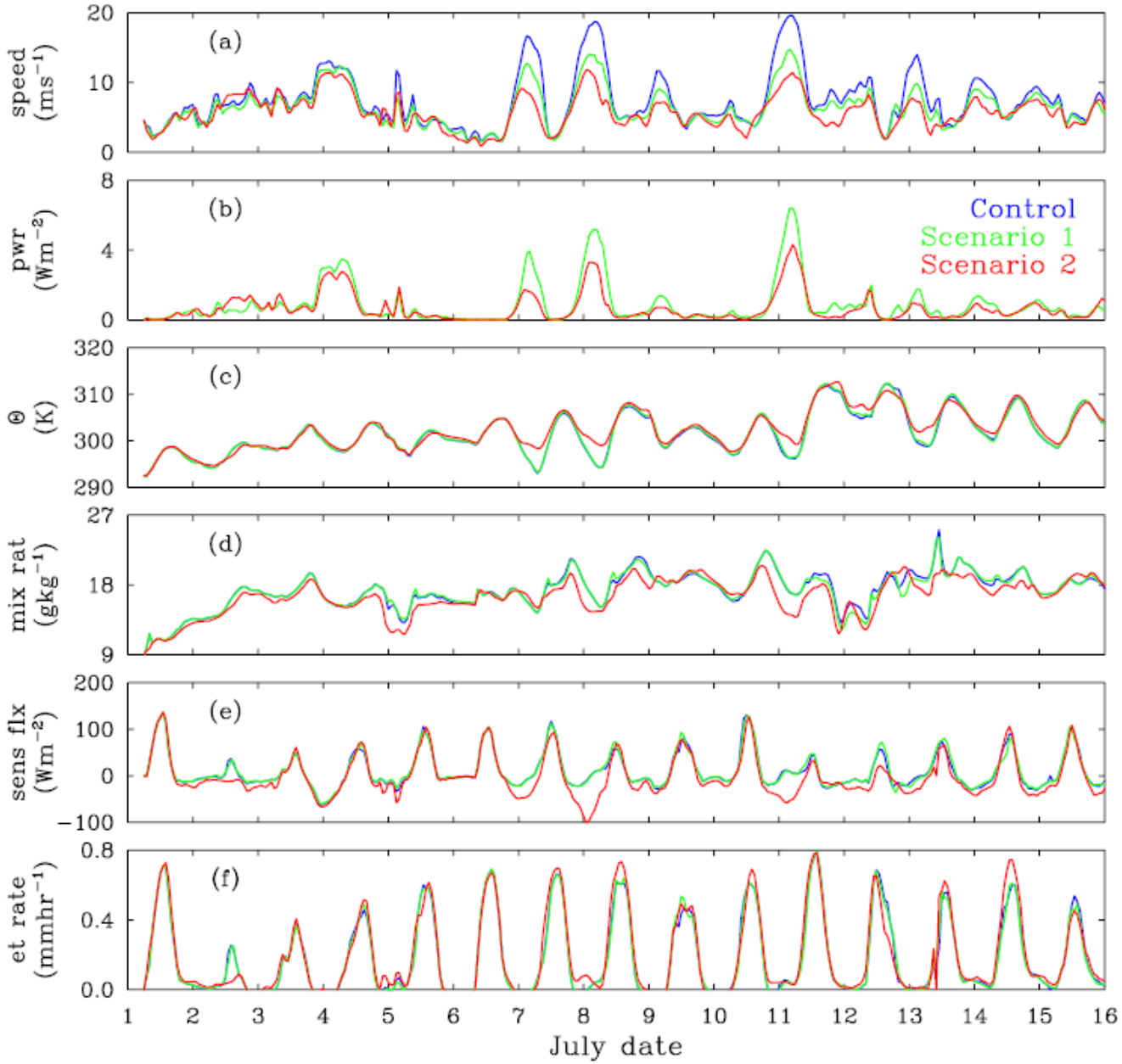


Figure 3. Time series of (a) hub-height horizontal wind speed, (b) power extracted, (c) surface air θ, (d) total water mixing ratio, (e) surface sensible heat flux, and (f) surface evapotranspiration rate over the wind farm.

The history of the failure of war can almost be summed up in two words:

too late.

– General Douglas Macarthur

- Too late in comprehending the deadly purpose of a potential enemy.
- Too late in realizing the mortal danger.
- Too late in preparedness.
- Too late in uniting all possible forces for resistance.
- Too late in standing with one's friends.