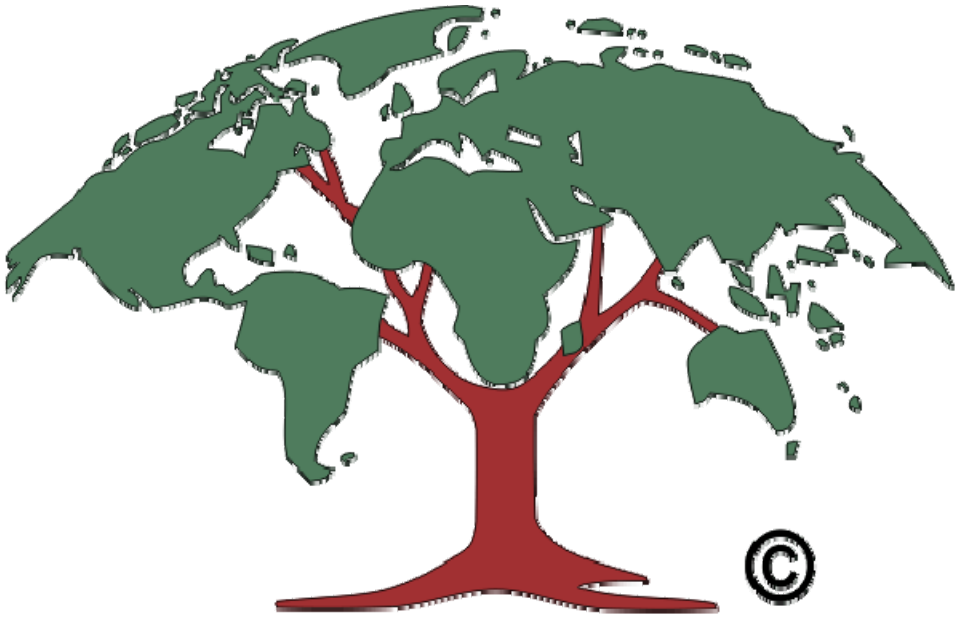

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THE WOODS HOLE RESEARCH CENTER

The nature of the necessity

- Global climate change is real, accelerating, and caused mainly by emissions from civilization's energy system.
- The changes are already causing significant harm:
  - increased frequency and intensity of floods, droughts, heat waves, wildfires
  - expanded ranges of temperature-dependent pests & pathogens
  - other unwelcome changes in species ranges and abundances

The necessity (continued)

- Much greater damage is ahead on the "business as usual" trajectory, including likelihood of:
  - loss of coral reefs, polar bears, and as much as 30% of global biodiversity in this century;
  - reduced agricultural productivity;
  - greater frequency of extreme tropical storms;

  and a real possibility of

  - rapidly accelerating sea-level rise (2-5 m/century??)
- Significantly improving our chances of escaping an unmanageable degree of climatic disruption requires that a major change of direction be underway, worldwide, by 2015.
- If the United States leads, others will follow.

Energy-sector CO_2 is the biggest problem

- CO_2 contributed 47% of the cumulative positive anthropogenic forcing up to 2000.
- It's share is increasing: Under BAU, it will have contributed over 60% as of 2100.
- Currently 75-80% of the CO_2 emissions come from fossil-fuel burning, 20-25% from land-use change (mostly tropical deforestation), and 2-3% from cement production.
- The fossil-fuel contribution resists reduction because
  - fossil fuels are 80% of world energy supply;
  - volume of combustion-product CO_2 is huge;
  - part of atmospheric increase persists for centuries.

Options for reducing fossil CO_2 emissions

Reduce growth of energy use by…

- reducing population growth
- reducing growth of GDP/person
- reducing E/GDP ratio by
  - increasing efficiency of conversion to end-use forms
  - increasing technical efficiency of energy end-use
  - changing mix of economic activities

Reduce CO_2/E ratio by…

- substituting natural gas for oil & coal
- replacing fossil fuels with renewables
- replacing fossil fuels with nuclear energy
- capturing & sequestering CO_2 from fossil-fuel use

There is no silver bullet

All of the options have limitations & liabilities (some of which translate into increased energy costs).

- limiting population: social & political sensitivities
- slowing GDP/person: economic aspirations
- expanding natural gas: resource size & distribution
- wind: siting (NIMBY→BANANA), intermittency
- biofuels: net energy, land, food/ecosystem impacts
- photovoltaics: cost, intermittency, toxics
- nuclear fission: cost, waste, safety, proliferation
- nuclear fusion: doesn't work yet
- CO_2 capture/sequestration: cost, scale, complexity
- end-use efficiency: education, other barriers

Big problem & lack of silver bullet mean…

- We'll need a portfolio of approaches
  - Not just one or two, but many;
  - although not necessarily everything on the menu, as developing the better options to their full potential may allow foregoing some that prove very costly or risky.
- We need increased research & development on all of the options to try to
  - raise their limits,
  - lower their liabilities, and
  - reduce the uncertainties,

  so that the future menu can be both better than today's and more transparent about what one is buying.

To be clear…

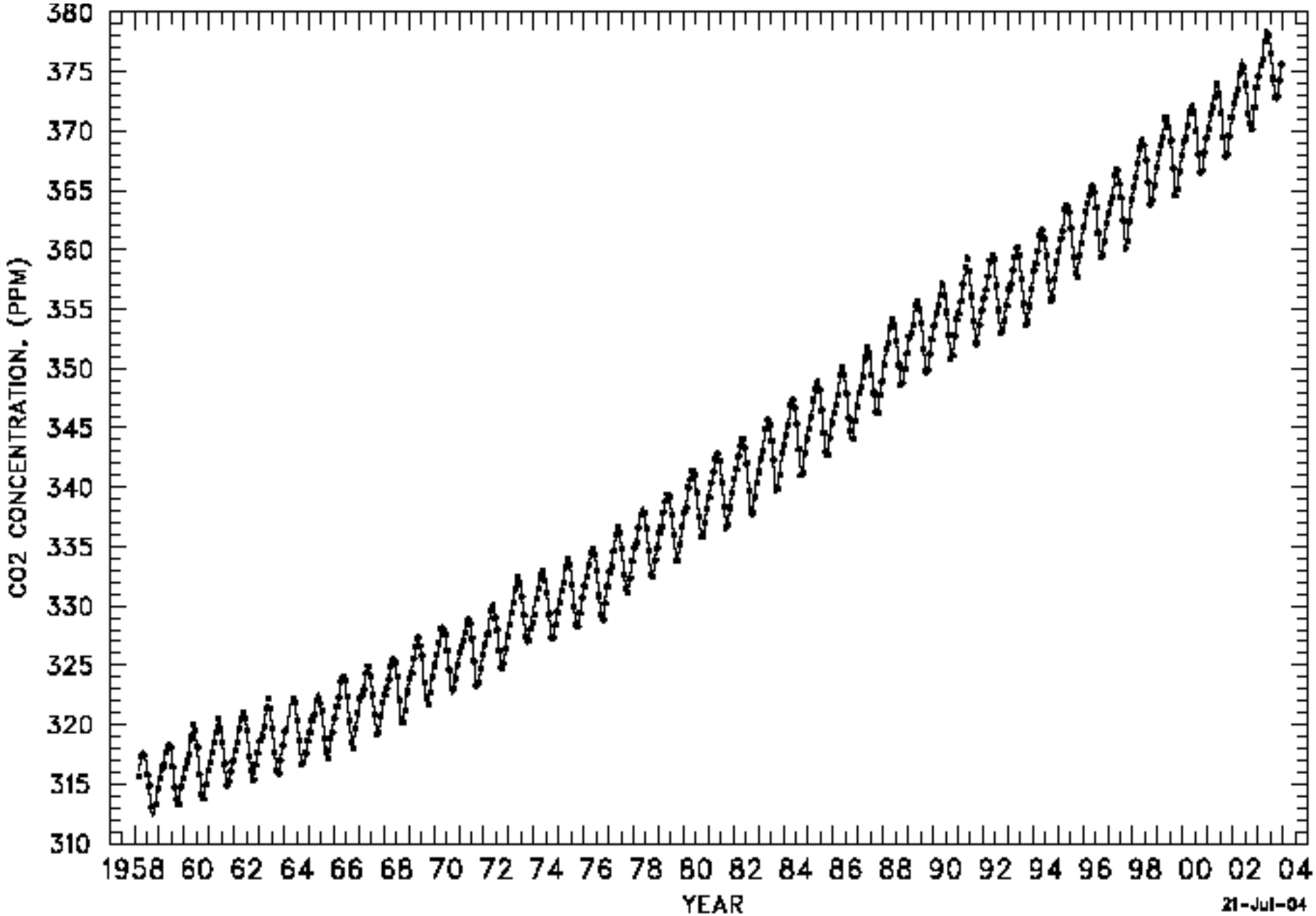
The climate challenge gives us only three options:

- greatly increased efforts at mitigation;
- greatly increased efforts at adaptation;
- greatly increased suffering.

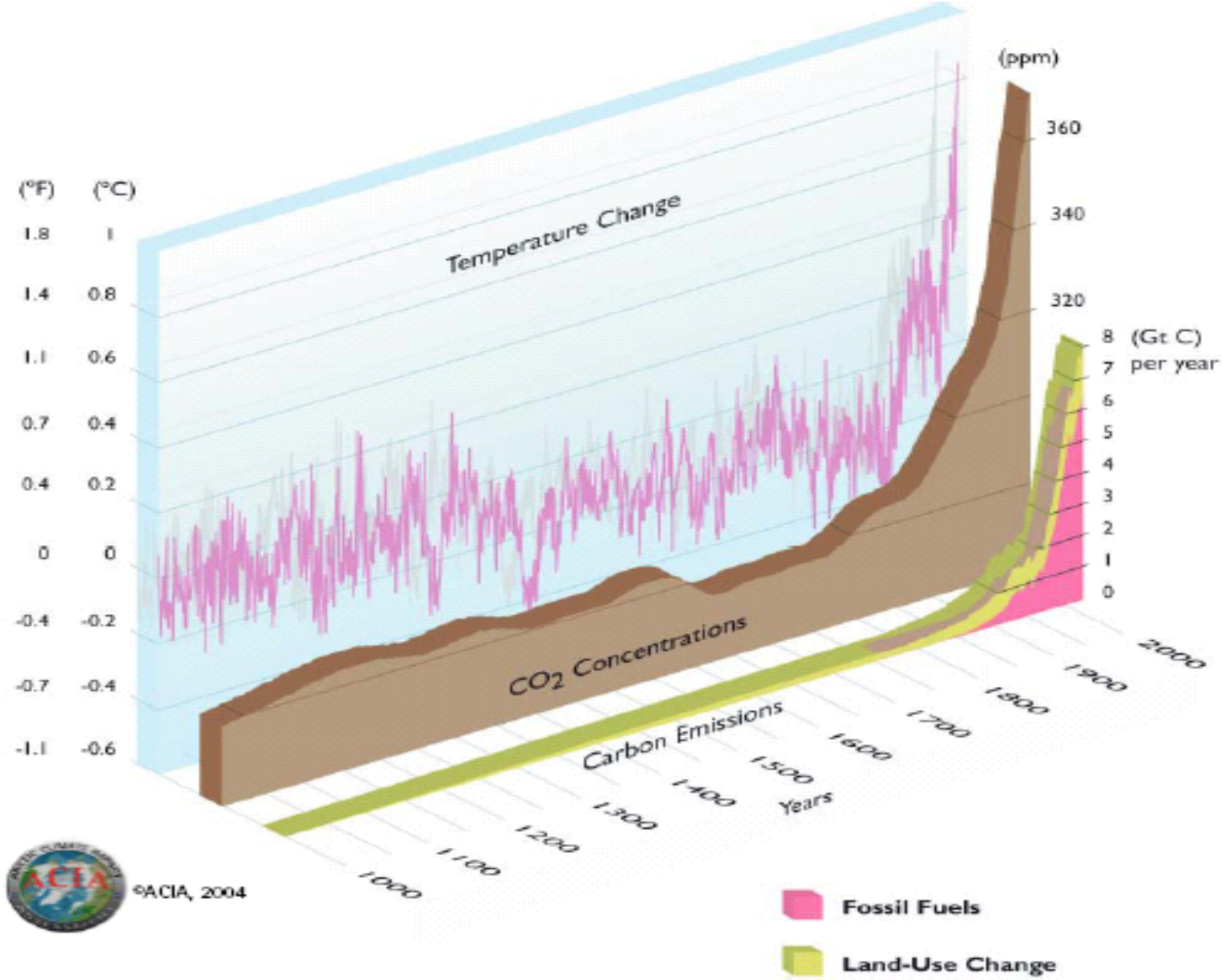
We are already doing some of each; what's up for grabs is the future mix.

  - Mitigation alone won't work because climate change is already occurring & can't be stopped quickly.
  - Adaptation alone won't work because adaptation gets costlier & less effective as climate change grows.
  - The more mitigation we can manage, the more likely that adaptation can avoid the worst of the suffering.

Measured CO2 concentration at Mauna Loa



1000 years of global C emissions, CO_2 concentrations, and temperature



Coastal glaciers are retreating

Muir Glacier, Alaska, 1941-2004

August 1941

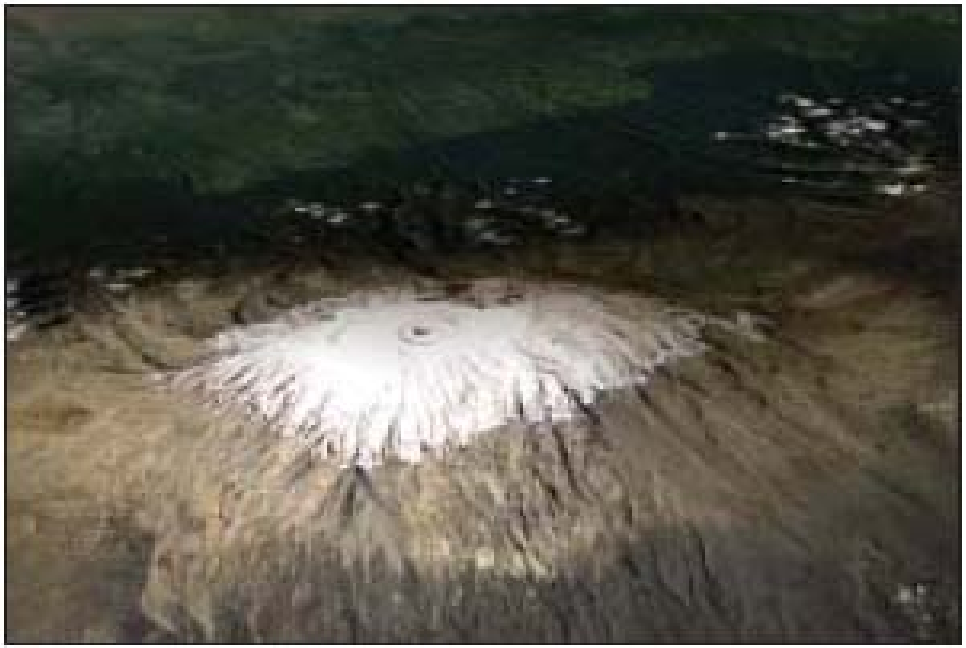
August 2004

NSIDC/WDC for Glaciology, Boulder, compiler. 2002, updated 2006. *Online glacier photograph database.* Boulder, CO: National Snow and Ice Data Center.

Kilimanjaro, 1993-2000

The famous snows of Kilimanjaro have been shrinking rapidly in recent decades.

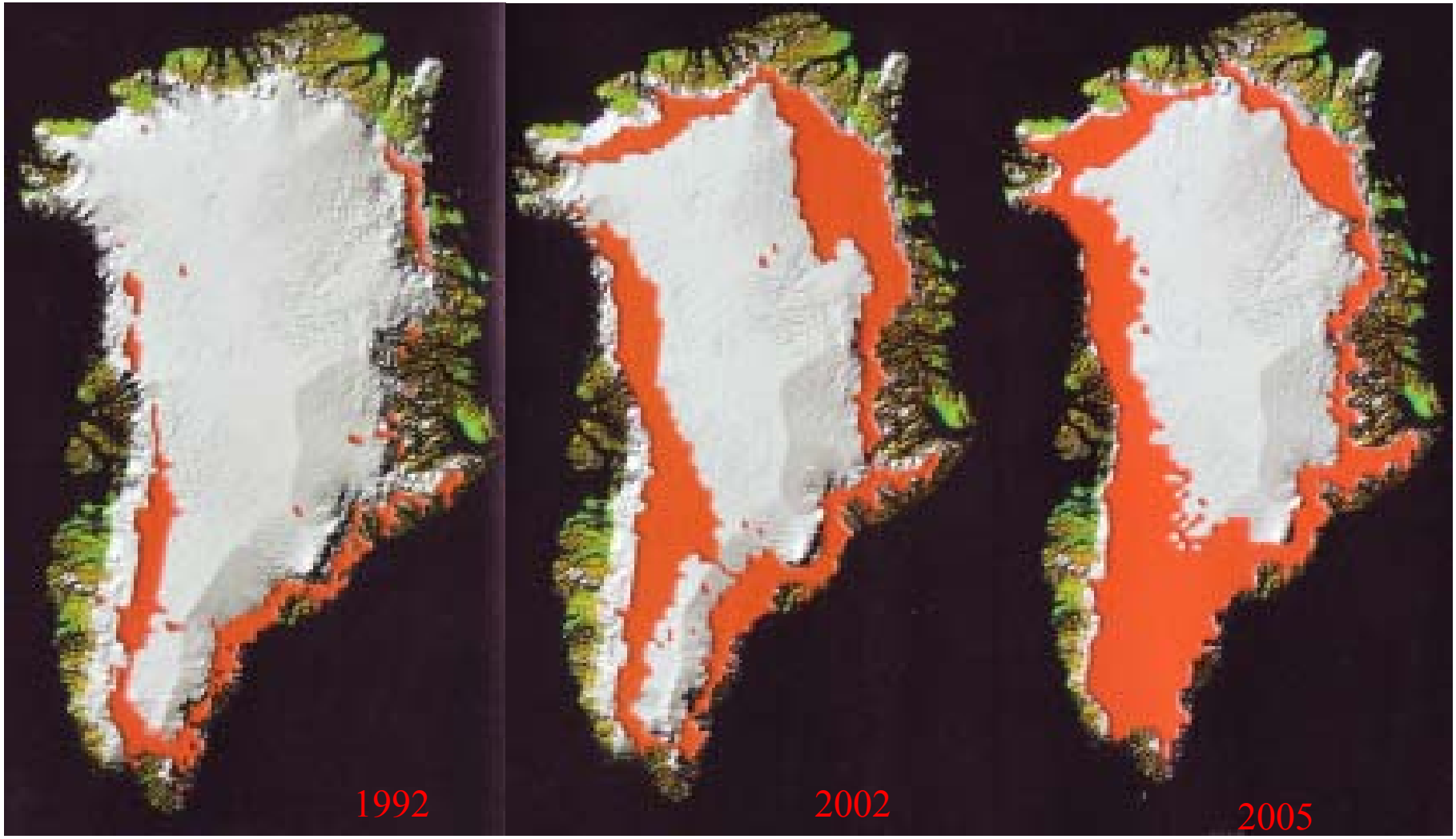
This is particularly significant because high-elevation ice and snow near the equator do not vary much <u>except</u> when climate is changing globally.



Mt. Kilimanjaro, 1993 © NASA

Mt. Kilimanjaro, 2000 © NASA

Surface melting on Greenland is expanding

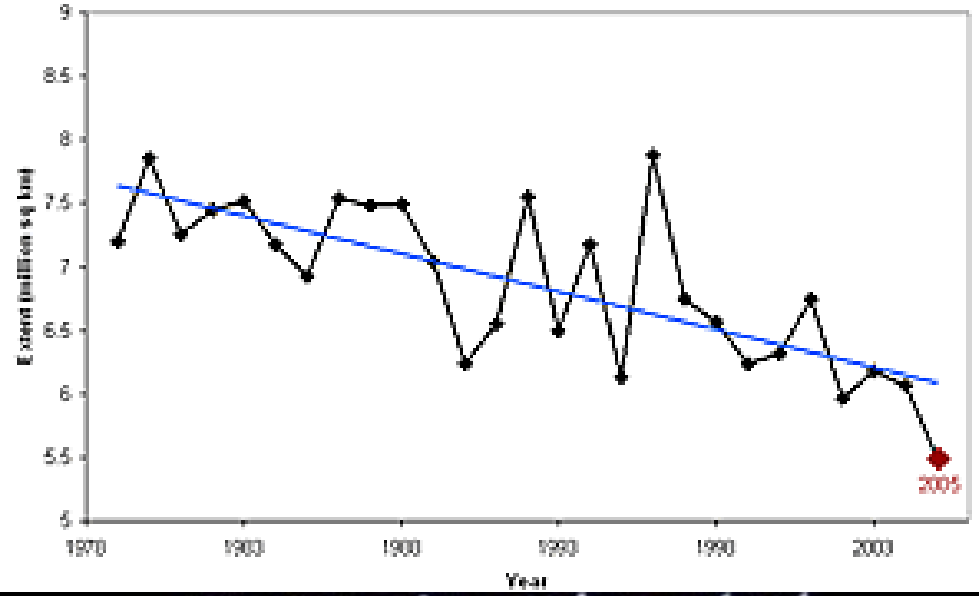


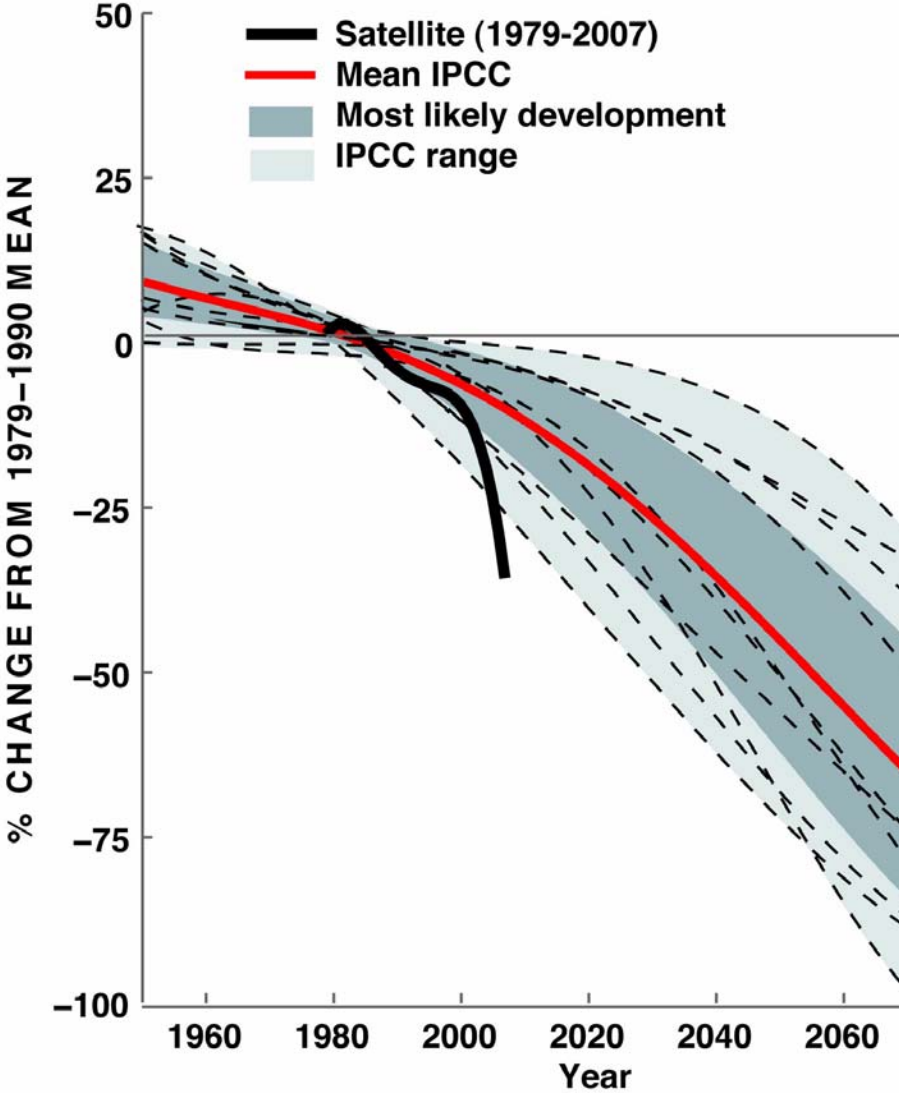
In 1992 scientists measured this amount of melting in Greenland as indicated by red areas on the map

Ten years later, in 2002, the melting was much worse

And in 2005, it accelerated dramatically yet again

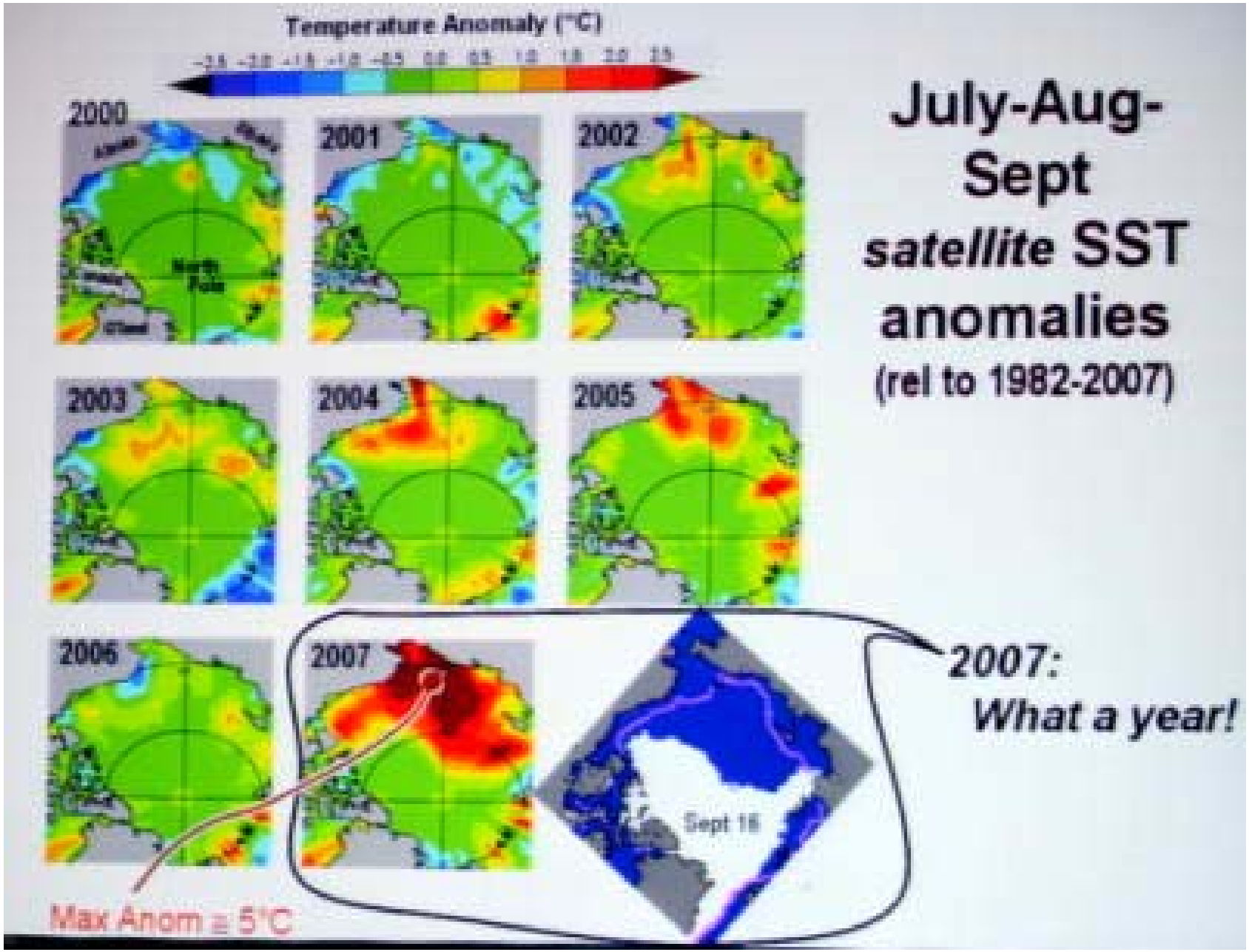
Source: ACIA, 2004 and CIRES, 2005





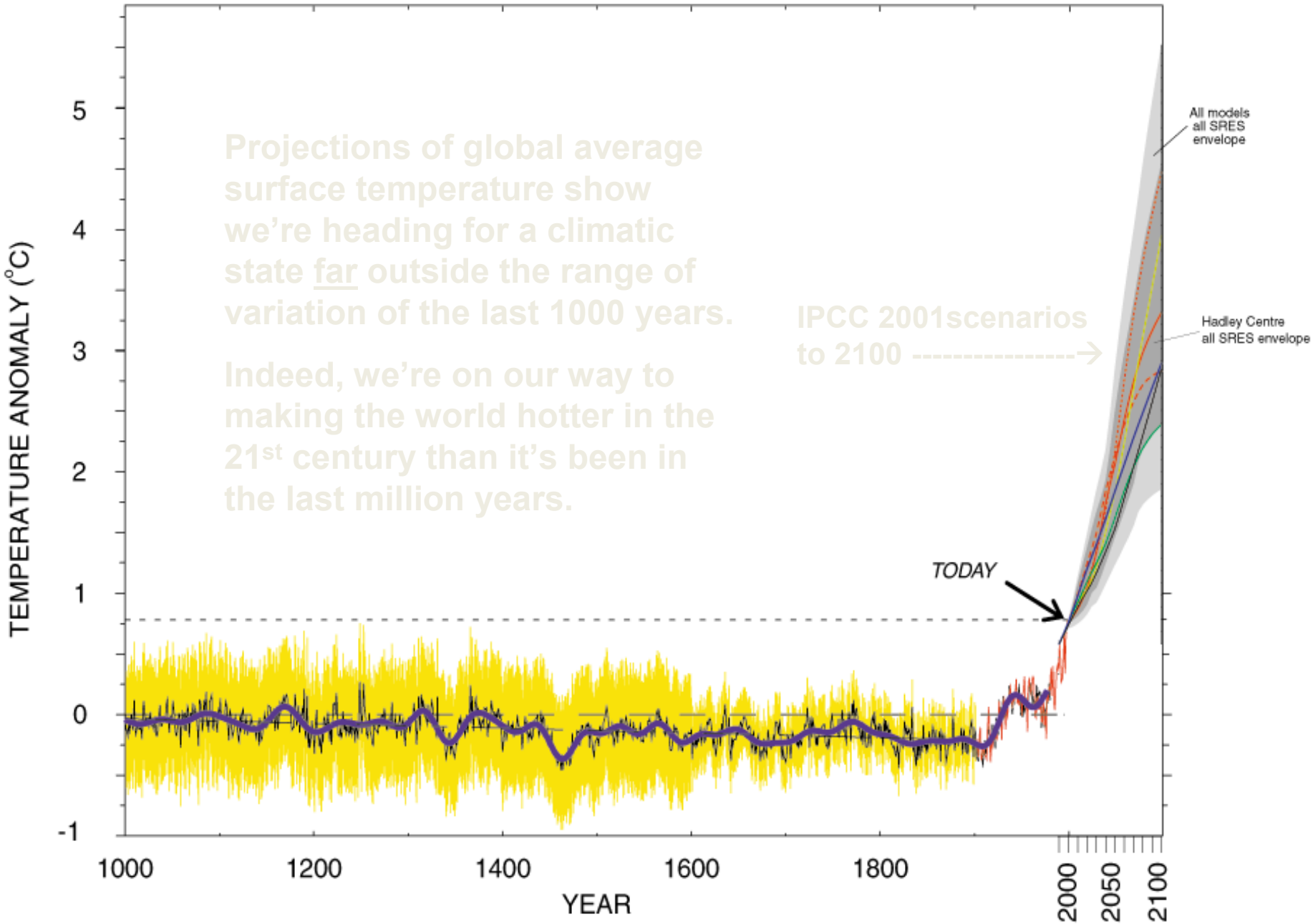
Arctic sea ice loss compared to IPCC

Arctic ice extent loss to September 2007 compared to IPCC modelled
using the SRES A2 CO2 scenario (IPCC high CO2 scenario). Septem
from satellite observations. Data smoothed with a 4th order polynomia
out the year-to-year variability. Chart courtesy Dr Asgeir Sorteberg, Bj
Centre for Climate Research and University Center at Svalbard, Norw
Date: 23 September 2007 www.carbonequity.info/images/seaice07

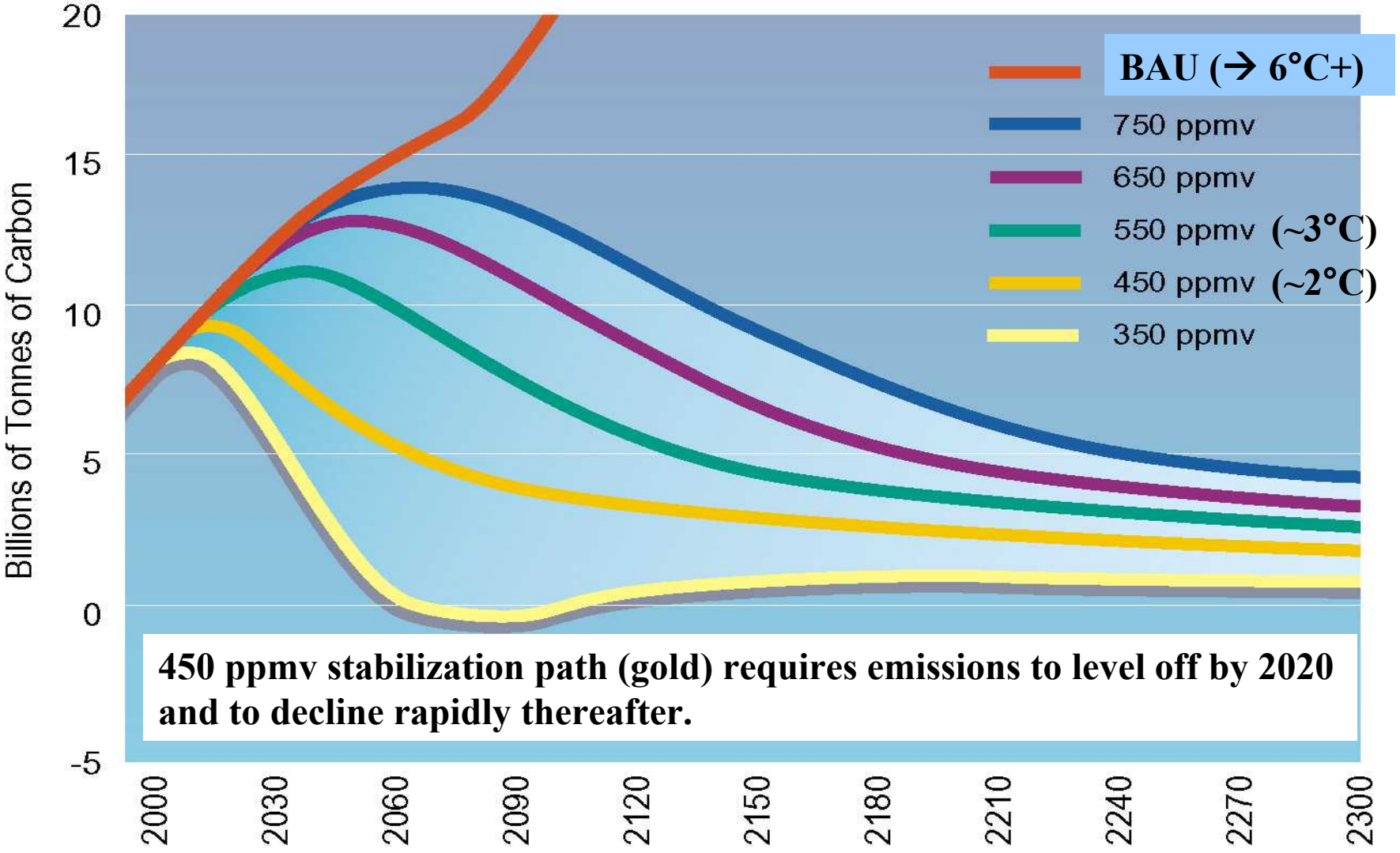


http://www.news.com/8301-13580_3-9833022-39.html

The next 100 years compared to the last 1000

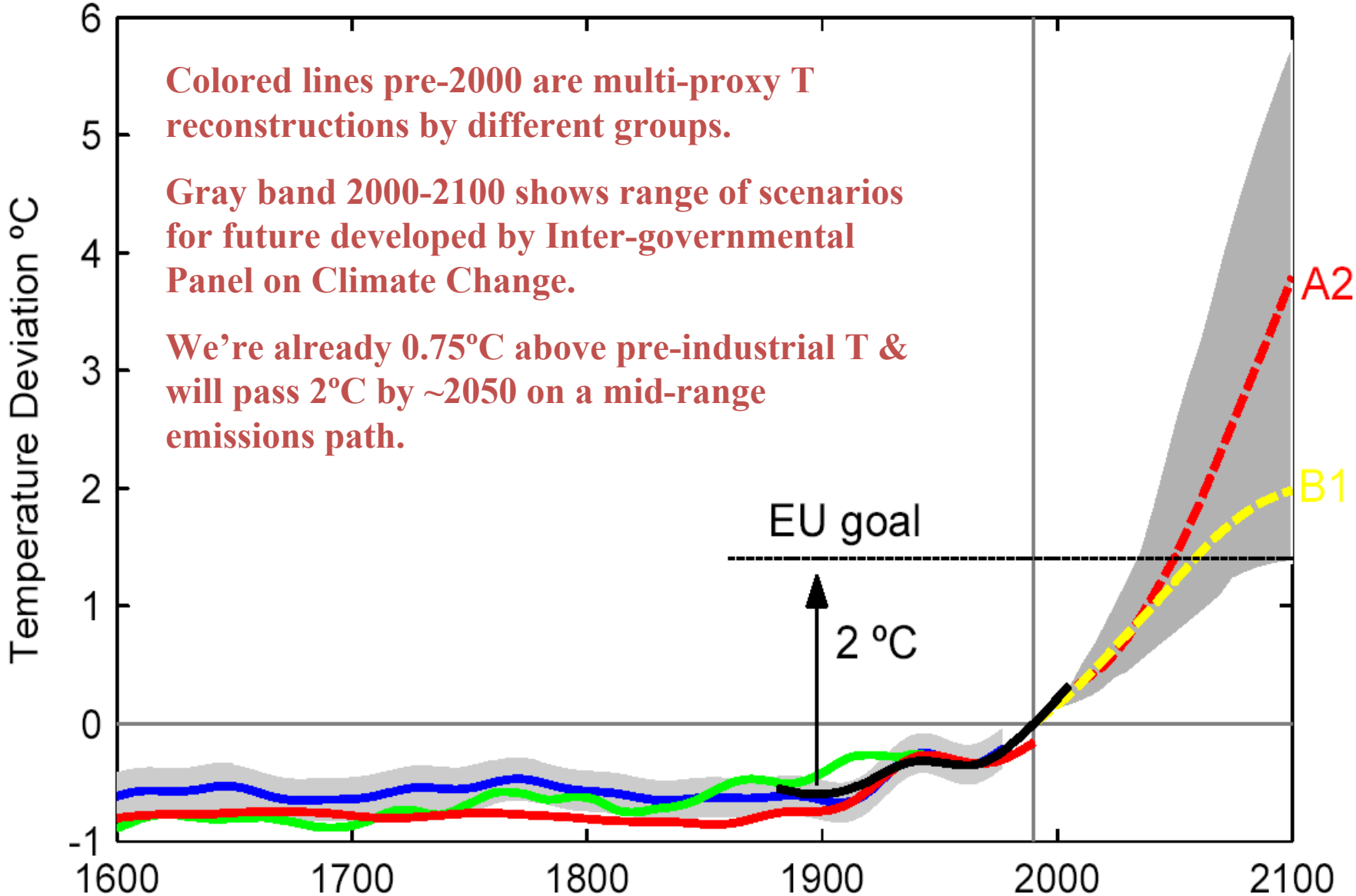


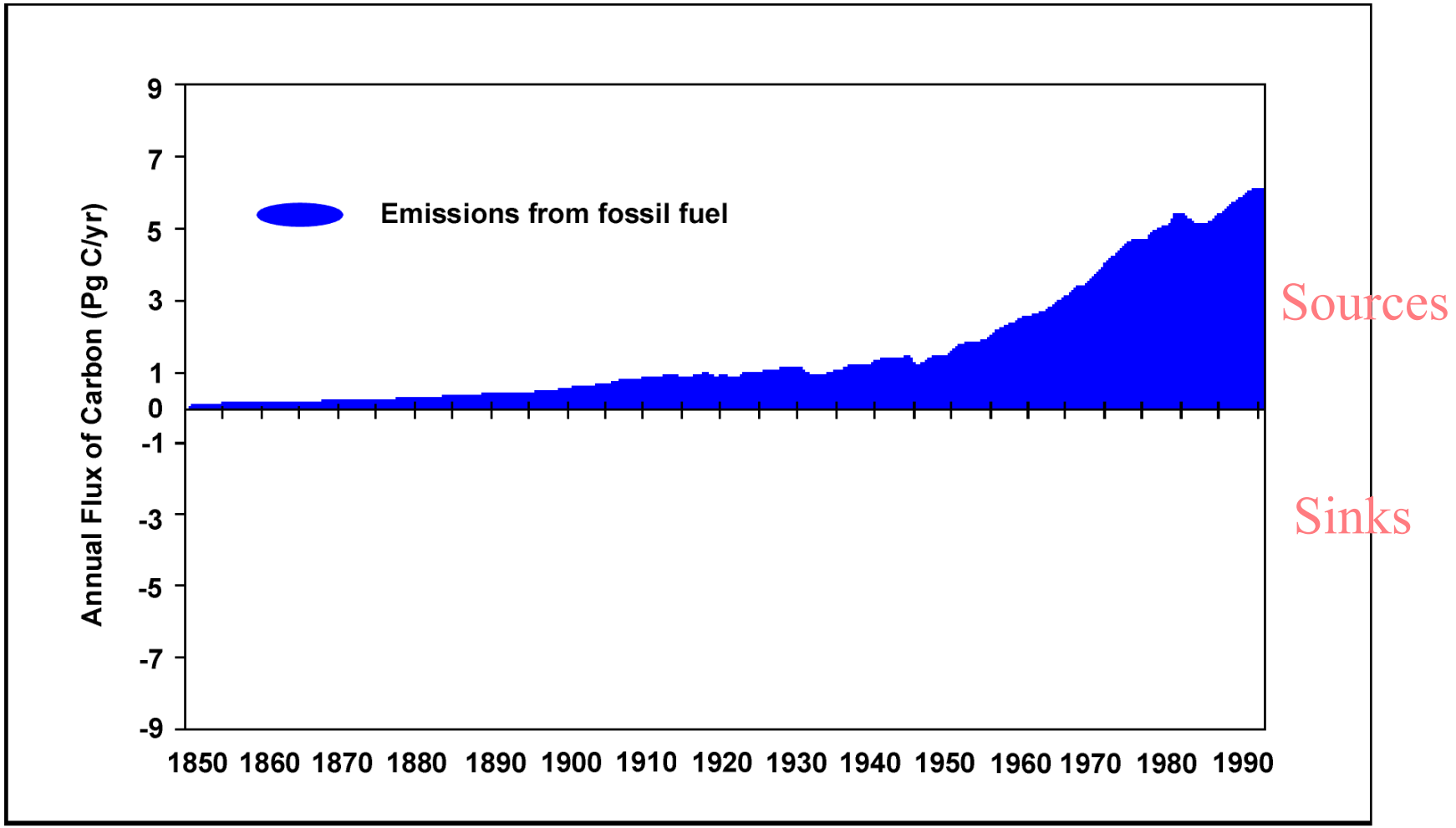
If biosphere is CO_2-neutral and if non-CO_2 influences cancel, fossil CO_2 emission trajectories relate to different stabilization levels as follows:

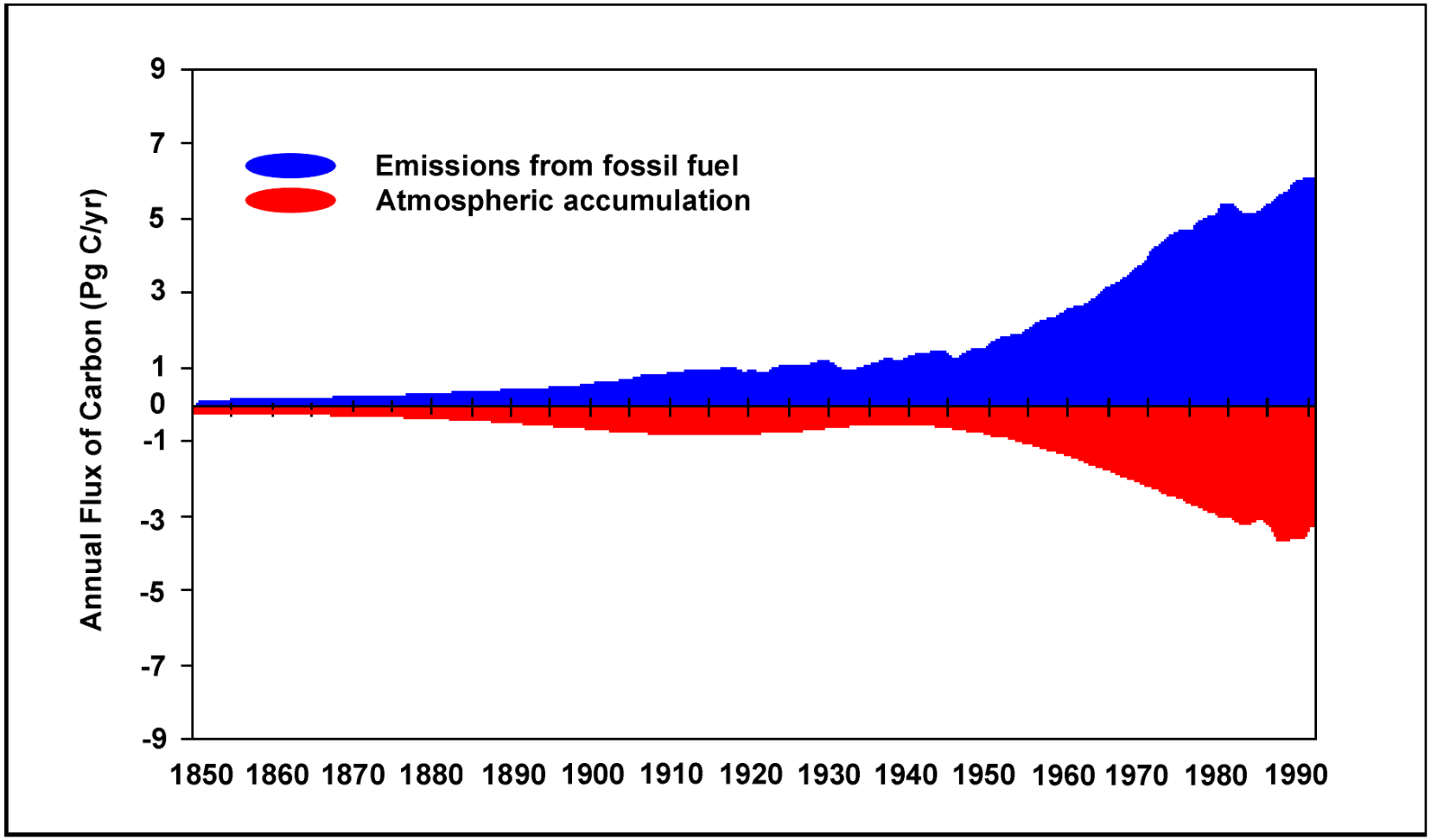


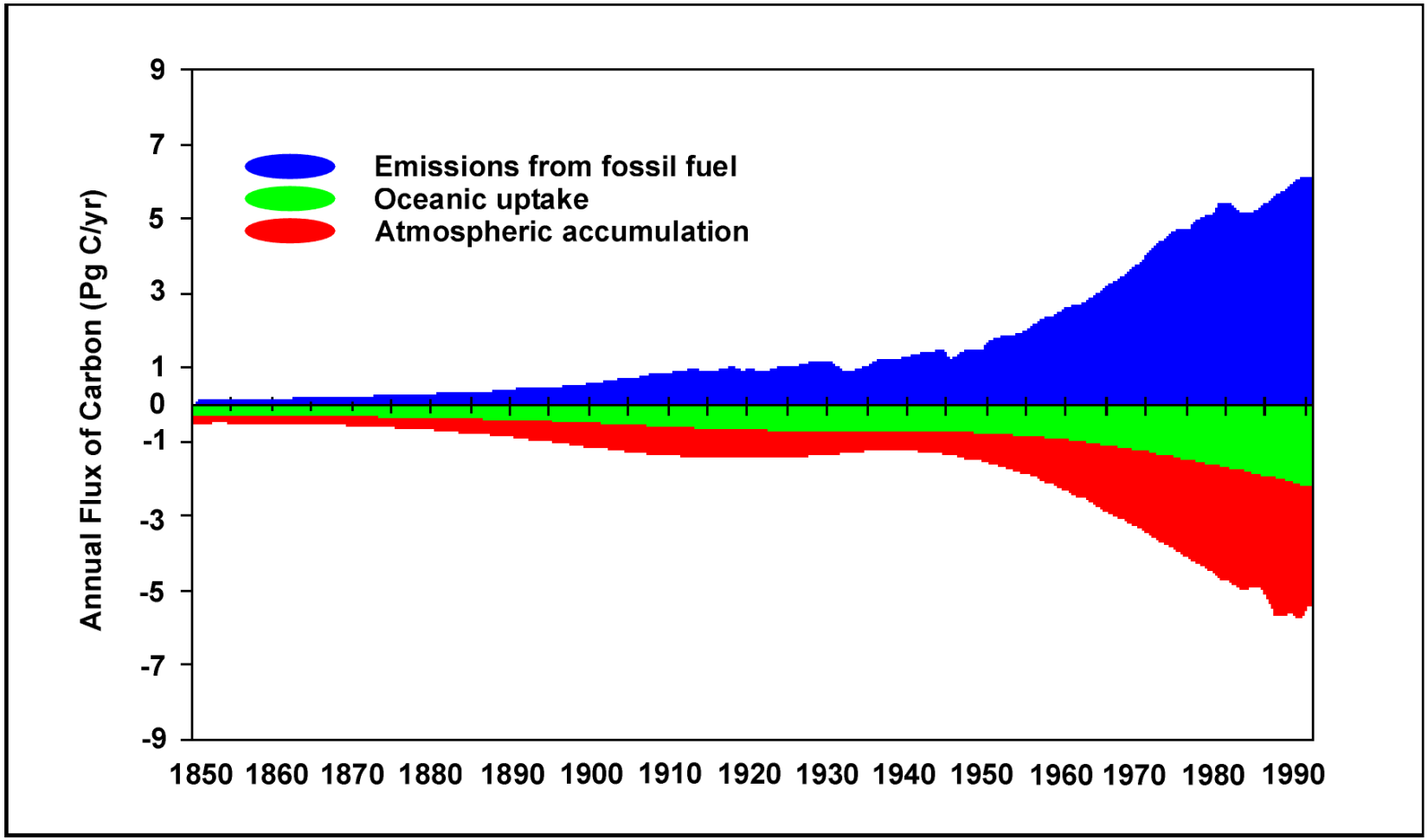
Where we're headed under BAU:

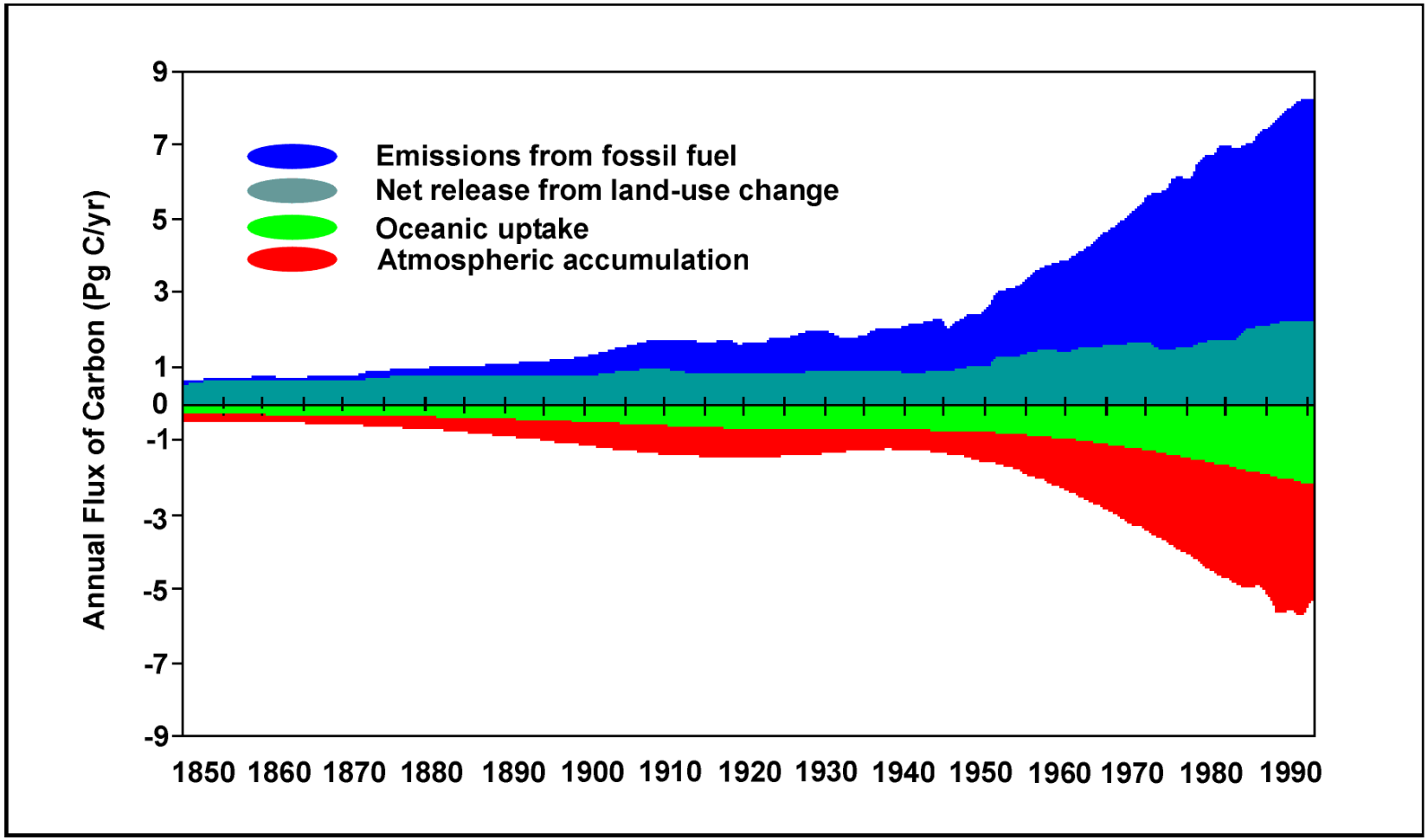
The next 100 years compared to the last 400

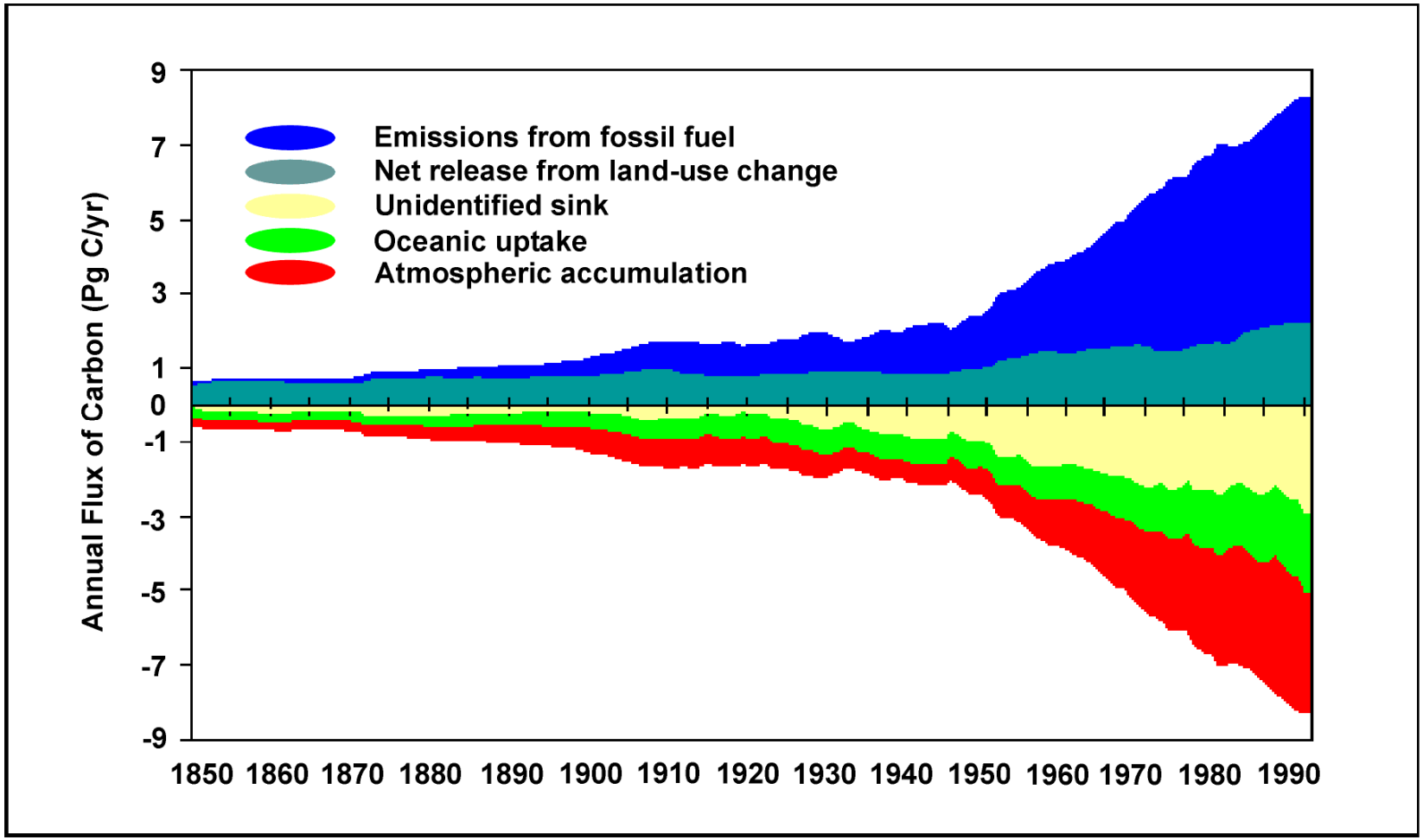


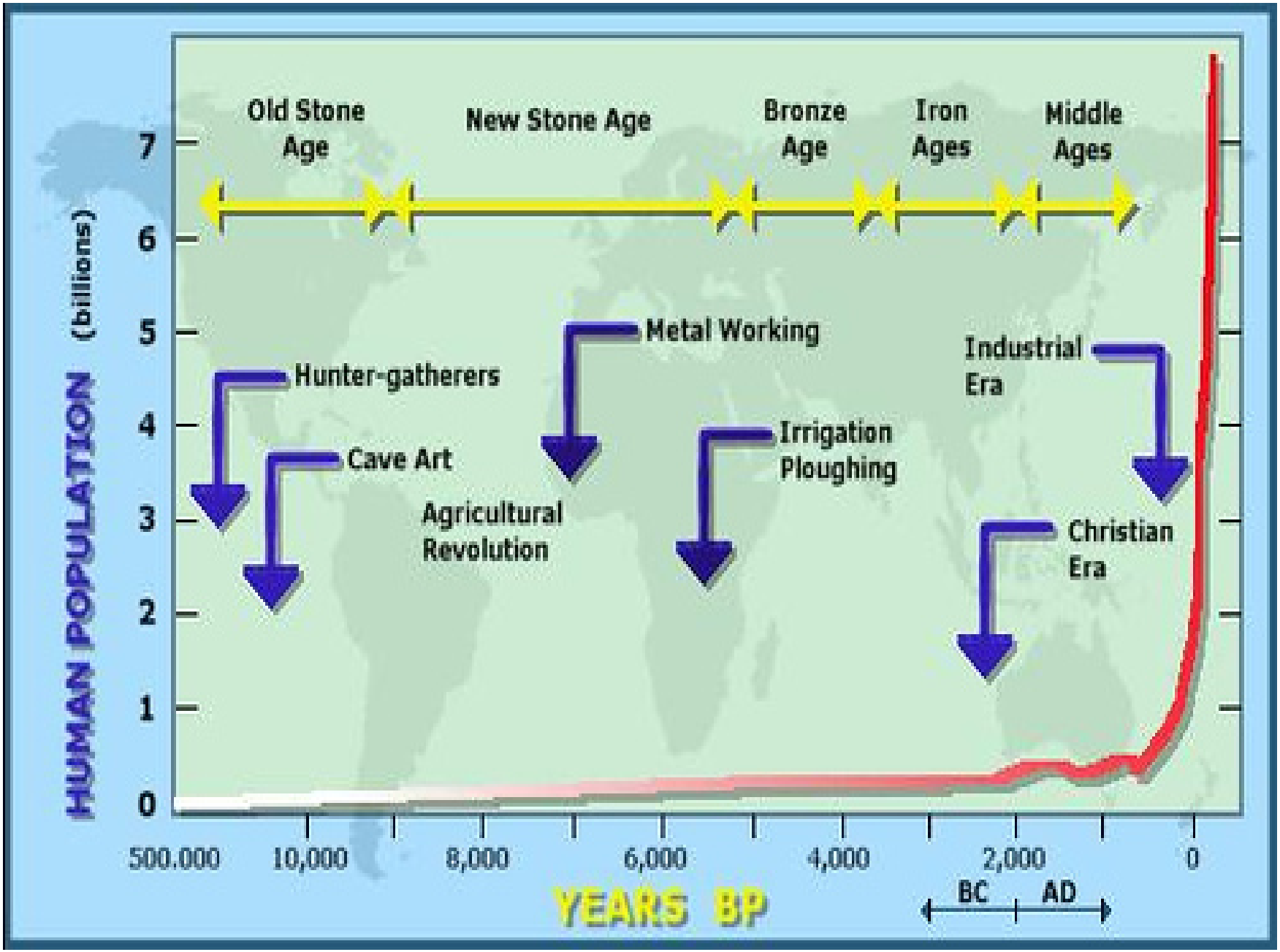

Annual Flux of Carbon (Pg C/yr)
9
7
5
3
1
0
-1
-3
-5
-7
-9
Emissions from fossil fuel
1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Sources
Sinks


Emissions from fossil fuel
Atmospheric accumulation
Annual Flux of Carbon (Pg C/yr)
9
7
5
3
1
0
-1
-3
-5
-7
-9
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990

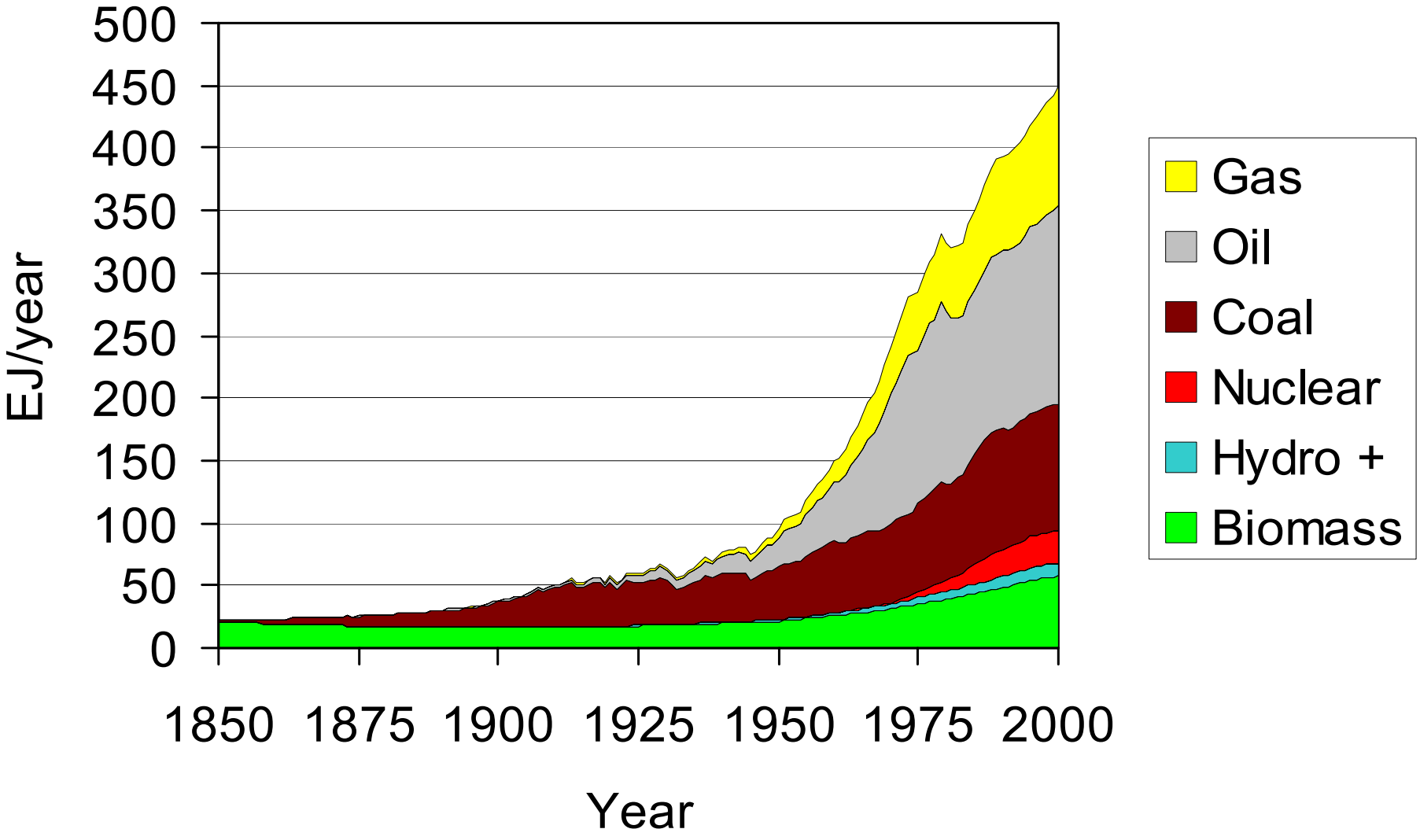

Emissions from fossil fuel
Oceanic uptake
Atmospheric accumulation
Annual Flux of Carbon (Pg C/yr)
9
7
5
3
1
0
-1
-3
-5
-7
-9
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990

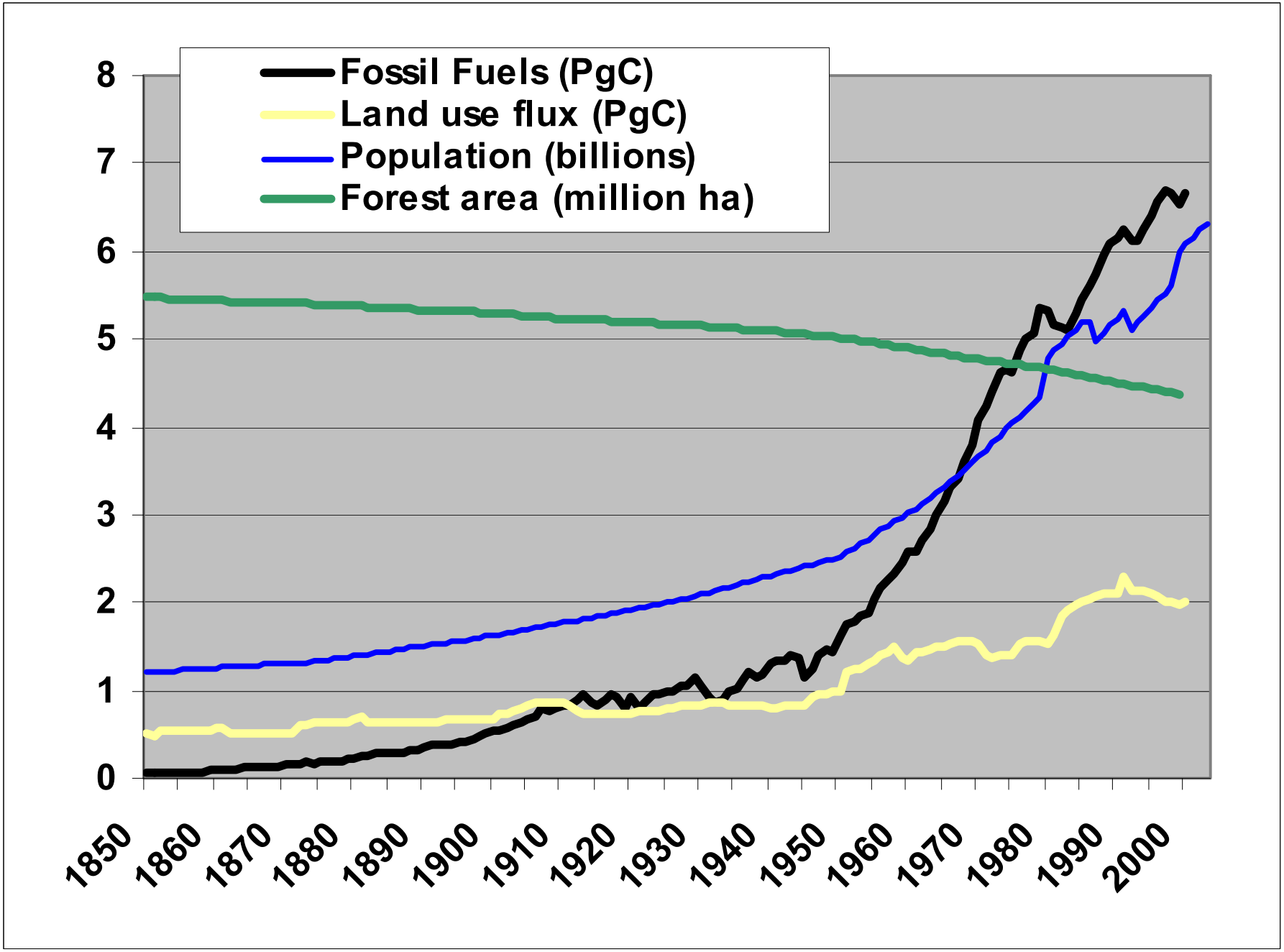

Emissions from fossil fuel
Net release from land-use change
Oceanic uptake
Atmospheric accumulation
Annual Flux of Carbon (Pg C/yr)
9
7
5
3
1
0
-1
-3
-5
-7
-9
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990

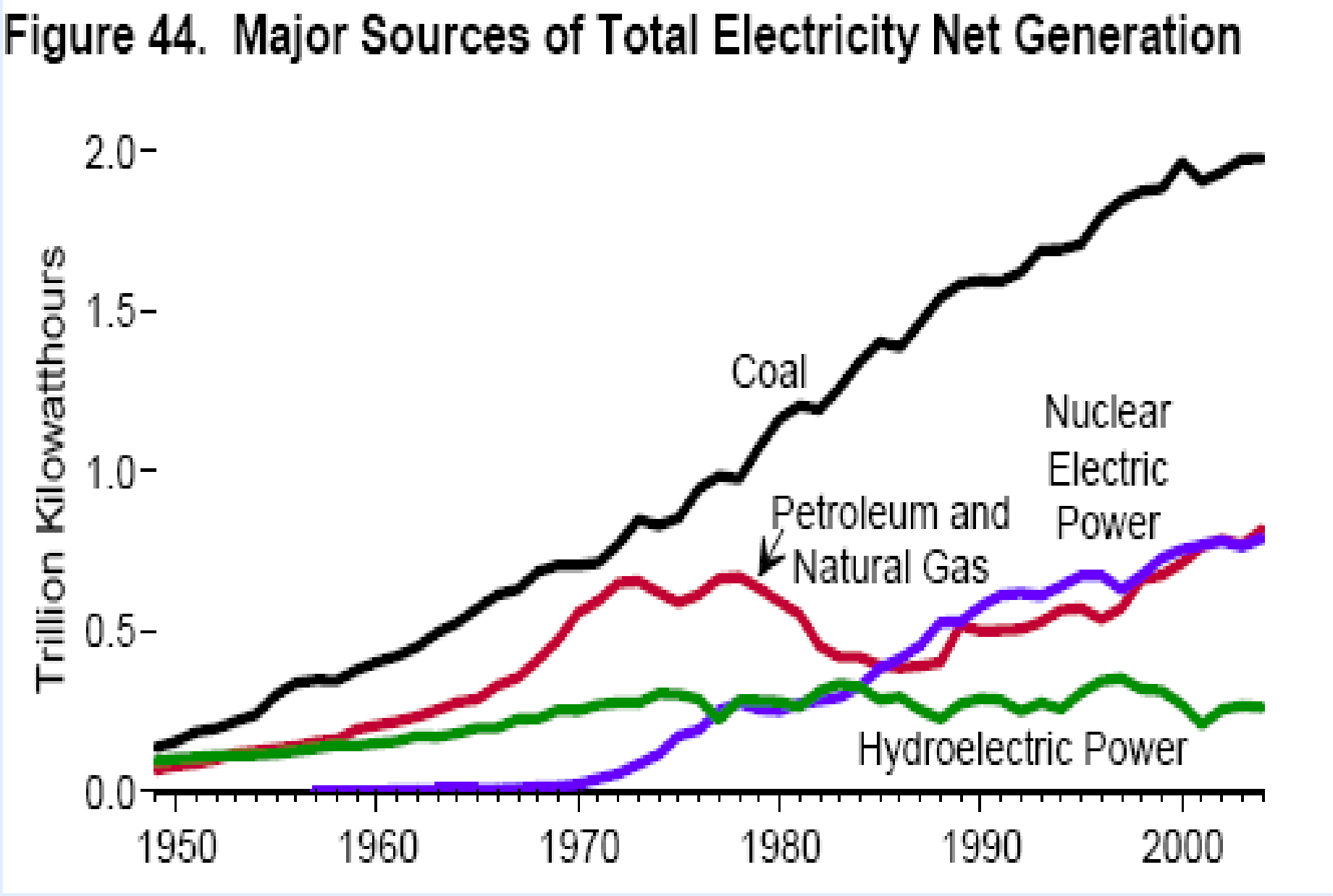

Emissions from fossil fuel
Net release from land-use change
Unidentified sink
Oceanic uptake
Atmospheric accumulation
Annual Flux of Carbon (Pg C/yr)
9
7
5
3
1
0
-1
-3
-5
-7
-9
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990


Old Stone Age
New Stone Age
Bronze Age
Iron Ages
Middle Ages
Hunter-gatherers
Cave Art
Agricultural Revolution
Metal Working
Irrigation Ploughing
Industrial Era
Christian Era
HUMAN POPULATION (billions)
0
1
2
3
4
5
6
7
500.000
10,000
8,000
6,000
4,000
2,000
0
YEARS BP
BC
AD

World Energy 1850-2000

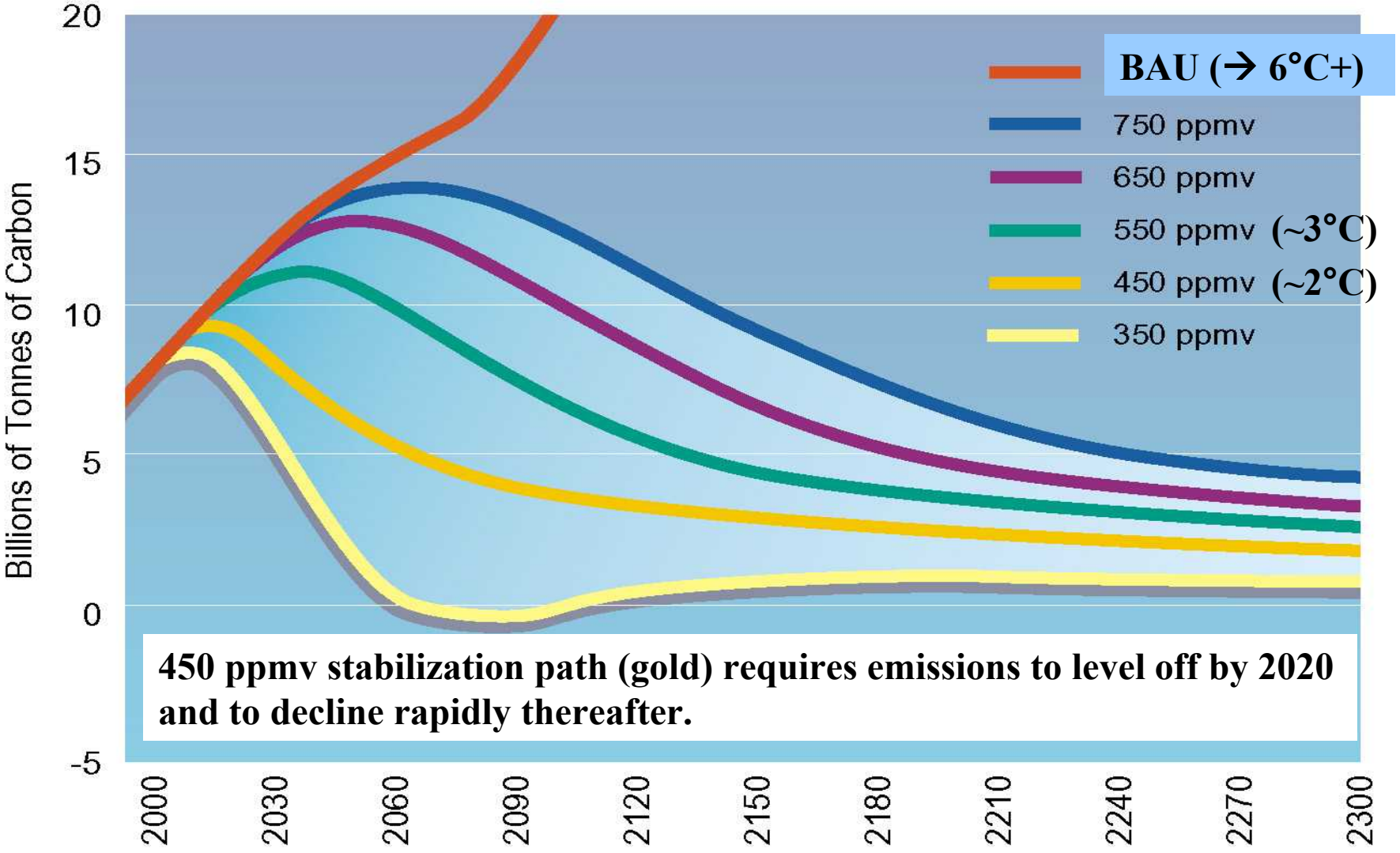



Fossil Fuels (PgC)
Land use flux (PgC)
Population (billions)
Forest area (million ha)
0
1
2
3
4
5
6
7
8
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000



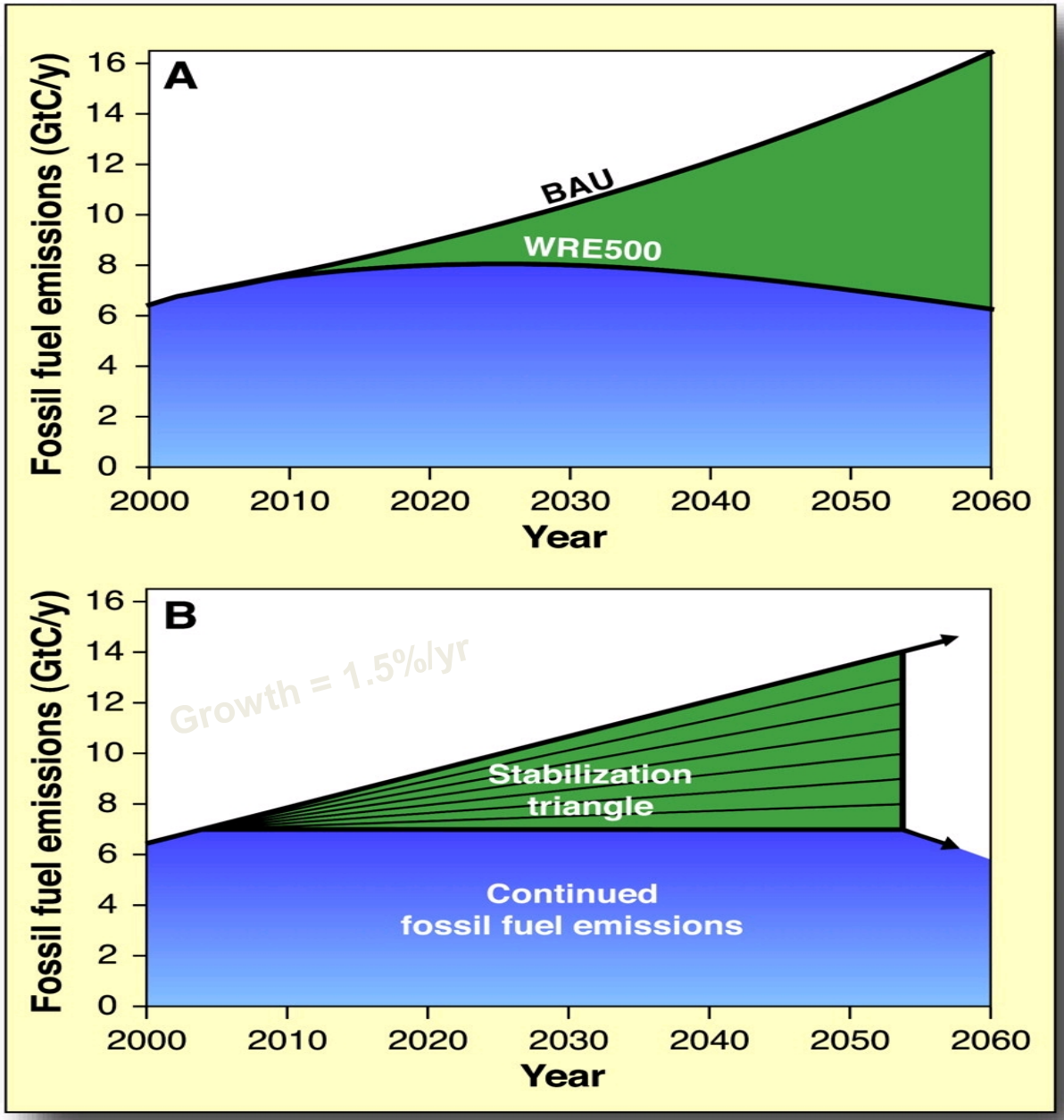
Half of U.S. electricity comes from coal.

If biosphere is CO_2-neutral and if non-CO_2 influences cancel, fossil CO_2 emission trajectories relate to different stabilization levels as follows:

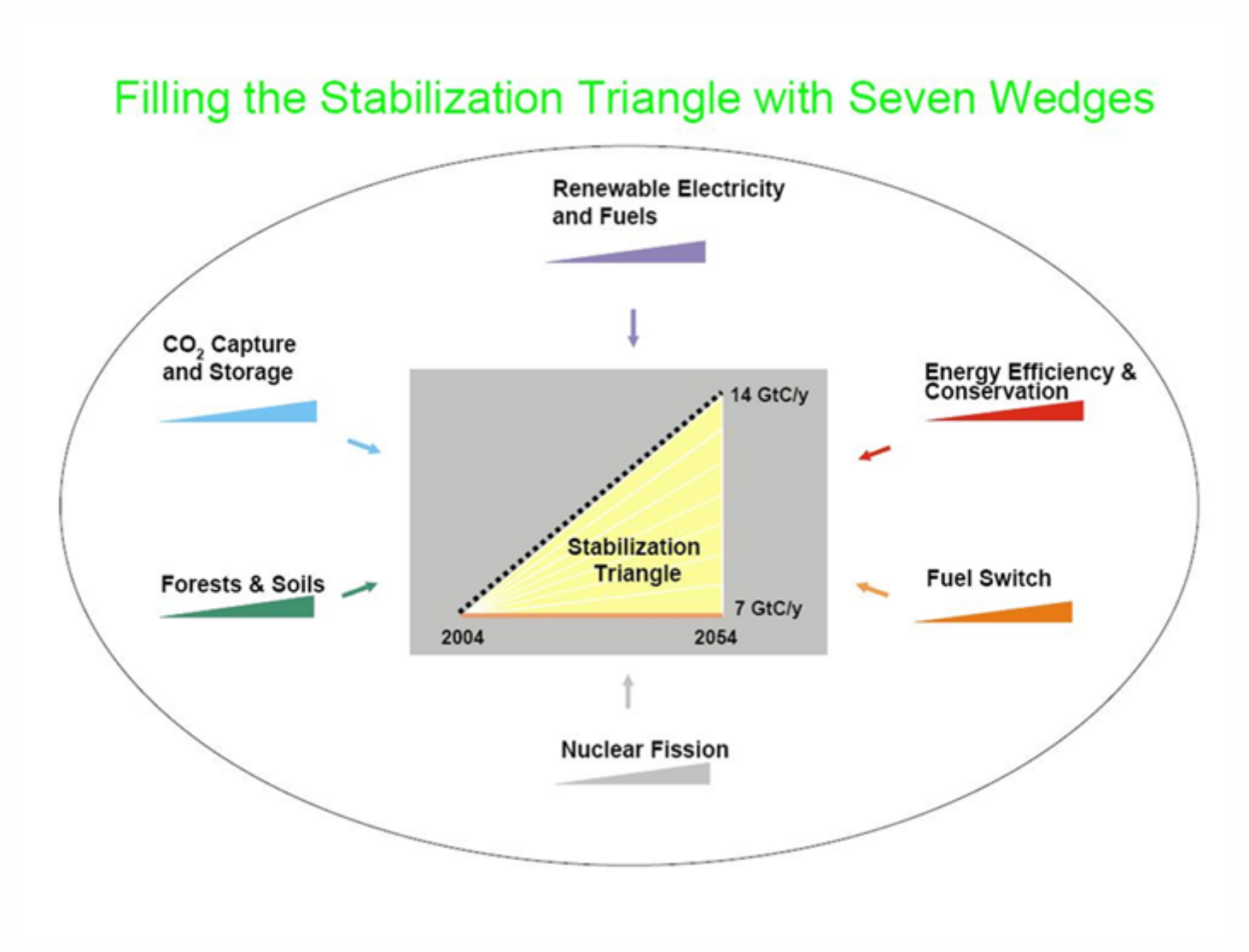


Socolow-Pacala "wedge" model approximates the trajectory for 500 ppmv CO_2-equivalent as level 2005-55, then declining

Difference between BAU and the 500 ppmv stabilization trajectory is seven "wedges", each of which avoids 1 GtC per year in 2055.



Source: Stabilization Wedges: Pacala and Socolow, Science Vol 305, page 968



"The wedge concept decomposes a heroic challenge – filling the stabilization triangle – into a limited set of monumental tasks. But an excuse for inaction based on the world's lack of technological readiness does not exist."

One wedge is a lot: Some examples…

CO_2 Capture & Storage (CCS)

CO_2 capture:

1. Introduce CCS at 800 GW coal or 1600 GW natural gas plants (1100 GW coal today)
2. Introduce CCS at plants producing 250 MtH_2/yr from coal or 500 MtH_2/yr from natural gas (40 MtH_2/yr today)
3. Introduce CCS at synfuels plants producing 30 mbd from coal (200x Sasol)

H_2 safety, infrastructure

Geologic storage:
Create 3500 Sleipners

Durable storage

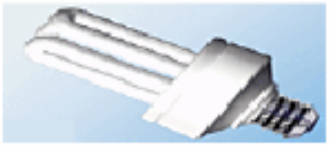
Wind and Solar

4. Add 2 million 1-MW-peak windmills (50 times current level) on 30 Mha, displacing coal electricity
5. Add 2000 GW-peak PV plants (700 times current level) on 2 Mha, displacing coal electricity

6. Add 4 million windmills or 4000 GW-peak PV plants generating 200 MtH_2/yr, displacing gasoline hybrid cars

Energy storage, H_2 safety, infrastructure
PV production cost

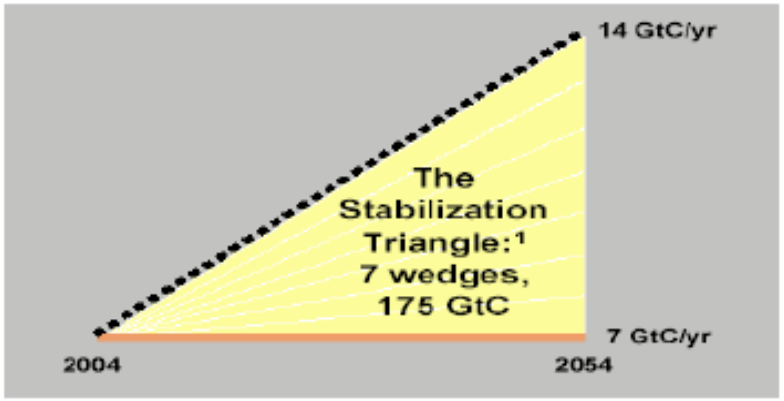
Energy Efficiency & Conservation



Increase economy-wide emissions/GDP reduction by additional 0.15%/yr (e.g. increase US goal of 1.96%/yr to 2.11%/yr):

8. Increase fuel economy for 2 billion cars from 30 to 60 mpg
9. Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles/yr
10. Cut carbon emissions in buildings/appliances by 1/4 over 2054 projection
11. Produce twice today's coal output at 60% efficiency instead of 40% (compare with 32% today)

Weak incentives, urban design, lifestyle changes



Forests & Soils

14. Decrease tropical deforestation to zero instead of 0.5 GtC/yr, and establish 300 Mha of new tree plantations (twice current level)
15. Implement conservation tillage on all cropland (10 times current level)

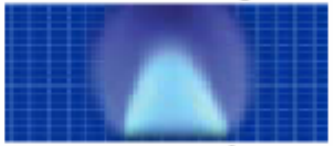
Competing land use, verification, reversibility

Nuclear Fission

13. Add 700 GW nuclear plants (compare with 350 GW today) replacing coal

Nuclear proliferation, terrorism, waste

Fuel Switching



12. Replace 1400 GW coal plants with natural gas plants (compare with 350 GW natural gas today)

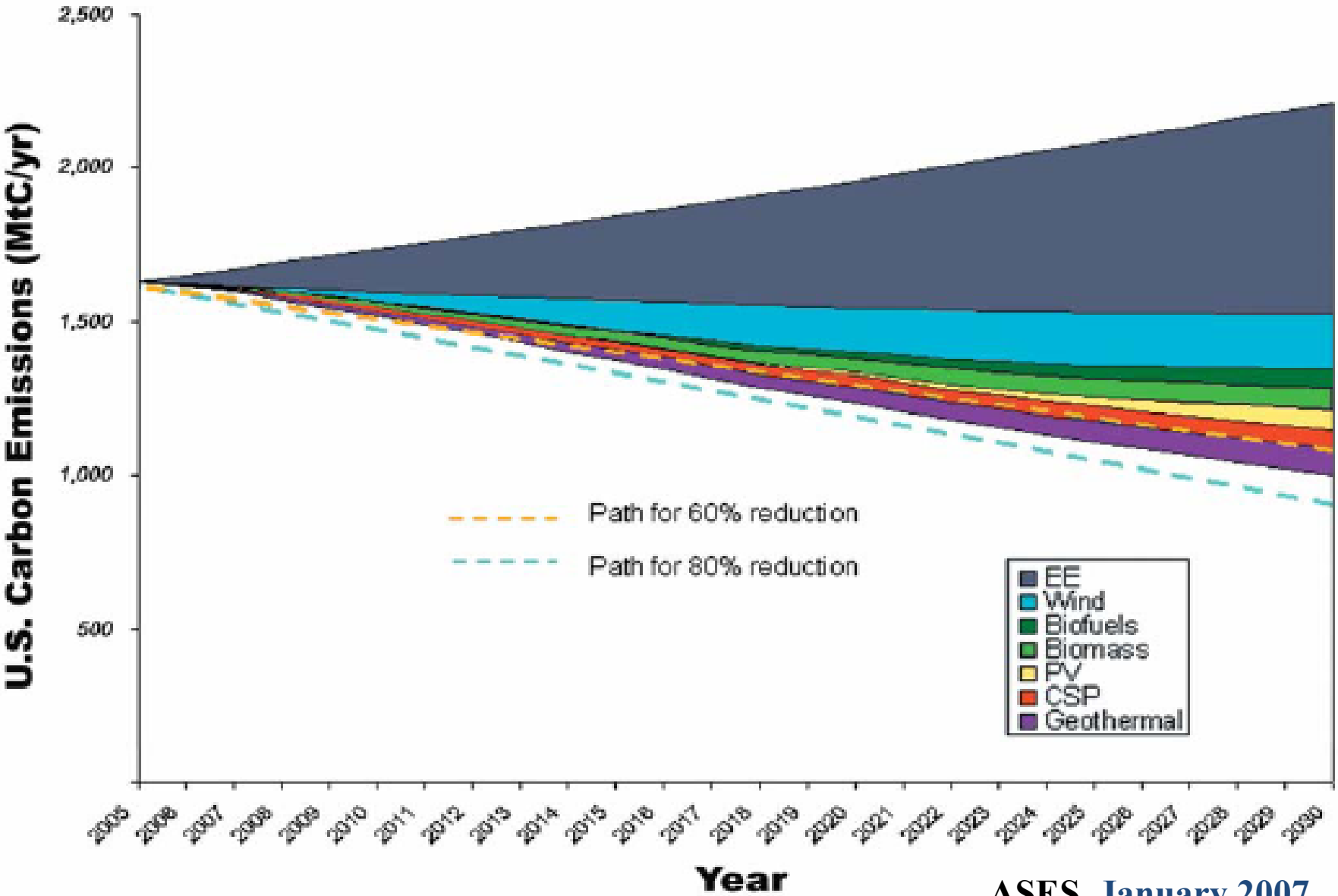
Competing demands for natural gas

Biomass Fuel

7. Add 50 times current US and Brazil ethanol production on 250 Mha (1/6 world cropland)

Biodiversity, competing land use

Ingredients of potential U.S. reductions



ASES, January 2007

Wind Hydrogen

Prototype of 80 m tall Nordex 2,5 MW wind turbine located in Grevenbroich, Germany (Danish Wind Industry Association)

Effort needed by 2054 for 1 wedge:

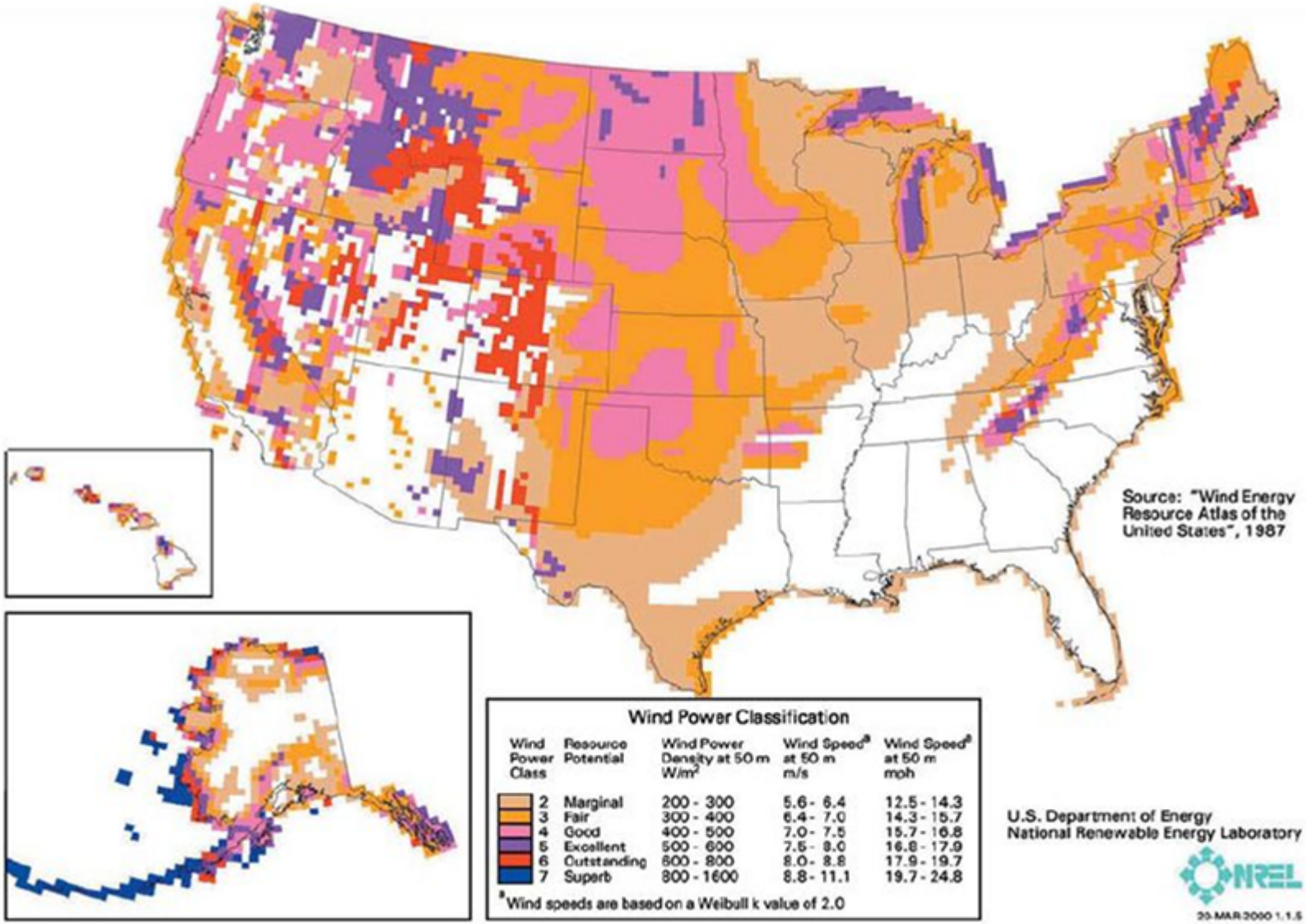
Displace gasoline or diesel in 2 billion 60 mpg hybrids, with 100 mpg H2 fuel cell cars, H_2 via 75% efficient electrolyzer (HHV).

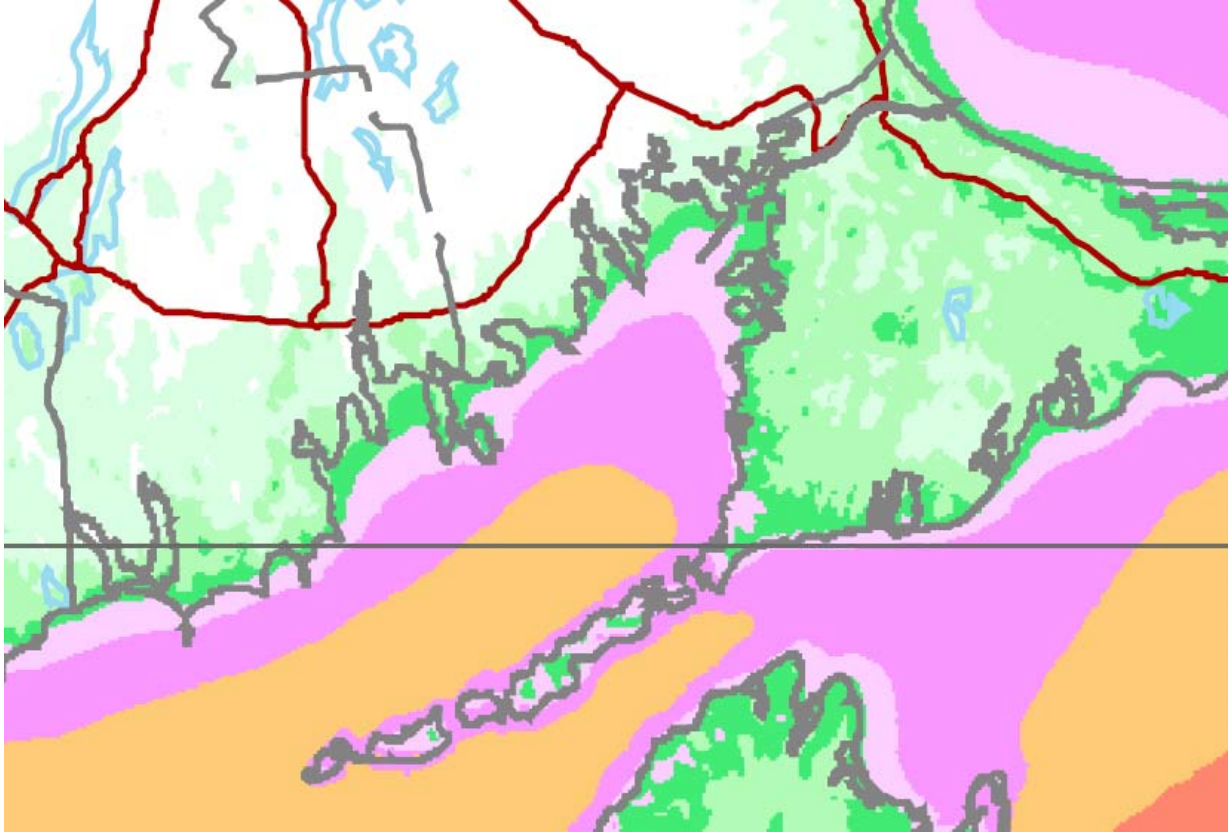
Install 4,000,000 1 MW_{peak} windmills by 2054 –

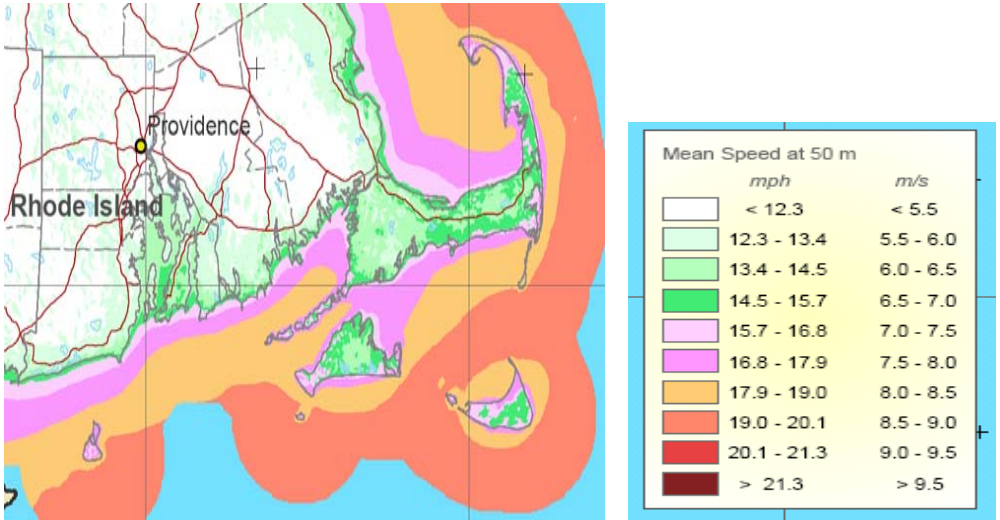
twice as many windmills as for a wedge of wind electricity.

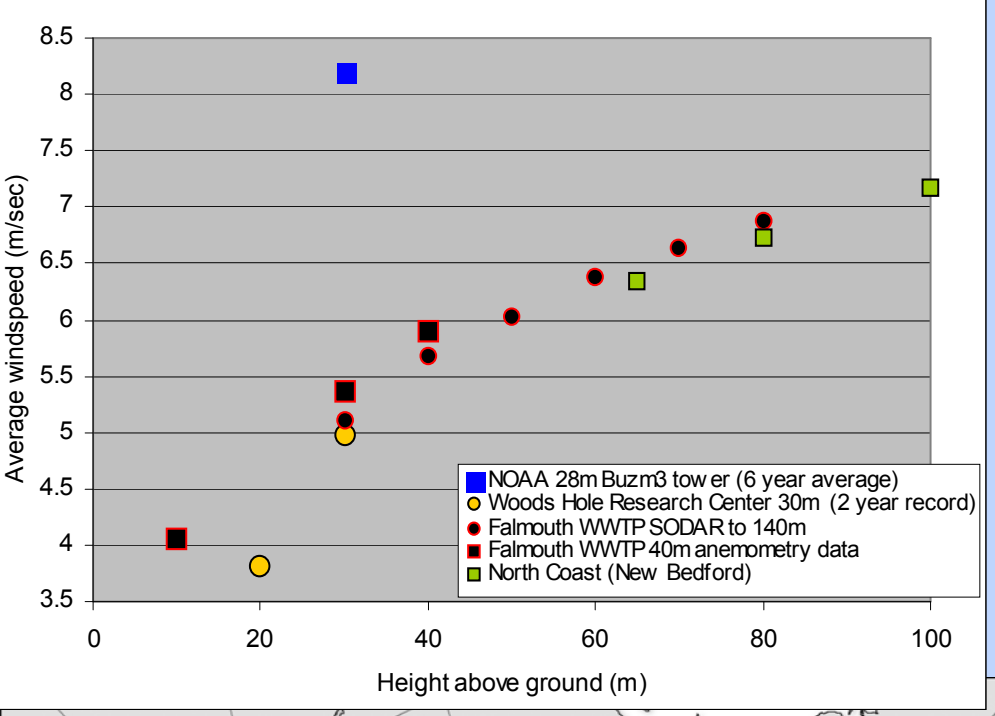
40,000 MW_{peak} in place today, rate of production growing 30%/yr

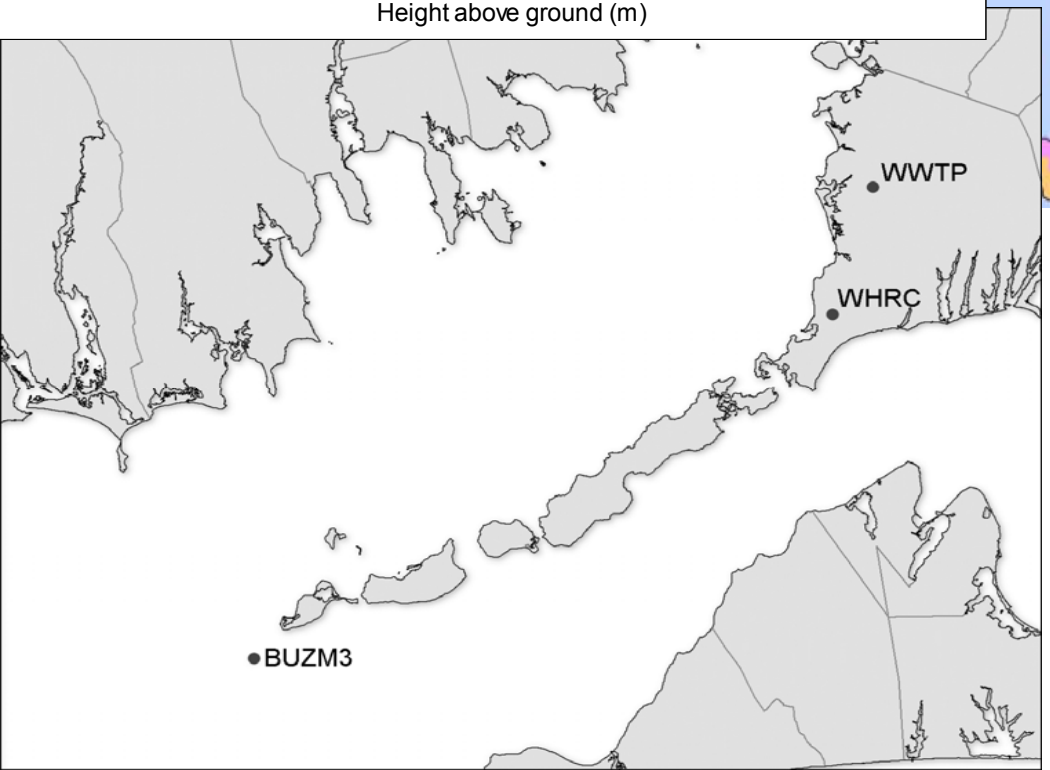
Potential Pitfalls:
NIMBY
Changes in regional climate?

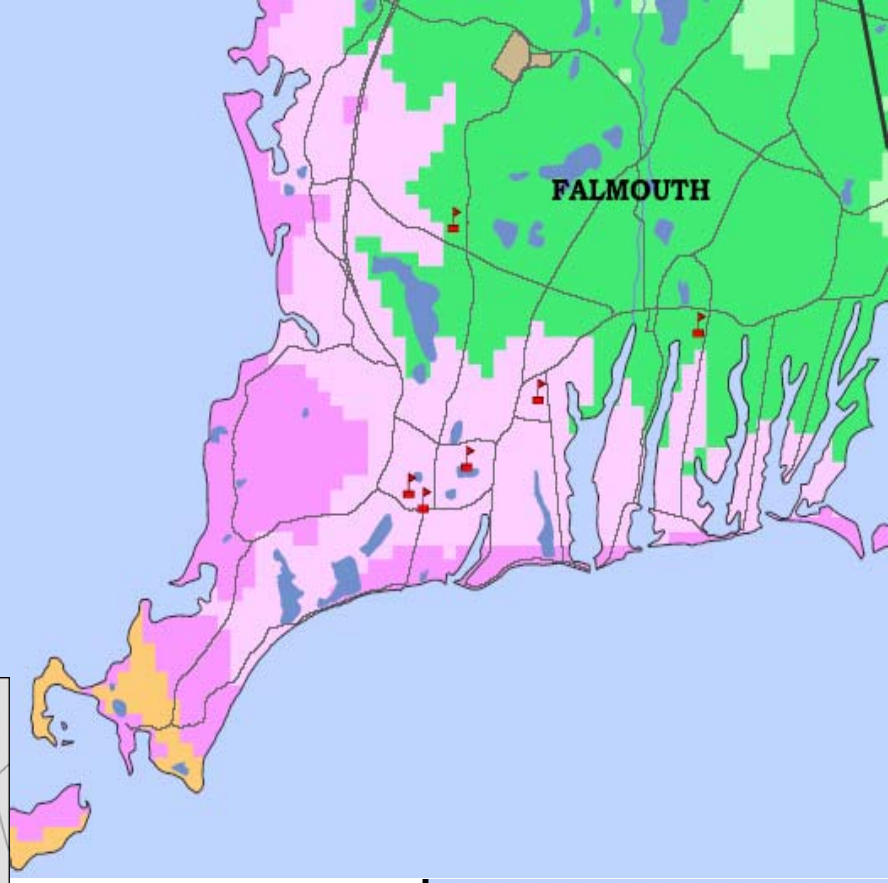

Source: "Wind Energy Resource Atlas of the United States", 1987
Wind Power Classification
Wind Power Class
Resource Potential
Wind Power Density at 50 m W/m²
Wind Speed[a] at 50 m m/s
Wind Speed[a] at 50 m mph
2 Marginal 200 - 300 5.6 - 6.4 12.5 - 14.3
3 Fair 300 - 400 6.4 - 7.0 14.3 - 15.7
4 Good 400 - 500 7.0 - 7.5 15.7 - 16.8
5 Excellent 500 - 600 7.5 - 8.0 16.8 - 17.9
6 Outstanding 600 - 800 8.0 - 8.8 17.9 - 19.7
7 Superb 800 - 1600 8.8 - 11.1 19.7 - 24.8
[a] Wind speeds are based on a Weibull k value of 2.0
U.S. Department of Energy
National Renewable Energy Laboratory
NREL
20-MAR-2000 1.1.5

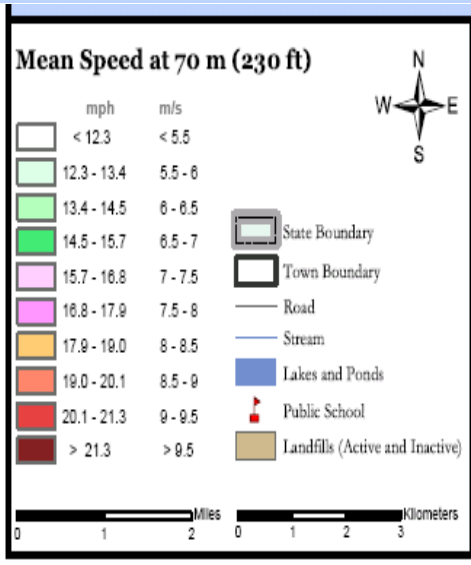


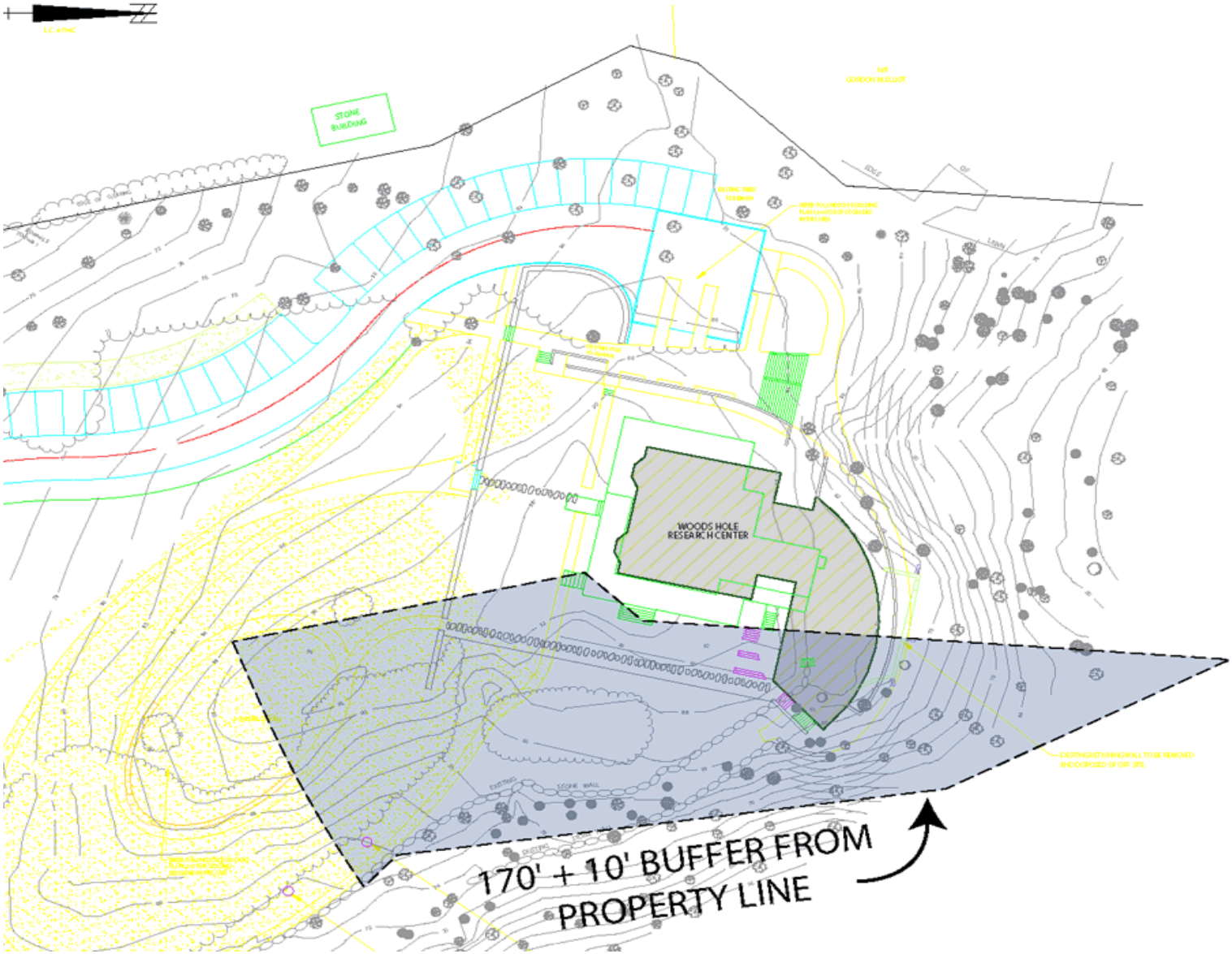

Providence
Rhode Island
Mean Speed at 50 m
mph
m/s
< 12.3
< 5.5
12.3 - 13.4
5.5 - 6.0
13.4 - 14.5
6.0 - 6.5
14.5 - 15.7
6.5 - 7.0
15.7 - 16.8
7.0 - 7.5
16.8 - 17.9
7.5 - 8.0
17.9 - 19.0
8.0 - 8.5
19.0 - 20.1
8.5 - 9.0
20.1 - 21.3
9.0 - 9.5
> 21.3
> 9.5


Average windspeed (m/sec)
Height above ground (m)
NOAA 28m Buzm3 tower (6 year average)
Woods Hole Research Center 30m (2 year record)
Falmouth WWTP SODAR to 140m
Falmouth WWTP 40m anemometry data
North Coast (New Bedford)

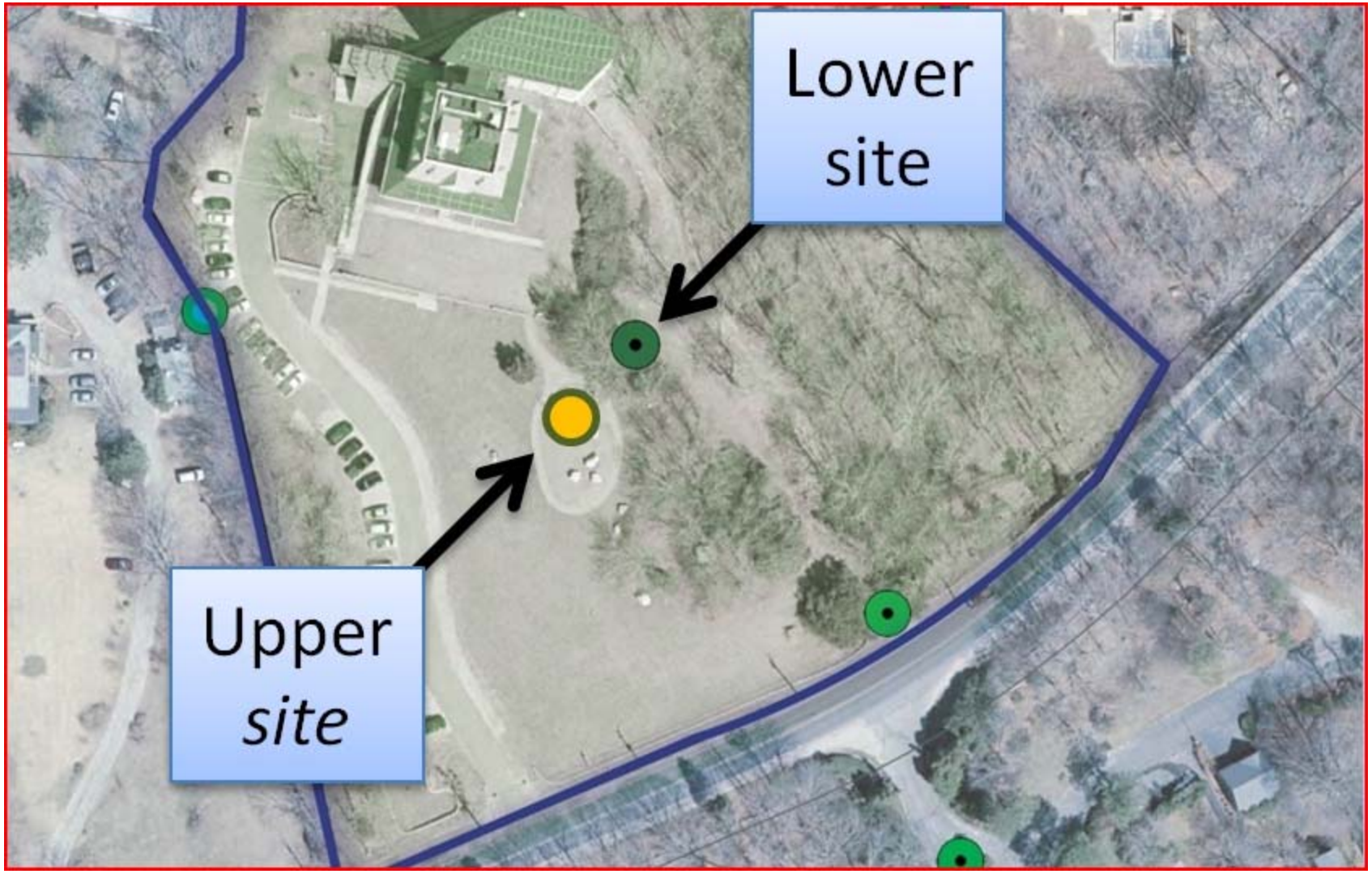

WWTP
WHRC
BUZM3

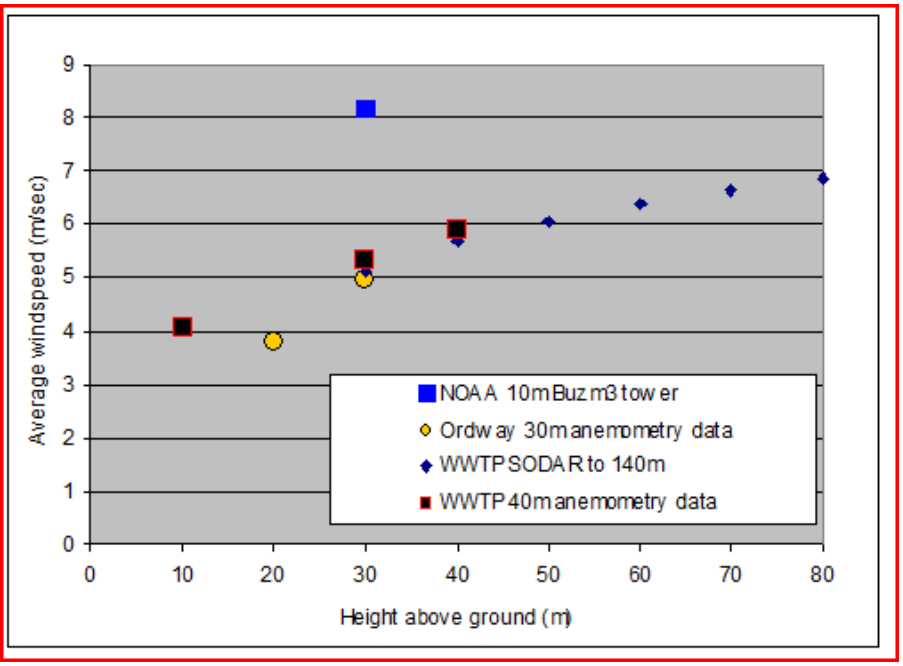

FALMOUTH

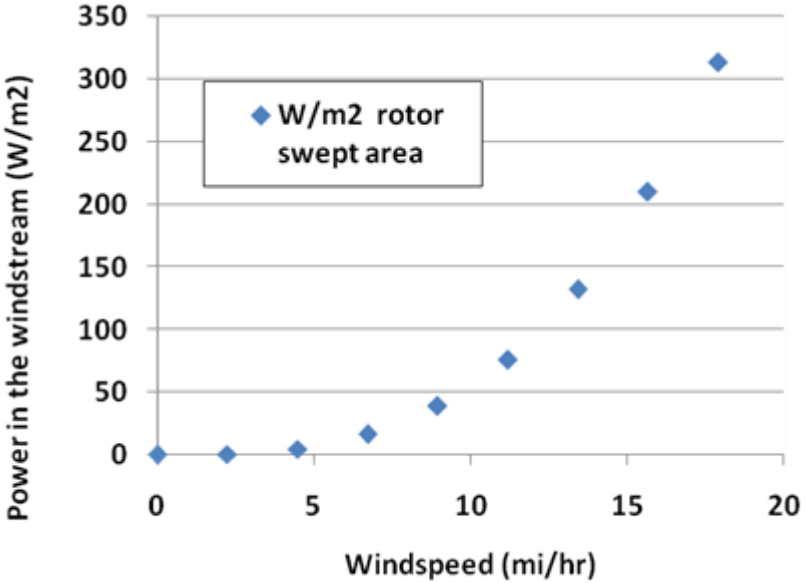

Mean Speed at 70 m (230 ft)
mph
m/s
< 12.3
< 5.5
12.3 - 13.4
5.5 - 6
13.4 - 14.5
6 - 6.5
14.5 - 15.7
6.5 - 7
15.7 - 16.8
7 - 7.5
16.8 - 17.9
7.5 - 8
17.9 - 19.0
8 - 8.5
19.0 - 20.1
8.5 - 9
20.1 - 21.3
9 - 9.5
> 21.3
> 9.5
State Boundary
Town Boundary
Road
Stream
Lakes and Ponds
Public School
Landfills (Active and Inactive)
N
W
E
S
Miles
Kilometers

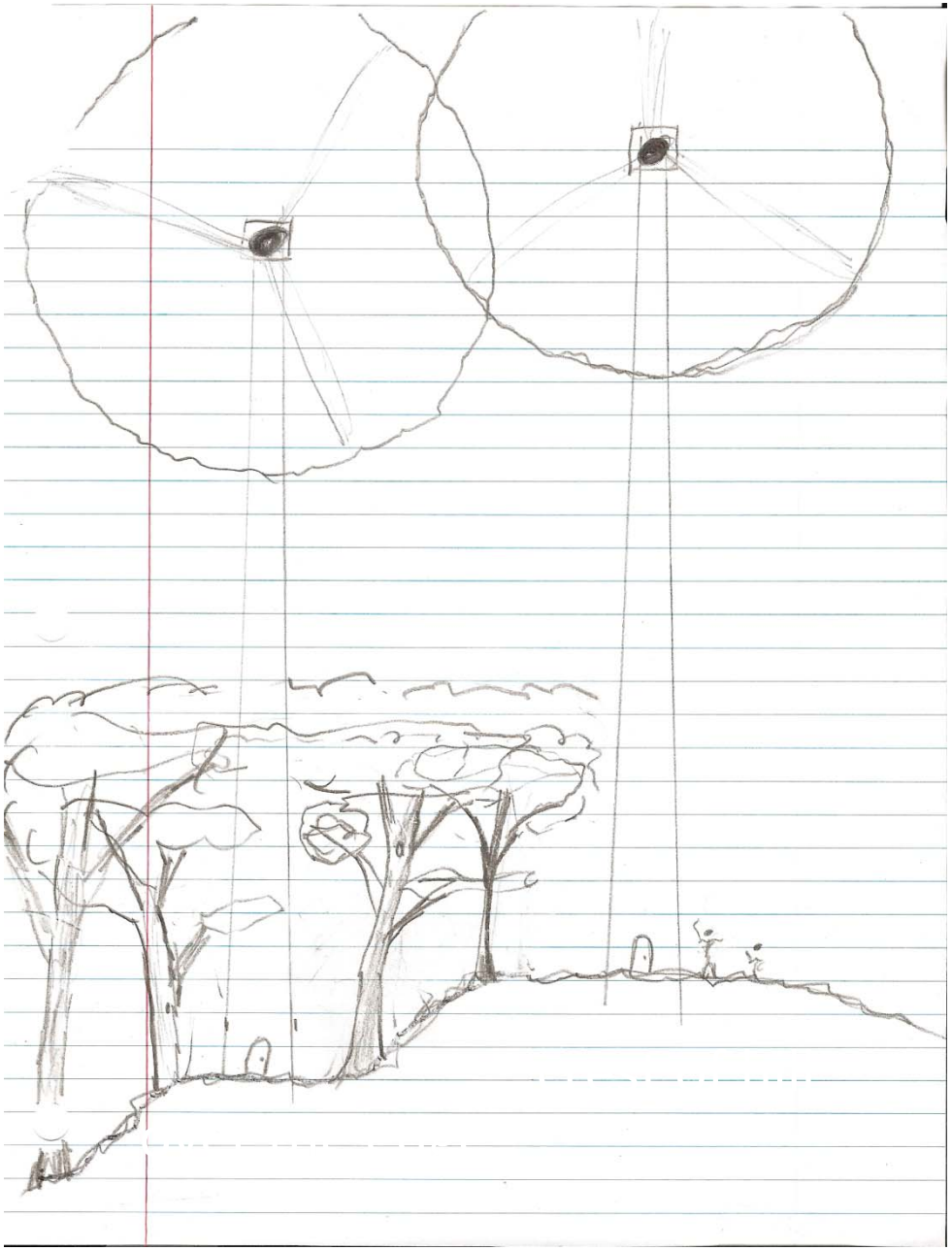

STONE BUILDING
WOODS HOLE RESEARCH CENTER
170' + 10' BUFFER FROM PROPERTY LINE

The Woods Hole Research Center

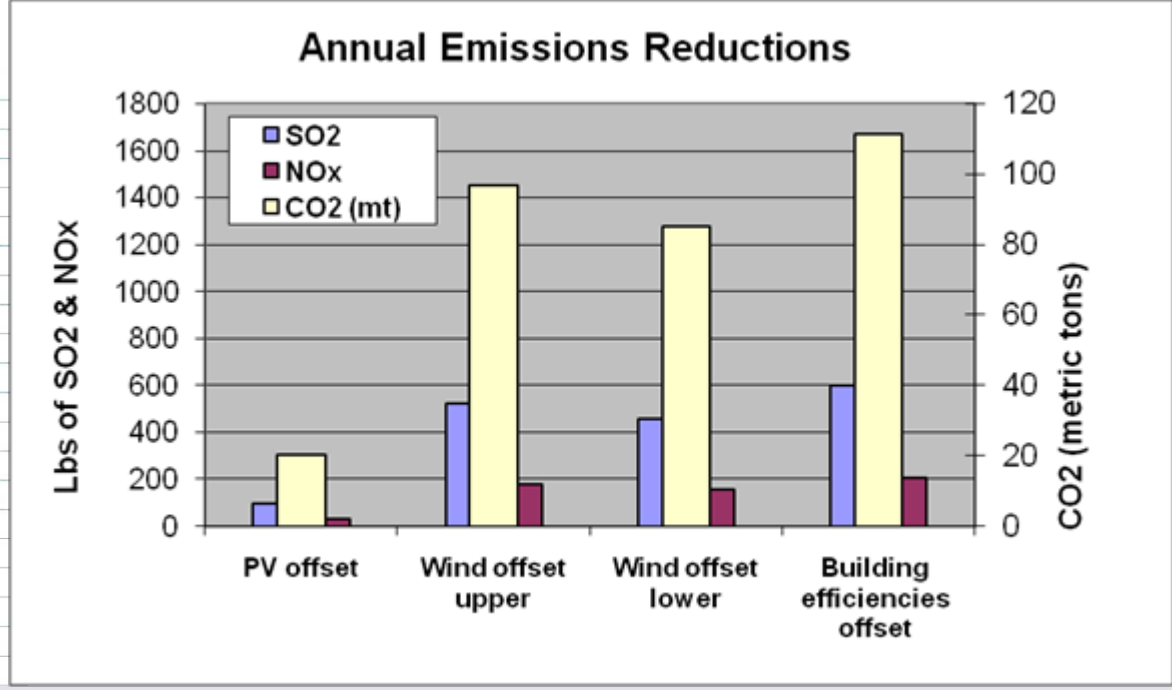

Lower
site
Upper
site


Average windspeed (m/sec)
Height above ground (m)
NOAA 10m Buzm3 tower
Ordway 30m anemometry data
WWTP SODAR to 140m
WWTP 40m anemometry data

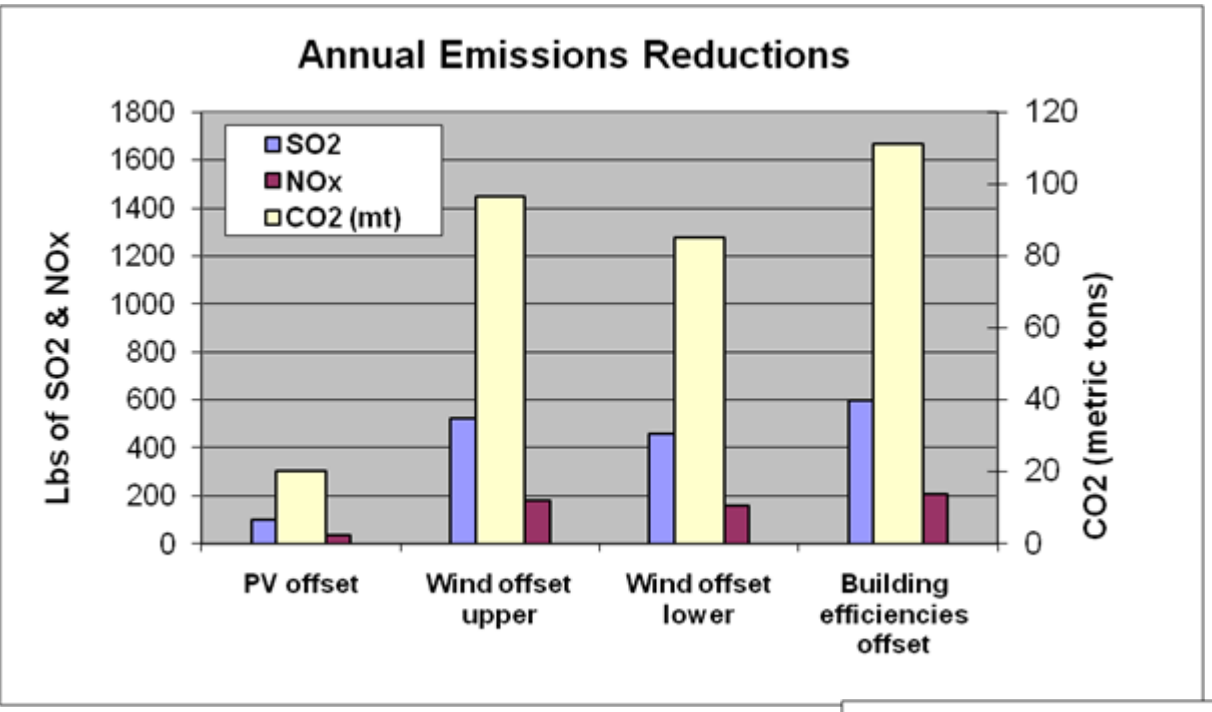

Power in the windstream (W/m2)
Windspeed (mi/hr)
W/m2 rotor swept area

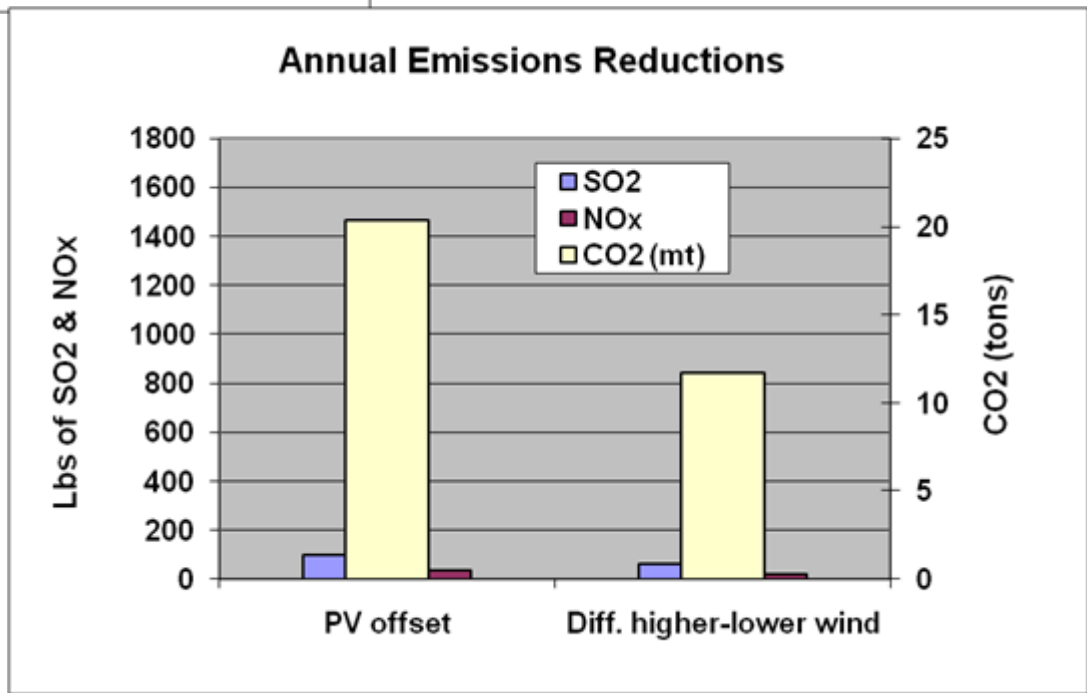


WWTP
WHRC
BUZM3

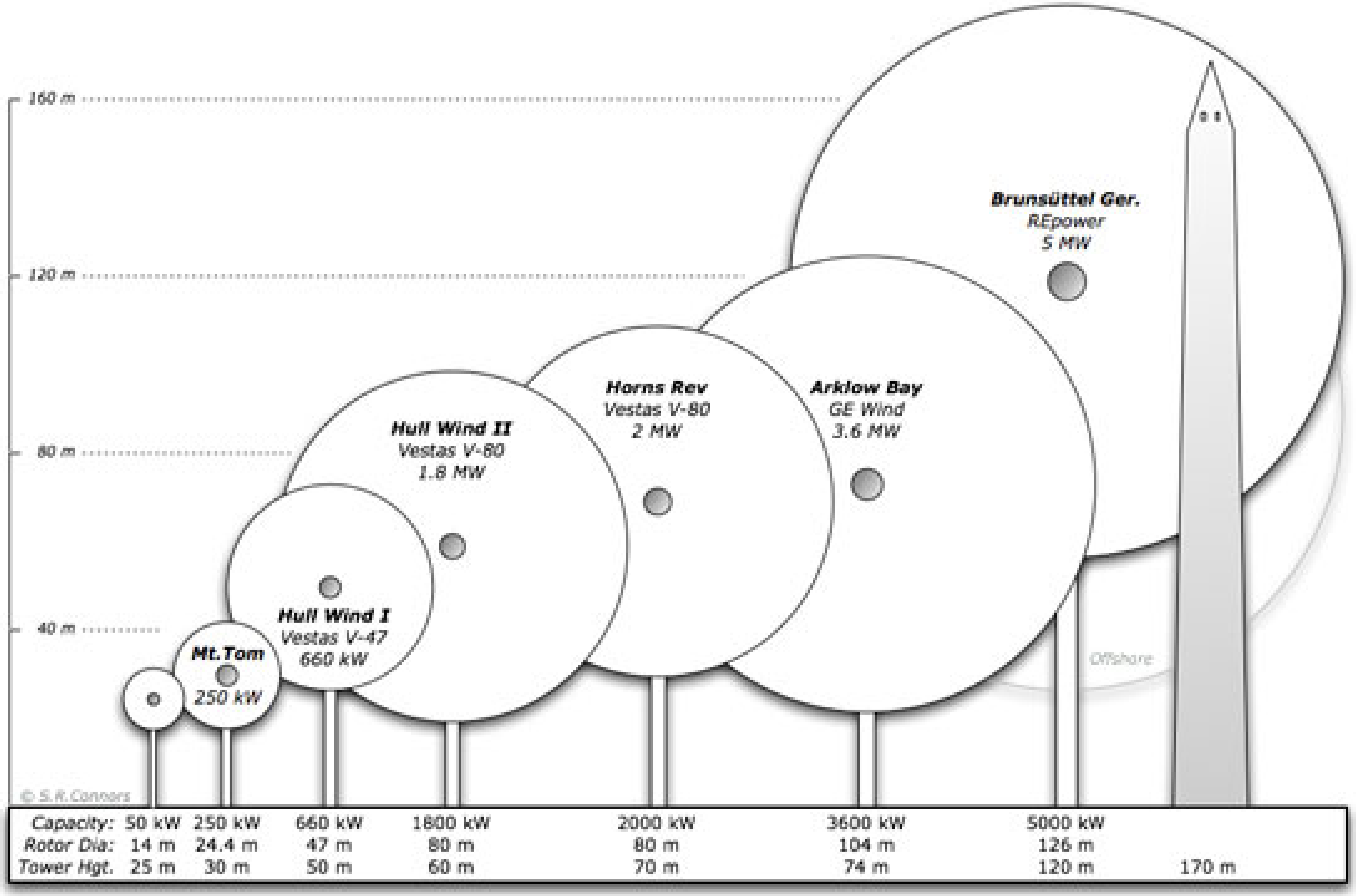


	Over the edge	Crest of Hill	PV
Power Production kWh/hr	140,000	160,000	30,410
Initial Cost	$ 550,000	$ 500,000	$ 225,000
Capacity Factor	16.0%	18.3%	13.1%
Avoided CO2 emissions (mt C)	85	97	18
Years to positive cash flow	14	11	19
Power Cost ($/kWh {simple 20yr})	$0.20	$0.16	$ 0.37
Shadow flicker	less flicker effect	flicker will occur on front of building during on sunny winter mornings	
Additional overhead (thos. replies)	"Why didn't-ya just put it on the top of the hill?"		


Annual Emissions Reductions
Lbs of SO2 & NOx
CO2 (metric tons)
SO2
NOx
CO2 (mt)
1800
1600
1400
1200
1000
800
600
400
200
0
120
100
80
60
40
20
0
PV offset
Wind offset upper
Wind offset lower
Building efficiencies offset


Annual Emissions Reductions
Lbs of SO2 & NOx
CO2 (tons)
SO2
NOx
CO2 (mt)
1800
1600
1400
1200
1000
800
600
400
200
0
25
20
15
10
5
0
PV offset
Diff. higher-lower wind

Wind Turbine Size



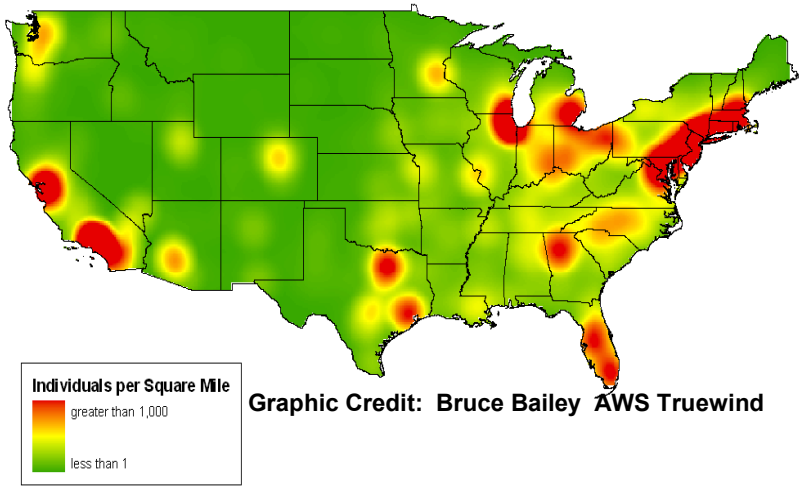
Why offshore ?

28 coastal states use 78% of the electricity in US

Many Coastal Load Centers Cannot Be Served by Land-based Wind

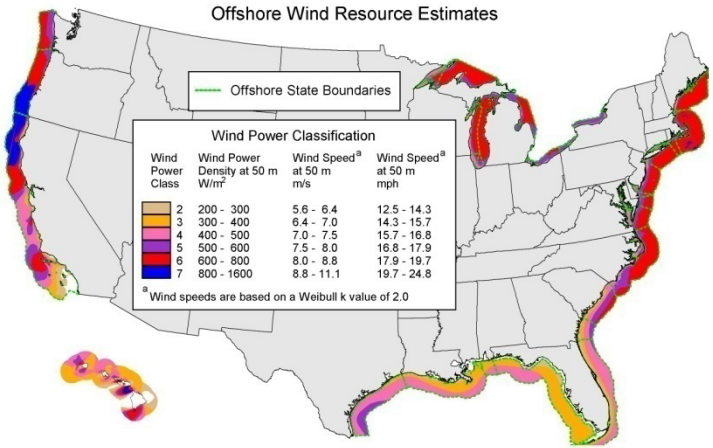
20% Wind Energy Goals Cannot be Achieved Without Offshore Contributions

US Population Concentration

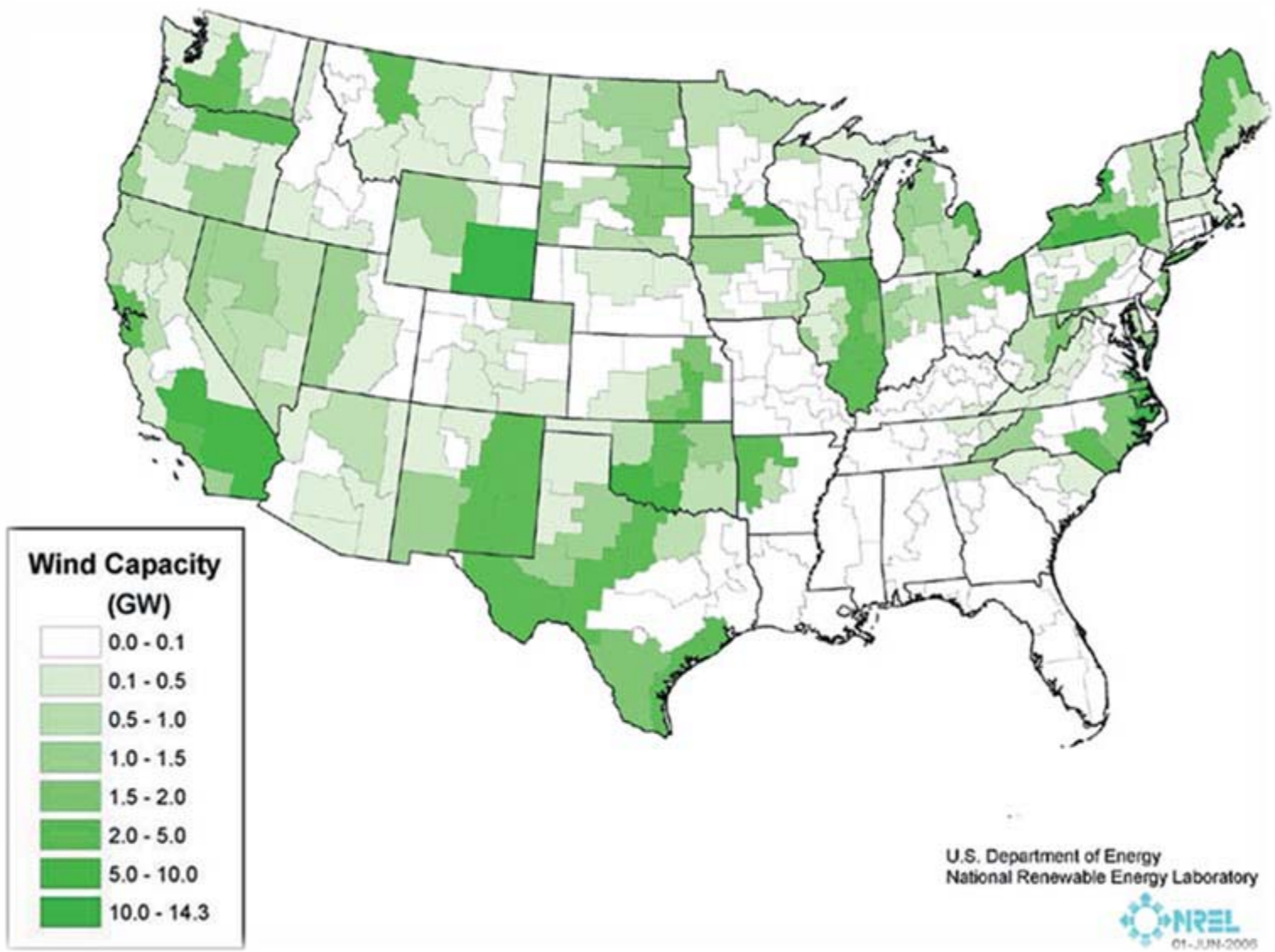


Graphic Credit: Bruce Bailey AWS Truewind

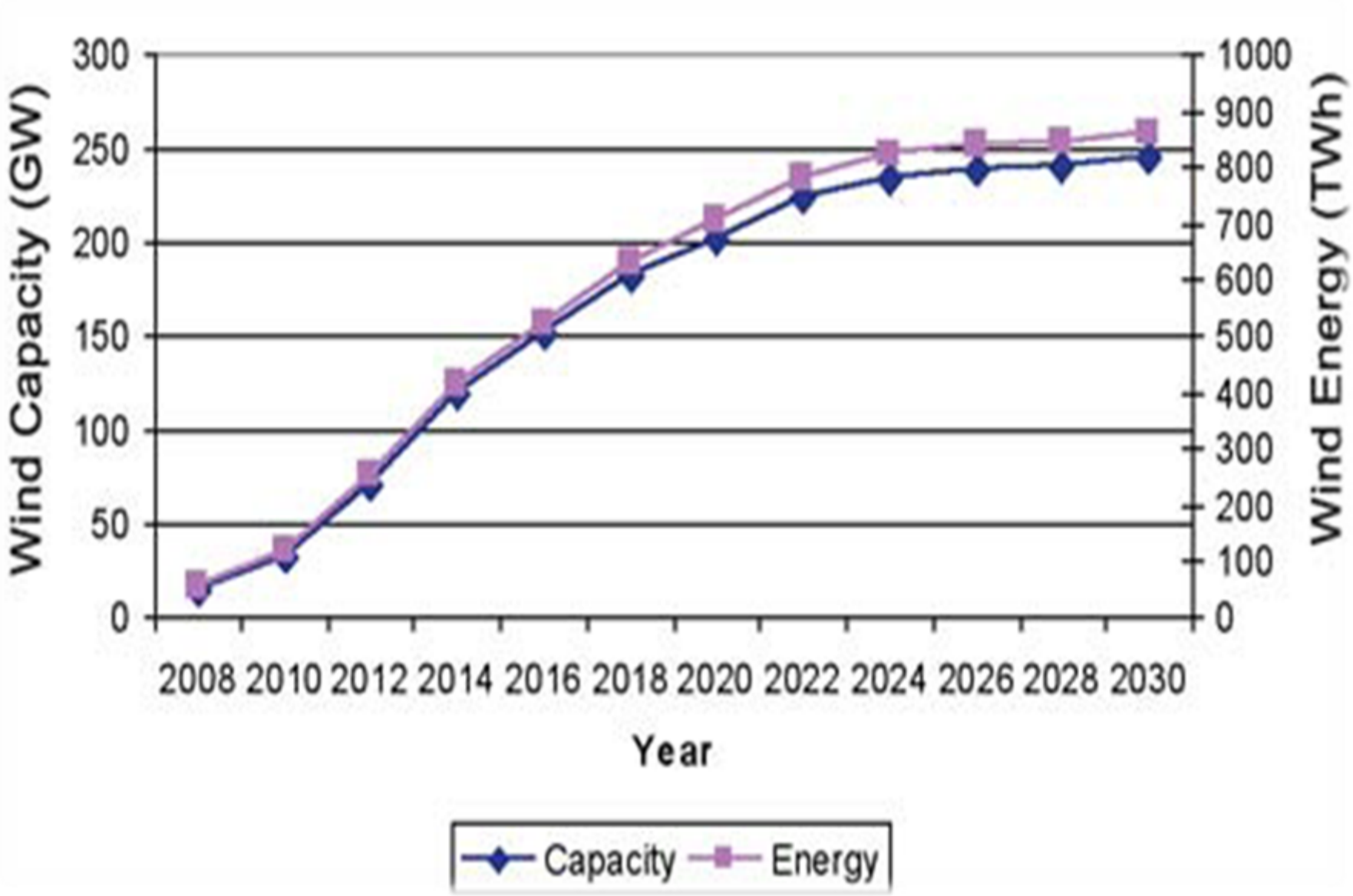
U.S. Wind Resource



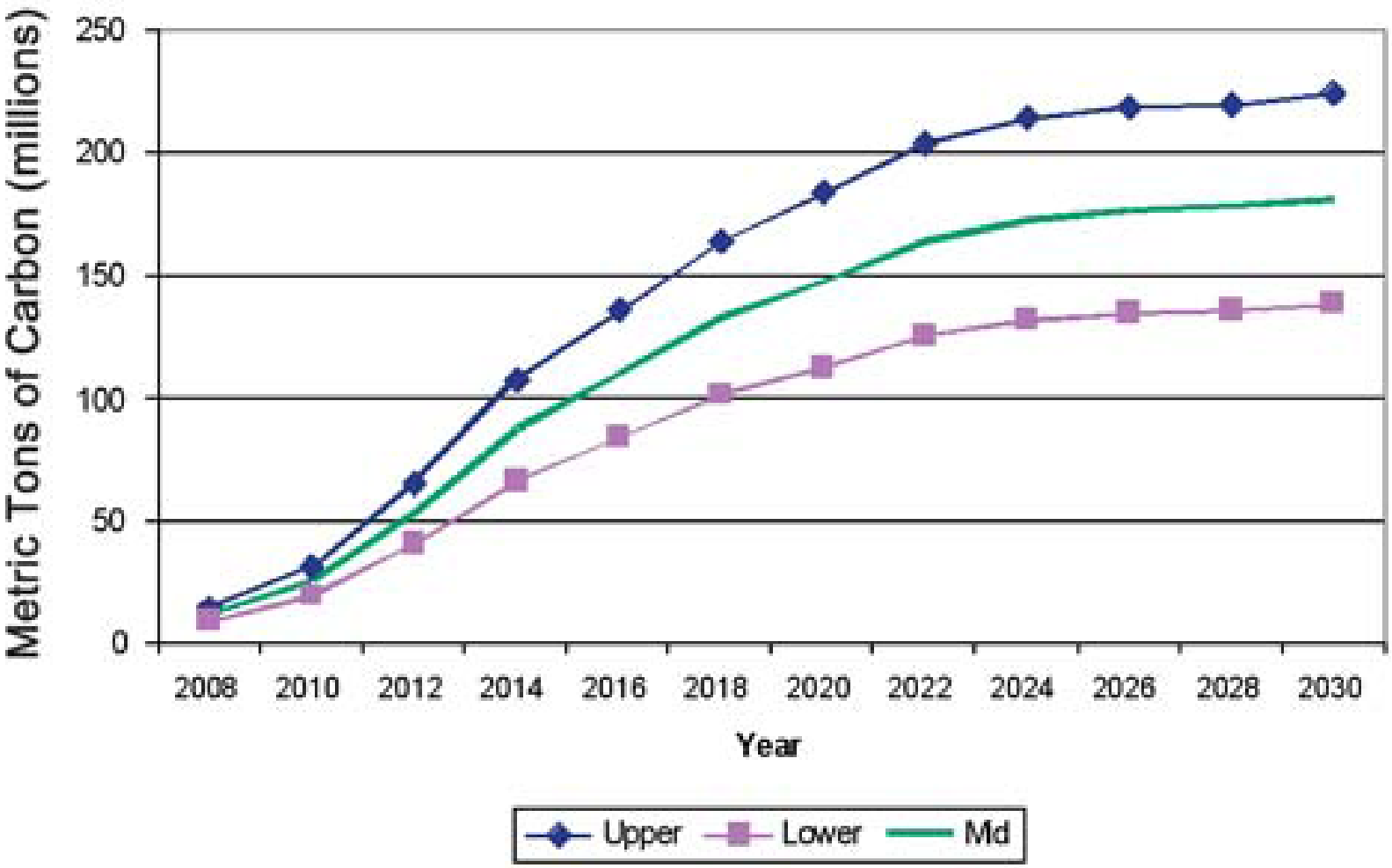
Musial: NREL 2007



The WinDS model scenario of approximate wind locations with 20% penetration of electric grid (energy).


Wind Capacity (GW)
300
250
200
150
100
50
0
Wind Energy (TWh)
1000
900
800
700
600
500
400
300
200
100
0
2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030
Year
Capacity
Energy

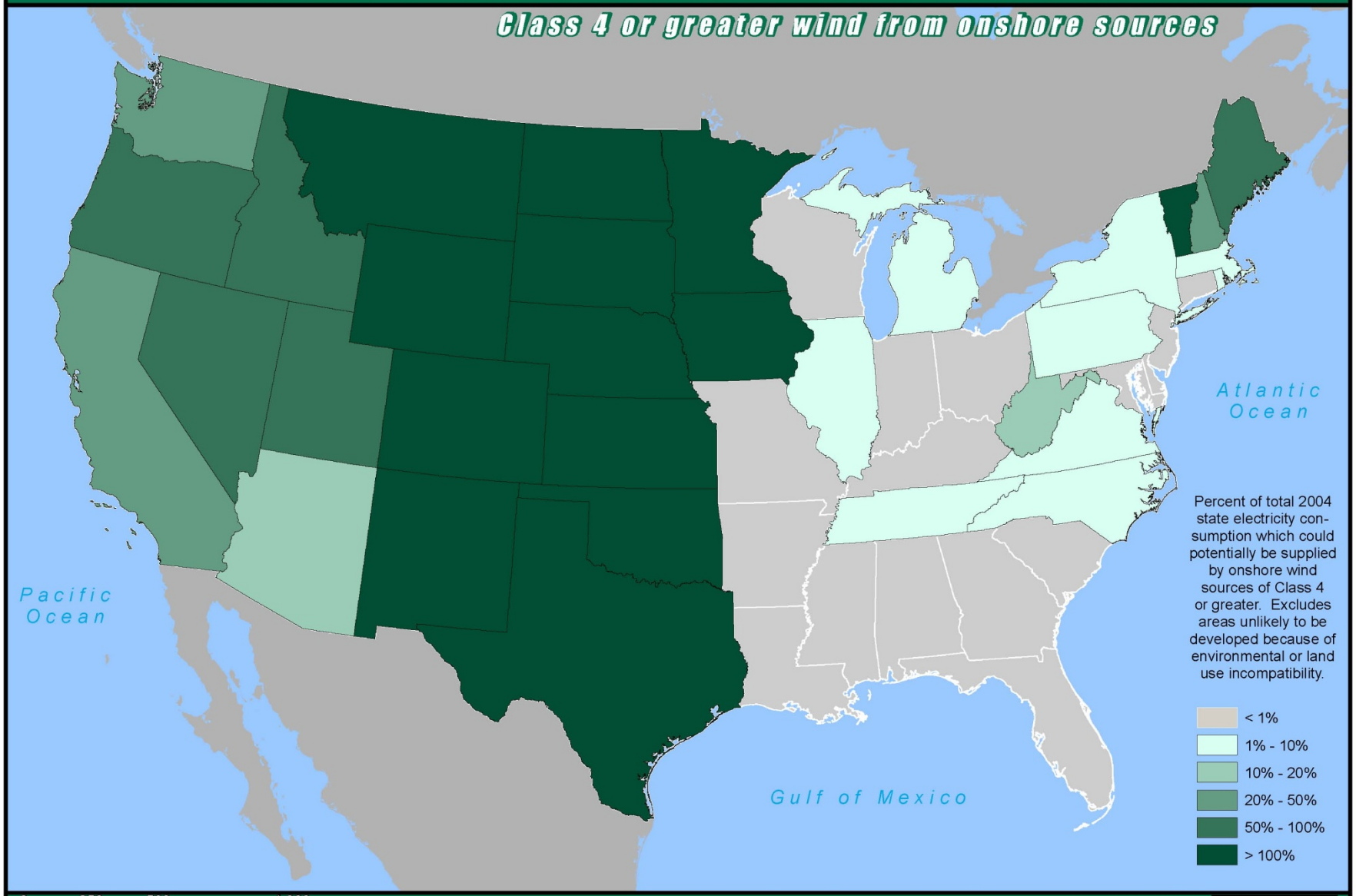
Range of annual carbon reduction from wind. rates— Represents 260 upper, 210 mid, and 160 metric tons per GWh of carbon offset.



Source: **Potential Carbon Emissions Reductions from Wind by 2030, NREL, Milligan**

Potential Electricity Supply from Onshore Wind by State

Class 4 or greater wind from onshore sources



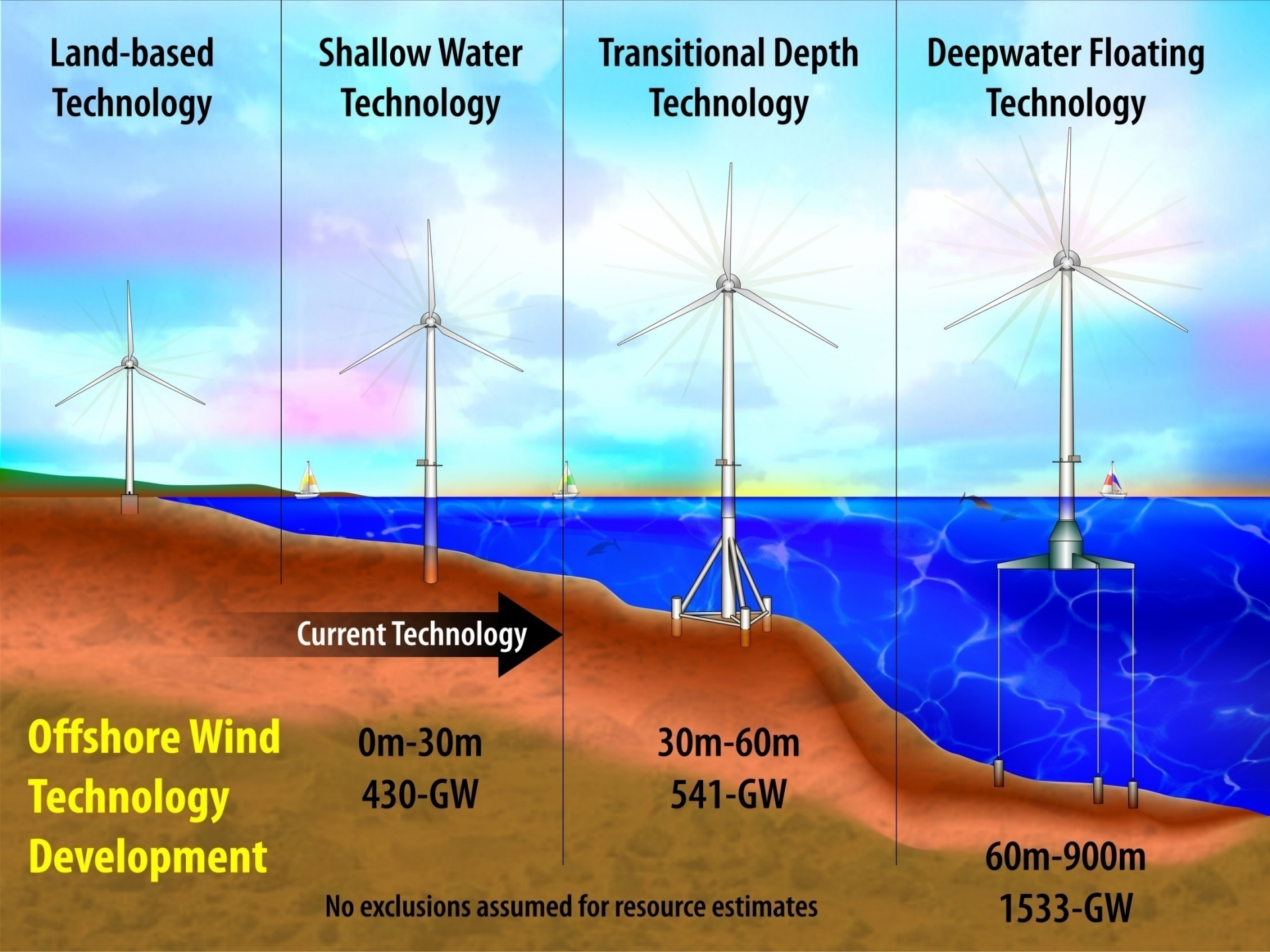
0 250 500 1,000 Kilometers

0 150 300 600 Miles

February 12, 2007
Data Source: 200702musial_osbystate_rev3.xls

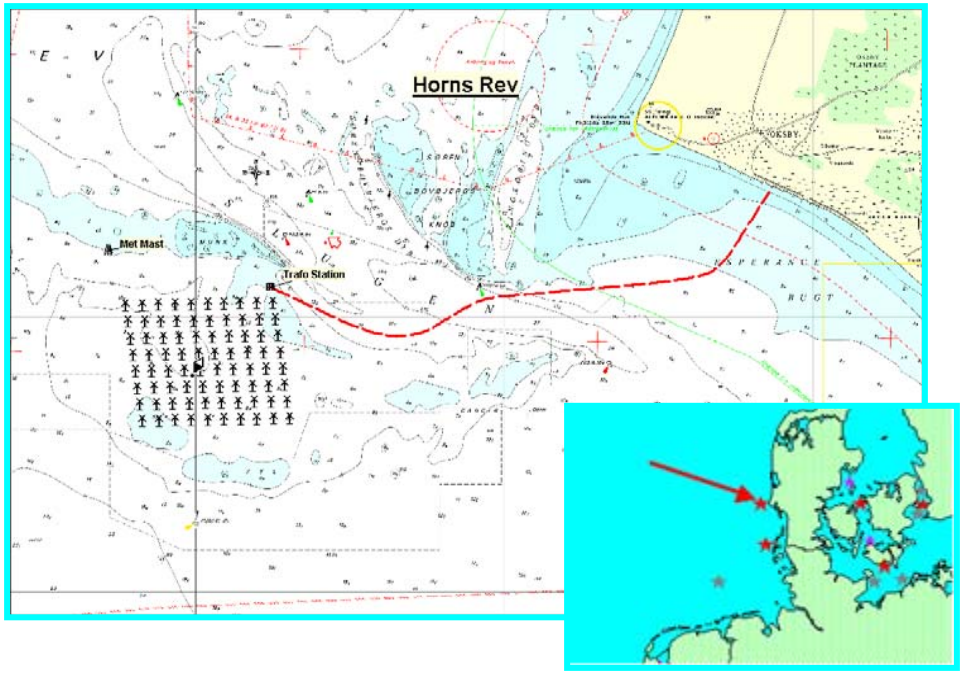
Map produced by
U.S. Department of Energy
National Renewable Energy Laboratory

NREL


Land-based Technology
Shallow Water Technology
Transitional Depth Technology
Deepwater Floating Technology
Current Technology
Offshore Wind Technology Development
0m-30m
430-GW
30m-60m
541-GW
60m-900m
1533-GW
No exclusions assumed for resource estimates

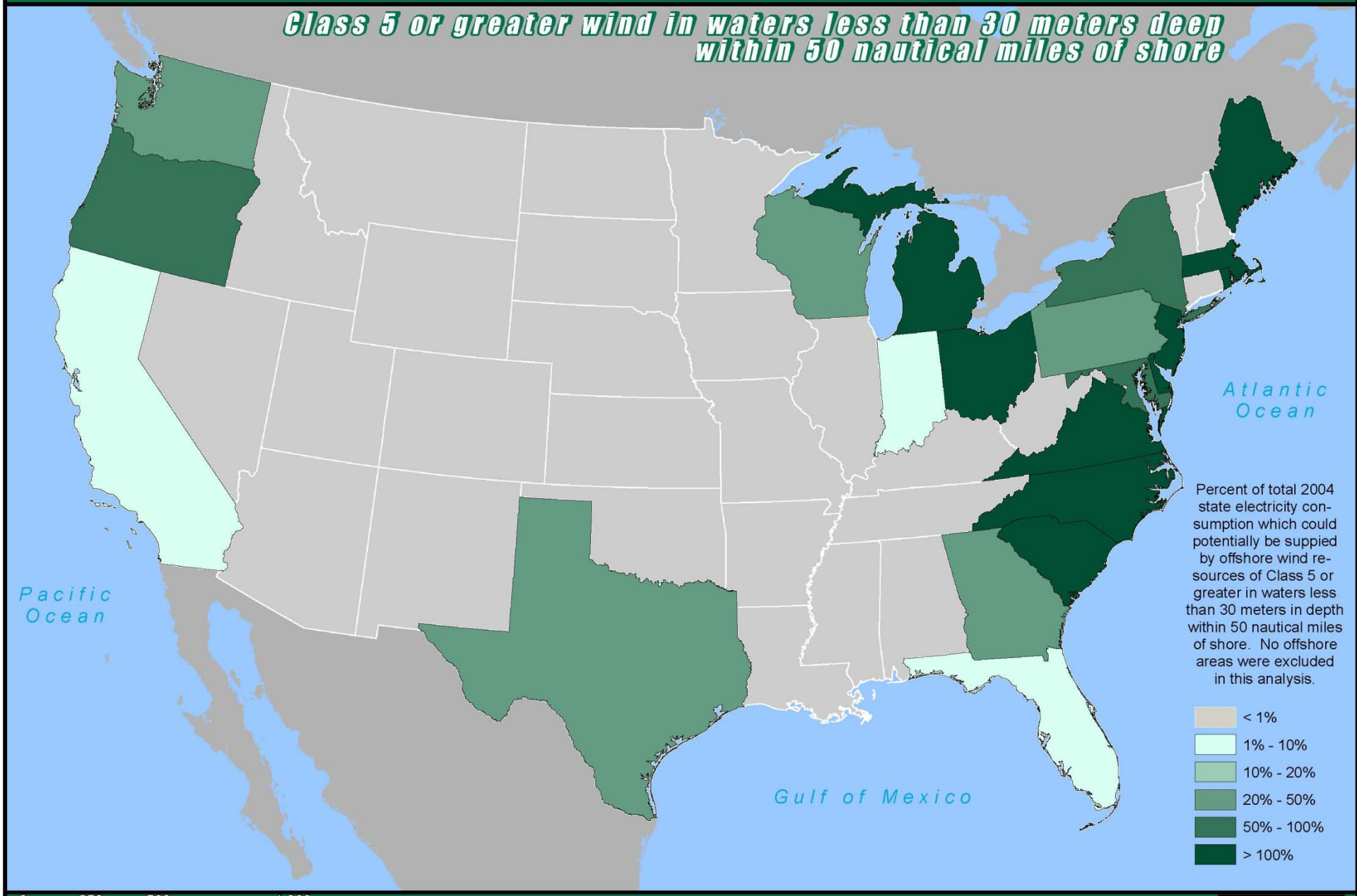
Horns Rev Wind Farm

Country: Denmark
Location: West Coast
Total Capacity: 160 MW
Number of Turbines: 80
Distance to Shore: 14-20 km
Depth: 6-12 m
Capital Costs: 270 million Euro
Manufacturer: Vestas
Total Capacity: 2 MW
Turbine-type: V80 - 80m diameter
Hub-height: 70-m
Mean Windspeed: 9.7 m/s
Annual Energy output: 600 GWh



Potential Electricity Supply from Shallow Offshore Wind by State

Class 5 or greater wind in waters less than 30 meters deep within 50 nautical miles of shore



0 250 500 1,000 Kilometers

0 150 300 600 Miles

February 12, 2007
Data Source: 200702musial_osbystate_rev3.xls

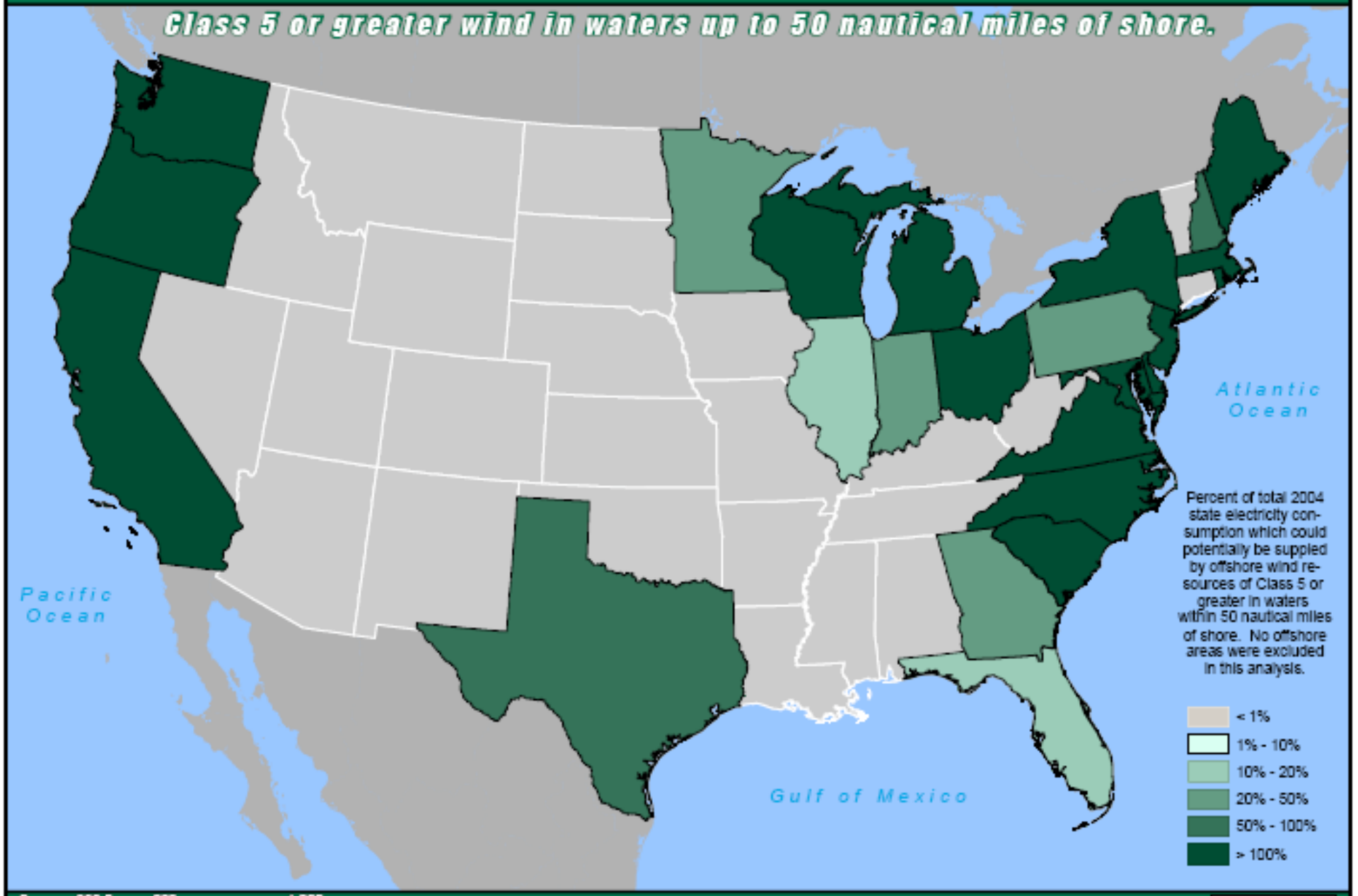
Map produced by
U.S. Department of Energy
National Renewable Energy Laboratory

45-m Depth Offshore Demonstration Project Talisman Energy in Beatrice Fields

- **5-MW Rating**
- **61.5-m Blade Length**
- **Worlds Largest Turbine**
- **Two Machines**
- **45-m Water Depths**

Potential Electricity Supply from Offshore Wind by State

Class 5 or greater wind in waters up to 50 nautical miles of shore.



0 262.5 525 1,050 Kilometers

0 150 300 600 Miles

March 8, 2007
Data Source: 200702musial_osbystate_rev3.xls

Map produced by
U.S. Department of Energy
National Renewable Energy Laboratory