Energy: Some Solutions for the Biggest Problem of our Century

Wolfgang Bauer

Yale University, February 2012

Top-10

BBC WORLD SERVICE

POLL

- 71%—extreme poverty
- 64%—the environment or pollution
- 63%—the rising cost of food and energy
- 59%—the spread of human diseases
- 59%—terrorism
- 58%—climate change
- 59%—human rights abuses
- 58%—the state of the global economy
- 57%—war or armed conflict
- 48%—violation of workers' rights

ENERGY

http://www.globescan.com/news_archives/bbcWorldSpeaks-2010/
Poll of 25,128 people form 22 countries by GlobeSpan, Jan. 2010

what we will cover

- Greenhouse gases and global warming
- Projected consequences of global warming
- Energy from fossil fuels
- Other options
- My project(s)

what we will cover

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Global Average Temperature

- Careful averaging needed (over *space* and *time*)

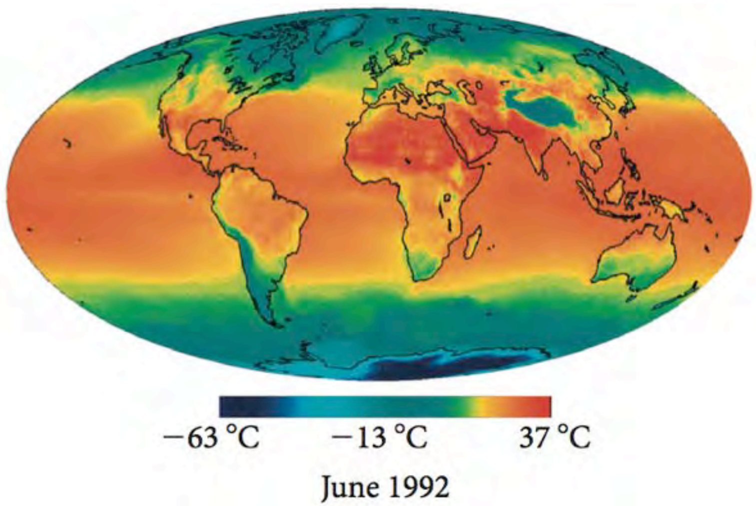
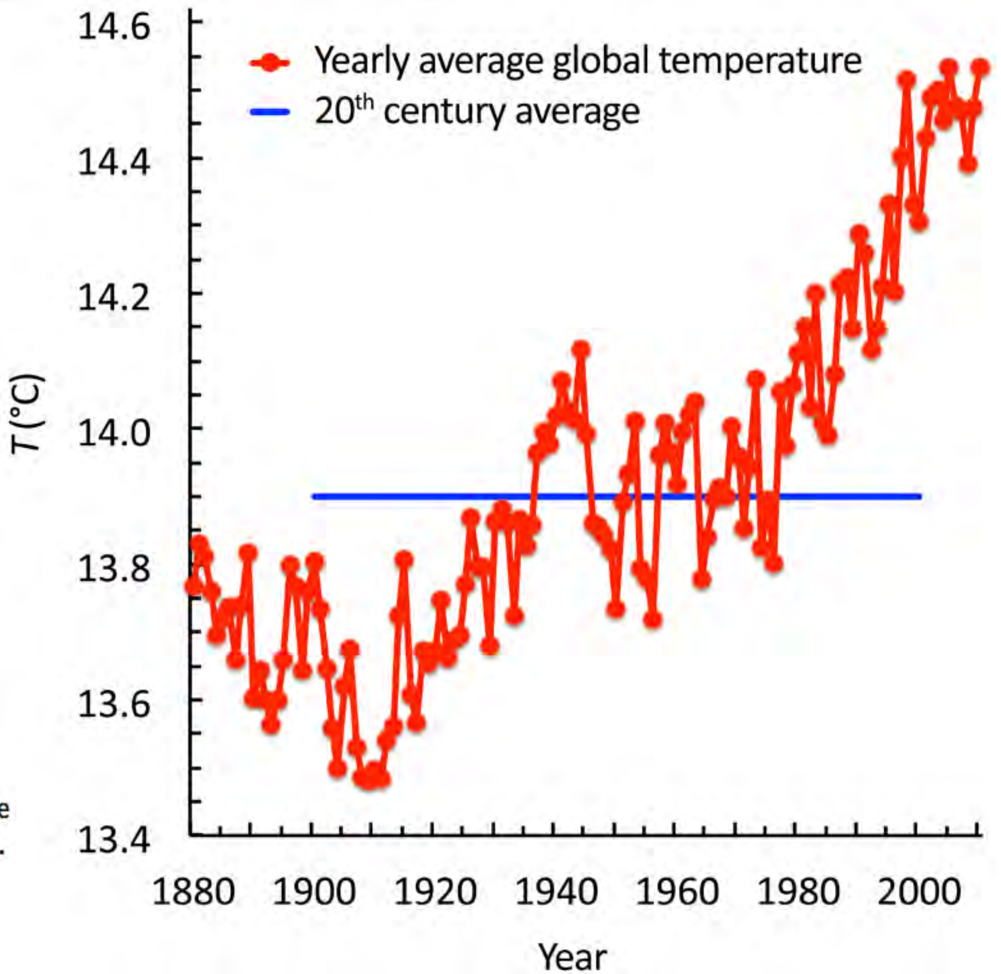
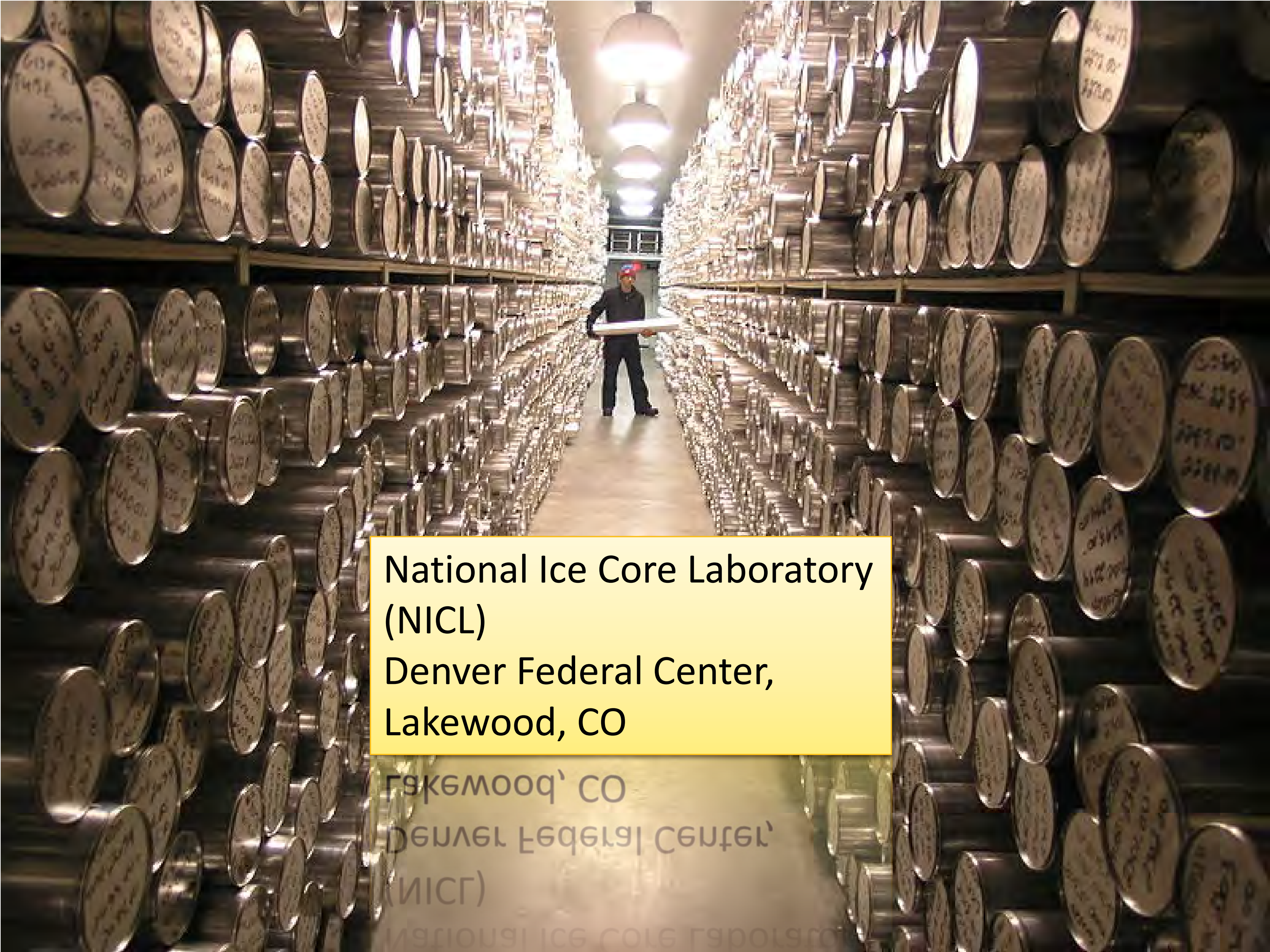


FIGURE 17.19 Time-averaged surface temperature of the Earth in June 1992. The colors represent a range of temperatures from −63 °C to +37 °C.

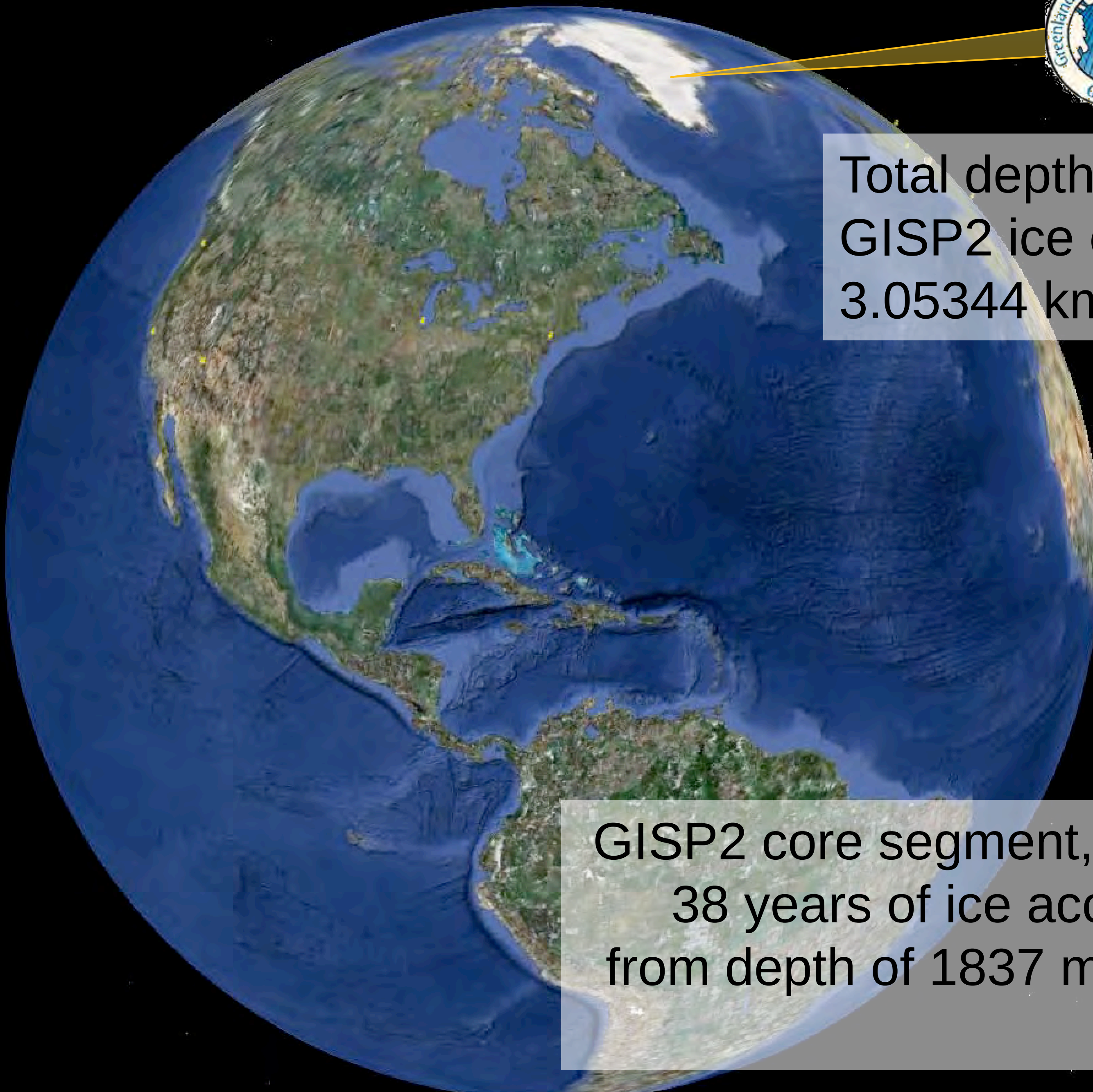


Global Warming of ~0.2° C/decade is happening. Is it man-made?

Data: National Climatic Data Center U.S. Department of Commerce

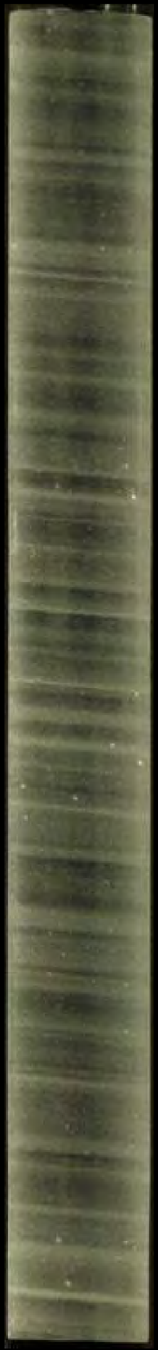


National Ice Core Laboratory (NICL)
Denver Federal Center,
Lakewood, CO



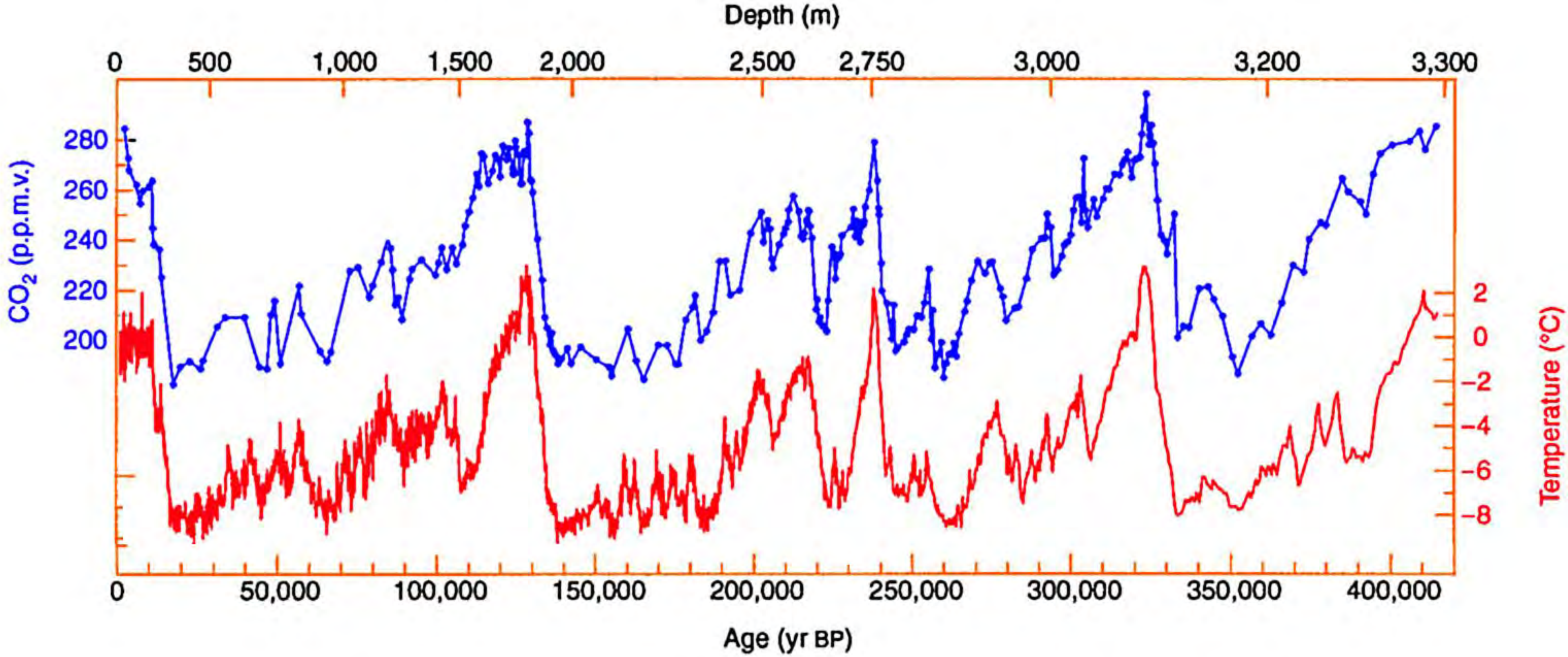
Total depth of GISP2 ice core: 3.05344 km

GISP2 core segment, 1 m long, 38 years of ice accumulated from depth of 1837 m, ~16,250 year old,



Total ice core depth
3645 m

The previous 400,000 years …



- CO_2 in the air between 190 and 290 ppm
- Temperature changes track CO_2 changes
- Average temperatures vary by 10° C (= 18° F)

Energy for Us

- We eat
  - 2500 calories/day = 10 MJ/day ~ 3.5 GJ/year ~1 MWh/year
- We do work (“energy = ability to do work”)
- We radiate
  - 80 W ~ 7 MJ/day
- Energy input > work output => we get fat
- Opposite sign: only way to drop weight

Energy for Earth

- It “eats”
  - Solar radiation 1370 W/m^2.
  - Multiply with area of Earth exposed to Sun: À(6370 km)^2(1370 W/m^2) = $1.75\cdot10^{17}$ W = 175 PW
  - **(~10,000 times World power consumption)**
- It radiates
  - Almost as much as it receives (T ~ 290 K)
- Energy input > radiation output
  - Storage of “fat” in form of fossil fuels

Atmosphere very important for the planet's temperature

Most important for the temperature of a planet:

* Distance to the Sun!

Second most important:

* Size of the planet

Third most important:

* Composition of atmosphere

Planet	$R_s/2r_p$	T_{calc} (F)	$T_{measured}$ (F)
Mars	$1.52 \cdot 10^{-3}$	-49	-78
Venus	$3.23 \cdot 10^{-3}$	136	867 (!!!)
Earth	$2.32 \cdot 10^{-3}$	44	61

Radiation Energy Balance

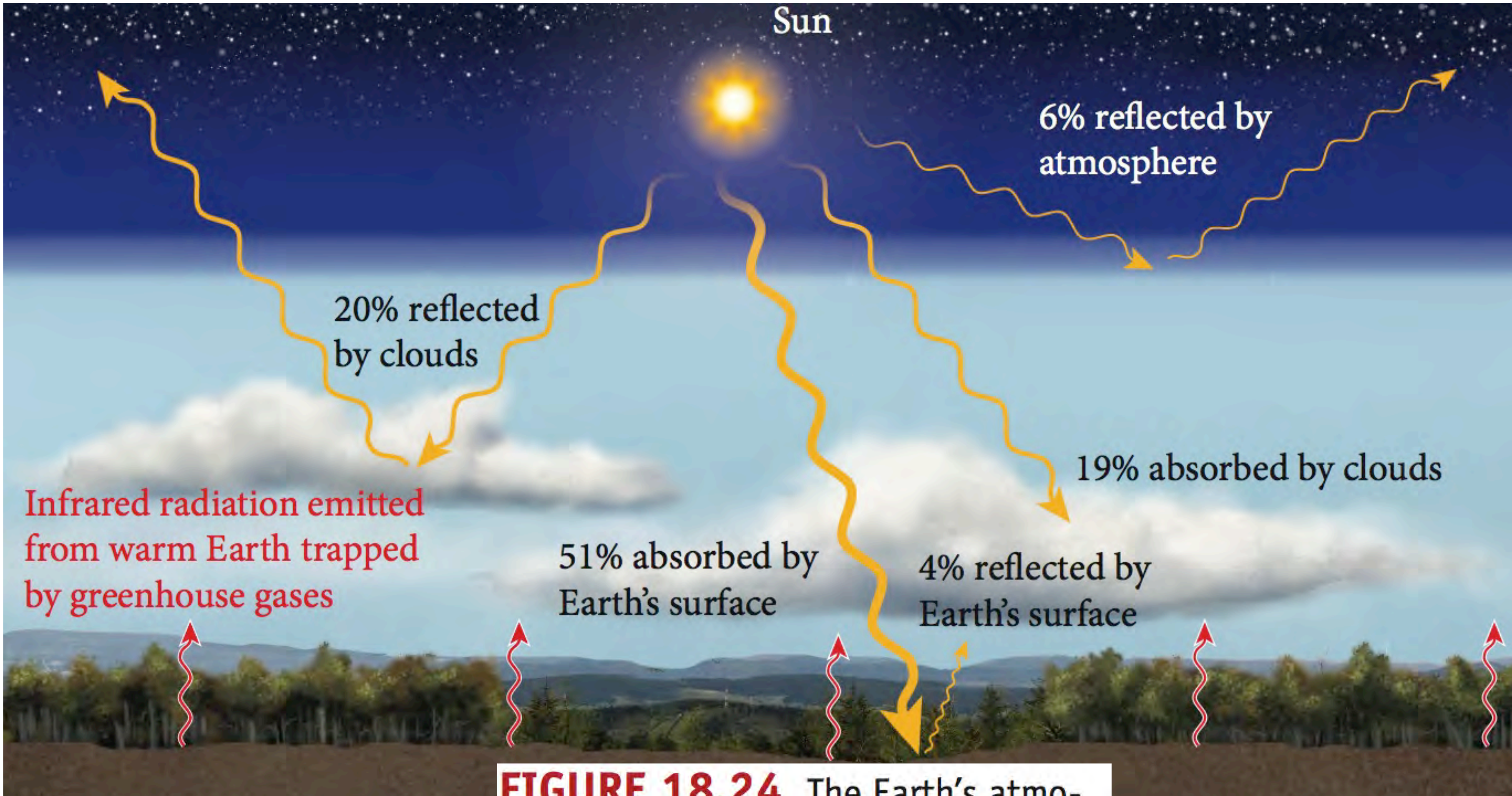


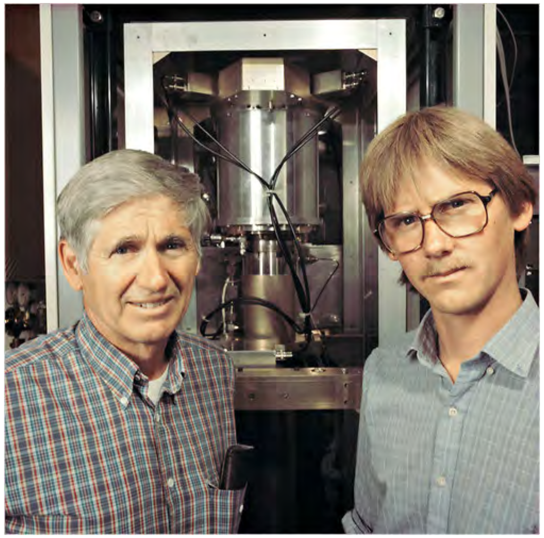
FIGURE 18.24 The Earth's atmosphere strongly affects the amount of energy absorbed by the Earth from the Sun.

Atmosphere

- Thickness > 100 km
- Composition
  78.08% nitrogen, 20.95% oxygen,
  0.93% argon, 0.039% (= 390 ppm) CO_2
- Total mass = $5.2 \cdot 10^{18}$ kg
- 1 ppm_{volume} CO_2 = $7.9 \cdot 10^{9}$ tons

Keeling Curve

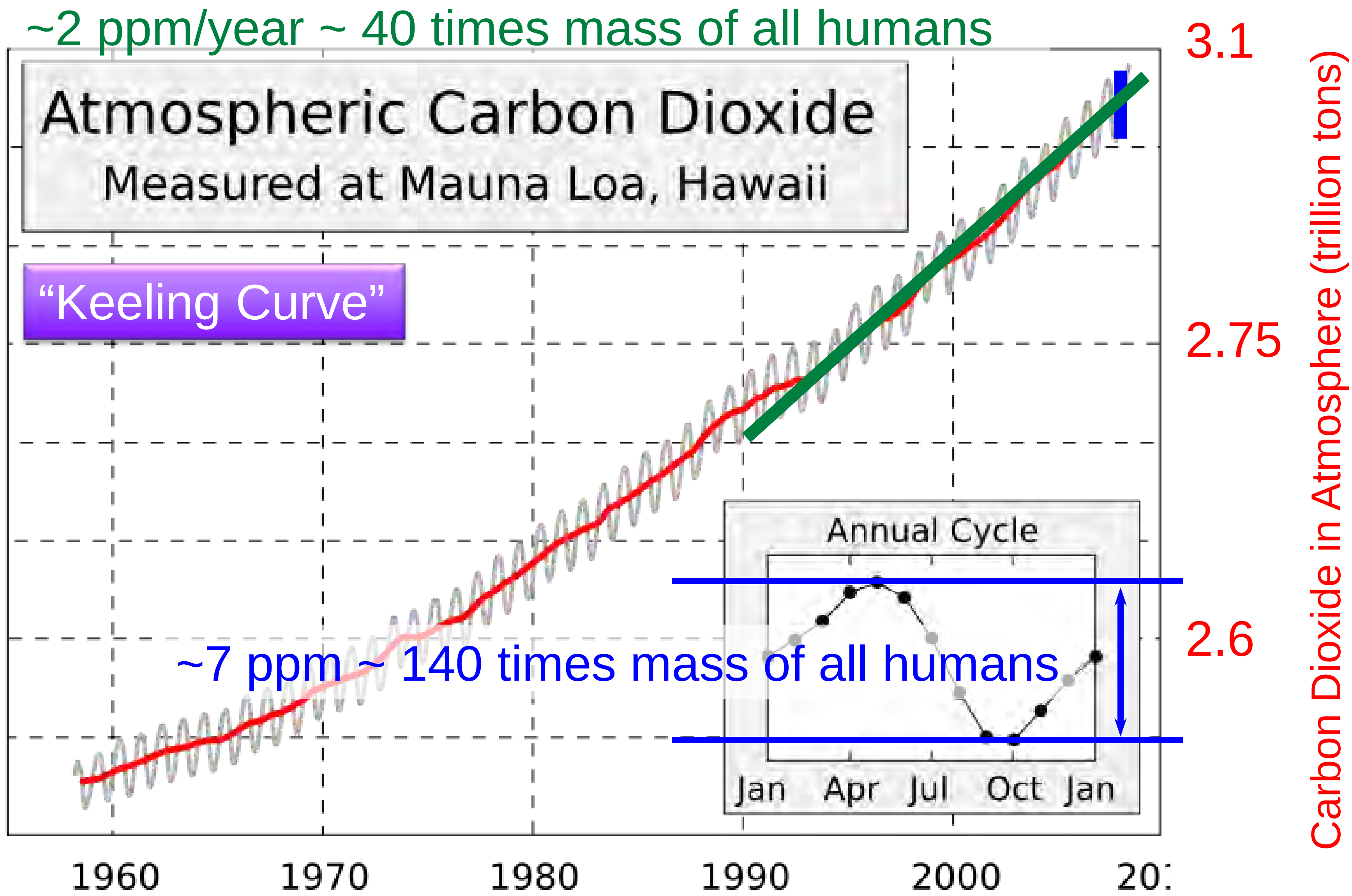
Mauna Loa Observatory
Jonathan Kingston/Aurora Select, for The New York Times

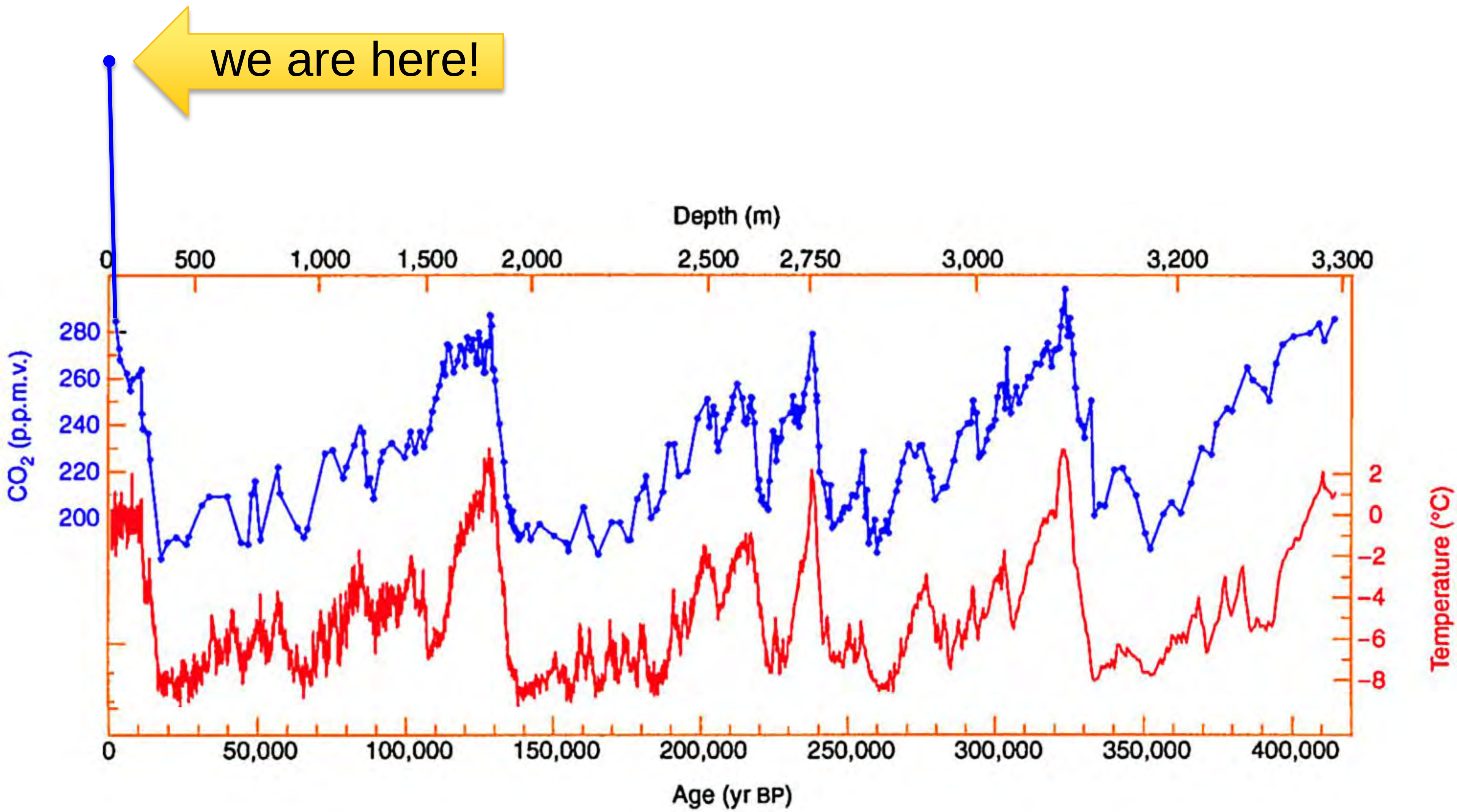


C. & R. Keeling, 1989
Scripps Institution of Oceanography / UC San Diego

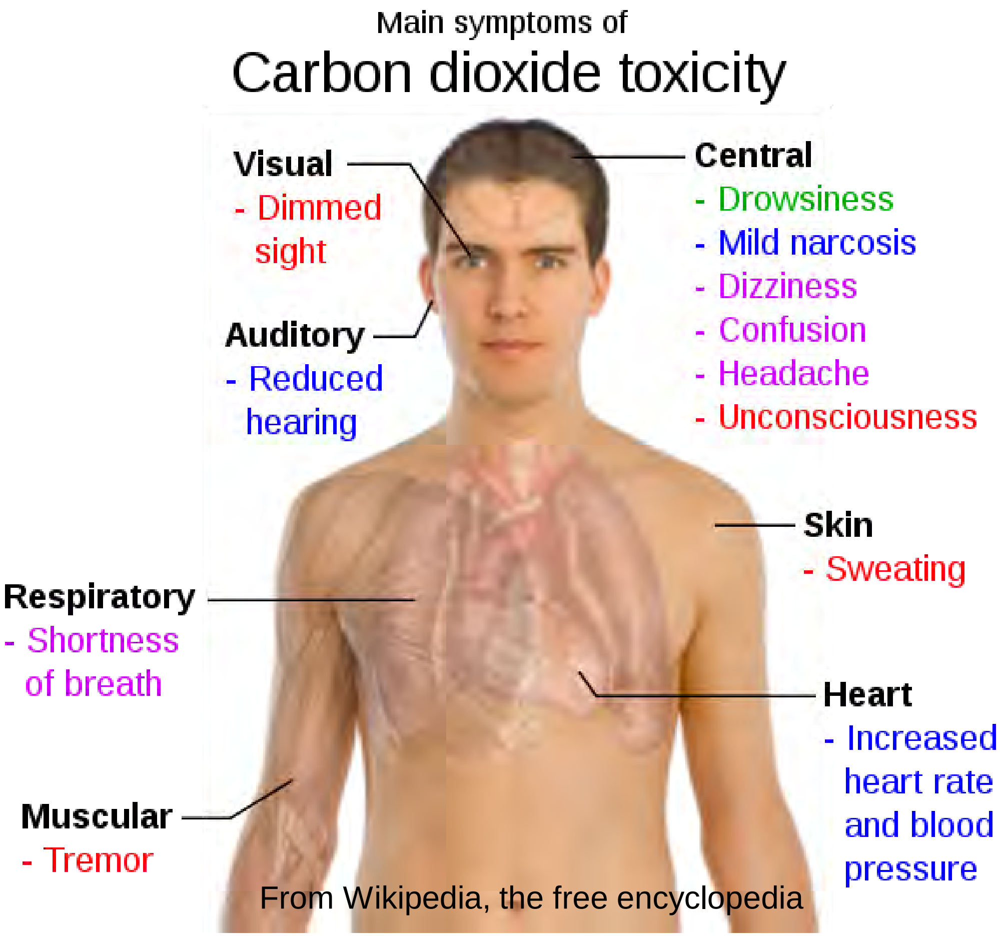
- Charles Keeling (1958): Measure CO_2 concentration in atmosphere periodically at Mauna Loa observatory
- Ralph Keeling continues work of his father after Charles' death in 2005

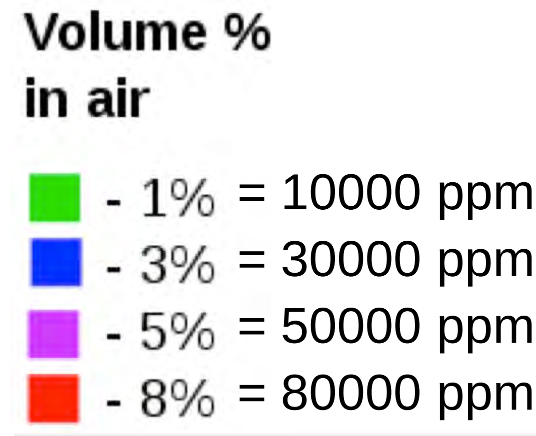
How big is the problem?




we are here!
Depth (m)
0
500
1,000
1,500
2,000
2,500
2,750
3,000
3,200
3,300
CO_2 (p.p.m.v.)
280
260
240
220
200
Temperature (°C)
2
0
−2
−4
−6
−8
0
50,000
100,000
150,000
200,000
250,000
300,000
350,000
400,000
Age (yr BP)

Good news: we can still breathe!





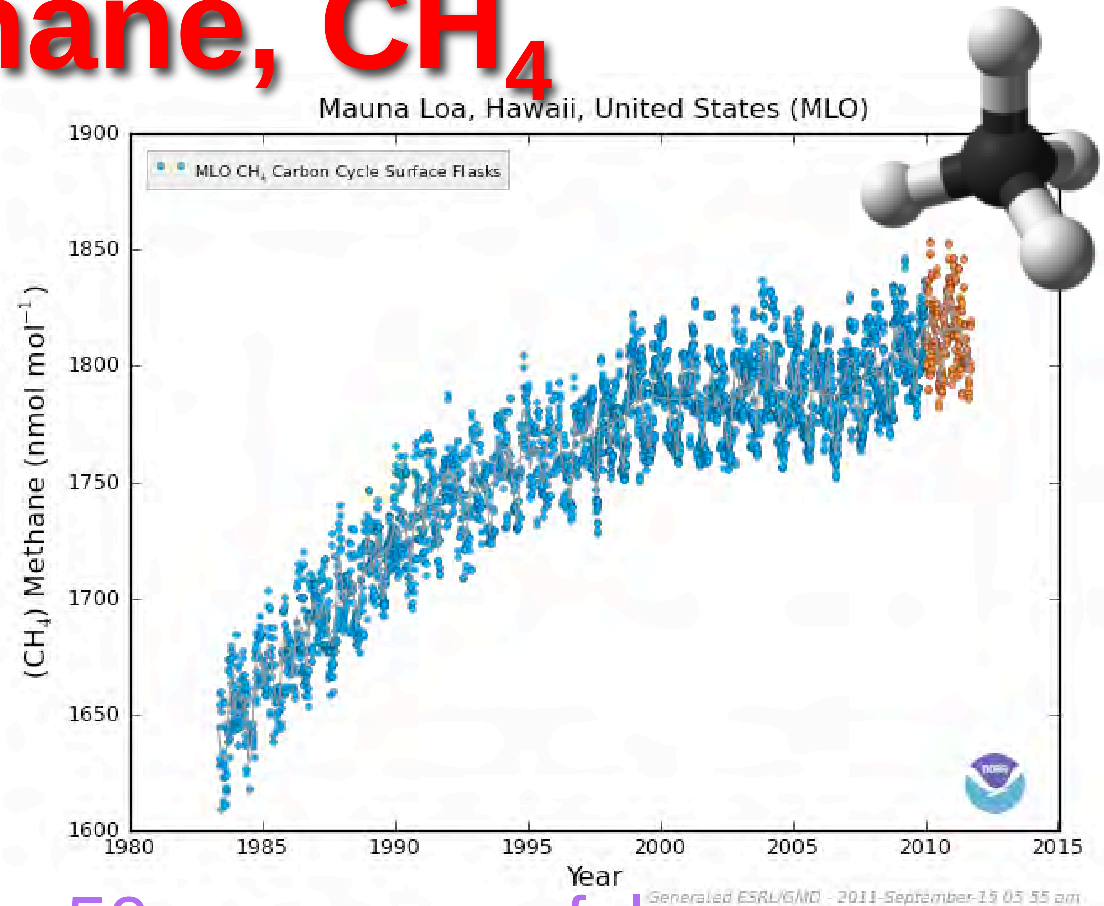
CO_2 level in atmosphere still a factor of ~20 below danger level

Interesting fact:

Humans breathe out ~ $3 \cdot 10^9$ tons of CO_2 (~ 0.4 ppm) per year

Very potent greenhouse gas: Methane, CH_4

- “Natural” gas
- Most important reaction
  $CH_4 + 2O_2$ ’
  $CO_2 + 2H_2O$
- Heat of combustion: 802 kJ/mol (~1 MJ/ft^3)

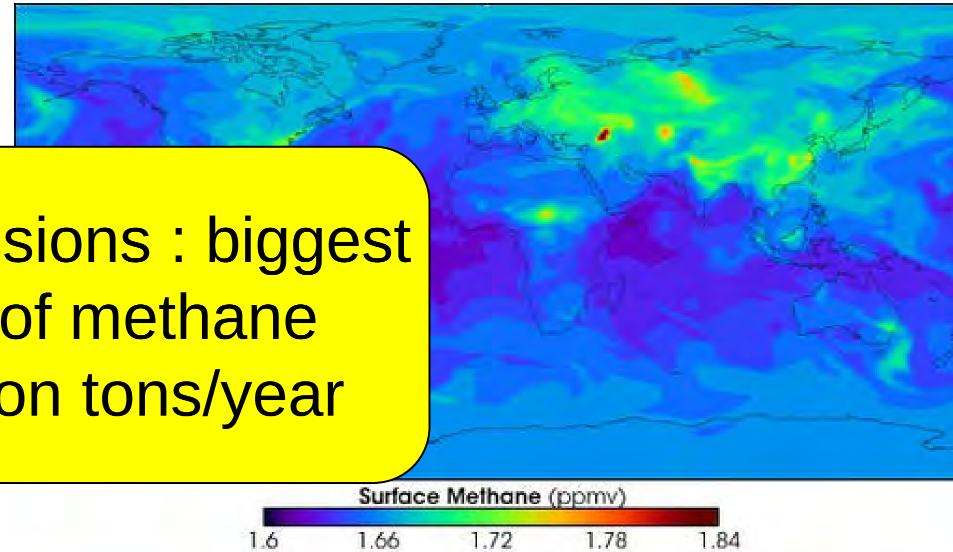


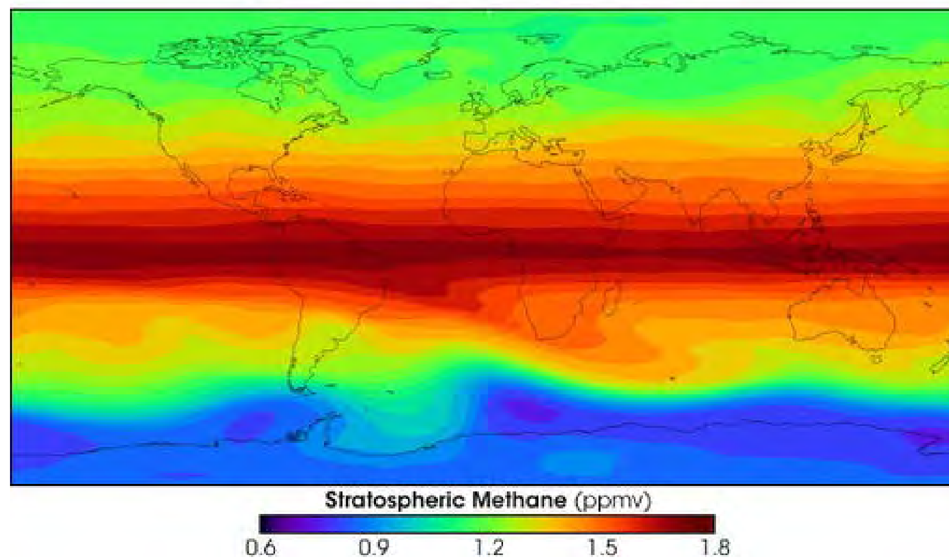
- CH_4 is a factor of 20 to 50 more powerful as a greenhouse gas than CO_2, responsible for ~20% of climate forcing from all greenhouse gases

Origin	CH$_4$ Emission		
	Mass (Tg/a)	Type (%/a)	Total (%/a)
Natural Emissions			
Wetlands (incl. Rice agriculture)	225		
Termites	20		
Ocean	15		
Hydrates	10		
Natural Total	270		
Anthropogenic Emissions			
Energy	110		
Landfills	40		7
Ruminants (Livestock)	115	35	19
Waste treatment	25	8	4
Biomass burning	40	12	7
Anthropogenic Total	330	100	55
Sinks			
Soils	-30	-5	-5
Tropospheric OH	-510	-88	-85
Stratospheric loss	-40	-7	-7
Sink Total	-580	-100	-97
Emissions + Sinks			
Imbalance (trend)	+20	~2.78 Tg/ppb	+7.19 ppb/a

Houweling et al. *Climate Change 2001*

Cows' emissions : biggest source of methane
115 million tons/year





http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=16827

Bottom Line: Greenhouse Gases

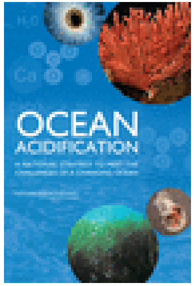
- Many feedback loops still poorly understood (see Carl Sagan's predictions after 1st Iraq war)
- Earth's climate may respond fairly linearly to changes from anthropogenic sources
- But there also may be a runaway solution
- **An experiment we really should not want to conduct!**

what we will cover

- Greenhouse gases and global warming
- Projected consequences of global warming
- Energy from fossil fuels
- Other options
- My pet project(s)

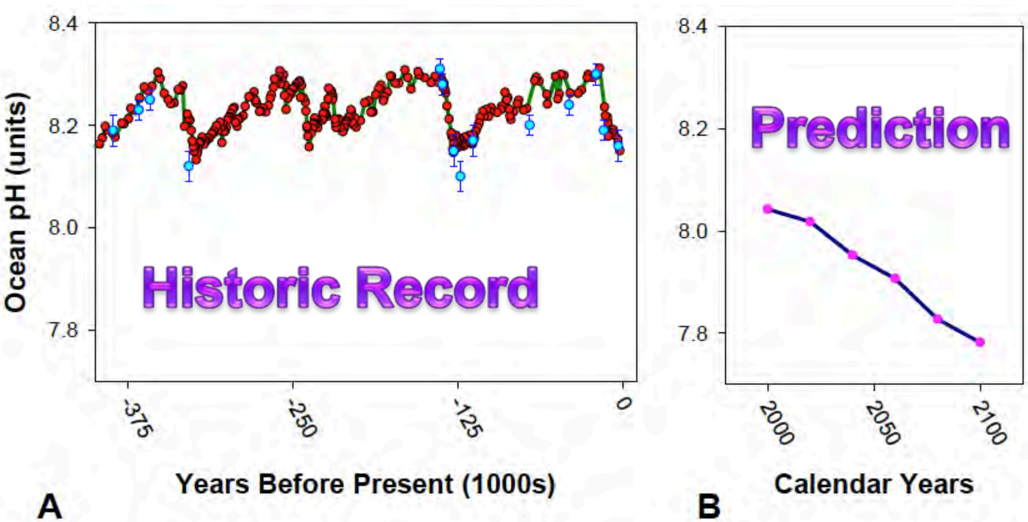
Consequences

- Temperature rise (not sure by how much …)
- Shift of climate zones
- Increase in frequency and strength of violent weather events
- Rise in sea level
- Ocean acidification
- Species mass migration / likely mass extinction



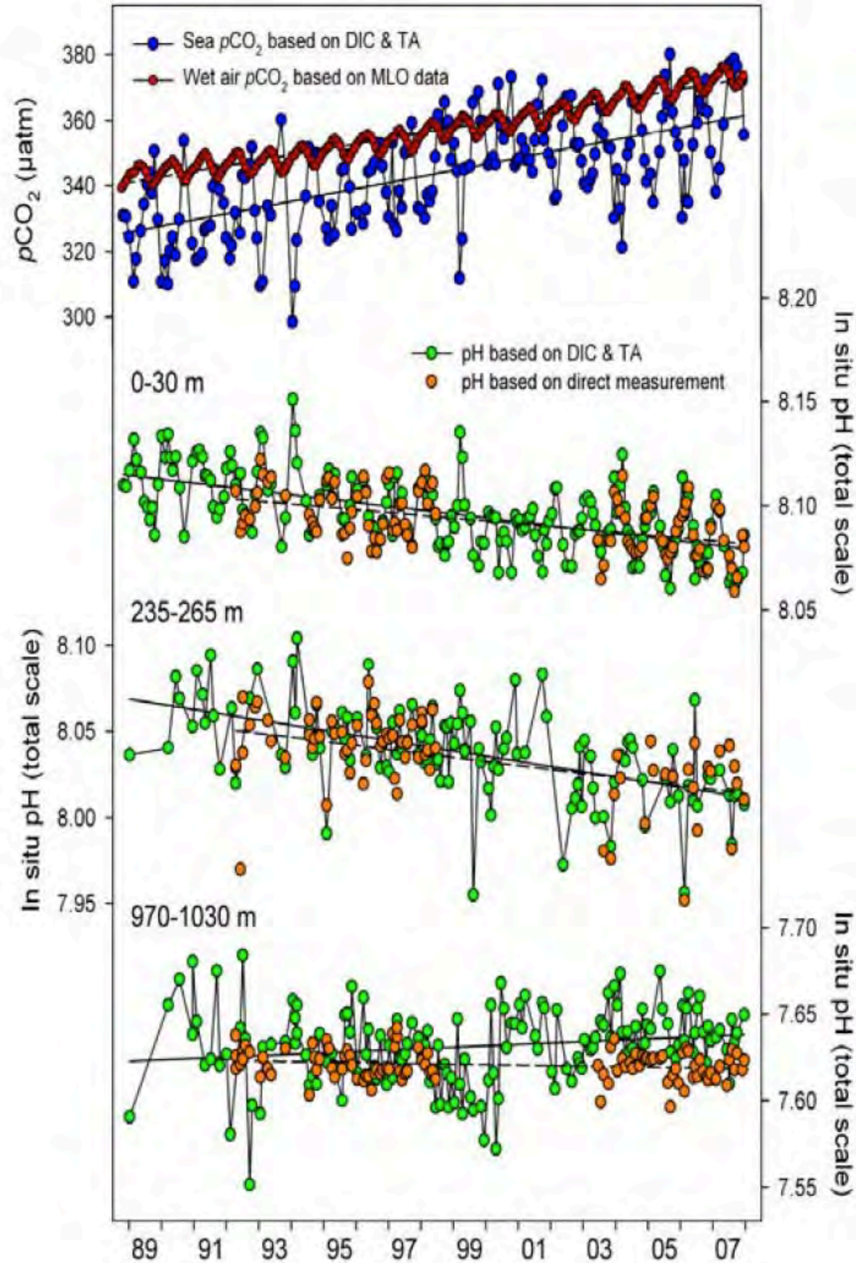
Ocean Acidification

- ~10 billion tons/year of CO2 absorbed in oceans
- Changes pH value!



"Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean", NRC Report

http://www.nap.edu/catalog.php?record_id=12904



Dore, J.E., et al. 2009.
PNAS 106(30): 12235–12240.

Global Warming makes oceans rise!
By how much? How Fast?

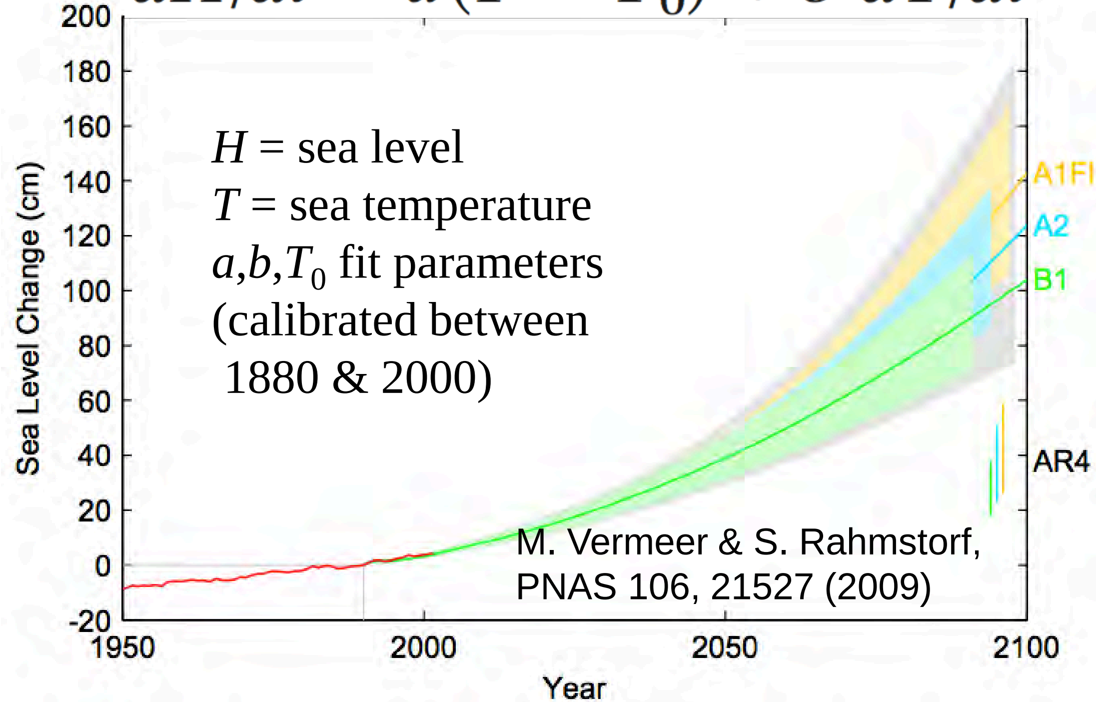
Earth surface area = 510M km^2,
361M km^2 covered by oceans
40-50M km^2 covered by ice

Message:
do not buy beachfront property!

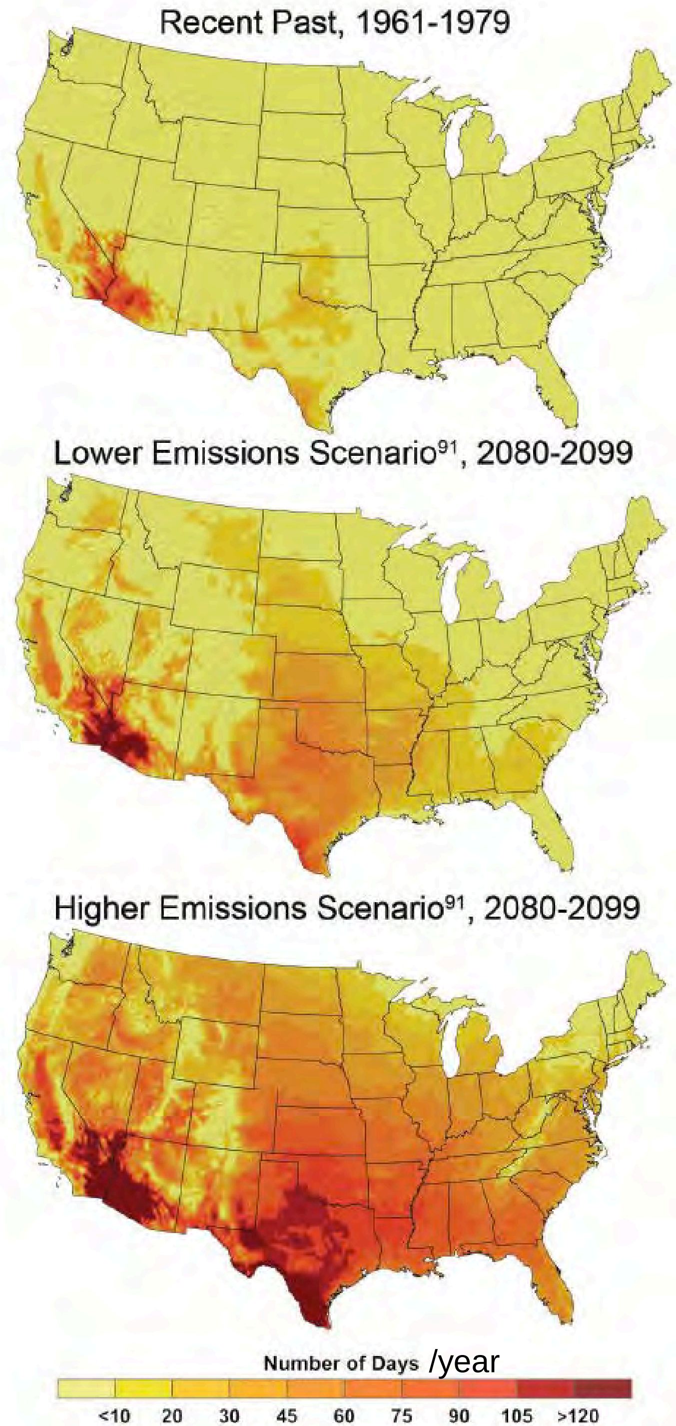
Ice melting

	Ice Volume	Sea rise
Greenland	2.8M km^3	7.2 m
Antarctic	30M km^3	76 m
North Pole	5-25M km^3	0
Total	**33M km^3**	**83 m**

$$dH/dt = a(T - T_0) + b\, dT/dt$$

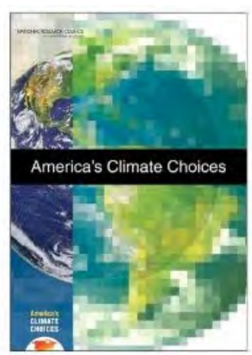


More >100° F days



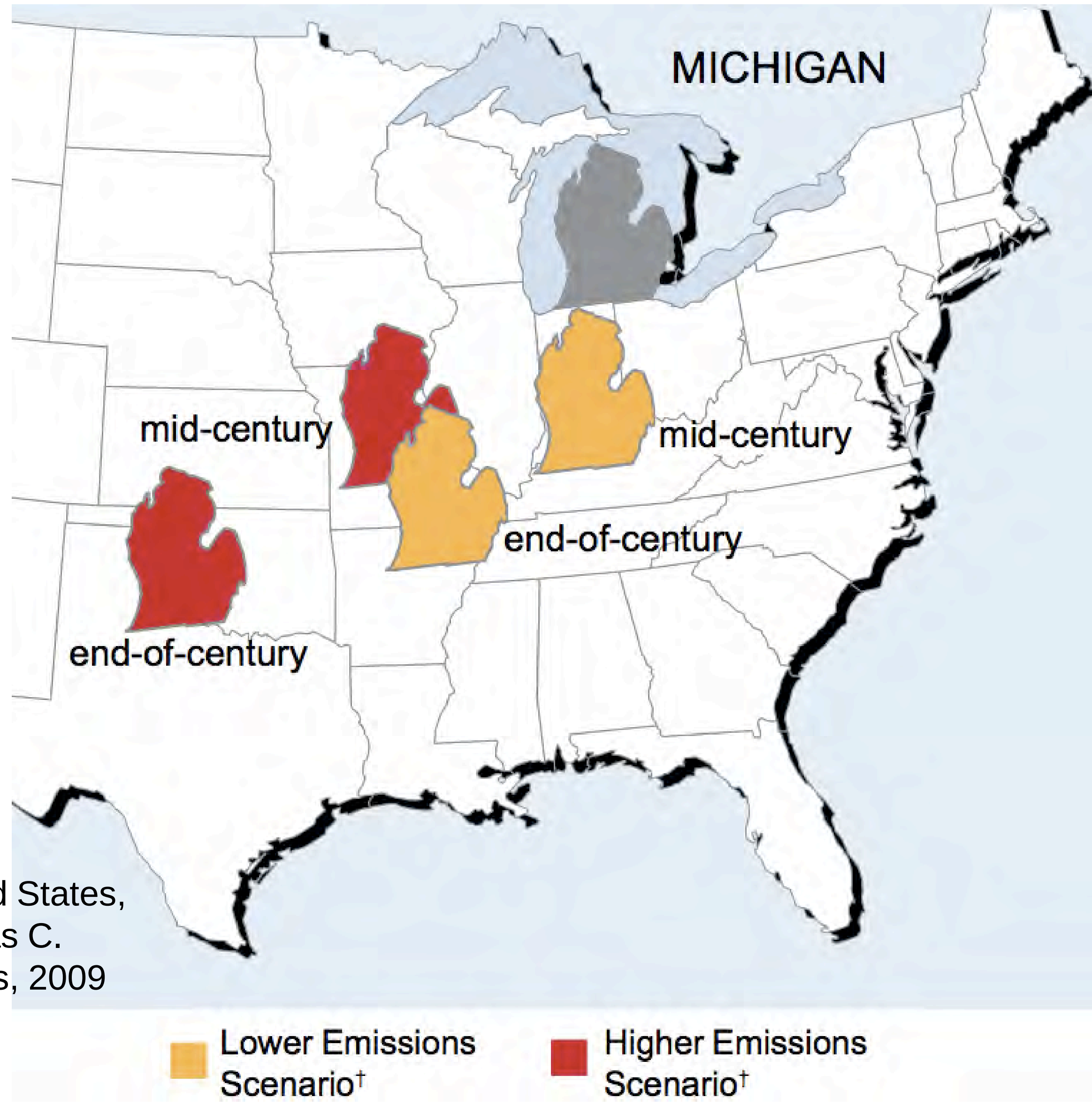
"America's Climate Choices", NRC Report

http://www.nap.edu/catalog.php?record_id=12781



Michigan

- Climate projections for this century
- Global warming **is on our side**!



Global Climate Change Impacts in the United States, Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson, (eds.). Cambridge University Press, 2009 p. 117

www.globalchange.gov/usimpacts

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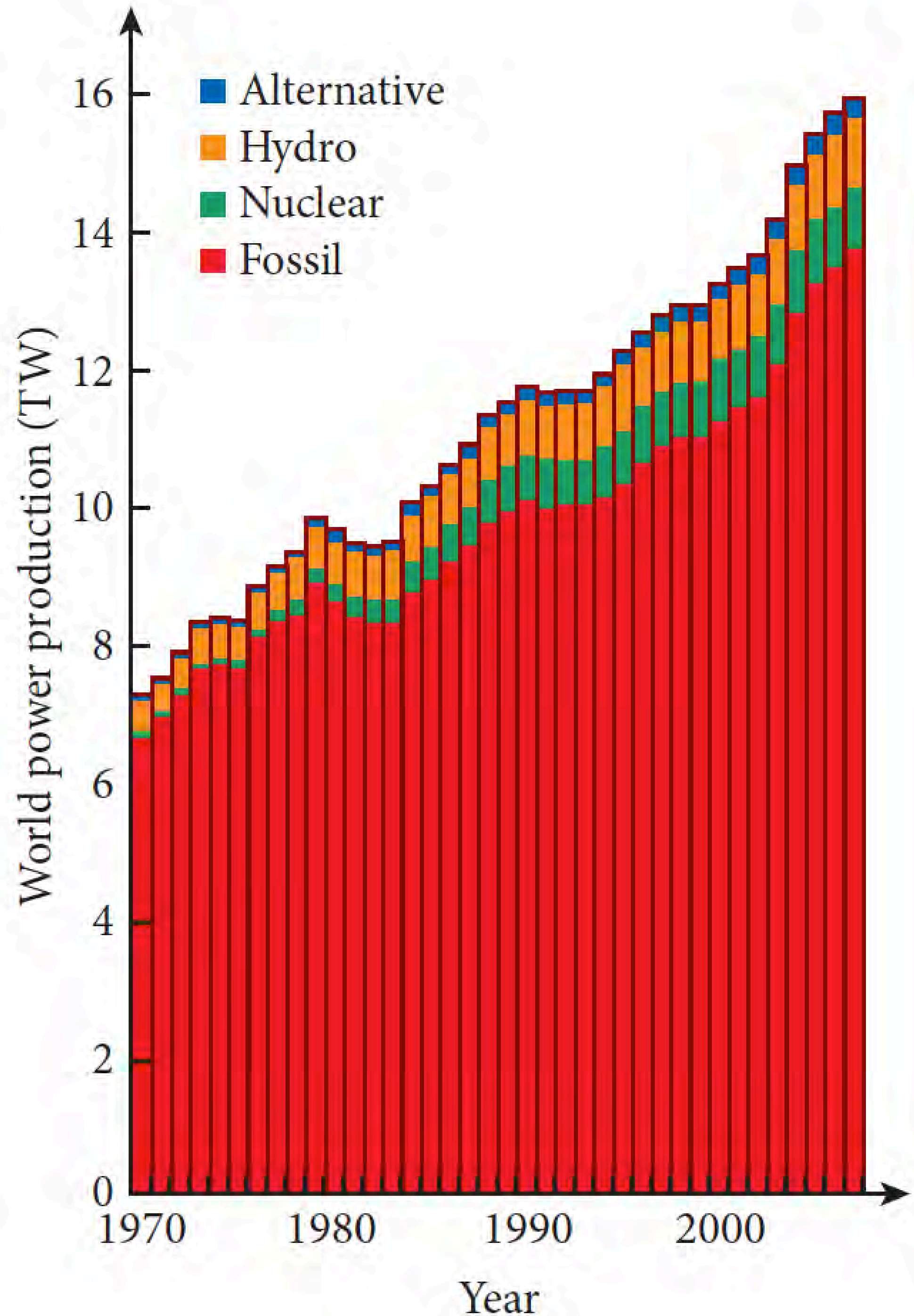
Global Power Production



Bauer & Westfall, 2nd edition
Data: US DOE EIA

Physics unit for money?

"Time is money"

$$t = \$$$

"Location, location, location"

$$L^2 = \$$$

My answer:

$$E = \$$$

(more important than $E=mc^2$)

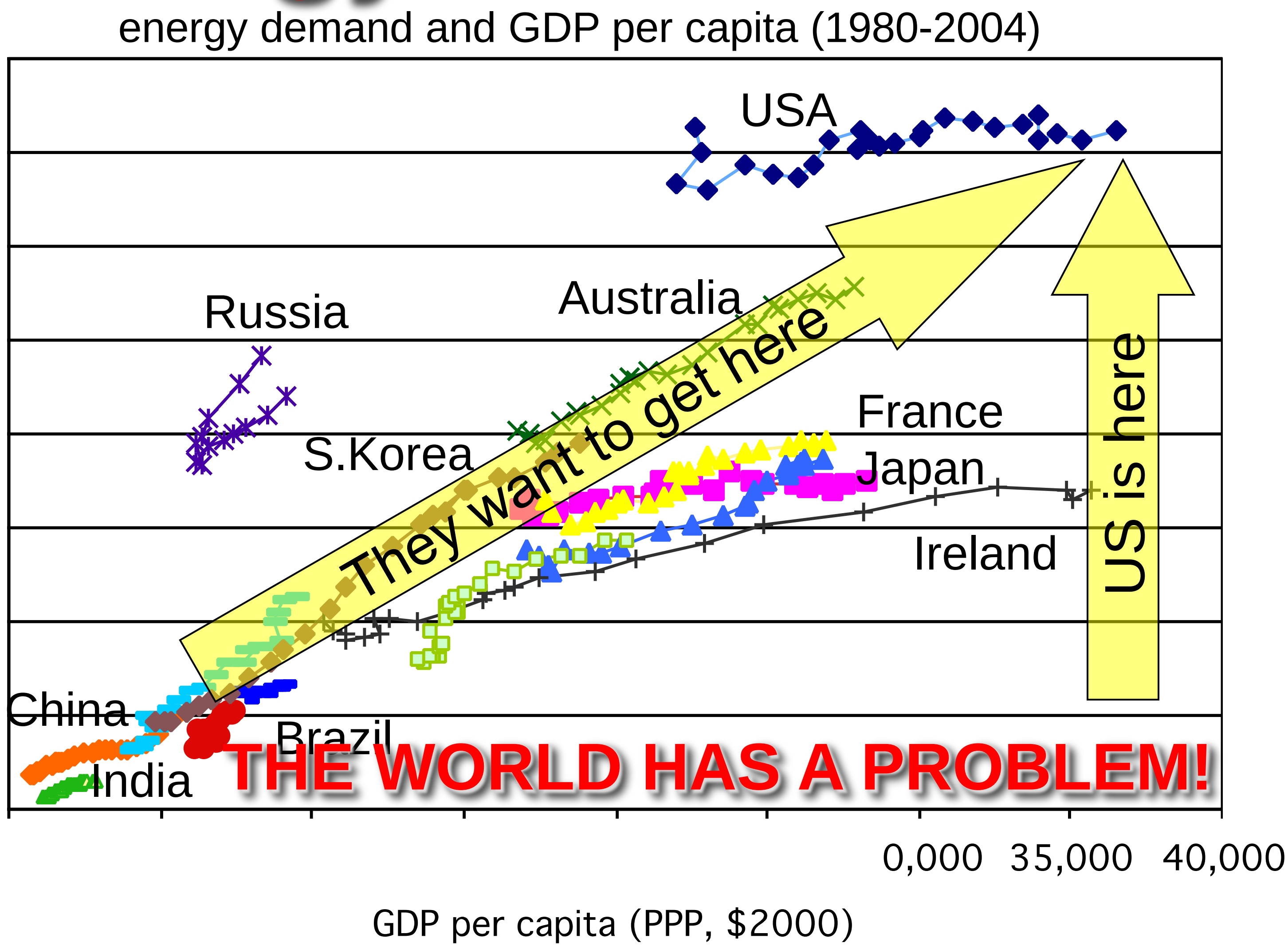
Table 1.1 Unit Names and Abbreviations for the Base Units of the SI System of Units

Unit	Abbreviation	Base Unit for
meter	m	length
kilogram	kg	mass
second	s	time
ampere	A	current
kelvin	K	temperature
mole	mol	amount of a substance
candela	cd	luminous intensity

Table 1.2 Common SI Derived Units

Derived or Dimensionless Unit	Name	Symbol	Equivalent	Expressions
Absorbed dose	gray	Gy	J/kg	m2 s^{-2}
Activity	becquerel	Bq	—	s^{-1}
Angle	radian	rad	—	—
Capacitance	farad	F	C/V	$m^{-2}\,kg^{-1}\,s^4\,A^2$
Catalytic activity	katal	kat	—	s^{-1} mol
Dose equivalent	sievert	Sv	J/kg	$m^2\,s^{-2}$
Electric charge	coulomb	C	—	s A
Electric conductance	siemens	S	A/V	$m^{-2}\,kg^{-1}\,s^3\,A^2$
Electric potential	volt	V	W/A	$m^2\,kg\,s^{-3}\,A^{-1}$
Electric resistance	ohm	Ω	V/A	$m^2\,kg\,s^{-3}\,A^{-2}$
Energy	joule	J	N m	$m^2\,kg\,s^{-2}$
Force	newton	N	—	$m\,kg\,s^{-2}$
Frequency	hertz	Hz	—	s^{-1}
Illuminance	lux	lx	lm/m^2	m^{-2} cd
Inductance	henry	H	Wb/A	$m^2\,kg\,s^{-2}\,A^{-2}$
Luminous flux	lumen	lm	cd sr	cd
Magnetic flux	weber	Wb	V s	$m^2\,kg\,s^{-2}\,A^{-1}$
Magnetic field	tesla	T	Wb/m^2	$kg\,s^{-2}\,A^{-1}$
Power	watt	W	J/s	$m^2\,kg\,s^{-3}$
Pressure	pascal	Pa	N/m^2	$m^{-1}\,kg\,s^{-2}$
Solid angle	steradian	sr	—	—
Temperature	degree Celsius	°C	—	K

Energy Use = Wealth



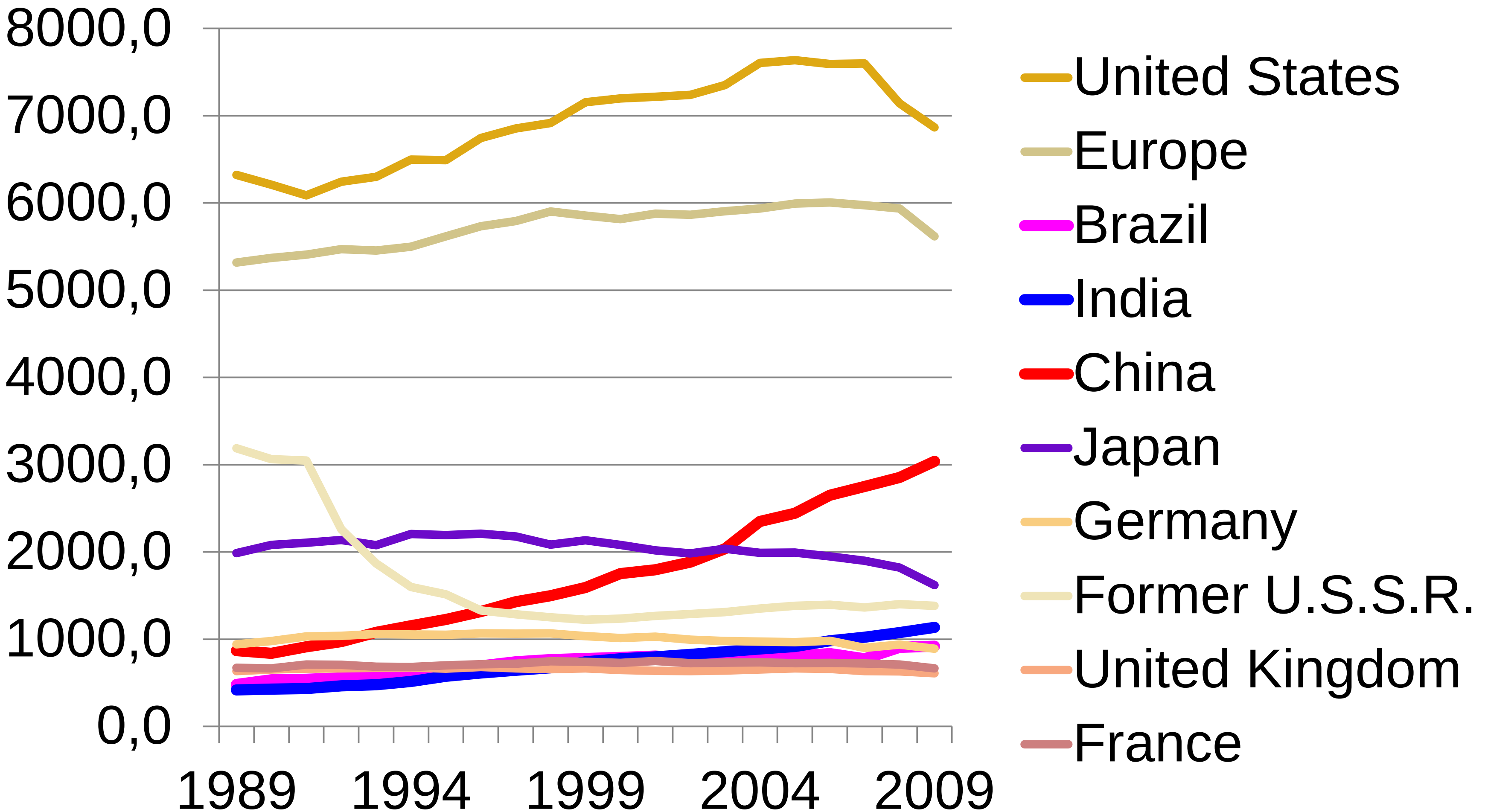
Source: UN and DOE EIA, BP (Koonin)
Russia data 1992-2004 only

How much is 350 GJ/year?

- We eat about 2,500 Cal/day (~10 MJ/day)
- Food consumption/year: ~3.5 GJ
- 350 GJ = food consumption of 100 people
- "is the equivalent of having ~ 100 energy 'servants' " (Steve Chu)

World Oil Consumption

US oil consumption ~ 25% of world consumption
US population ~ 5% of world population



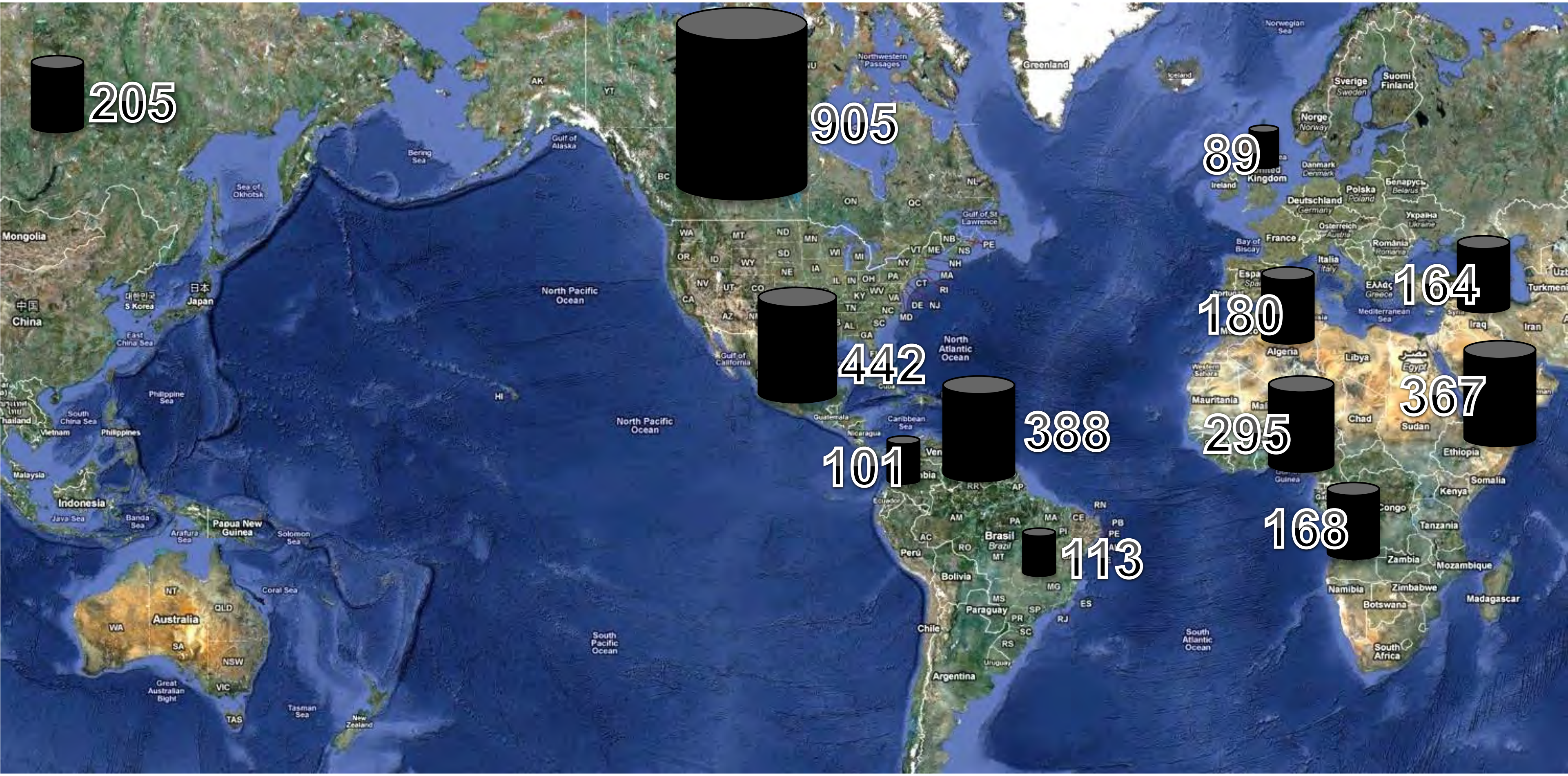
(in billion barrels per year)

Data source: US Energy Information Administration

US Oil Imports 2010

Source:
U.S. Energy Information Administration
Independent Statistics and Analysis

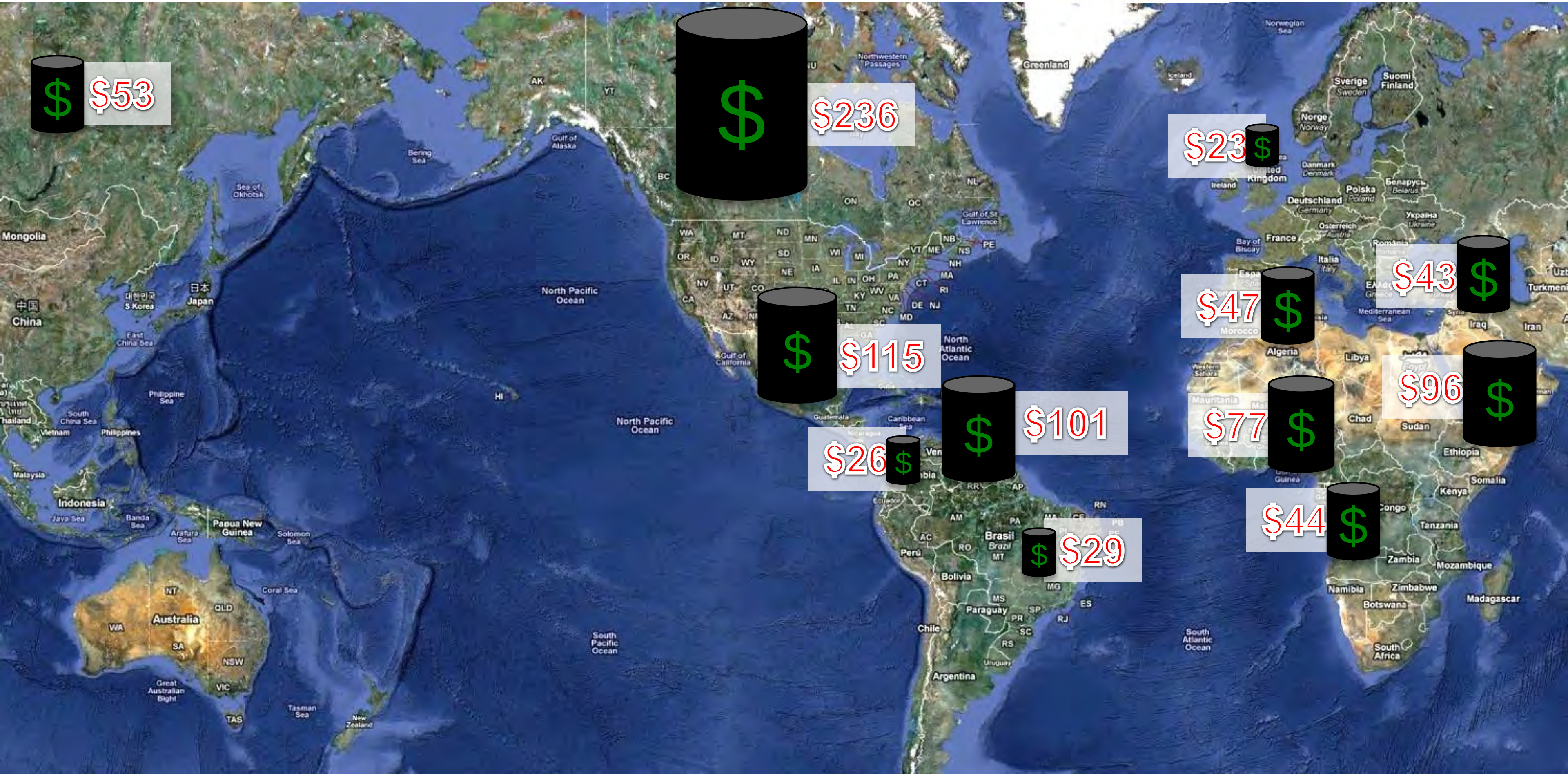
(by country, in million barrels)



Top imports from: Canada, Mexico, Venezuela, Saudi Arabia, Nigeria, Russia, Algeria, Angola, Iraq, Brazil, Columbia, United Kingdom

Total: 4267 million barrels

Costs for you



US population: 307 Million
Oil price in 2010: ~$80/barrel
Total oil *import* cost per US citizen in 2010: ~**$1100**

Total cost for the US economy in 2010: **$340 billion**

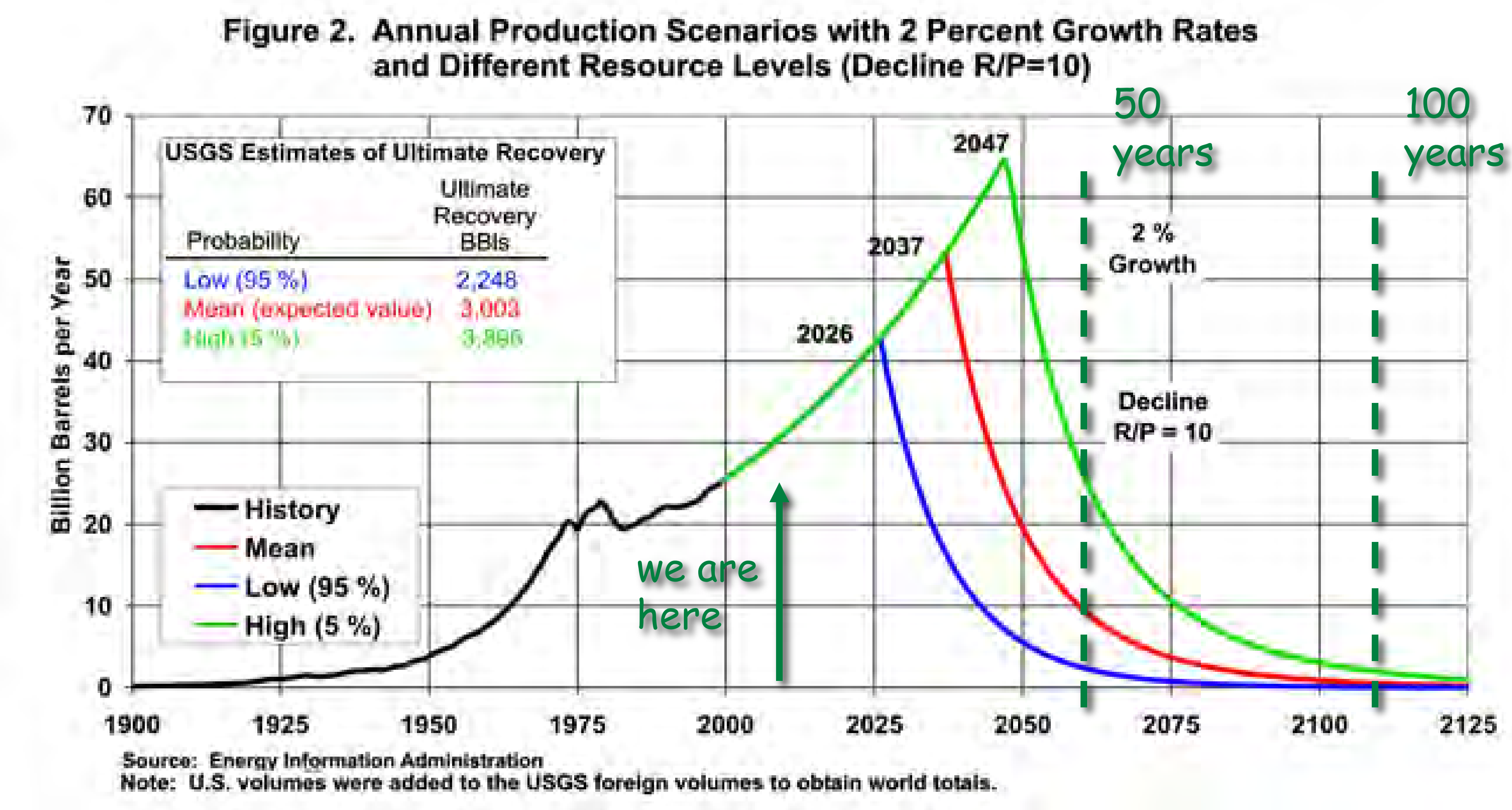
Where do oil, gas, coal come from?

Carboniferous period:

- – 360 million years ago plants evolved to grow wood (lignin)
- – 300 million years ago bacteria evolved to digest lignin

- Fossil fuels are a finite resource and do not renew
  - – All present resources were produced during ~60 million year
  - – We are using up fossil fuels at a ~500,000 times faster rate

We are running out of oil!



http://www.eia.doe.gov/

S.E. Koonin, BP

Drilling for oil gets more expensive and dangerous

http://gcaptain.com/wp-content/uploads/2011/01/Deepwater-Horizon-oil-rig-explosion.jpg

Fossil Fuel Summary

Fossil fuels have lots of problems:

- rapidly shrinking supplies
- get more dangerous to recover
- add billions of tons of greenhouse gases to the atmosphere each year
- cause global warming
- lead to geopolitical instabilities

what we will cover

- Greenhouse gases and global warming
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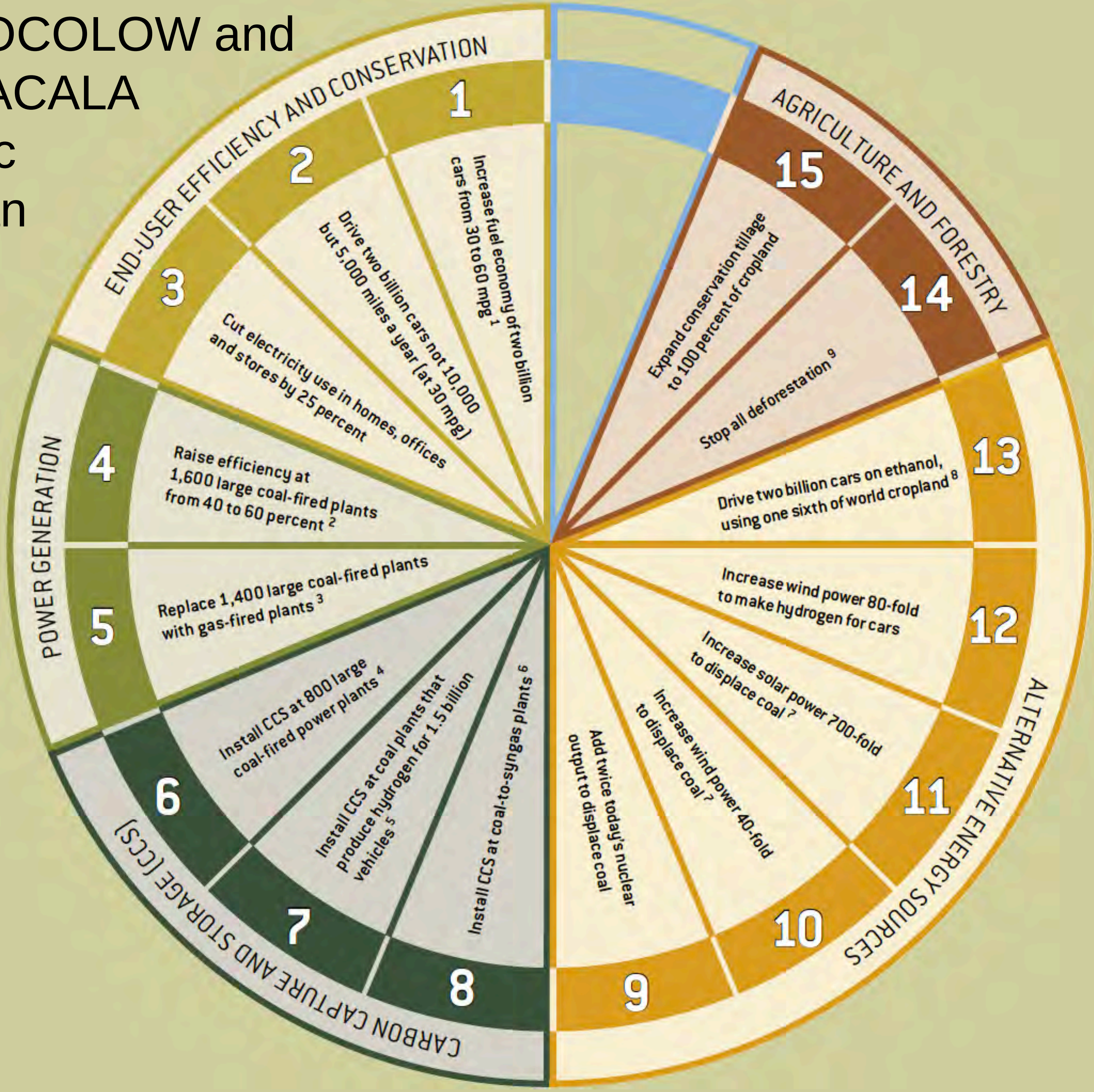
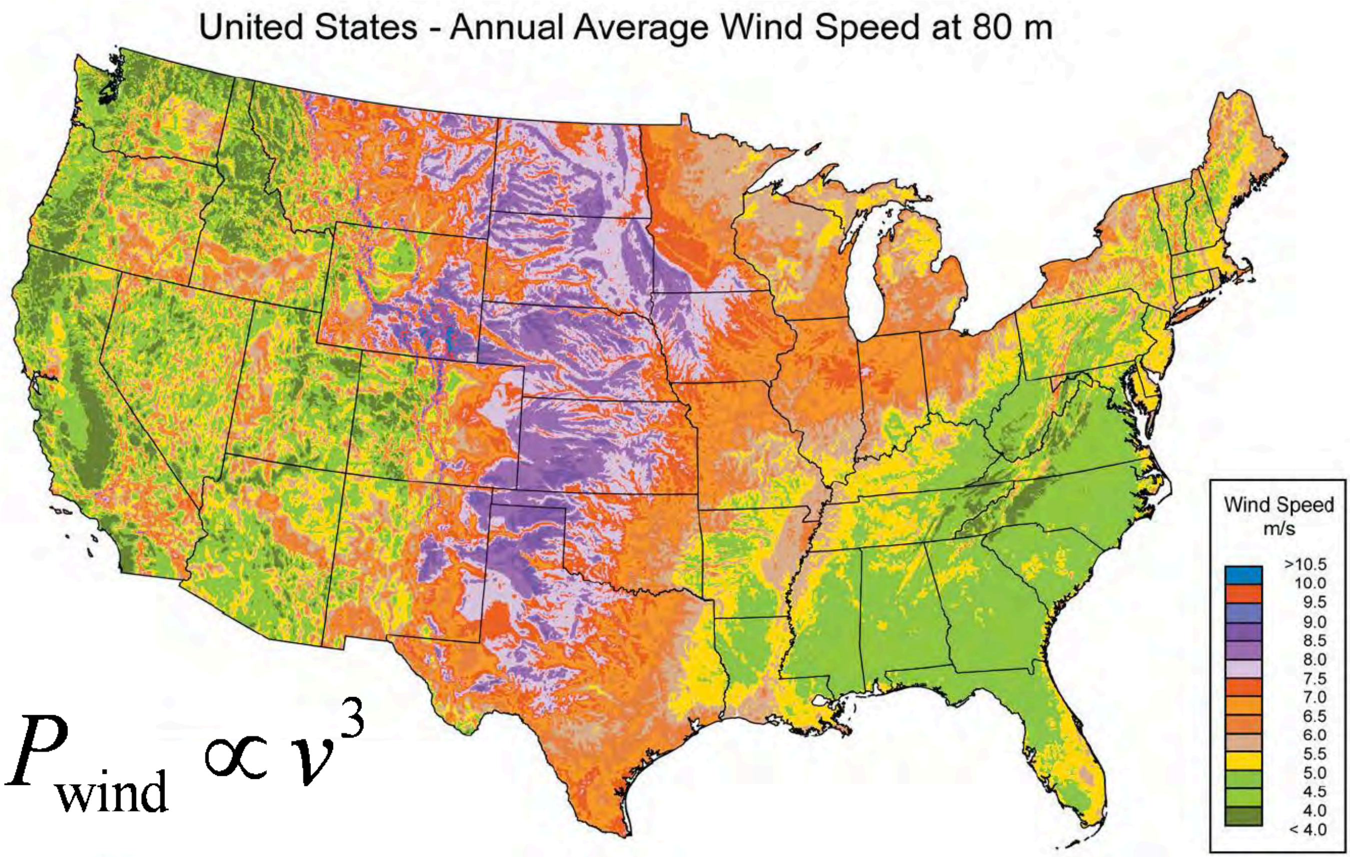
There is no magic bullet!

- Mixture of solar, hydro, wind, geo, bio
- Need also nuclear (“safe nuclear”)
  - Thorium fission cycle (breeder, fuel for 20,000 years)
- Long term: fusion (ITER, NIF) … maybe …
- All of the above: carbon neutral
- But: cannot do without fossil fuels in the near future.
  - Carbon sequestration
  - Clean coal (misnomer!)
- Energy conservation is part of the mixture!
  - Efficient light bulbs (LED)
  - Better insulation
  - Public transportation

R. H. SOCOLOW and S. W. PACALA Scientific American 2006

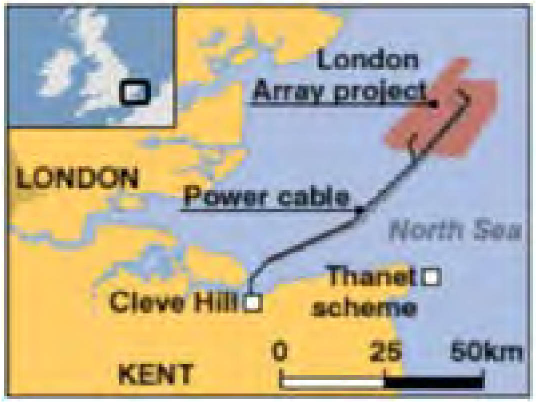


Wind



$$P_{\text{wind}} \propto v^3$$

Wind



Most efficient: Offshore wind farms

- Example: London Array
  - Completion in 2012
  - Cost: €2.2 billion (~$2.6 billon)
  - Capacity: 630 MW
  - Payoff time (@10¢/kWh): 5 years

Denmark: ~20% of electricity from wind, ~4 GW capacity.
Intermittency? Smoothing via Norwegian hydro.

Middelgrunden offshore wind farm near Copenhagen, Denmark
http://en.wikipedia.org/wiki/File:DanishWindTurbines.jpg

Hydro

Example: Three Gorges Dam

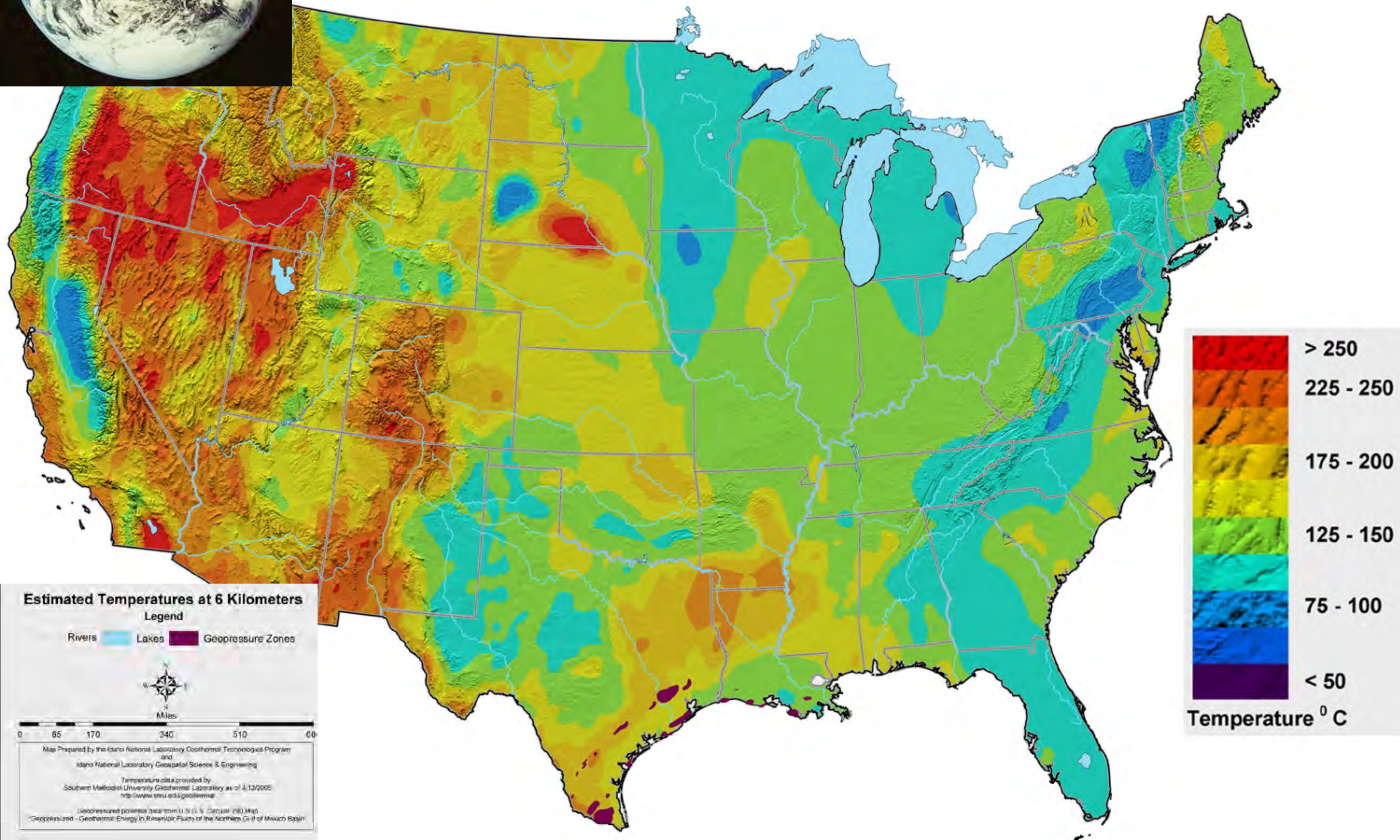
- Completion in 2008
- Cost: $26 billion (¥180 billion)
- Capacity: 18.2 GW
- Payoff time (@10¢/kWh): 2 years

Earth’s thermal energy ~ 10^{31} J

Heat flow density: 0.1 W/m^2

Total heat flow: 44 TW

Geo

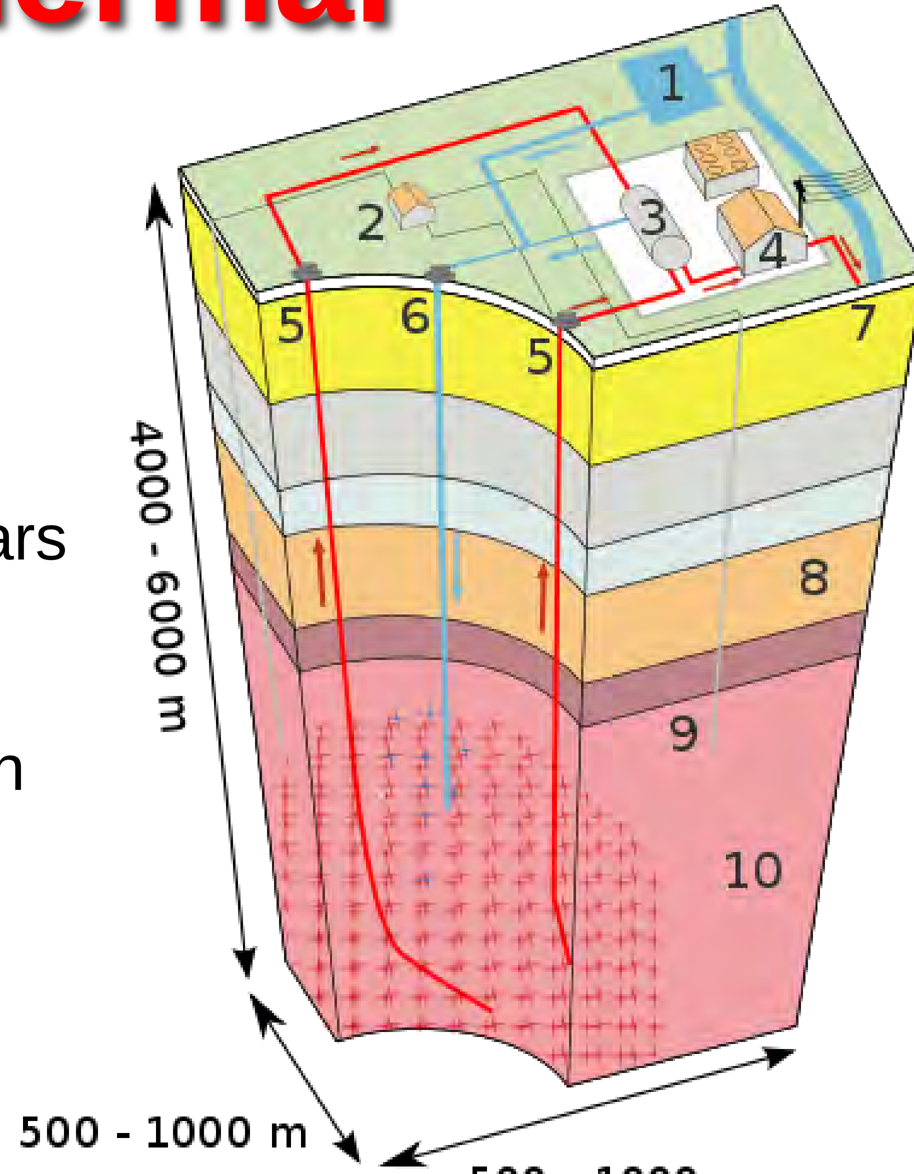


Geothermal

Enhanced **G**eothermal **S**ystem

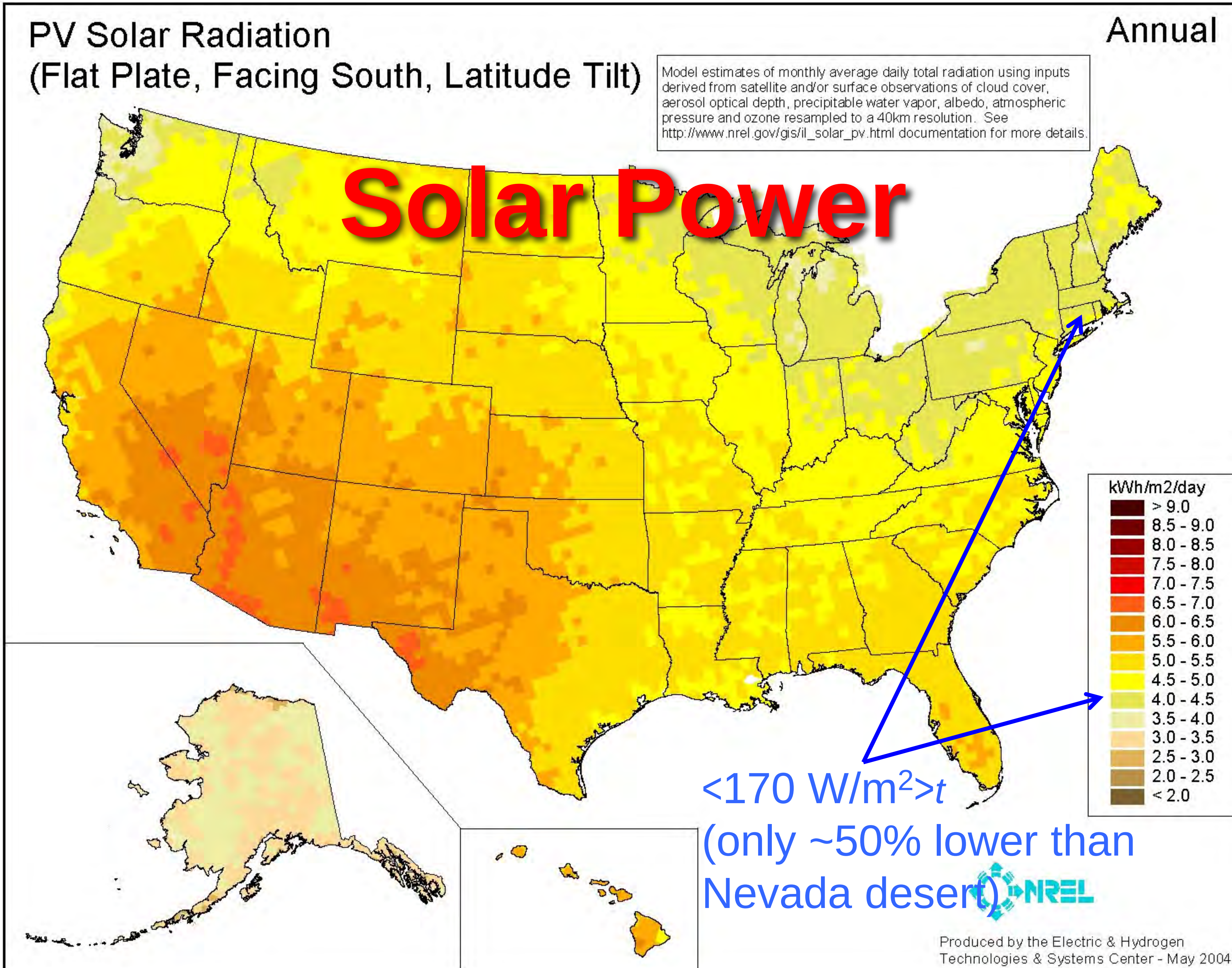
- 2 or more bore holes
- Hydraulic fracturing
- Cost: ~ $20 million
- Capacity: 4 MW
- Payoff time (@10¢/kWh): 6 years
- Risks
  - Induced seismicity
  - Ground water contamination

GSA Topical Session, Denver 2010
Warren Wood
Wolfgang Bauer



http://en.wikipedia.org/wiki/File:EGS_diagram.svg

Solar Power



$<170\ \mathrm{W/m^2}>t$
(only ~50% lower than Nevada desert)

Solar Power

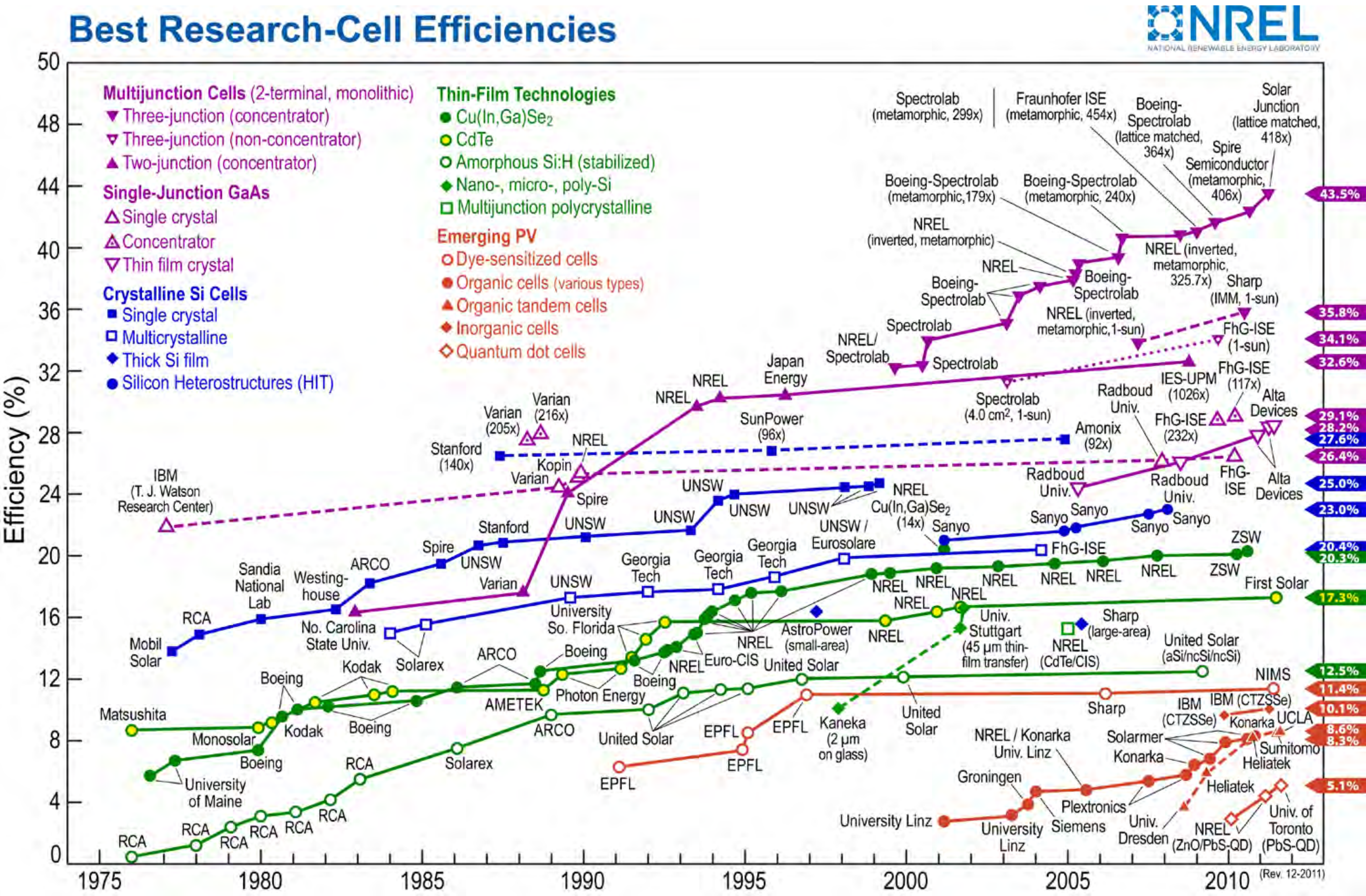
Example: Nellis Solar Power Plant
Nevada (Air Force base, Las Vegas)

- Photovoltaic
- 14 MW (peak)
- 57 ha land
- 70,000 solar panels
- Cost: ~$200 million
- Payoff time (@10¢/kWh): >16 years

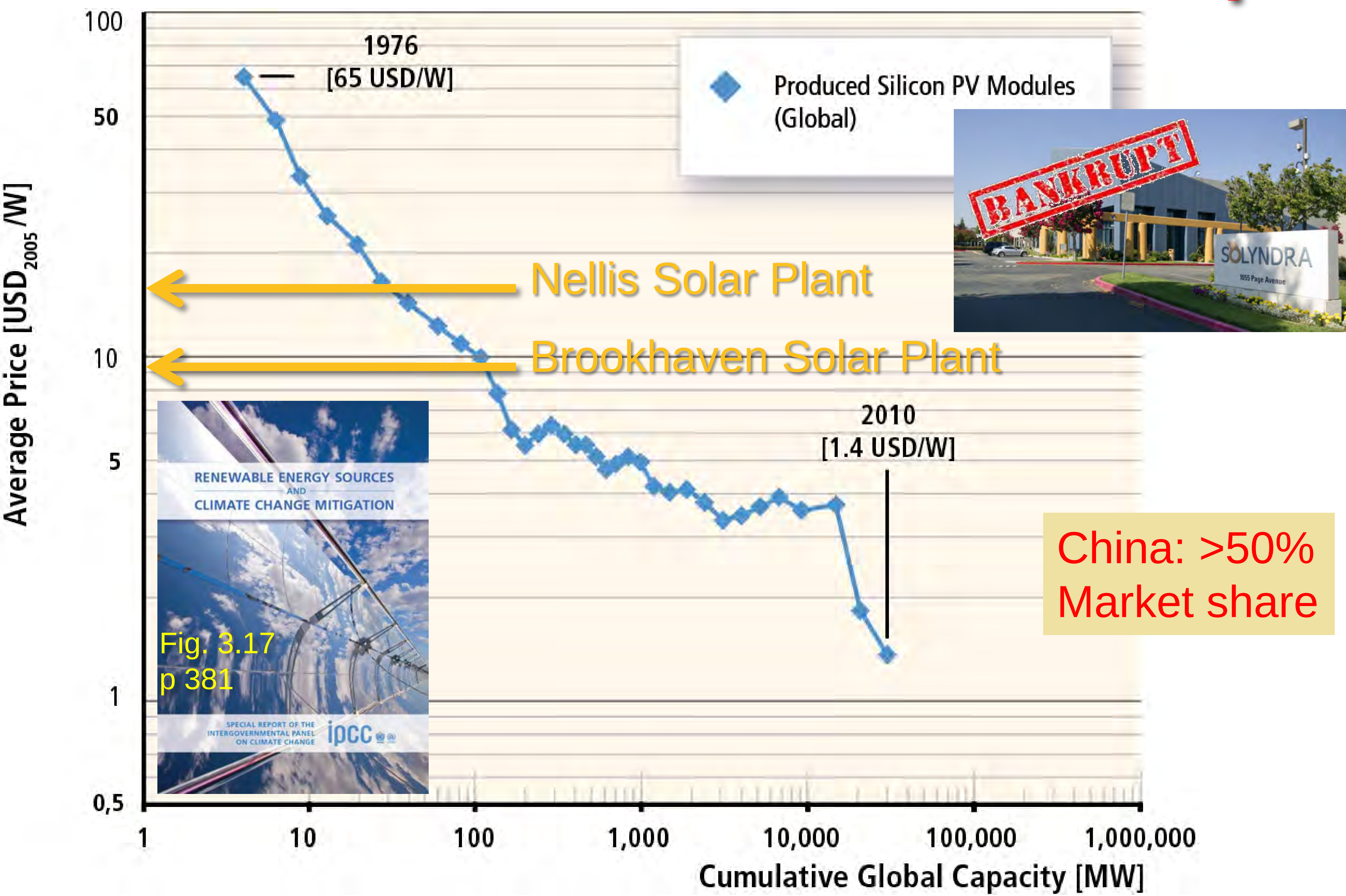
… across the Sound

32 MW (peak) Brookhaven solar farm (BP Solar, MetLife, LIPA, DOE)

Solar Power … getting more efficient

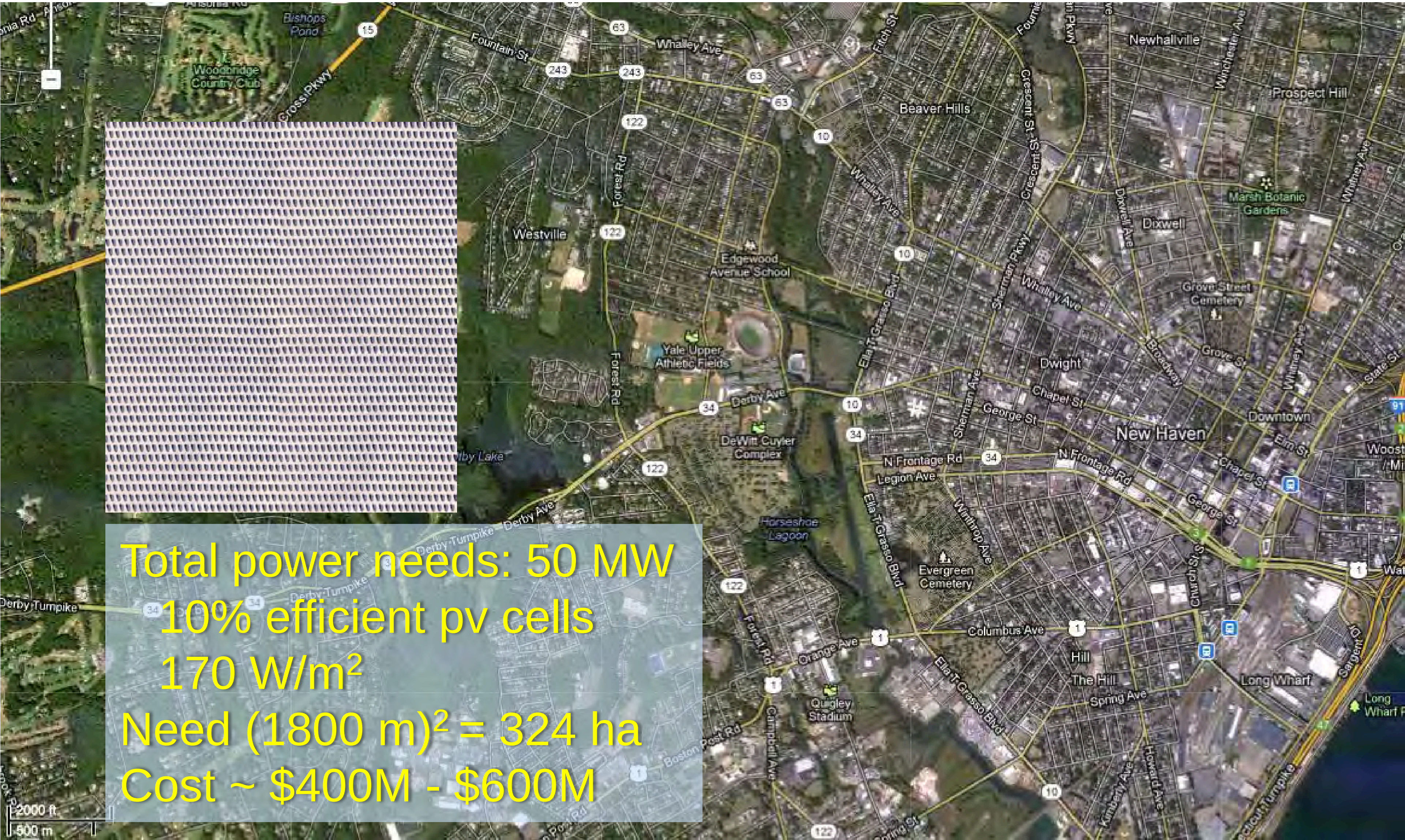


… and cheap!



Average Price [USD_{2005}/W]
100
50
10
5
1
0,5
1976
[65 USD/W]
Produced Silicon PV Modules (Global)
BANKRUPT
SOLYNDRA
Nellis Solar Plant
Brookhaven Solar Plant
2010
[1.4 USD/W]
RENEWABLE ENERGY SOURCES AND CLIMATE CHANGE MITIGATION
SPECIAL REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
ipcc
Fig. 3.17
p 381
China: >50%
Market share
1
10
100
1,000
10,000
100,000
1,000,000
Cumulative Global Capacity [MW]

Solar-Powered Yale?



Total power needs: 50 MW

- 10% efficient pv cells
- 170 W/m^2

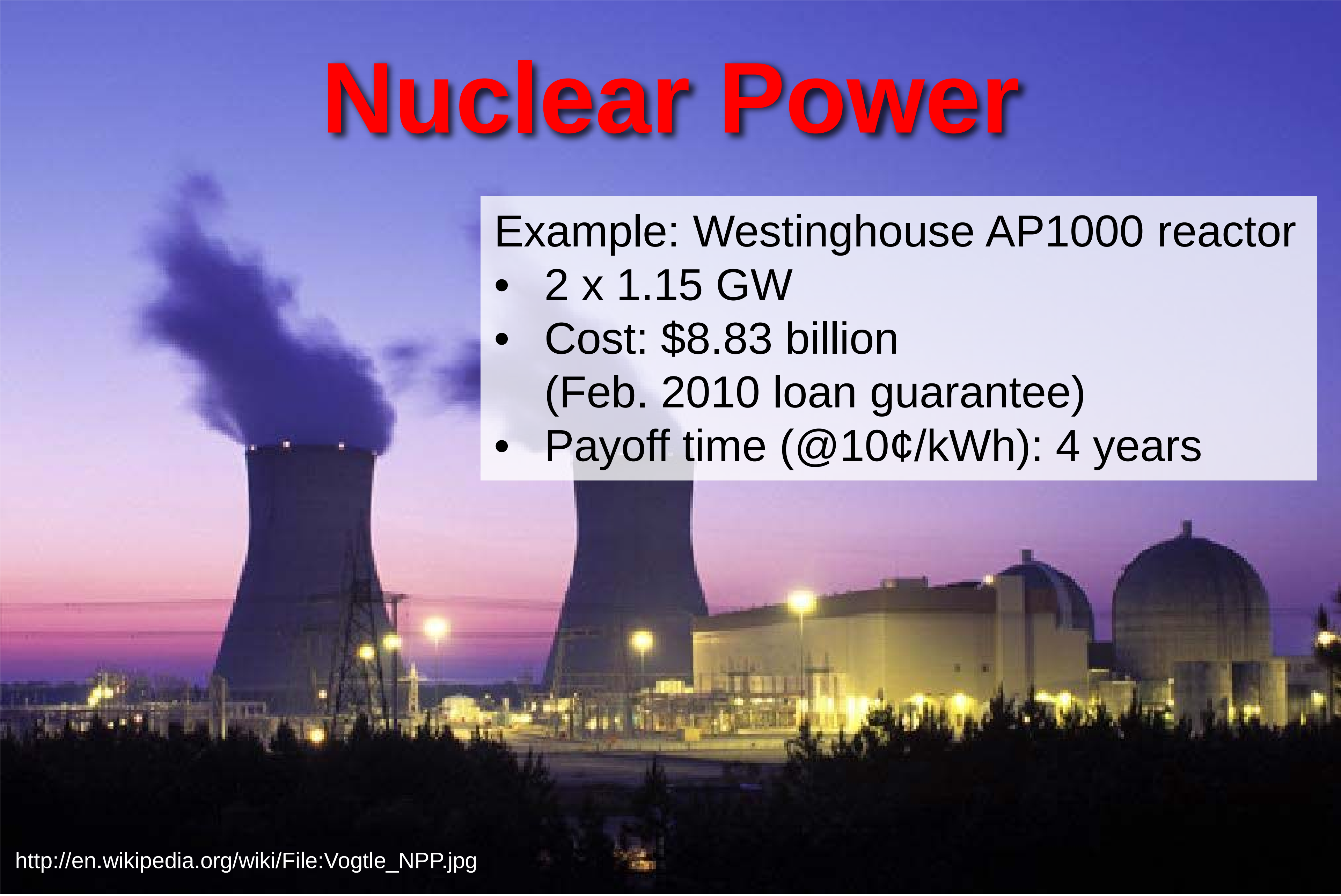
Need (1800 m)^2 = 324 ha

Cost ~ \$400M - \$600M

Nuclear Power

Example: Westinghouse AP1000 reactor

- 2 x 1.15 GW
- Cost: \$8.83 billion
  (Feb. 2010 loan guarantee)
- Payoff time (@10¢/kWh): 4 years



Alvin W. Vogtle Electric Generating Plant, Waynesboro, Georgia
(site for first new construction of 2 nuclear reactors in the USA since Three Mile Island)

Fukushima ...

Don't forget efficiency!

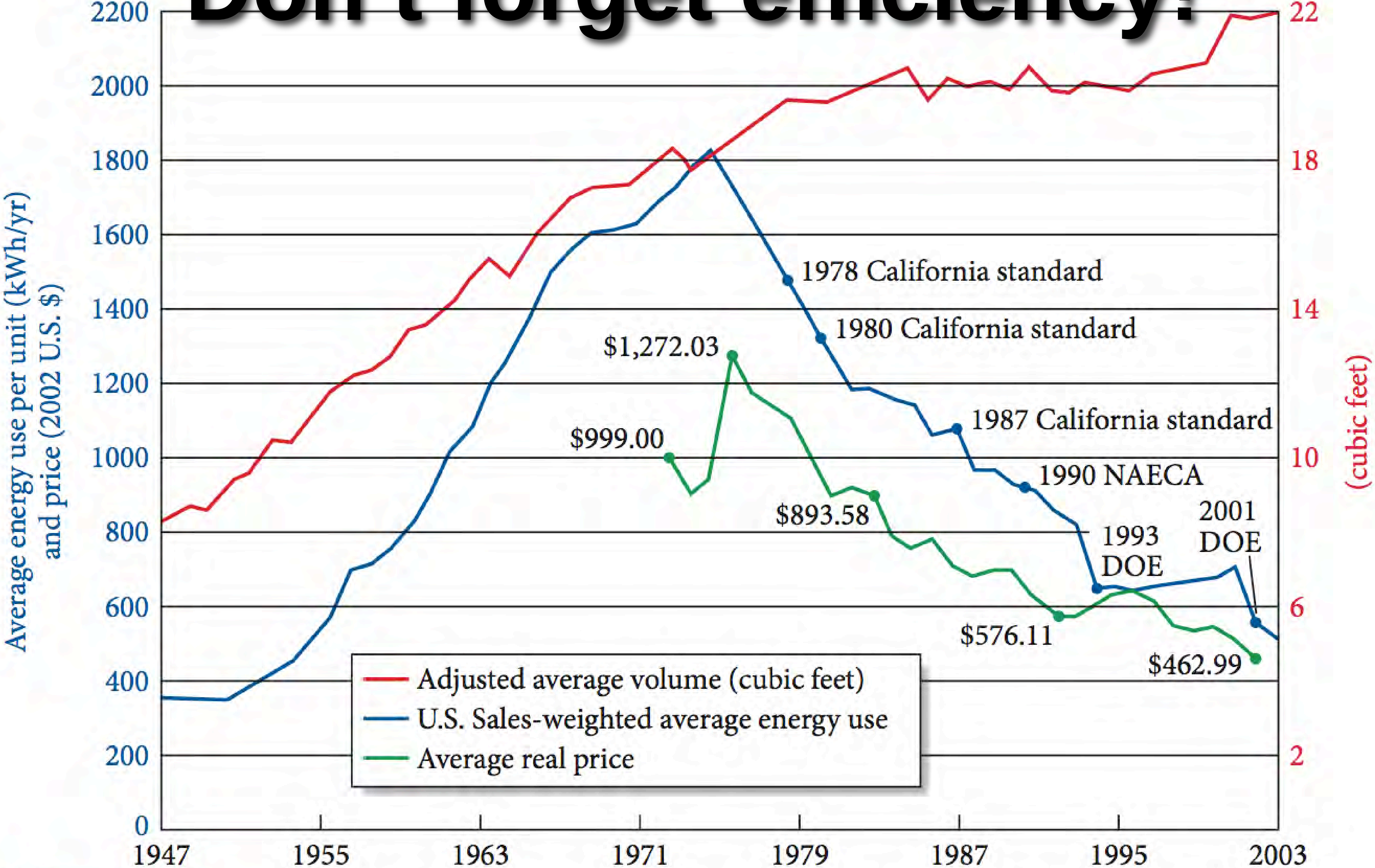
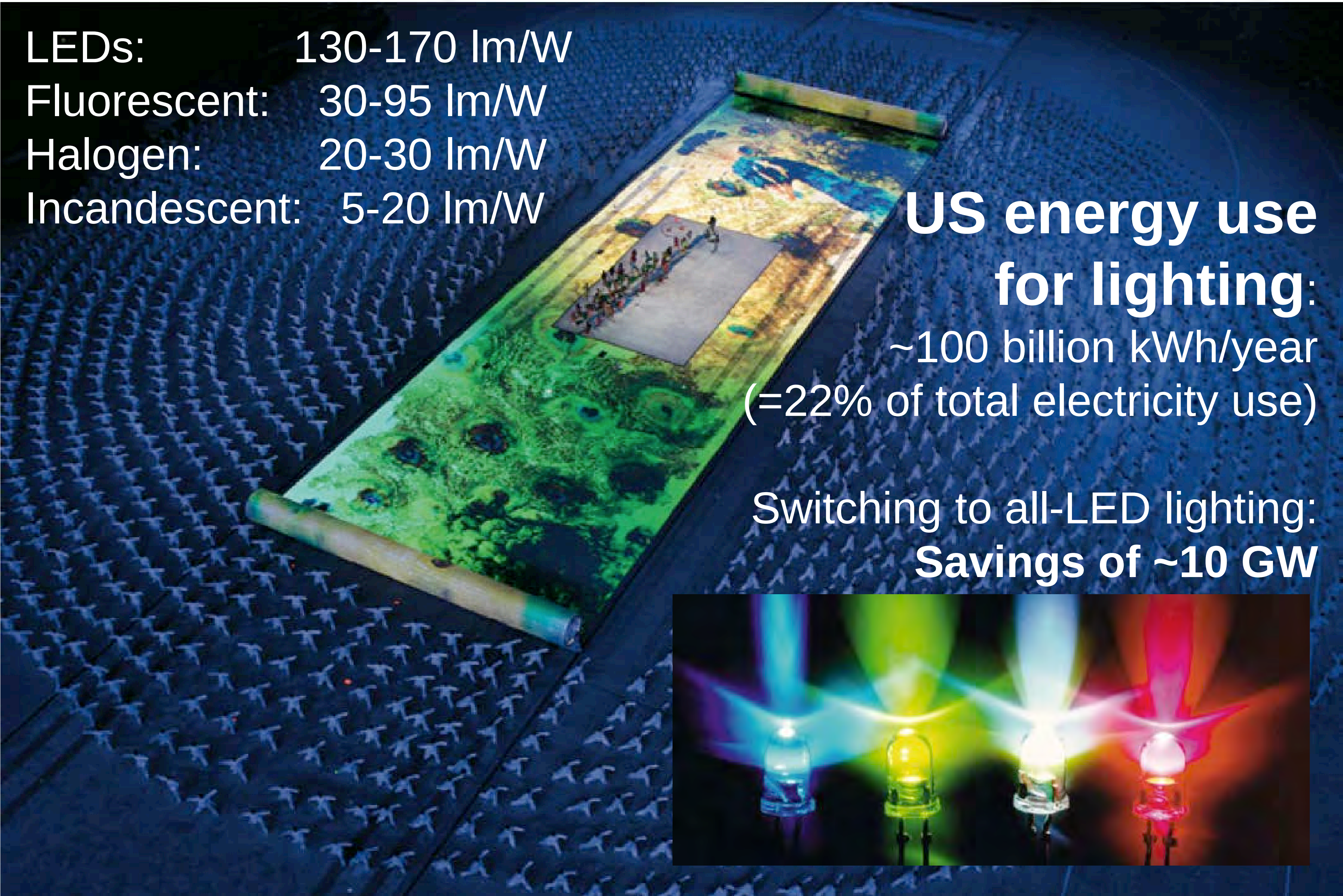


FIGURE 20.13 Average U.S. refrigerator volume (red line), price (green line), and energy use (blue line) from 1947 to 2003. (Original figure: Steve Chu)

Efficiency Example: Lighting



LEDs:	130-170 lm/W
Fluorescent:	30-95 lm/W
Halogen:	20-30 lm/W
Incandescent:	5-20 lm/W

US energy use for lighting:
~100 billion kWh/year
(=22% of total electricity use)

Switching to all-LED lighting:
Savings of ~10 GW

Bio-Ethanol: not worth it

- Ethanol production receives > $3 billion/year in subsidy in US
- Goal: become independent of fossil fuels
- But: corn ethanol production requires 29% more fossil energy input than the energy output in the fuel produced (switch-grass 45%, wood 57%)
- Bio-diesel from soybeans or sunflowers (27%, 118%)

David Pimentel & Tad Patzek,
Natural Resources Research (Vol. 14:1, 65-76)

Cellulosic Bio-Ethanol

- Future: perhaps cellulosic ethanol
- $500M BP grant to Berkeley, LBNL, Illinois
- $125M DoE grant to MSU, Wisconsin
- Nature's expert: microbes in termite gut (break down wood cellulose into "fuel")

what we will cover

- Greenhouse gases and global warming
- Projected consequences of global warming
- Energy from fossil fuels
- Other options
- My project(s)

Biogas Power Plant

Basic Operation

- Plants convert solar radiation, ground water, and atmospheric CO_2 into biomass
- Fermenting the shredded plants releases methane, which is burned to liberate some of the original solar energy

- **CARBON - NEUTRAL energy "production"**

Raw material: Corn (whole plant)

Biomass Consumption / Day

- 25 tons of shredded corn silage
- 11 tons of cow dung


Mixer
EINTRAGSSYSTEME FÜR BIOGASANLAGEN

Fermenter

- Annual residue production:
  - 10,000 cubic yards of solid/liquid mixture
  - High quality (non-smelly!!!) fertilizer

Gas Storage

- 7,100 cubic yards of gas/day
- 60% methane
- Equivalent energy content of 4,500 cubic yards of natural gas

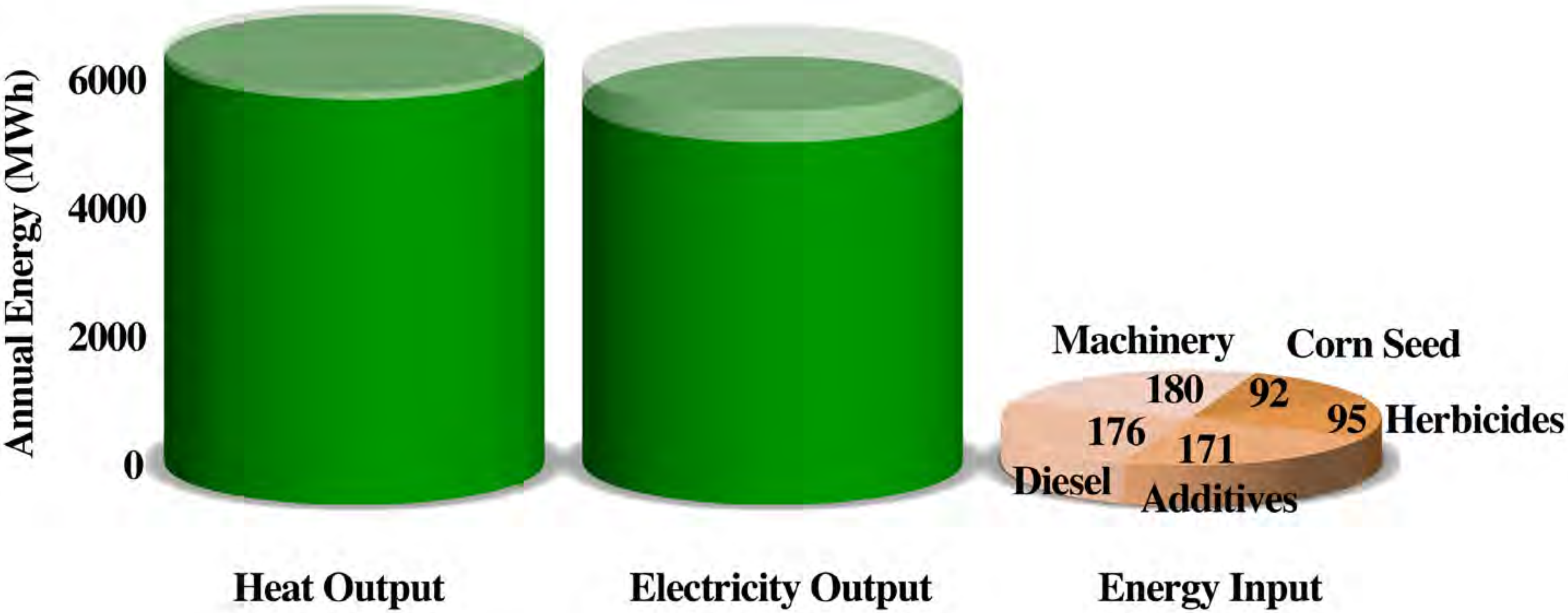
Generators (82% efficient)

- 2 engines rated at 526 kW electric power each (=705 horsepower)
- Another 540 kW of heat

Bottom Line

- Initial investment: ~ $3-5 million
- Land required to grow biomass: 150 hectares (= 370 acres)
- 6.2 million kWh of electrical energy/year
- 6.5 million kWh of thermal energy
- Payoff time (@10¢/kWh): 3-4 years

Energy Balance



Factor **8** more electricity output than total energy input!
(comparison bioethanol: energy-out/energy-in [0.75,2.2])

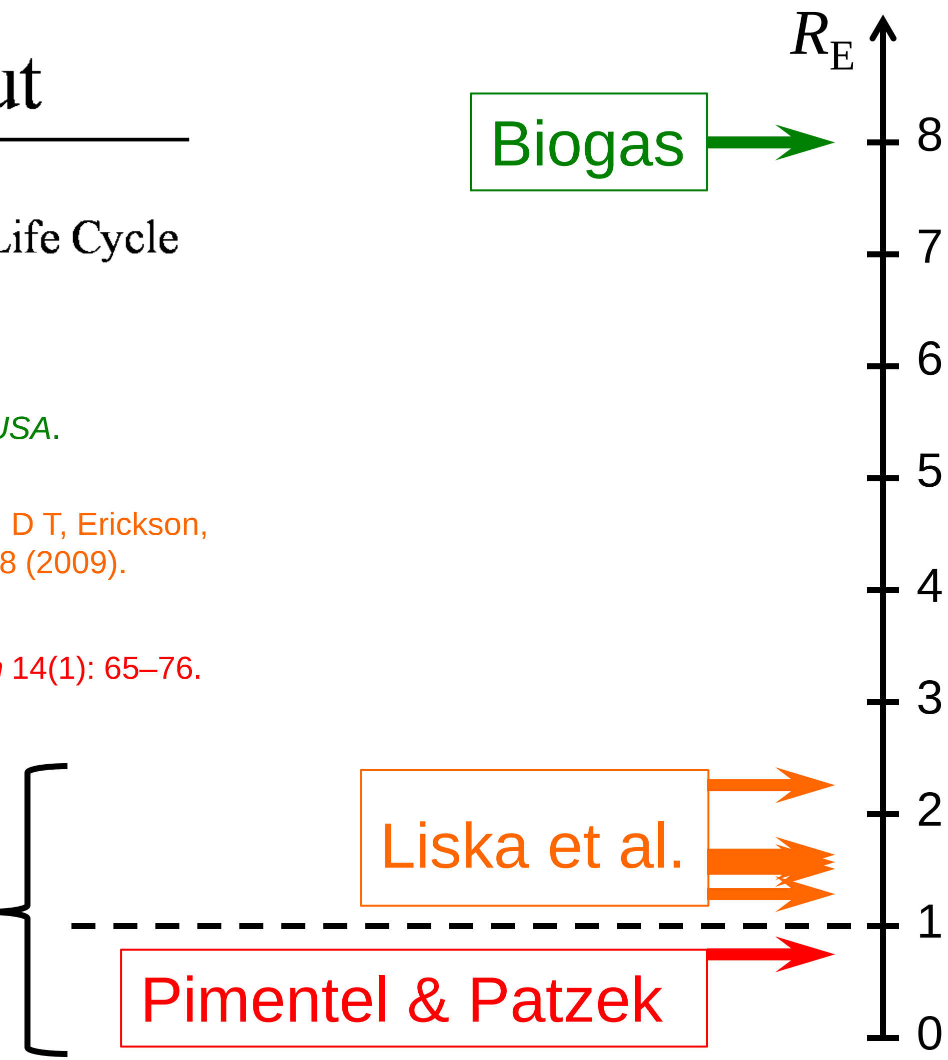
Net Energy Ratio

$$R_{\mathrm{E}} = \frac{\text{Net Energy Output}}{\langle \text{Fossil Energy Input} \rangle_{\text{Life Cycle}}}$$

Bauer, W, Bauer, S, Bauer, T (2011, sub) *Proc Natl Acad Sci USA*.

Liska, A J, Yang, H S, Bremer, V B, Klopfenstein, T J, Walters, D T, Erickson, G E, Cassman, K G (2009) Journal of Industrial Ecology 13: 58 (2009).

Pimentel, D, Patzek, T W (2005) *Natural Resources Research* 14(1): 65–76.



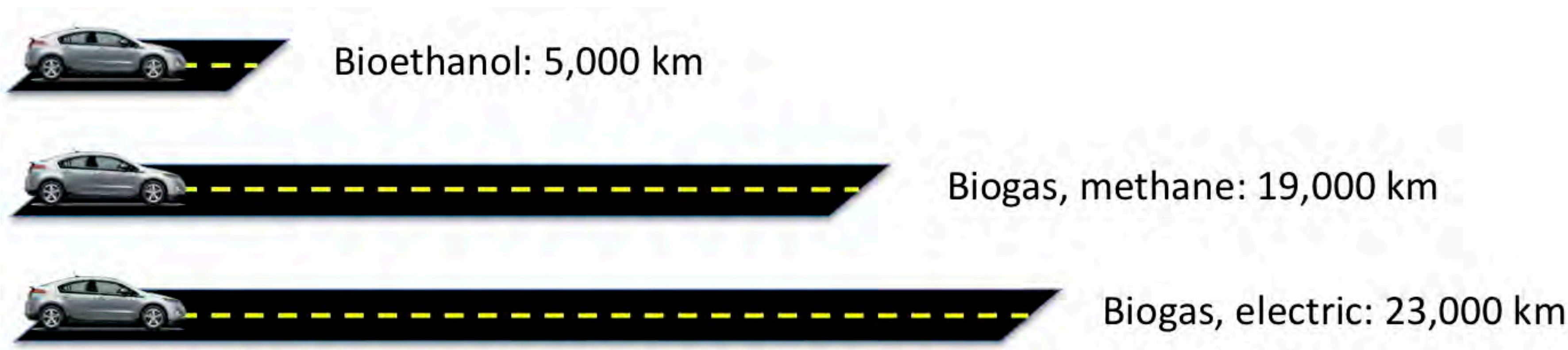
Bio-Ethanol from Corn

Figure of Merit

- Solar constant: 1.37 kW/m^2
- Real *average* value for Germany: ~75 W/m^2 (cos¸ , day/night, clouds, seasons…).
- 150 hectares = $1.5 \cdot 10^6$ m^2
- Maximum possible power capture: ~$1.1 \cdot 10^8$ W
- Present efficiency = 0.7 MW / 0.11 GW = 0.6%
- Room for improvement!
  - Research on better bacteria, better energy crops, better conversion processes
- (But already much better than covering 7 ha of land with 15% efficient photovoltaic cells)

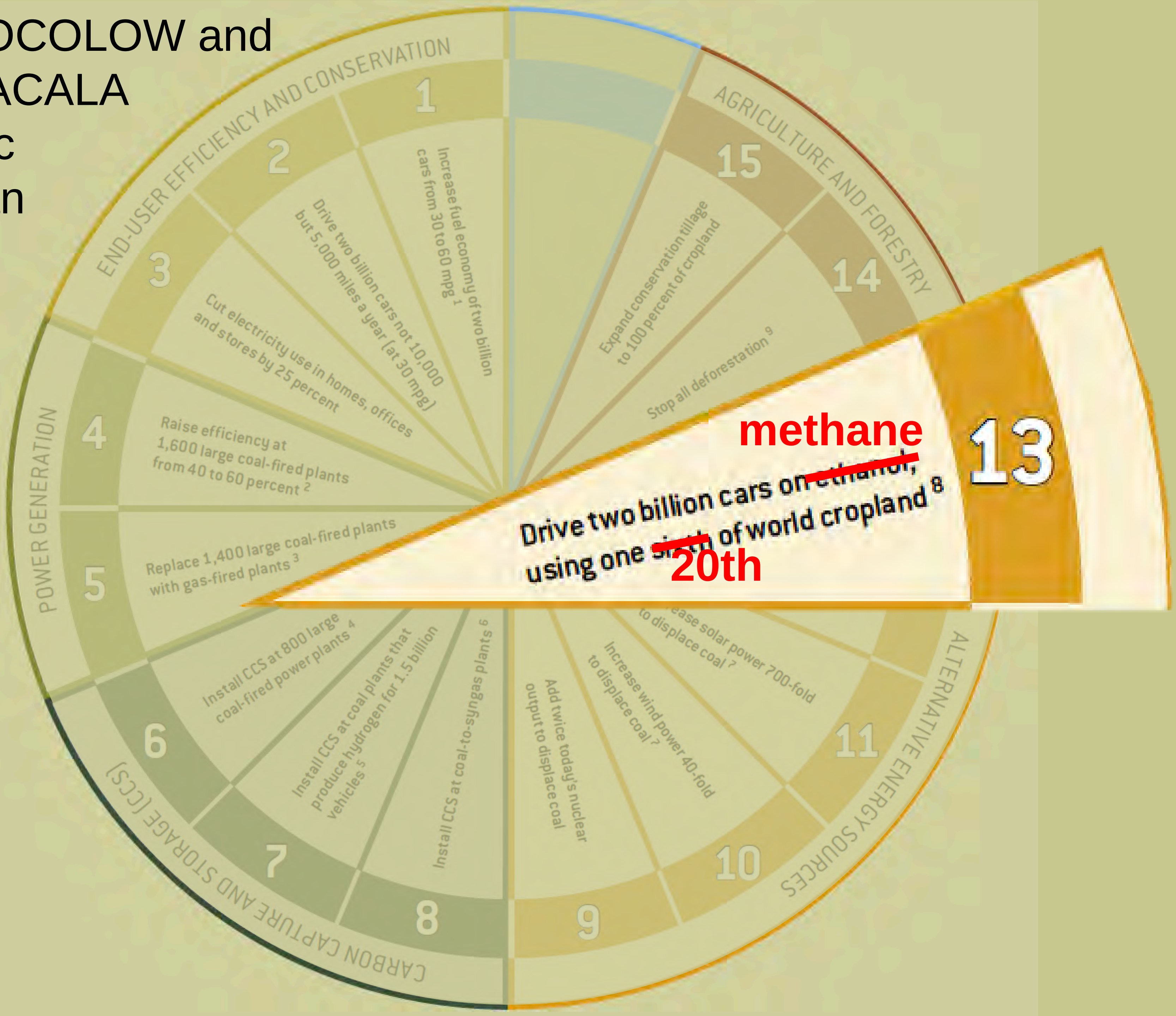
Transportation Fuel

- Could produce 0.68 M liter of ethanol / year
  - Industry standard output from our corn yield on 150 ha
- Are producing 2.6 M liter of (liquid) CH_4 / year
- Factor of **3.8** better yield!
  (heat of combustion per liter almost identical for ethanol and methane, ~ 2/3 of gasoline)



Driving distance per hectare (numbers for Chevy Volt)

R. H. SOCOLOW and
S. W. PACALA
Scientific
American
2006



US Economic Impact

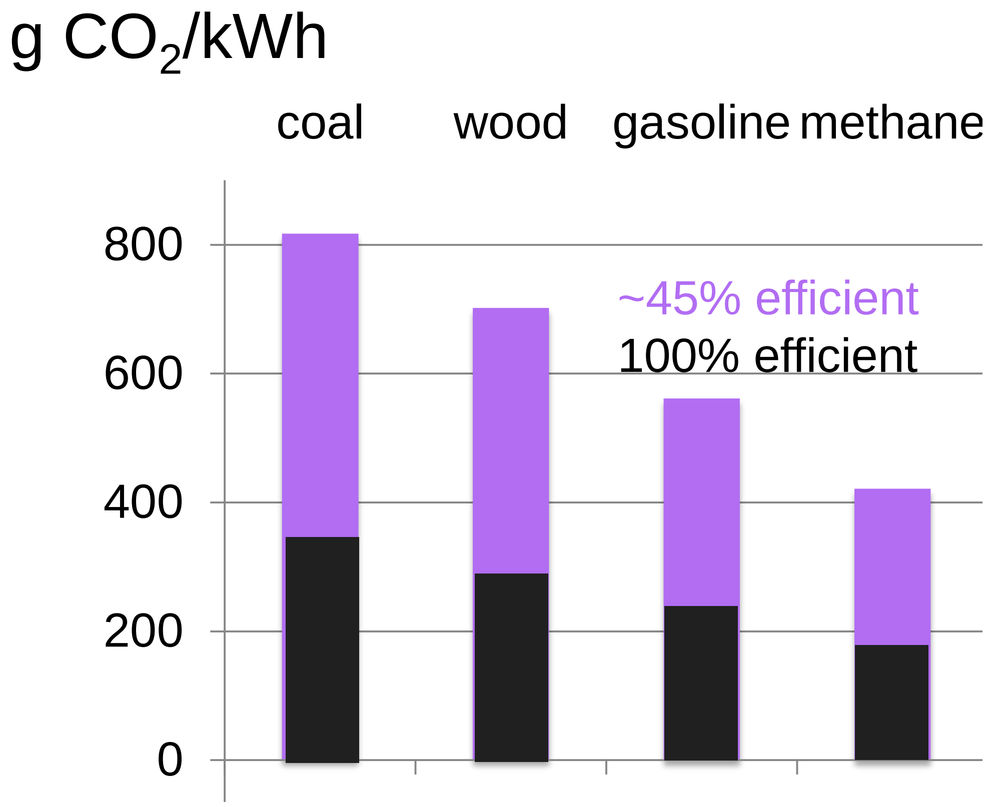
2015 projected bioethanol yield: 50 billion liters

Proposal: Convert to biogas reactors

Make 190 billion liters methane

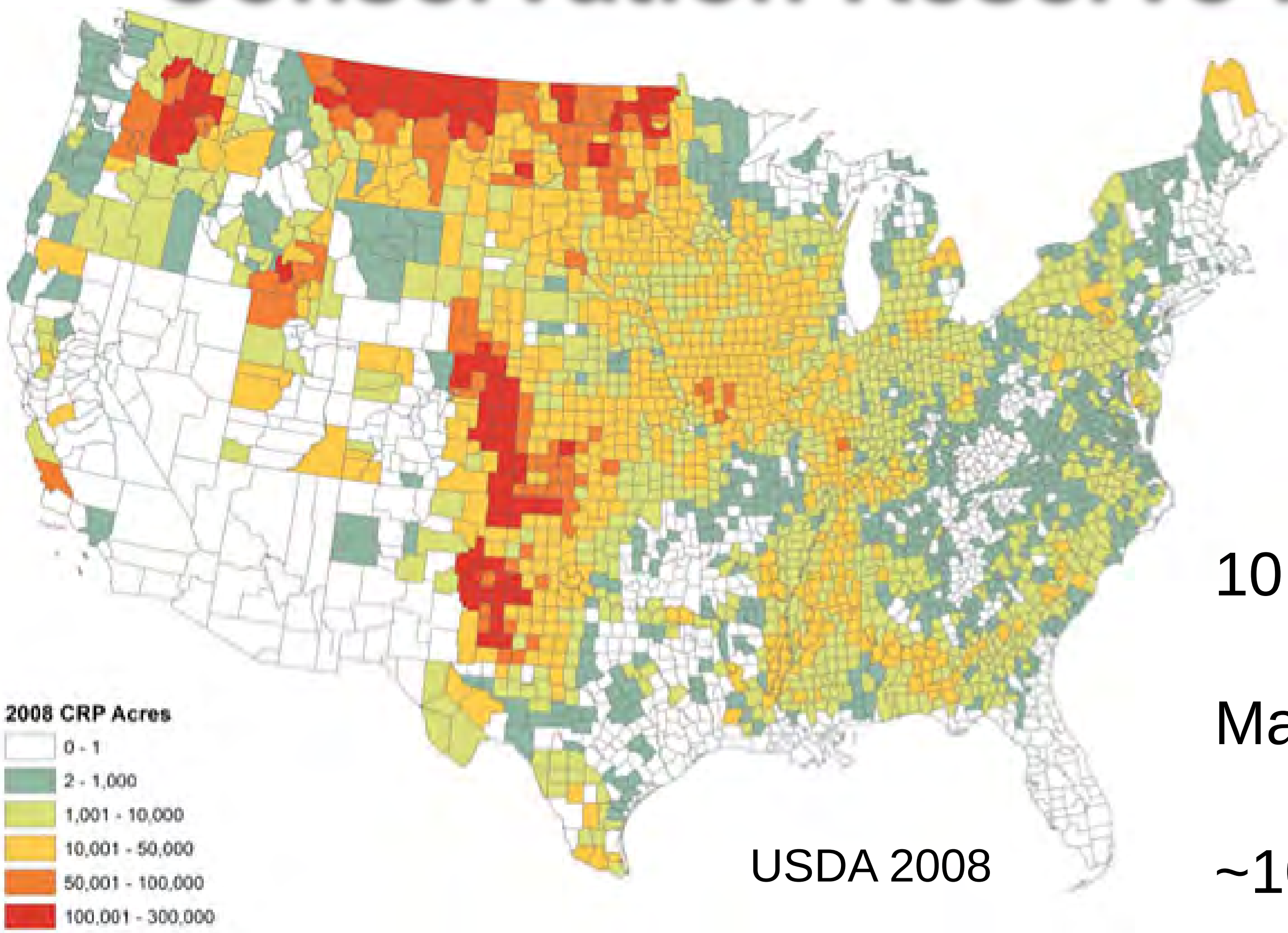
More than **$100 billion/year** profit!

Greenhouse Gas Balance



Methane is ~25 times more powerful greenhouse gas than CO_2
- our process prevents methane from cow dung to escape

Food vs. Fuel?
Conservation Reserve Program



USDA 2008

10 M hectare

Marginal land(?)

~100 GW potential

MSU Anaerobic Digester

- Approved by MSU Board of Trustees, Jan. 2012
- Research on better bacteria, plants, & processes

Summary: The Bad

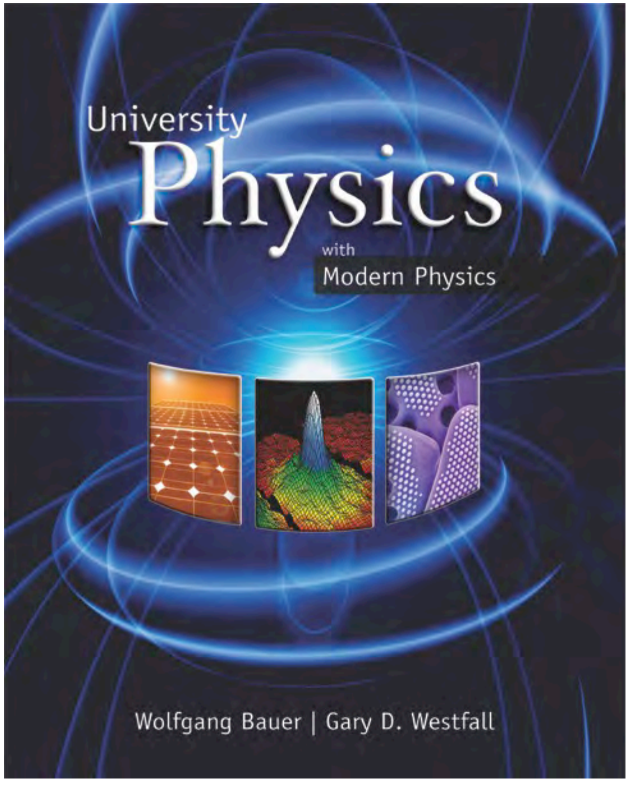
- CO_2 is increasing in the atmosphere at an alarming rate
- Global warming is happening, will make the oceans rise, and may have other unpredictable weather consequences
- We are running out of oil, and until we do the oil money contributes to geopolitical friction

Summary: The Good

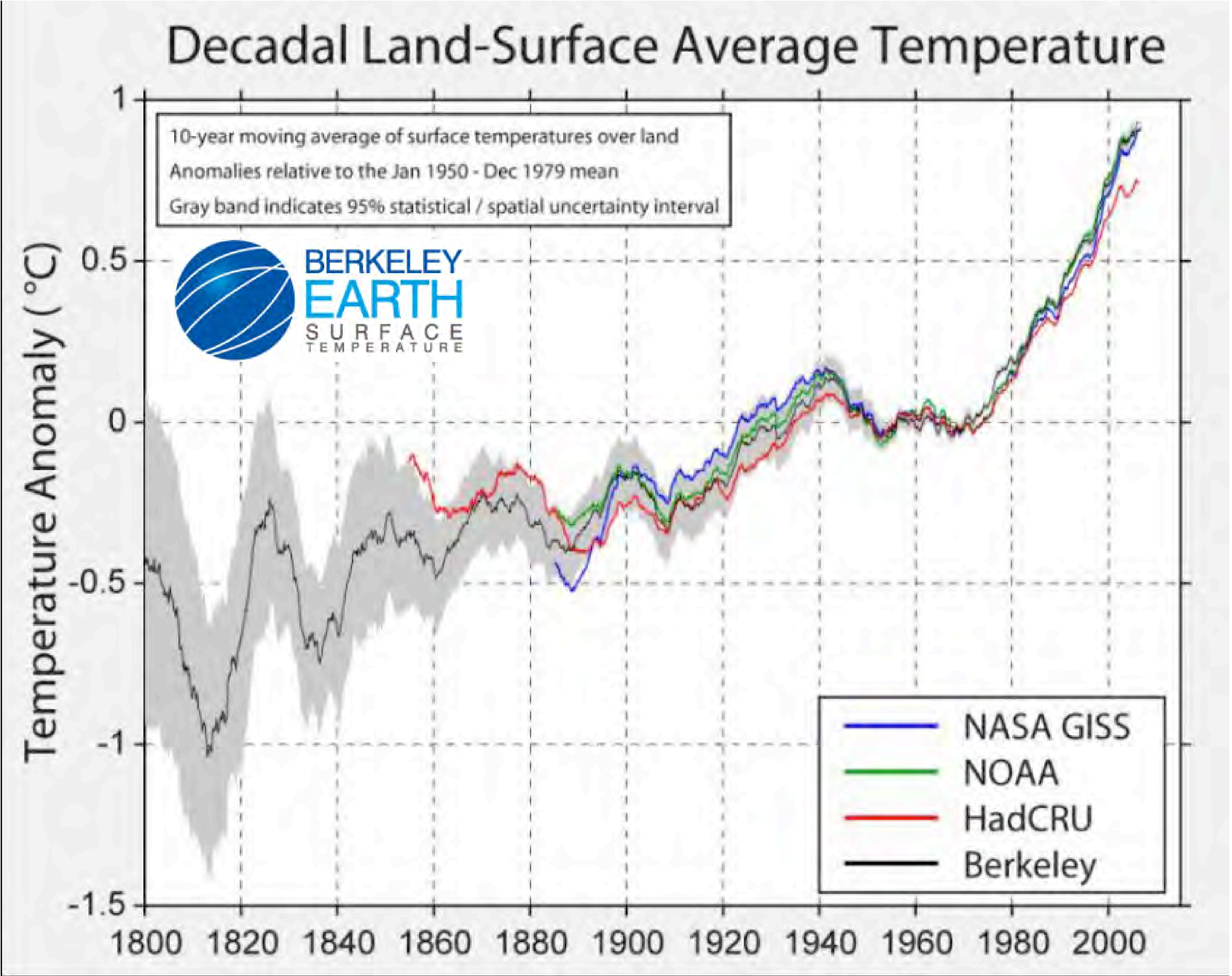
- We can produce lots of “green” energy
- We can build new environmentally friendly power plants
- We can make lots of small farms very profitable
- We can make $ from our waste
- We can create lots of great jobs in the process

Final Word

- You can follow my musings on Twitter: http://twitter.com/BauerWestfall
- Email contact: bauer@pa.msu.edu

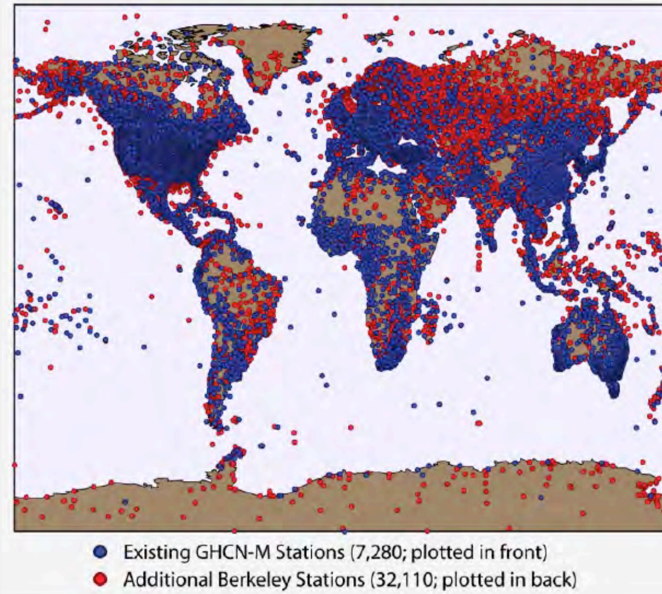


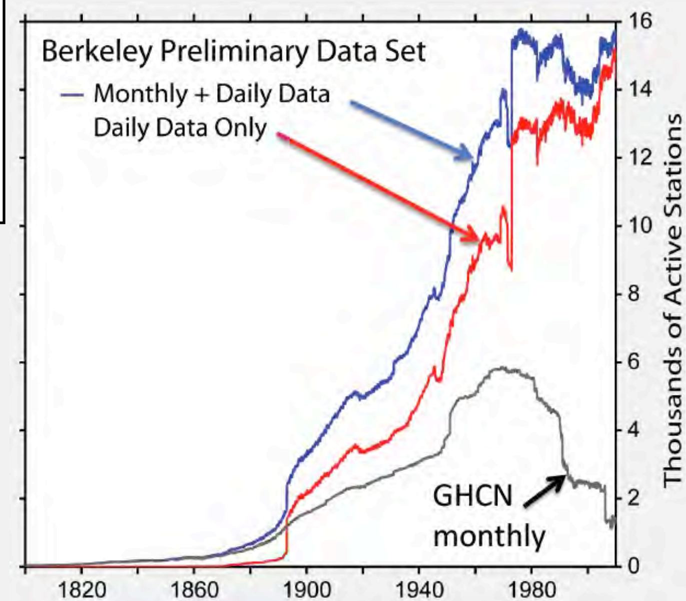
THANK YOU …



Rich Muller, BerkeleyEarthSantaFe.pdf

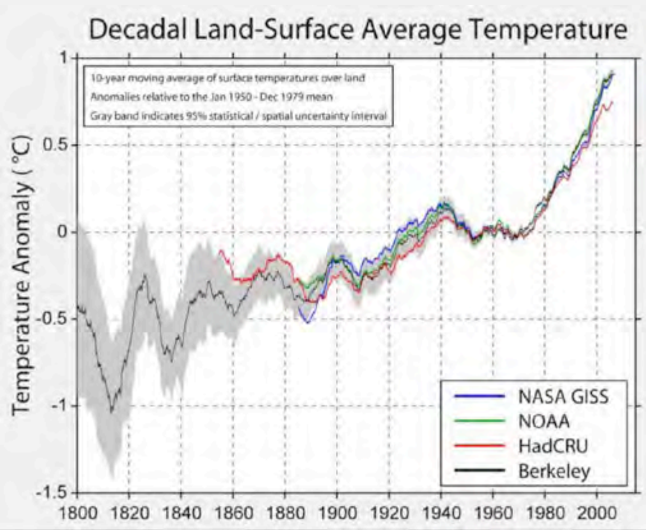
http://www.berkeleyearth.org/movies.php



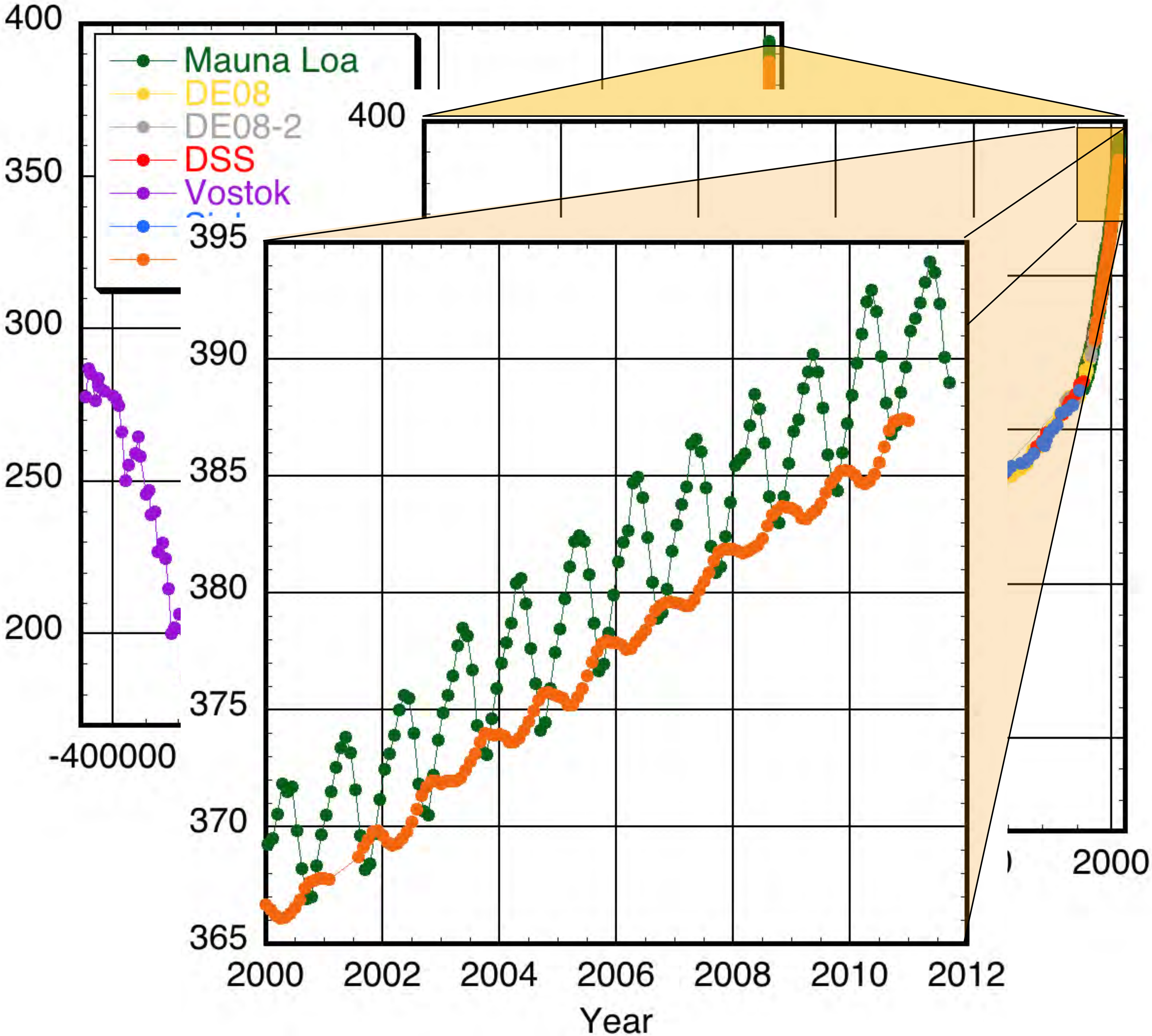


Richard Muller
Robert Rohde
Judith Curry
Donald Groom
Bob Jacobsen
Saul Perlmutter
Arthur Rosenfeld
Charlotte Wickham
Jonathan Wurtele

Elizabeth Muller



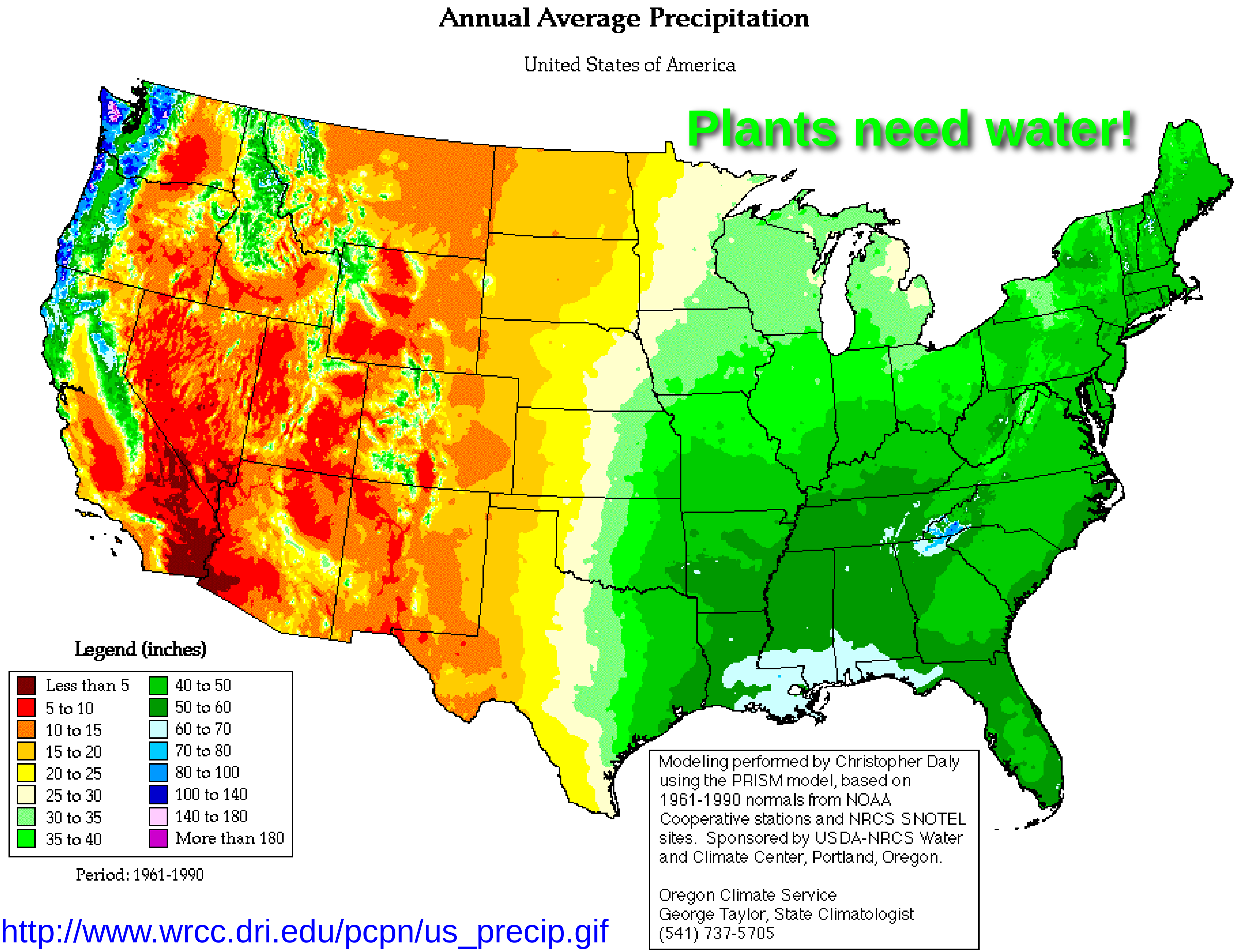
BERKELEY EARTH SURFACE TEMPERATURE



Bauer & Westfall, 2nd edition

Don’t forget the nuclear option!


Why here?



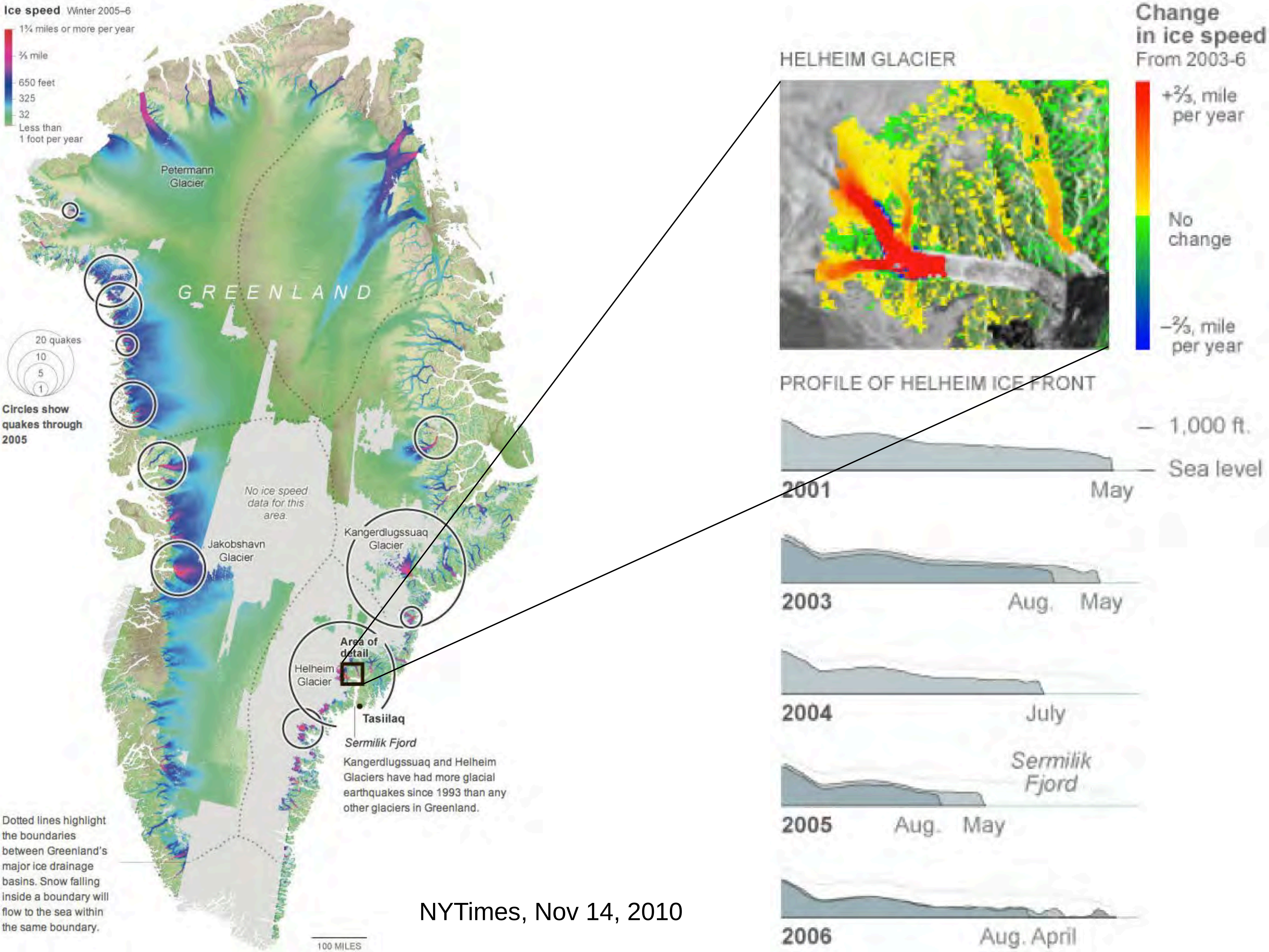
Plants need water!

http://www.wrcc.dri.edu/pcpn/us_precip.gif

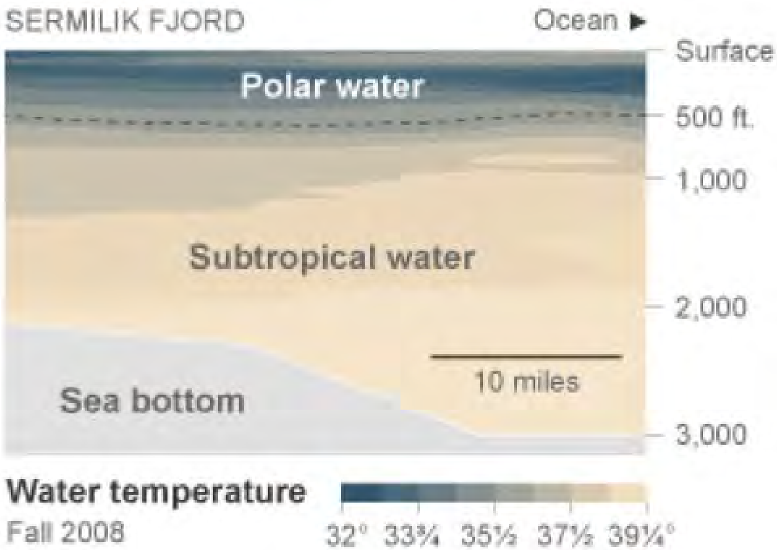
Global Warming makes oceans rise!
By how much **& how fast**?

Greenland: Helheim Glacier

NYTimes, Nov 14, 2010



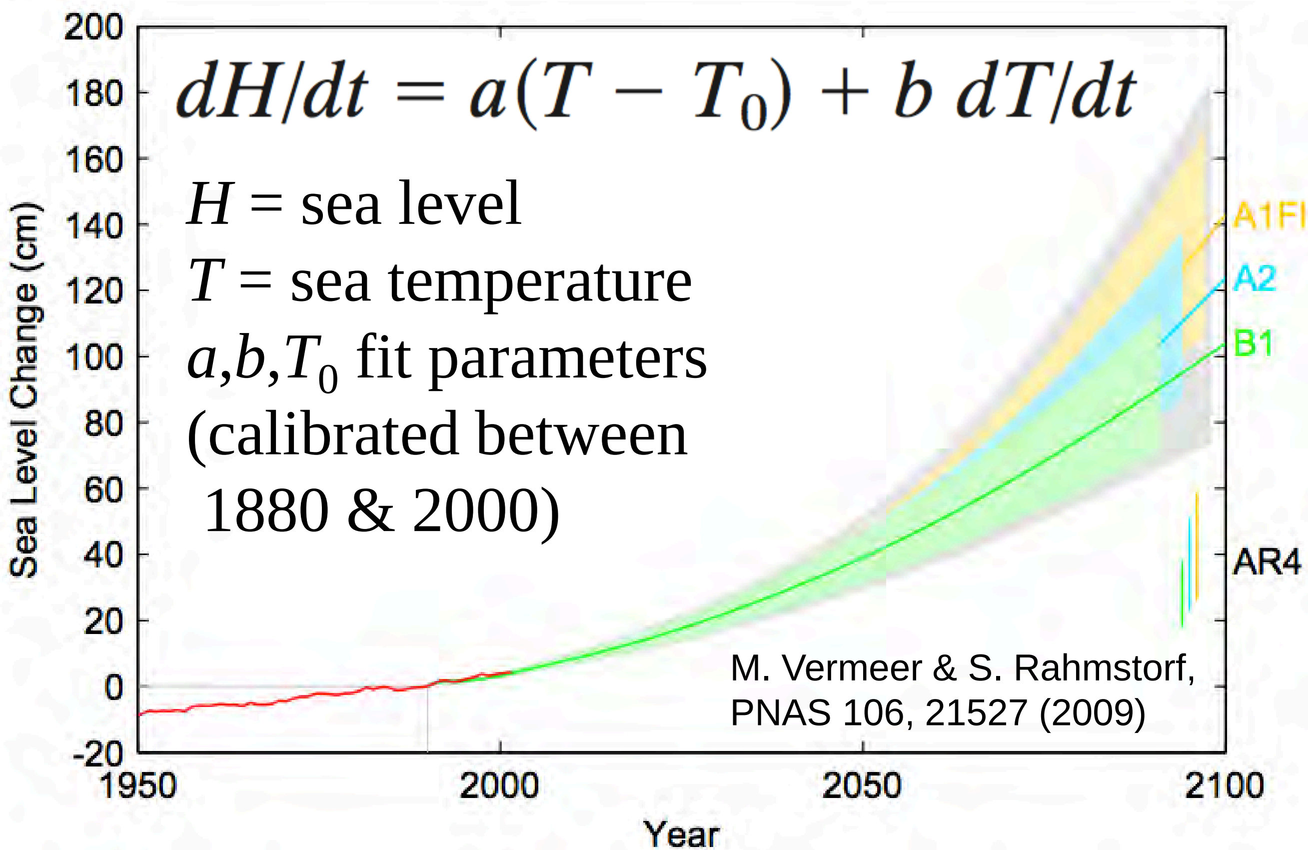
NYTimes, Nov 14, 2010



NYTimes, Nov 14, 2010

Message:
do not buy beachfront property!

Warm sea water accelerates ice melting

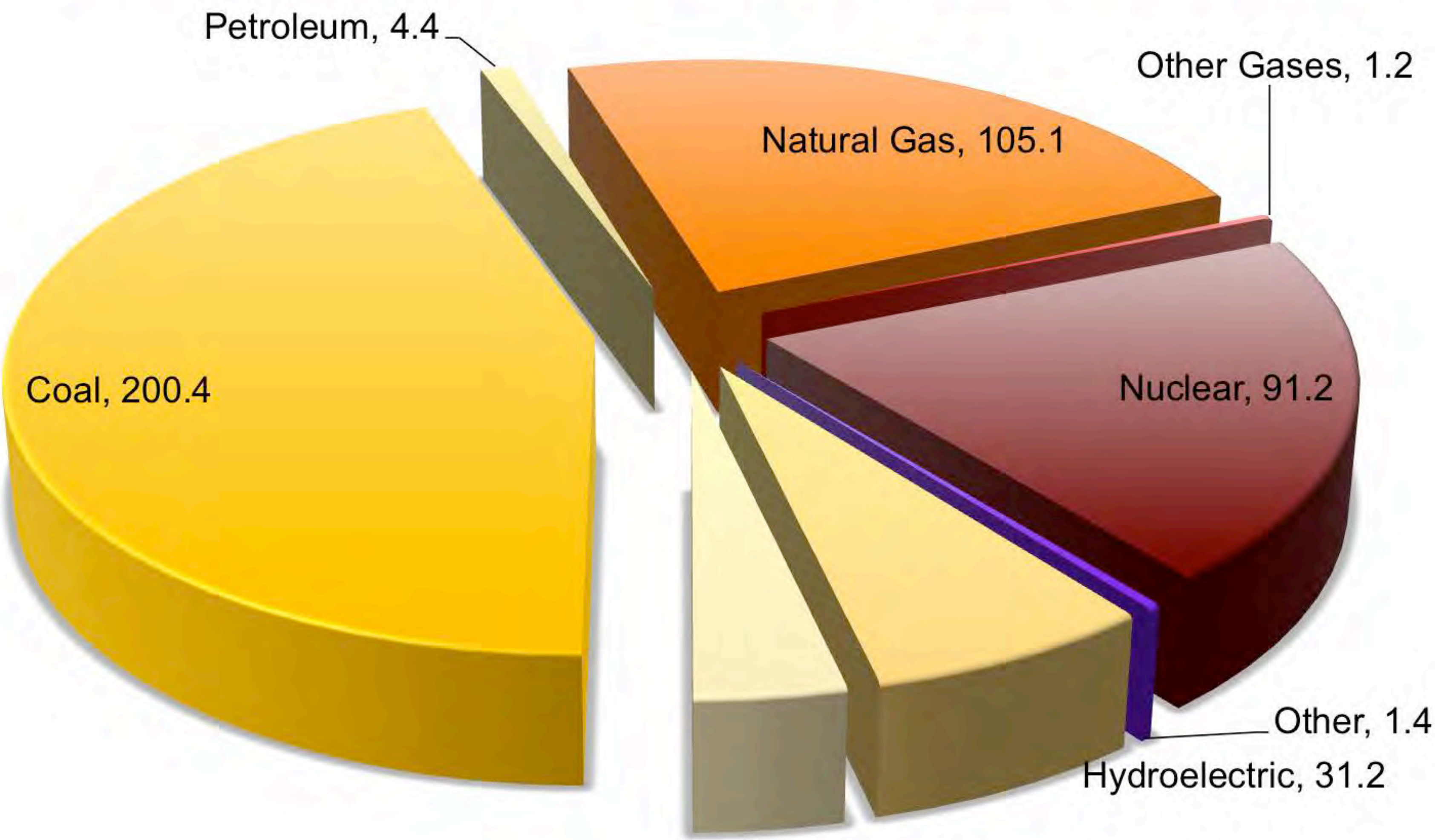


$$dH/dt = a(T - T_0) + b\, dT/dt$$

H = sea level
T = sea temperature
a, b, T_0 fit parameters
(calibrated between
1880 & 2000)

M. Vermeer & S. Rahmstorf, PNAS 106, 21527 (2009)

2009 US Electrical Power Generation (GW)

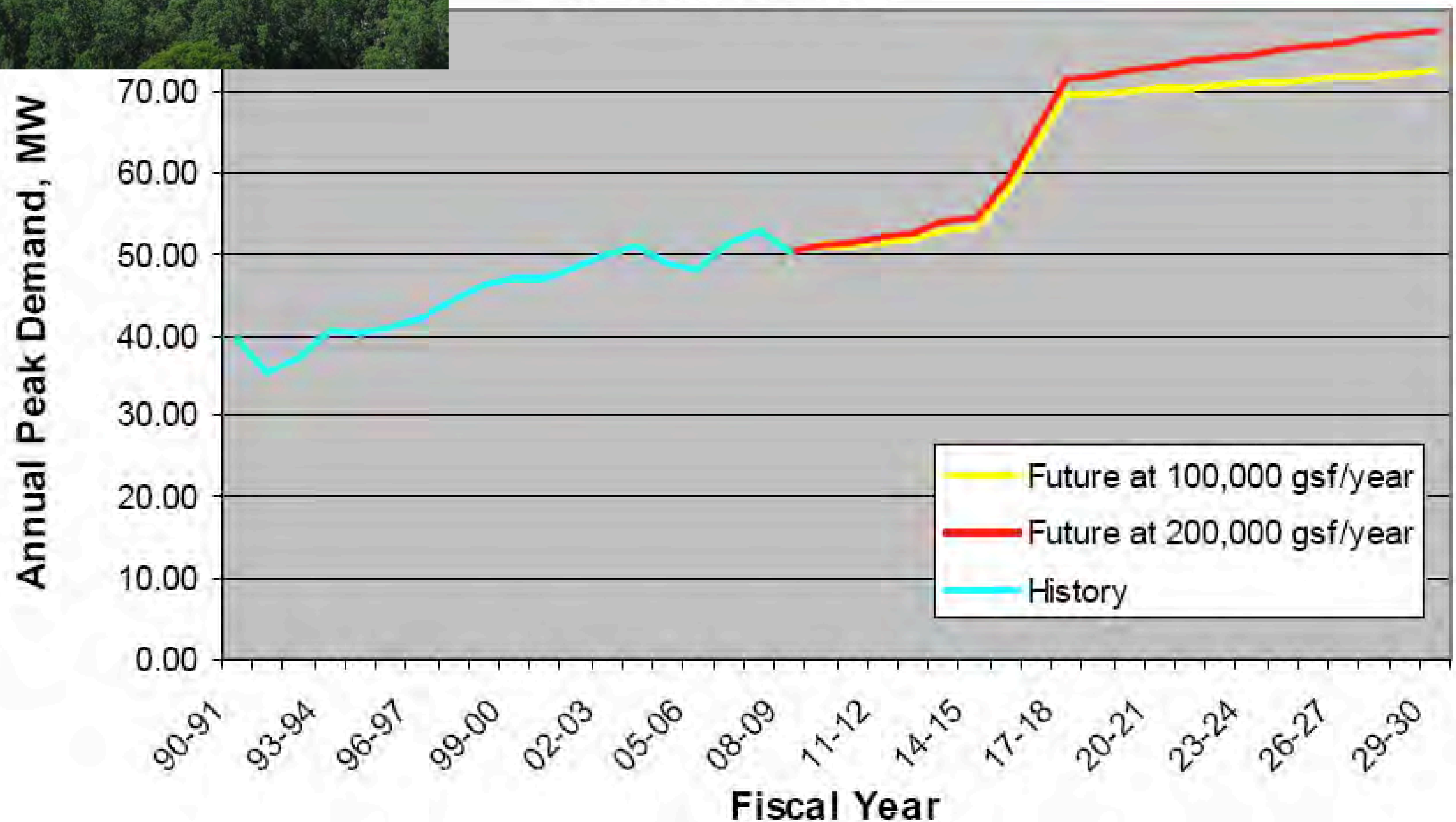


Renewables, 16.4

- Wind 8.43
- Solar 0.10
- Wood 4.06
- Geothermal 1.71
- Biomass 2.11

Source Data: US EIA

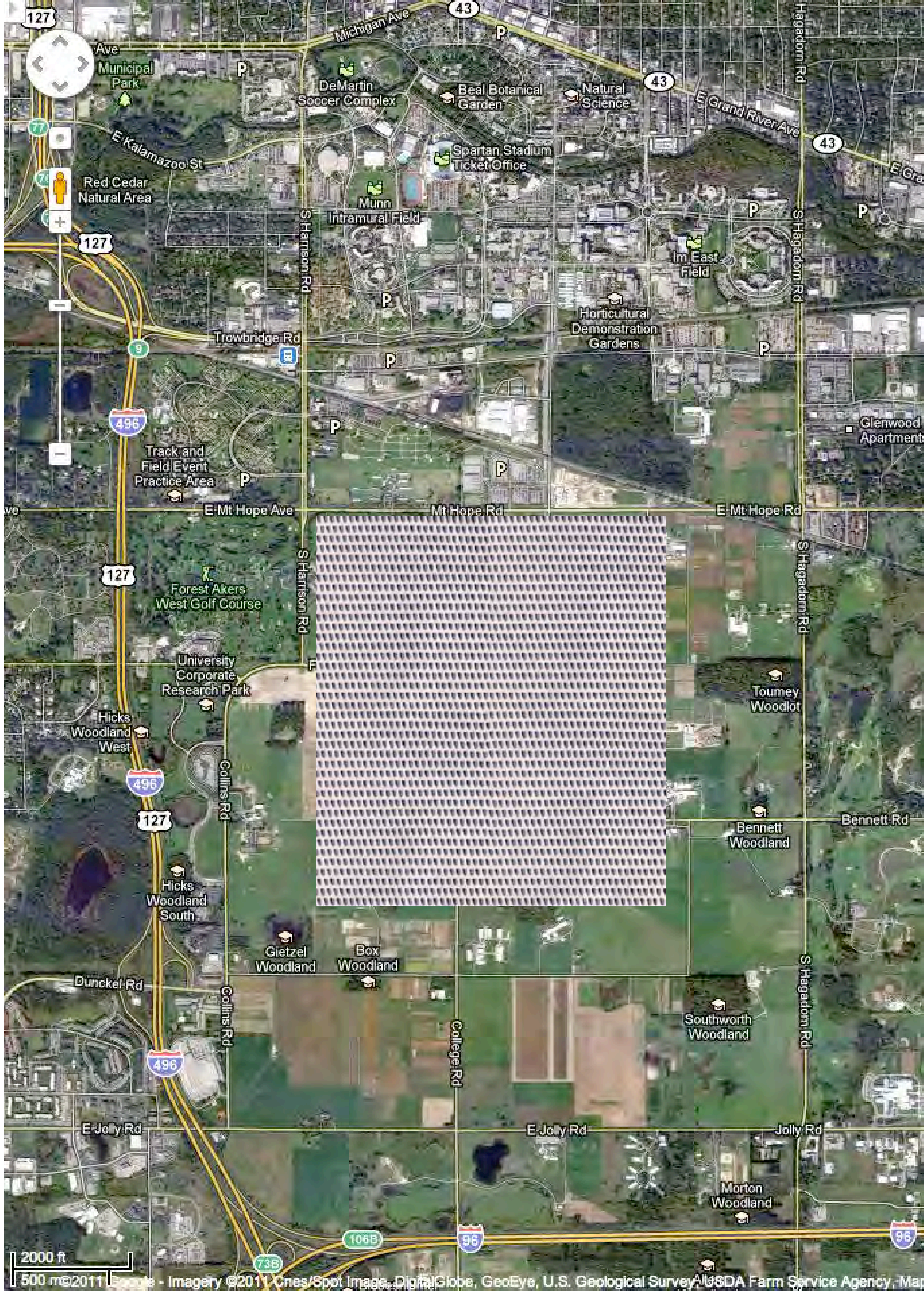
MSU: Electricity

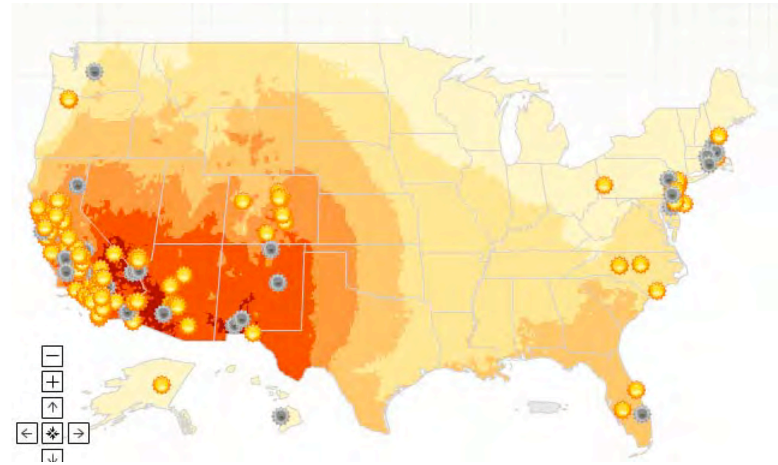


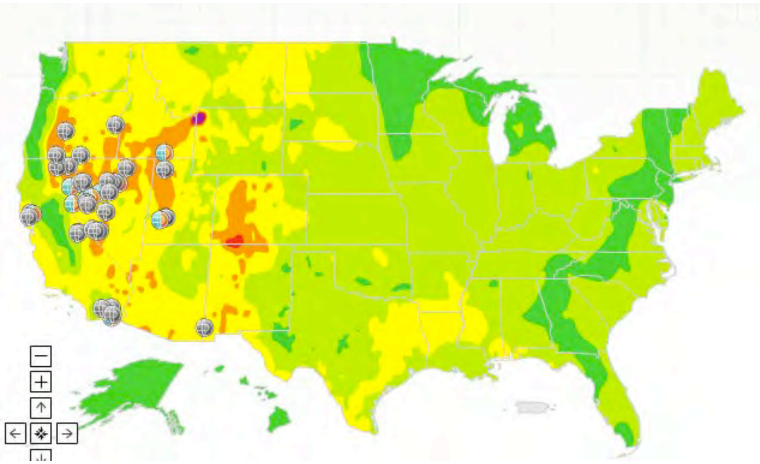
SOLAR-POWERED MSU?

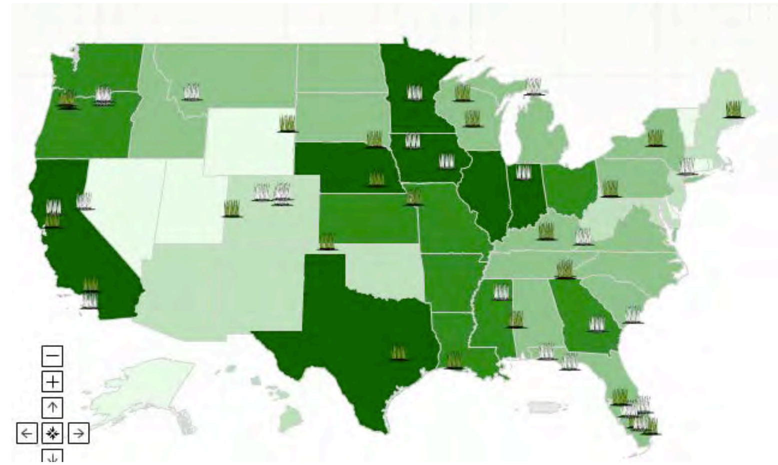
10% efficient pv cells
170 W/m^2

Need (1800 m)^2 = 324 ha

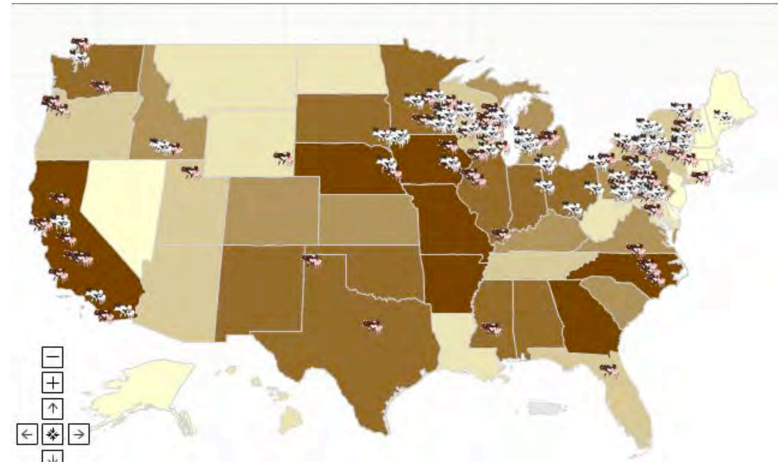








Earth, Wind, and Fire



NRDC NATURAL RESOURCES DEFENSE COUNCIL
THE EARTH'S BEST DEFENSE

http://www.nrdc.org/energy/renewables/energymap.asp