The Global Energy Problem

Wolfgang Bauer

MICHIGAN STATE UNIVERSITY

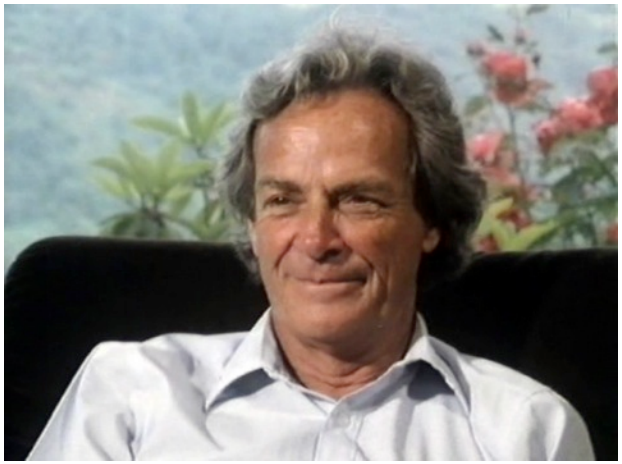
What is Energy?

W. Bauer
Oct. 2013

- (many textbooks): “Energy is the ability to do work.”

- “It is important to realize that in physics today, we have no knowledge of what energy *is*.”

Richard Feynman, 1963



Energy is Conserved

W. Bauer
Oct. 2013

- Energy can be transformed from one type to another, but the total sum of all energy types stays constant

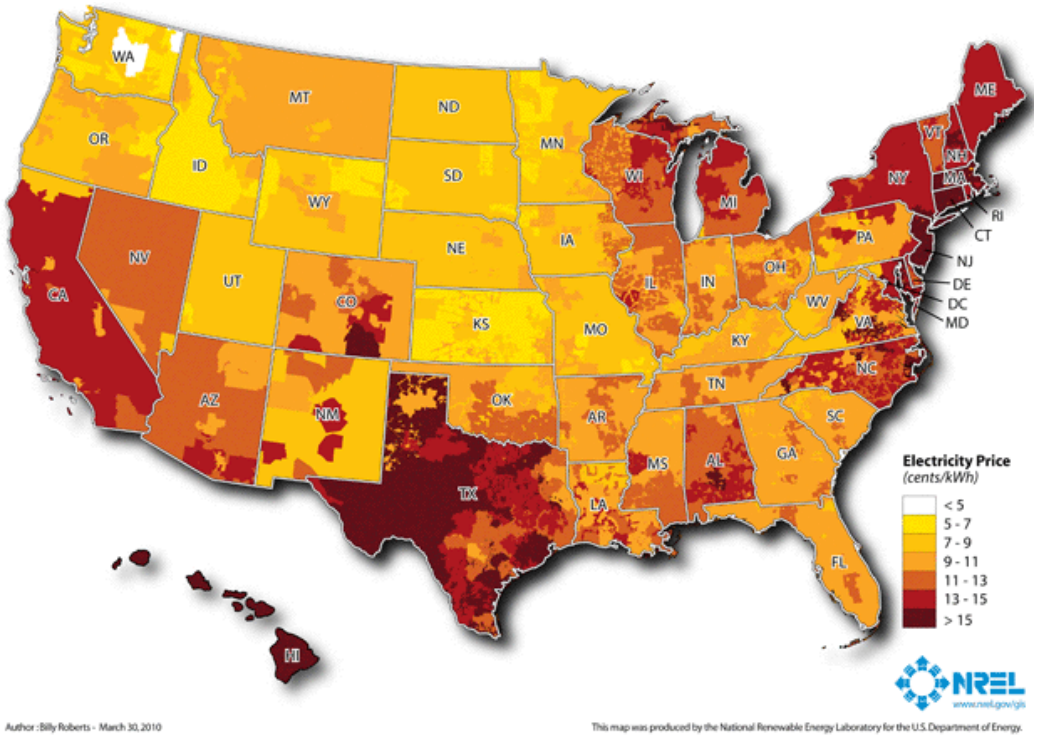
The most important equation of this presentation is …

E = $

International versions: *E* = €, *E* = ¥, *E* = £, …

E = $

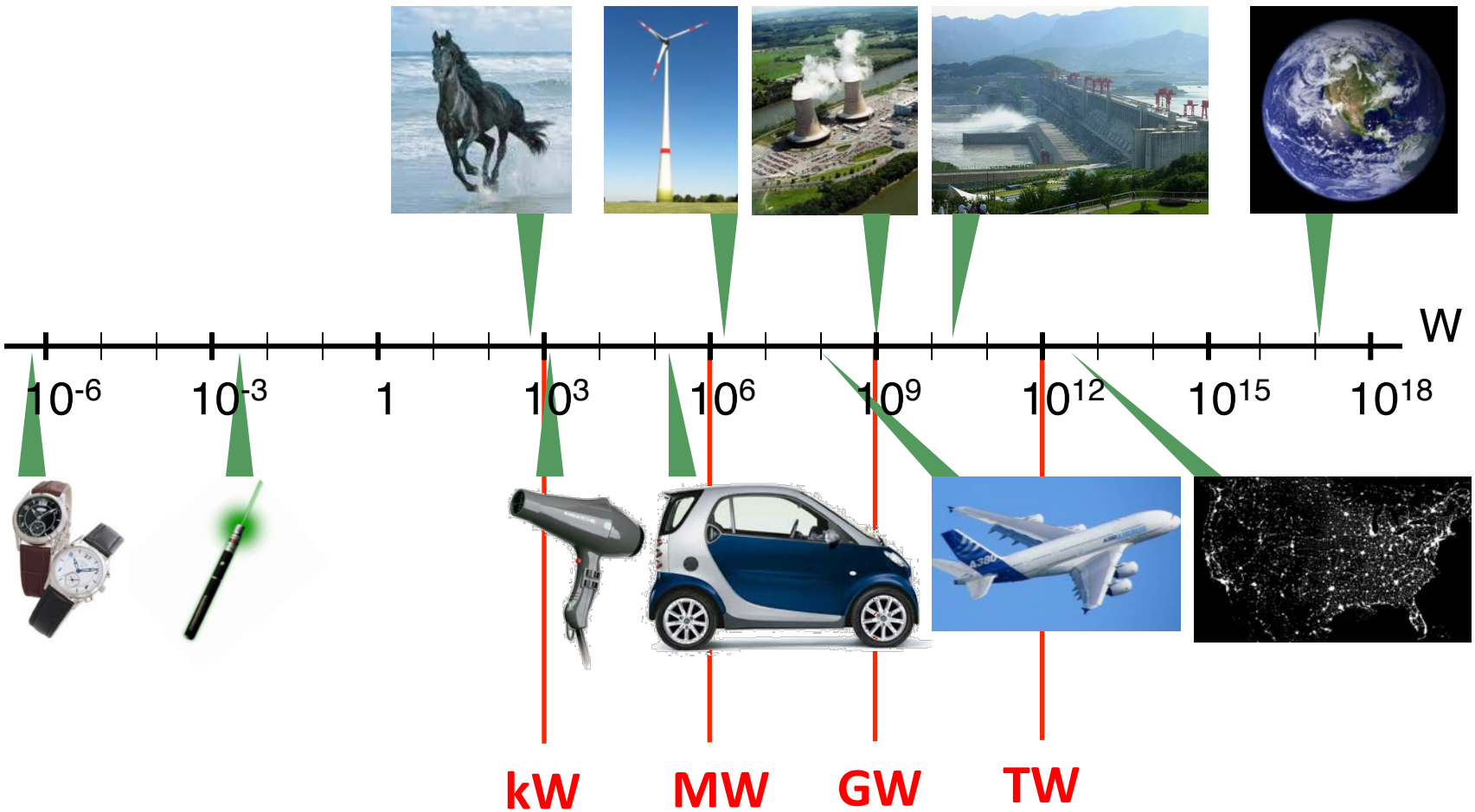
W. Bauer
Oct. 2013



- Electricity
  1 kWh ~ $0.1
- Gasoline (1 gal ~ $4, 35 MJ/L = 36.6 kWh/gallon)
  1 kWh ~ $0.1
- 2% Milk (122 Cal/cup = 2.28 kWh/gallon, 1 gal ~ $4)
  1 kWh ~$1.75
- Big Mac meal w large fries & coke (1350 Cal = 1.57 kWh, ~$6)
  1 kWh ~ $3.8

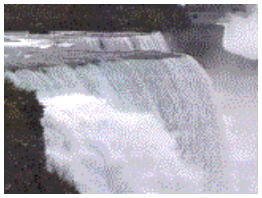
Power = Energy/Time

W. Bauer
Oct. 2013



Power of Niagara Falls

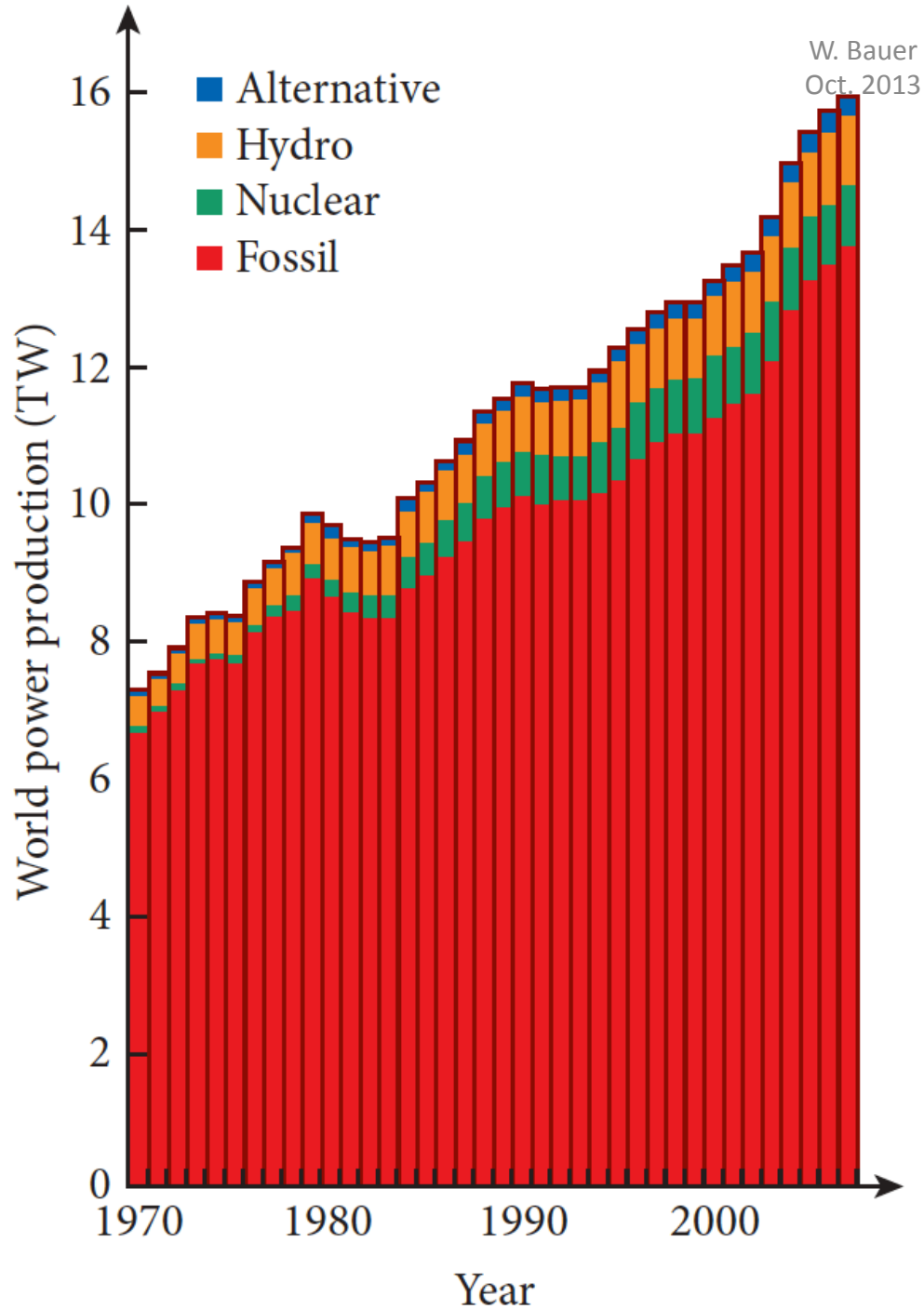
W. Bauer
Oct. 2013



- Flow volume ~ 3 million liters/second
- Height h = 50 m
- $Power = mgh/t$ = 1.5 GW

World Power Consumption

- Increasing strongly with time
- Overwhelmingly satisfied with fossil fuels
- ~~Biggest Problem facing the World~~
- **Biggest Opportunity of our lifetime**



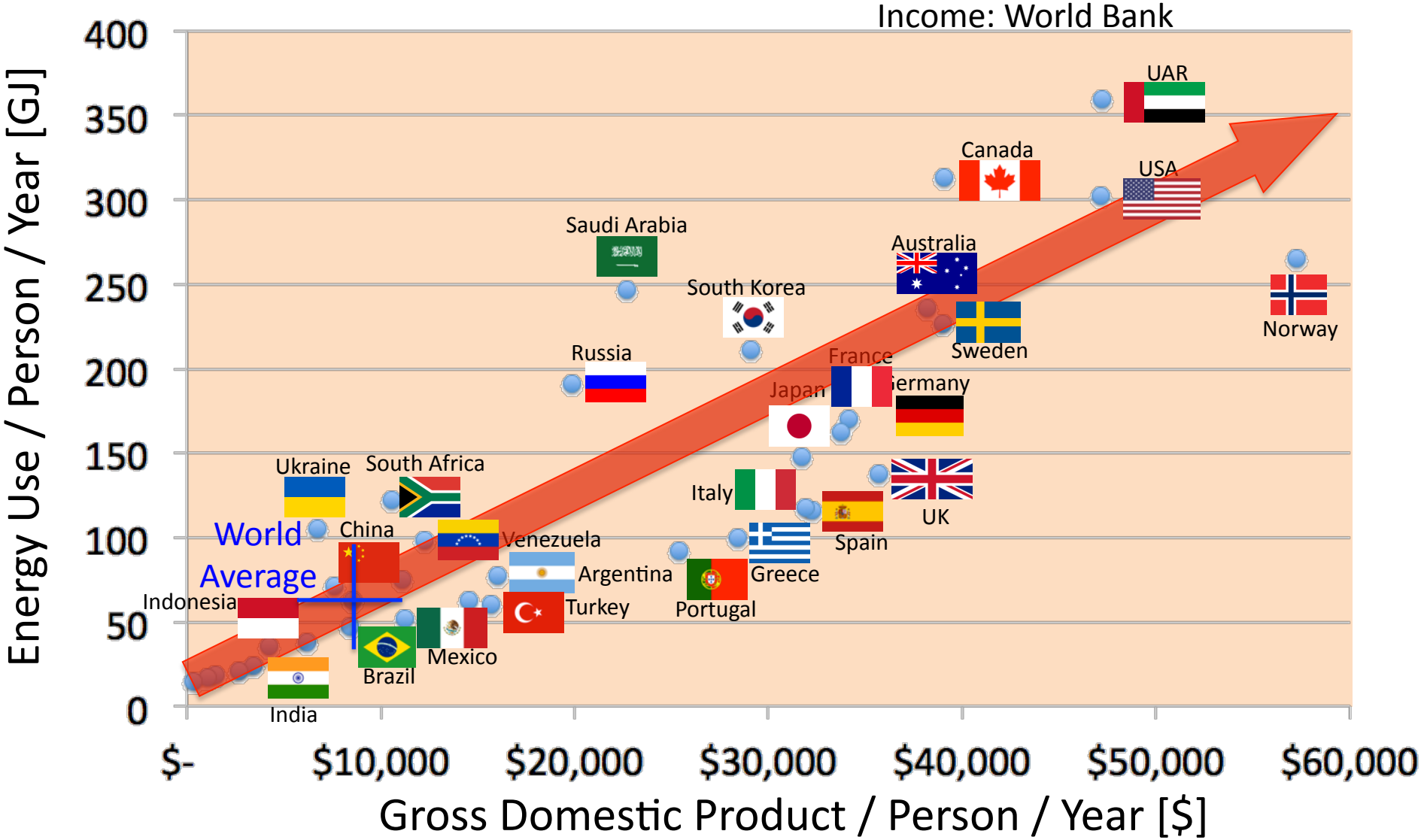
US Power Consumption ~ 4 TW

W. Bauer
Oct. 2013

Energy Use & Prosperity

W. Bauer
Oct. 2013

2010 Data
Energy: International Energy Agency
Income: World Bank



W. Bauer
Oct. 2013

PART 1:

Fossil Fuels

Where do fossil fuels come from?

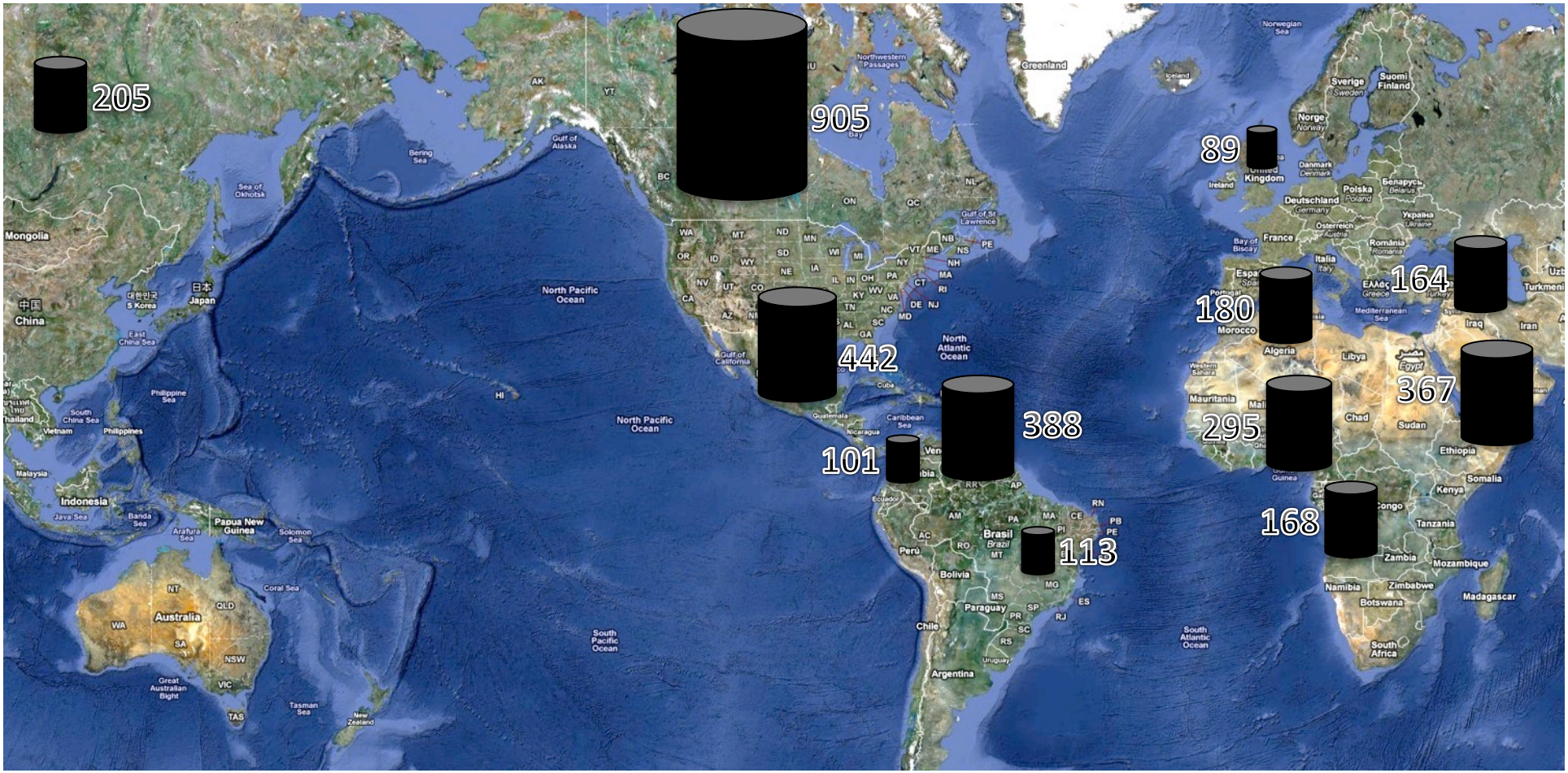
W. Bauer
Oct. 2013

- **Carboniferous period:**
  - 360 million years ago plants evolved to grow wood (lignin)
  - 300 million years ago microbes 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

US Oil Imports 2010

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

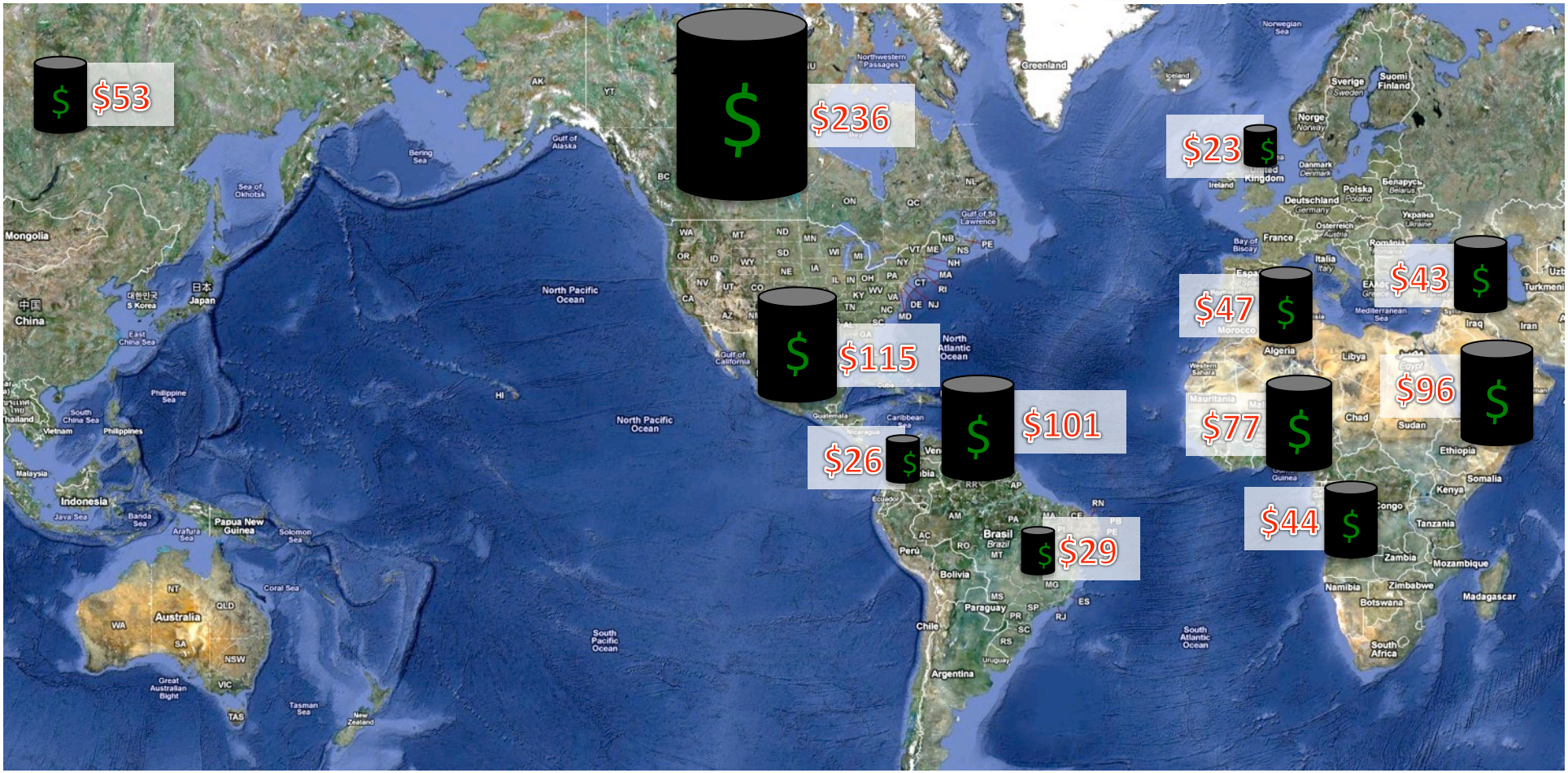
(by country, in million barrels)



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

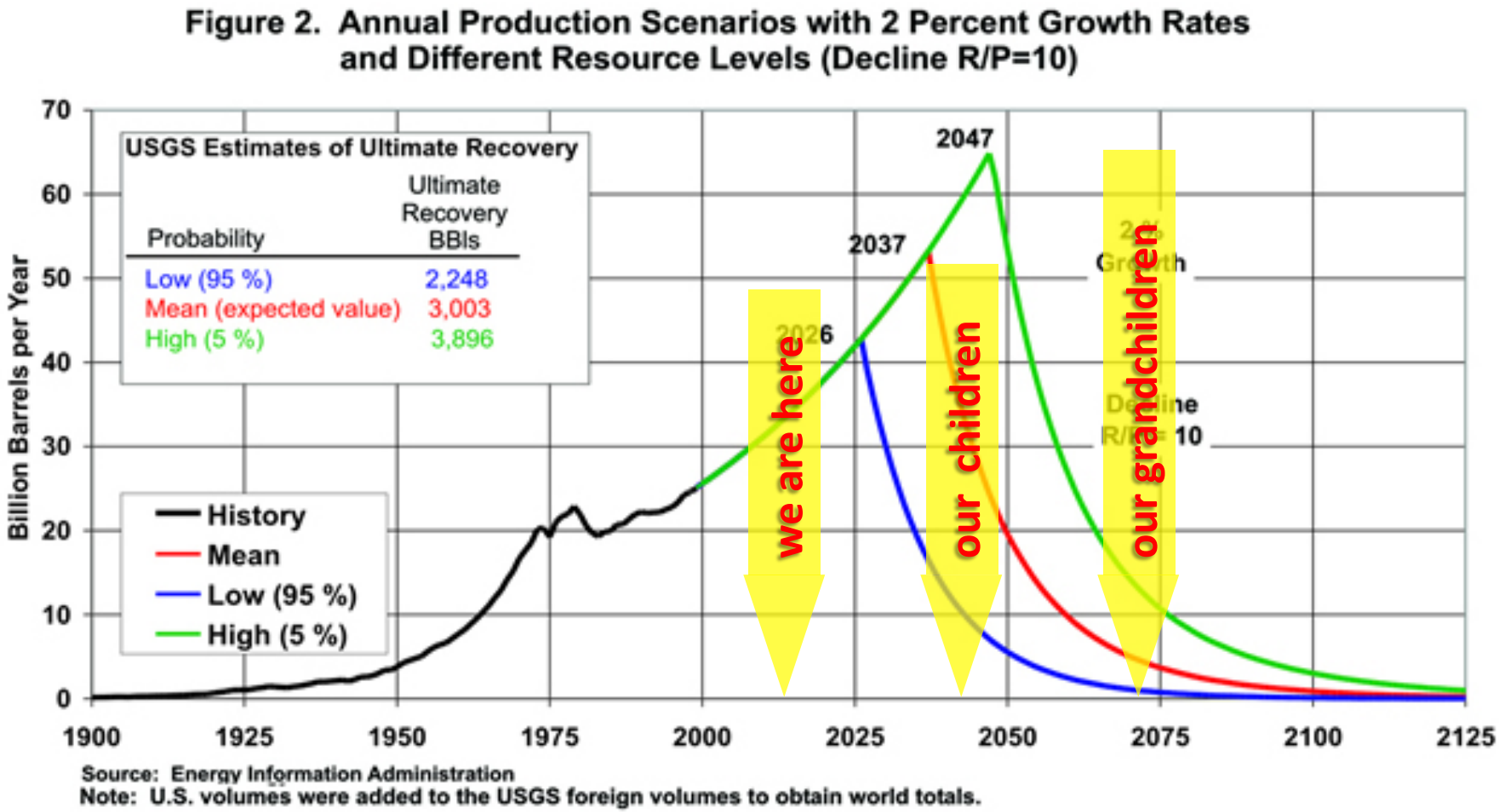
Total oil *import* cost per US citizen in 2010: ~**$1100**

Total cost for the US economy in 2010:

$340 billion

We are running out of oil!

W. Bauer
Oct. 2013



http://www.eia.doe.gov/
S.E. Koonin, BP

Drilling for oil gets more expensive and dangerous

W. Bauer
Oct. 2013

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

W. Bauer
Oct. 2013

PART 2:

Earth's Atmosphere

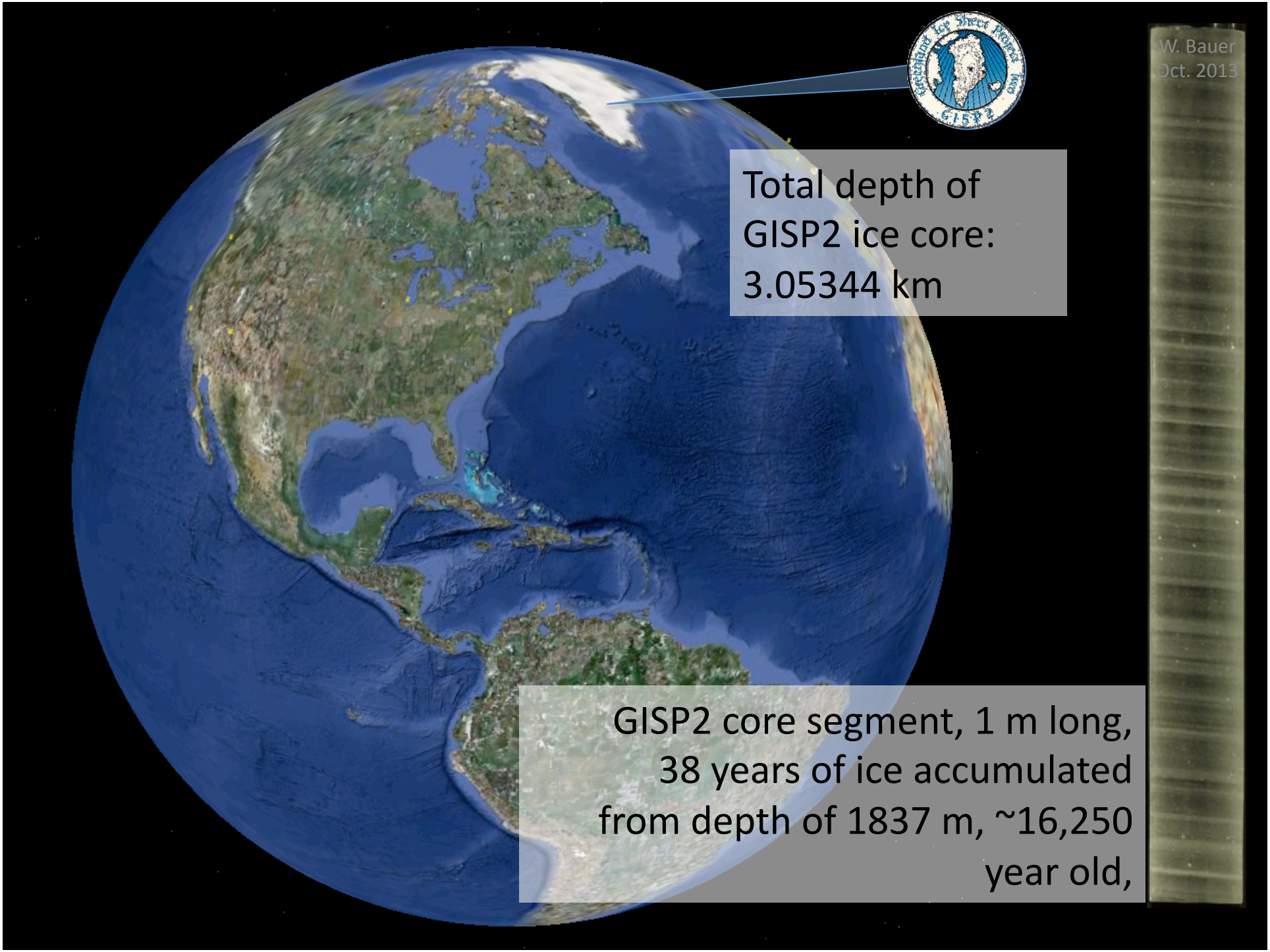
Atmosphere

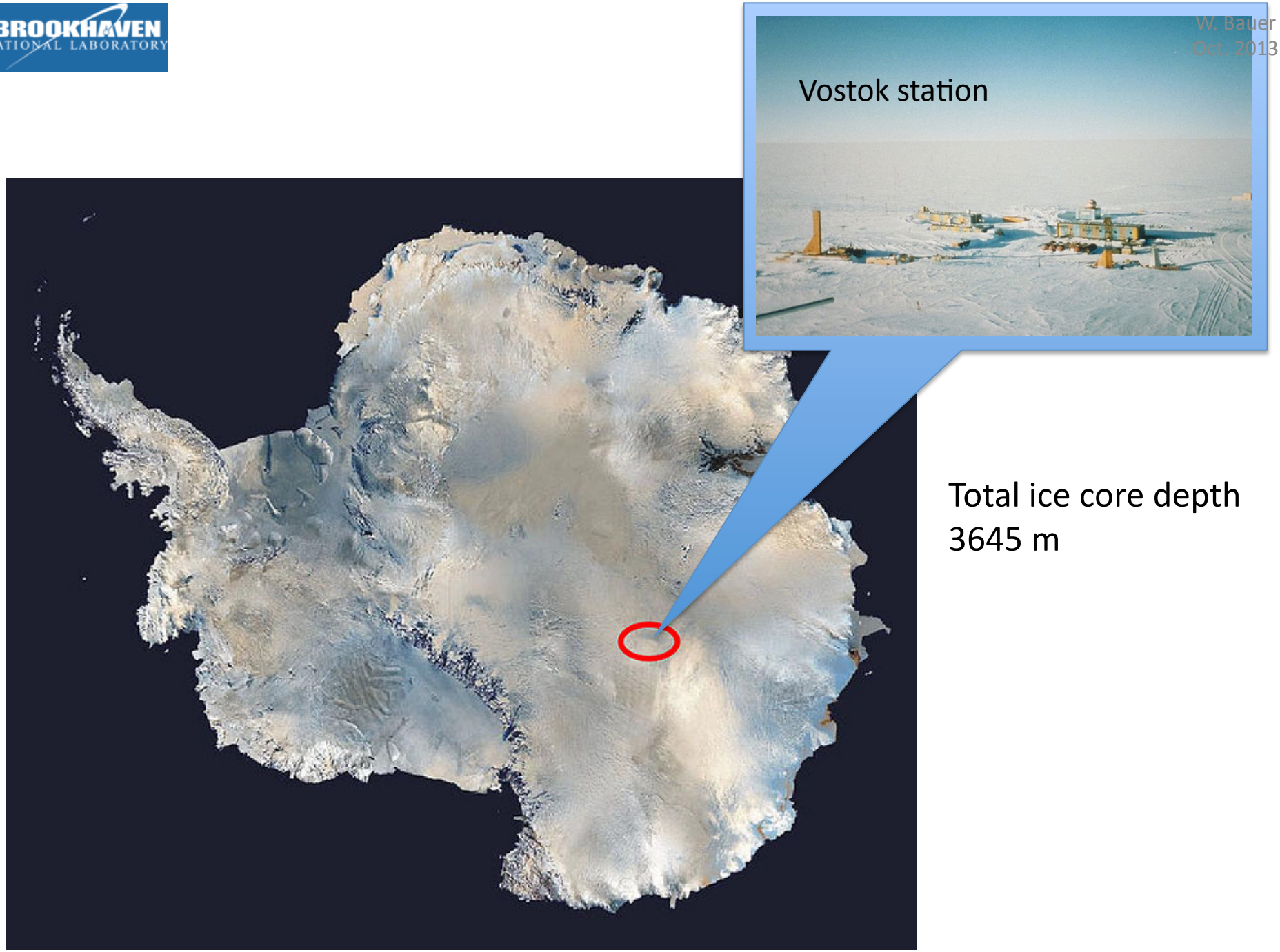
W. Bauer
Oct. 2013

- **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

W. Bauer
Oct. 2013

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

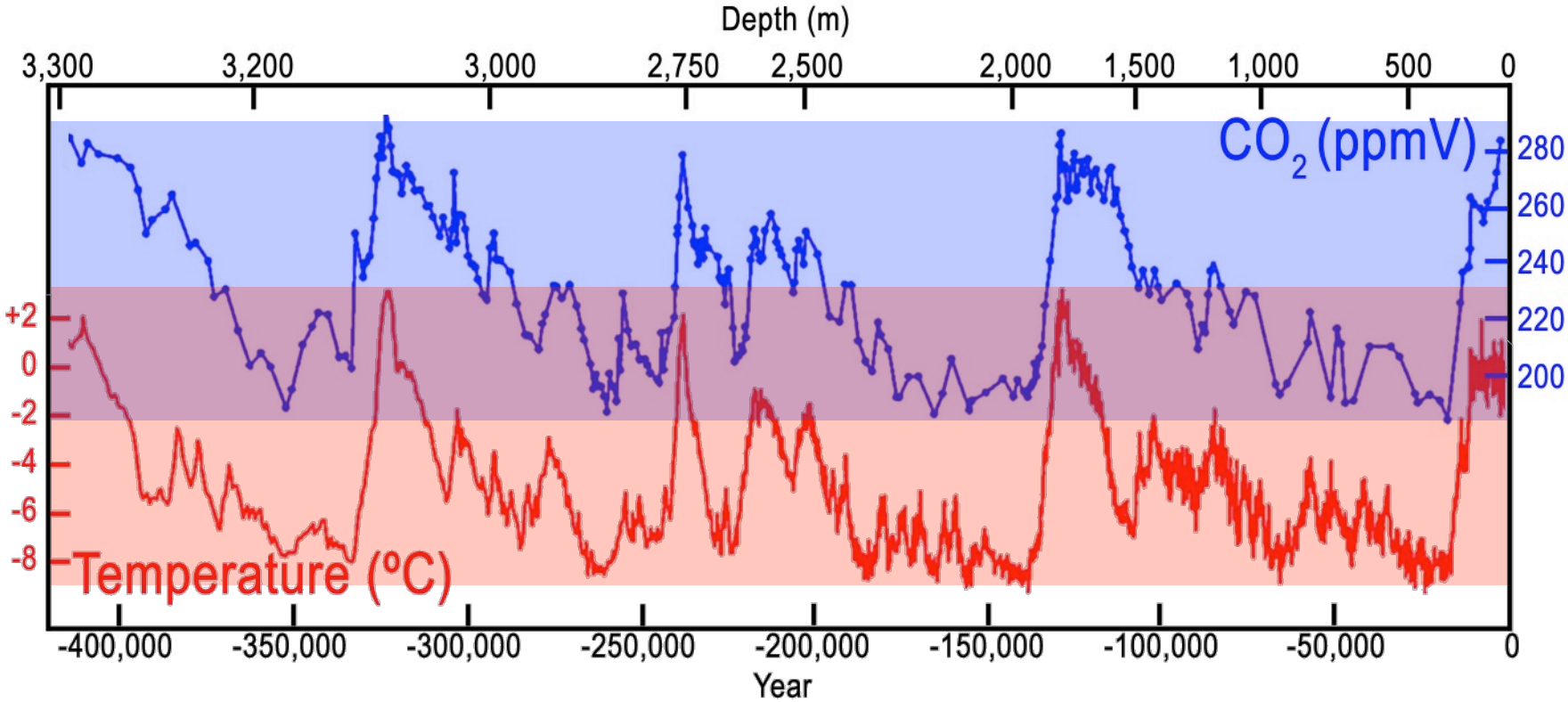

Total depth of GISP2 ice core: 3.05344 km
GISP2 core segment, 1 m long, 38 years of ice accumulated from depth of 1837 m, ~16,250 year old,
W. Bauer
Oct. 2013



Total ice core depth
3645 m

CO_2 and Surface Temperature

W. Bauer
Oct. 2013



CO_2 in a range between 190 and 290 ppmV during last ~ half million years

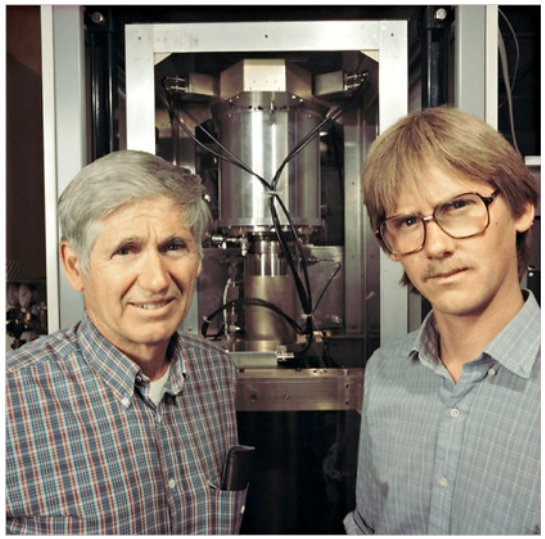
Relative temperature range +3 °C to -9 °C during last ~ half million years

Very strong correlations between the two data sets; indicates a **strongly coupled system**

Keeling Curve

W. Bauer
Oct. 2013

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

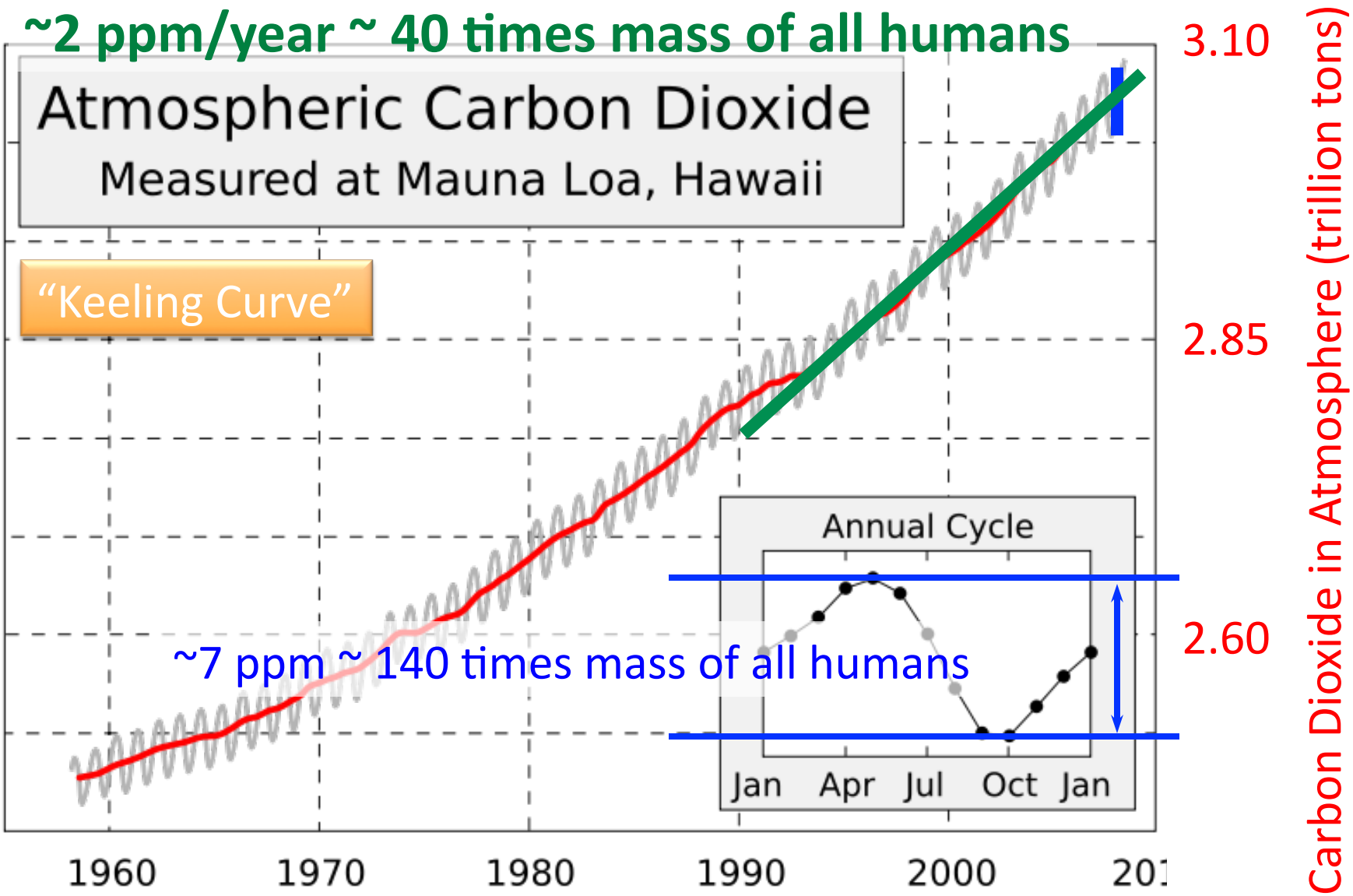


C. & R. Keeling, 1989
Scripps Institution of Oceanography / UC San Diego

- 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

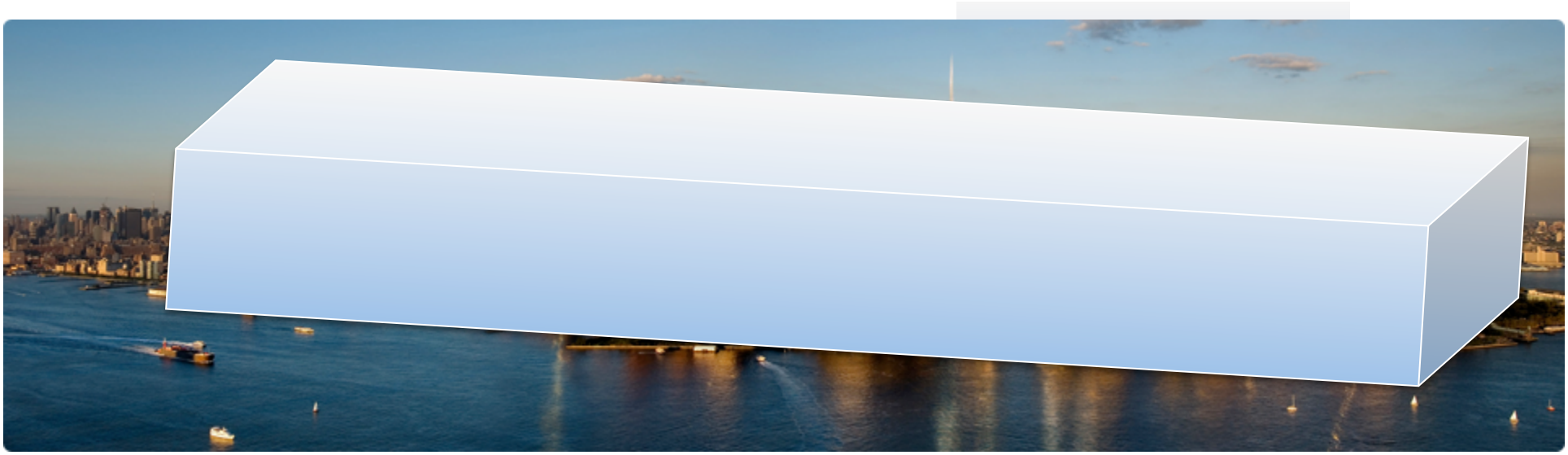
How big is the problem?

W. Bauer
Oct. 2013



16 Billion Tons of CO_2

W. Bauer
Oct. 2013



Dry ice: density ~ 1.5 kg/l

16 GT of CO_2 equivalent to ~ 10 km^3 of dry ice

Air Pollution

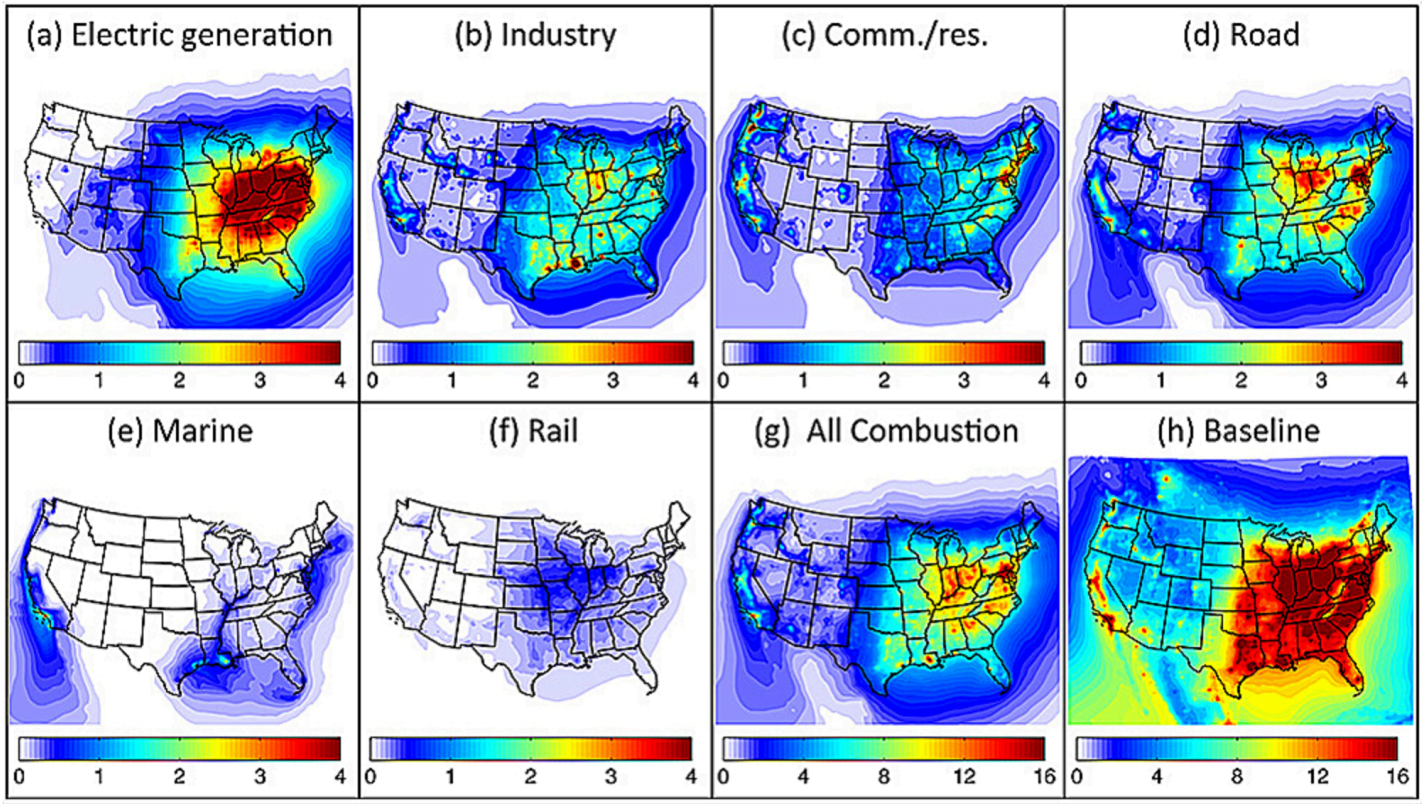
W. Bauer
Oct. 2013

200,000 early deaths in the USA per year from air pollution

- 53000 transportation
- 52000 power plants
- 41000 industry

Main pollutants:

- $PM_{2.5}$ particulates (diameter < 2.5 µm)
- Ozone

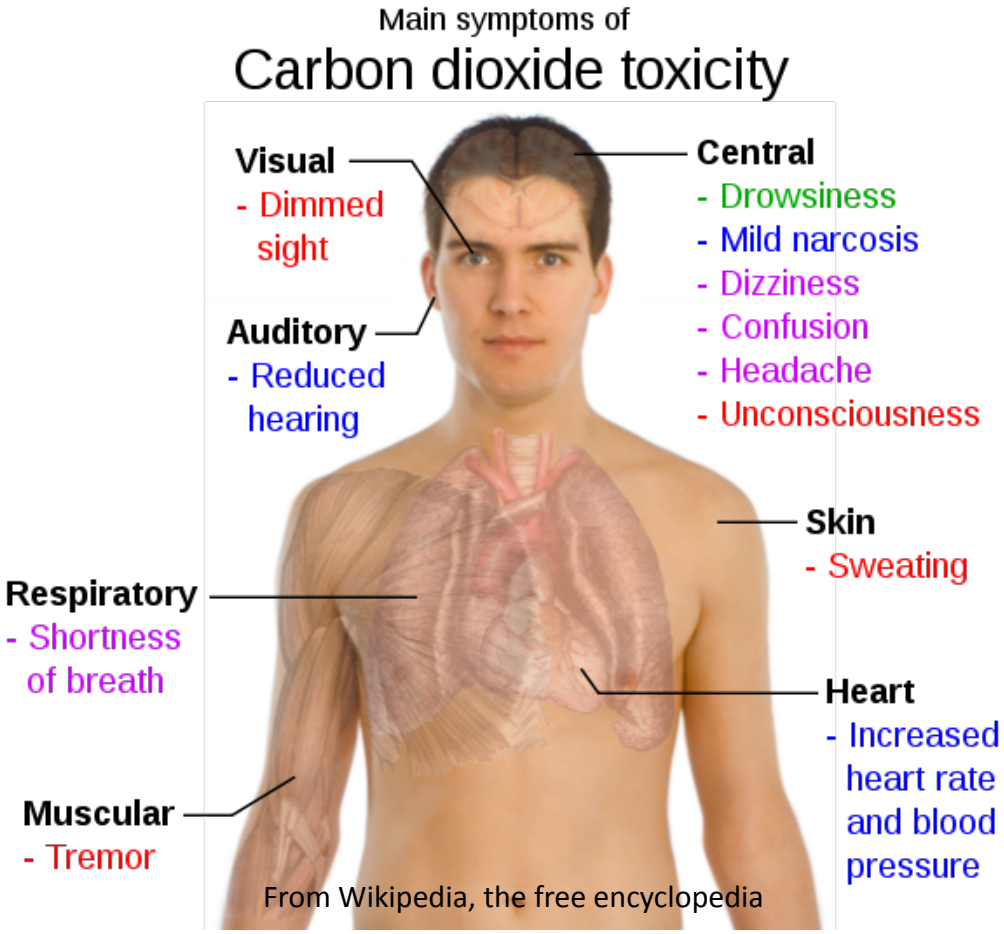


Fabio Caiazzo, Akshay Ashok, Ian A. Waitz, Steve H.L. Yim, Steven R.H. Barrett, Atmosperic Environment 79, November 2013, Pages 198–208

This graphic shows the annual average concentrations of fine particulates from U.S. sources of combustion emissions from (a) electric power generation; (b) industry; (c) commercial and residential sources; (d) road transportation; (e) marine transportation; (f) rail transportation; (g) sum of all combustion sources; (h) all sources.

GRAPHIC: LABORATORY FOR AVIATION AND THE ENVIRONMENT

Good news: we can still breathe!



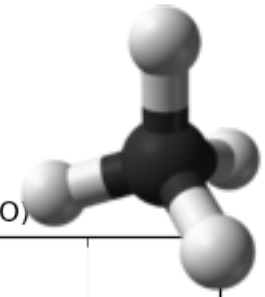
Volume % in air

- 1% = 10000 ppm
- 3% = 30000 ppm
- 5% = 50000 ppm
- 8% = 80000 ppm

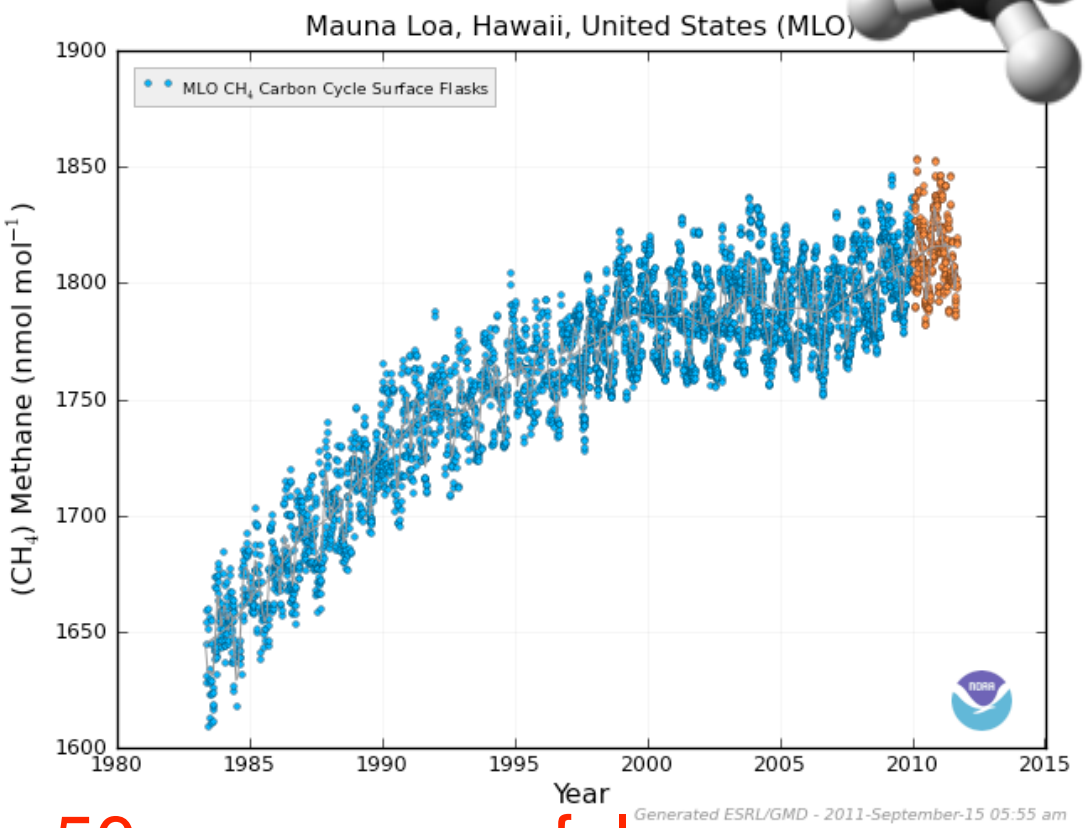
CO_2 level in atmosphere still a factor of ~20 below danger level

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
  $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
- Heat of combustion: 802 kJ/mol (~1 MJ/ft^3)

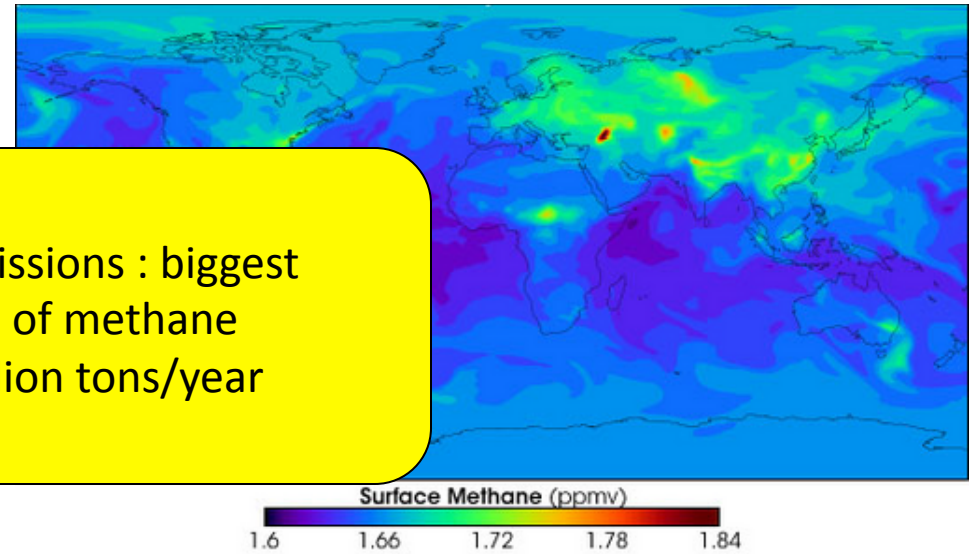


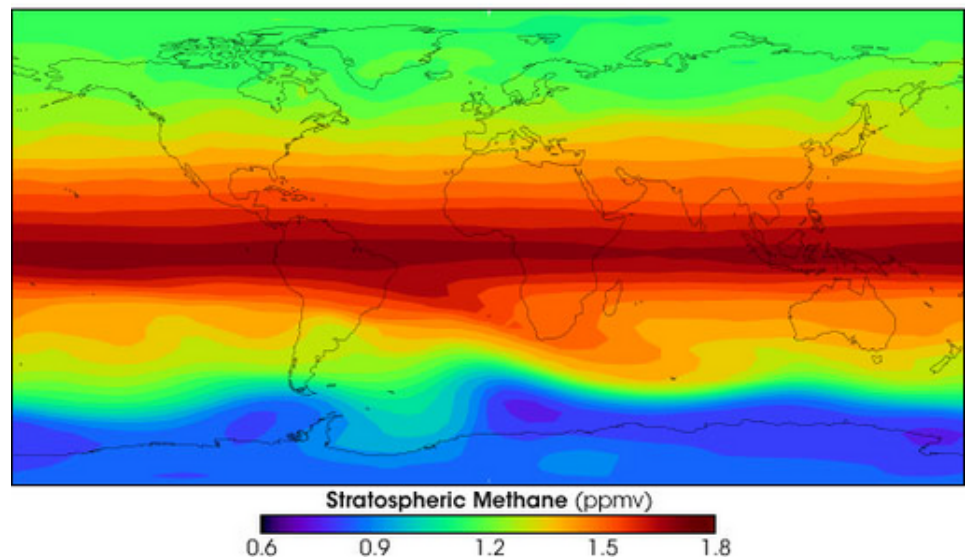
- CH_4 is a factor of 20 to 50 more powerful as a greenhouse gas than CO_2, responsible for ~20% of climate forcing from all greenhouse gases

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 Emission			
Energy	110		
Landfills	40	[illegible]	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



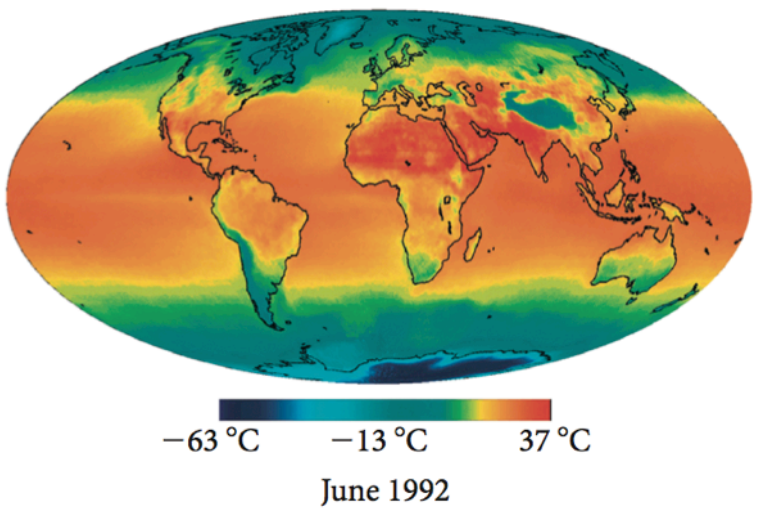


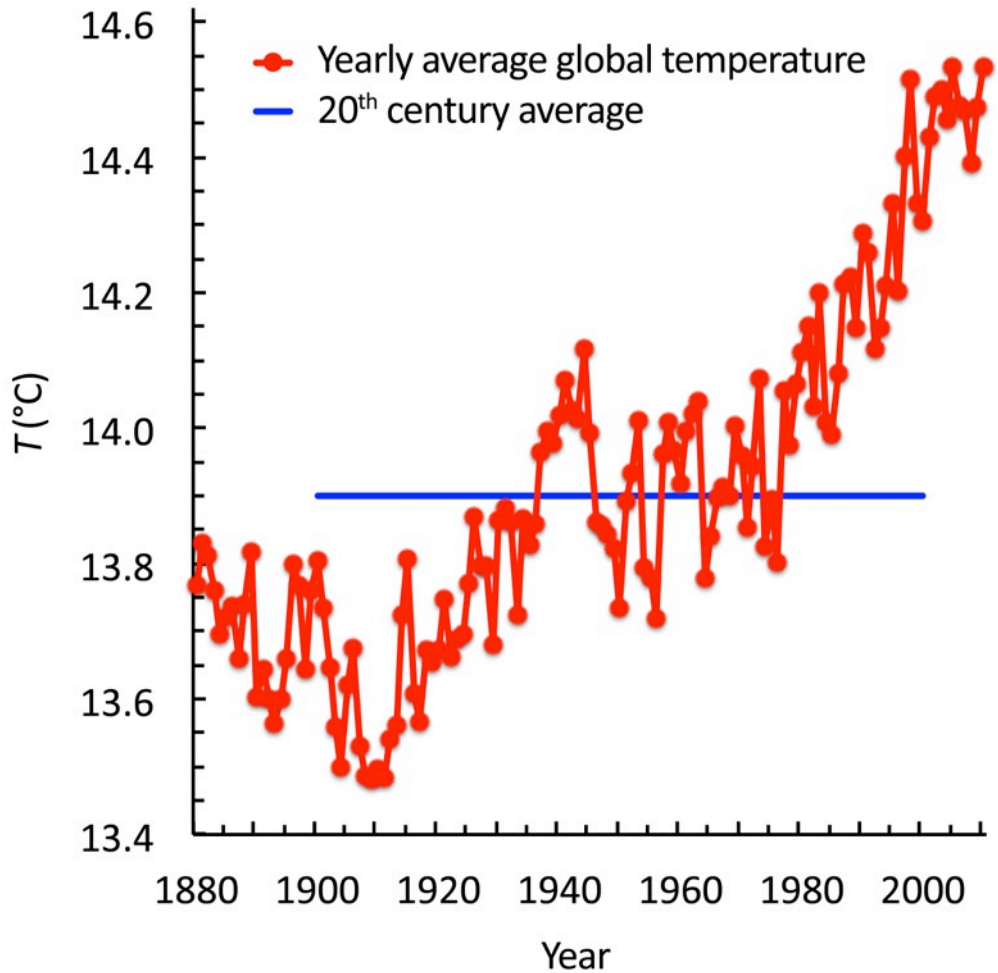
http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=16827

Global Temperature

W. Bauer
Oct. 2013

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





Global Warming of ~0.2°C/decade is happening

Is it man-made?

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

Predictions (1): More >100°F days

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

W. Bauer
Oct. 2013

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

"America's Climate Choices", NRC Report

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

/year

Predictions(2): Sea Level Rise

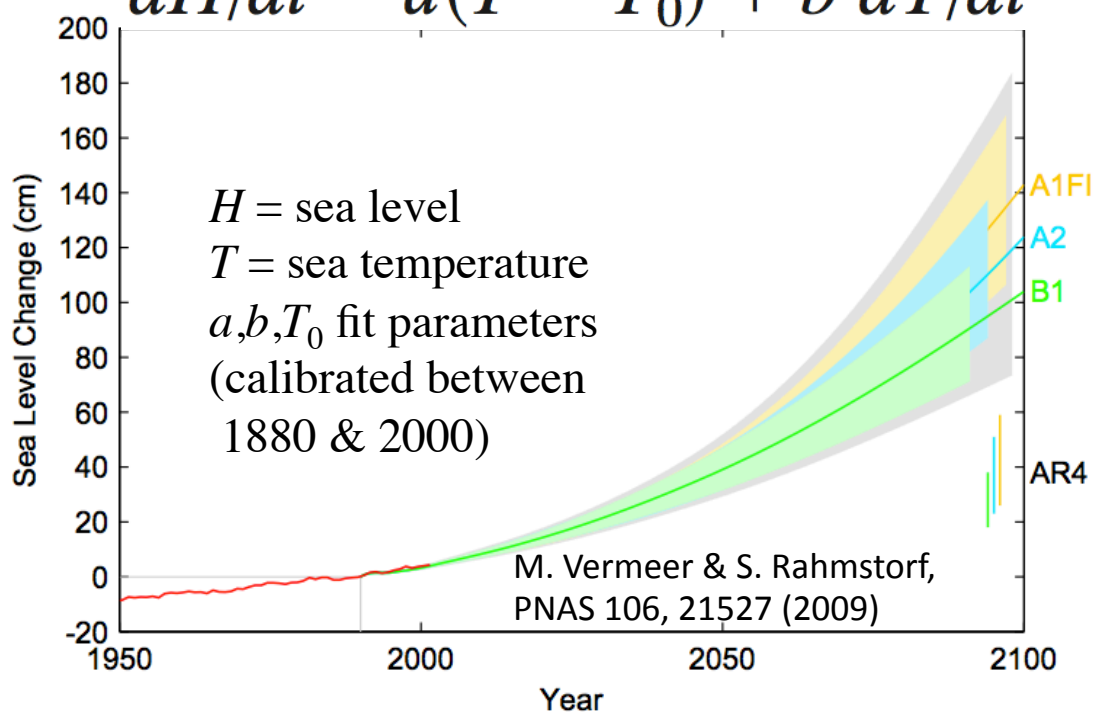
W. Bauer
Oct. 2013

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!

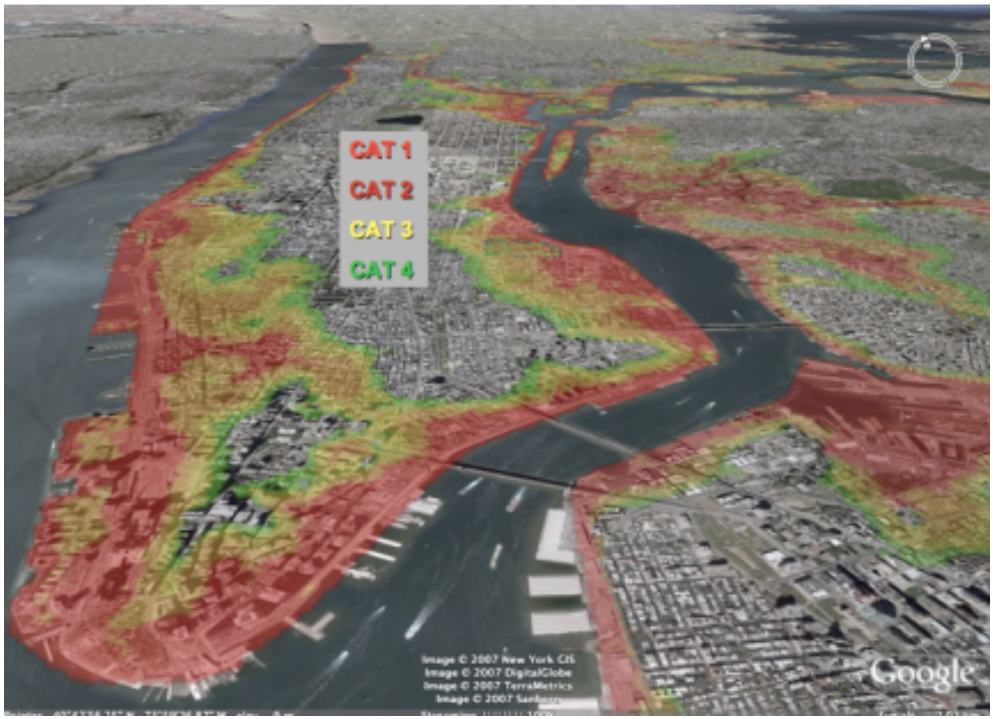
Ice source	Ice Volume	Sea rise
Greenland	2.8M km^3	7.2 m
Antarctic	30M km^3	76 m
North Pole	5-25M km^3	0
Total	**33M km^3**	**83 m**

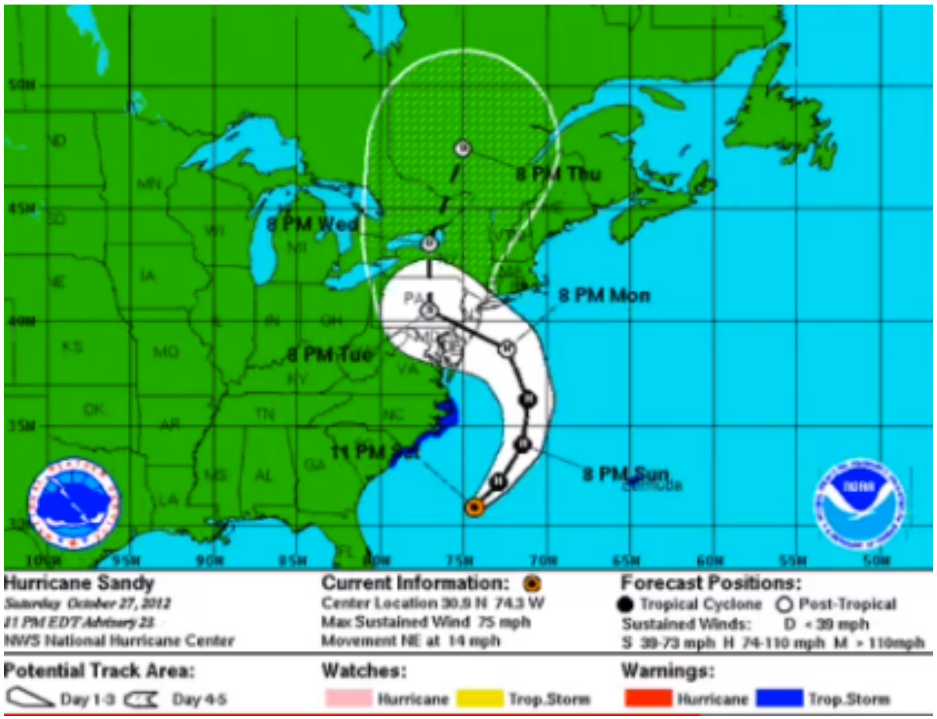
$$dH/dt = a(T - T_0) + b\, dT/dt$$



"Our climate is changing. And while the increase in extreme weather we have experienced in New York City and around the world may or may not be the result of it, the risk that it may be — given the devastation it is wreaking — should be enough to compel all elected leaders to take immediate action."

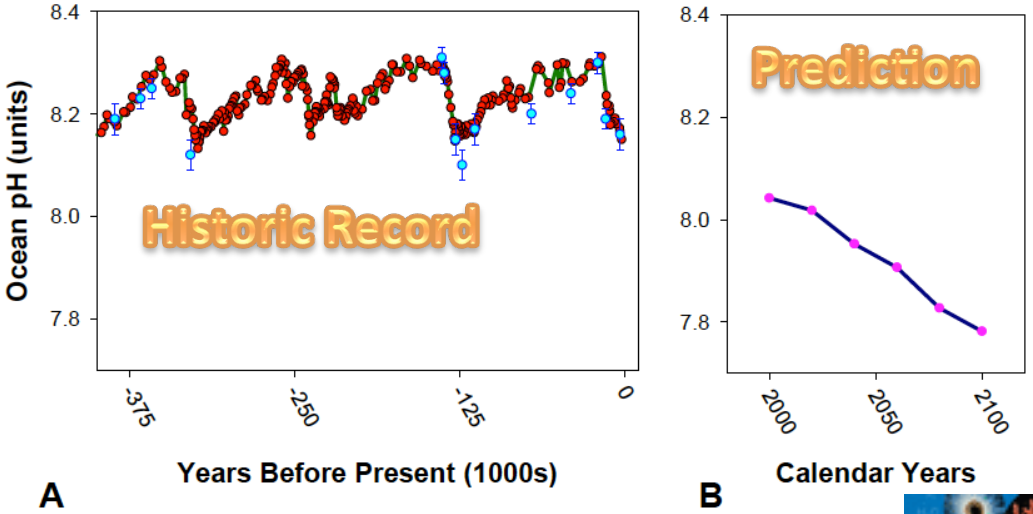
NYC Mayor Michael R. Bloomberg, Oct. 31, 2012





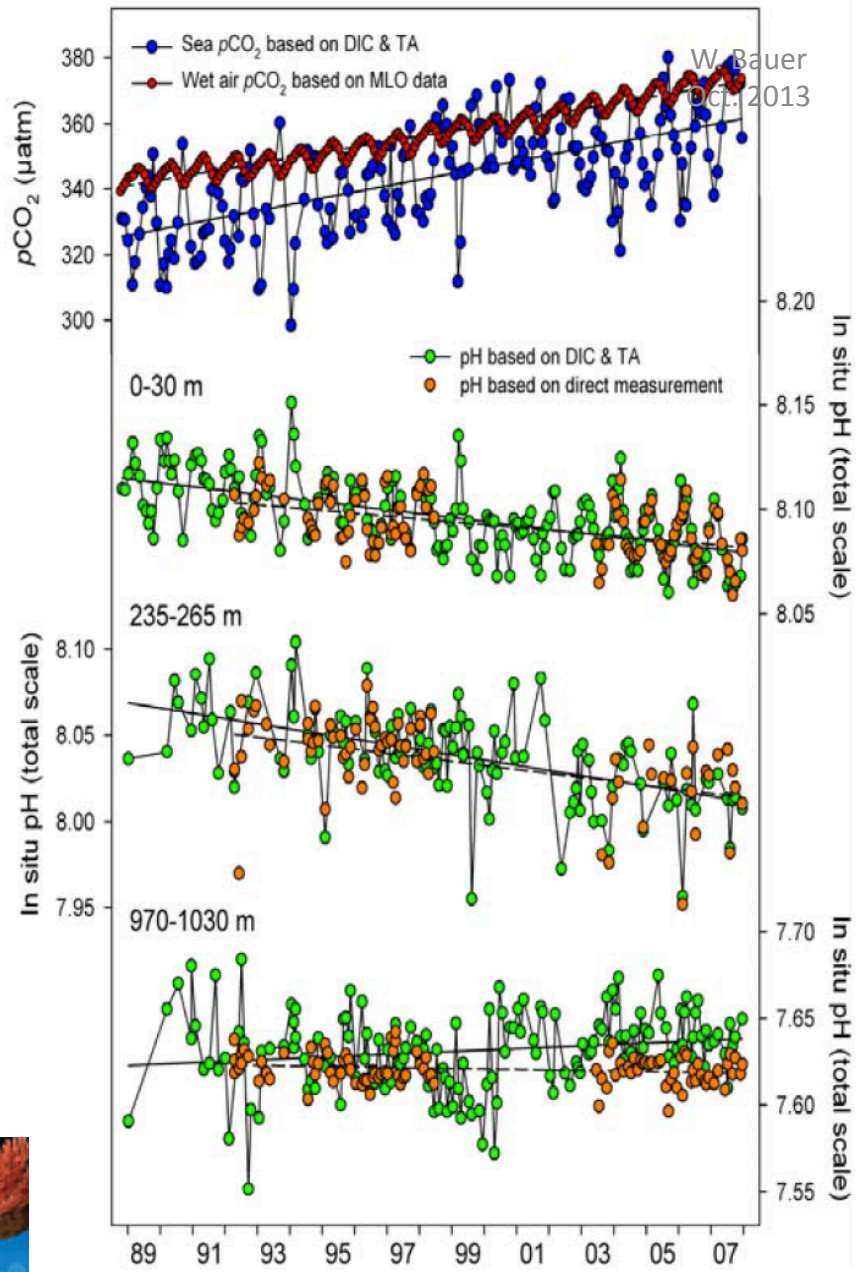
Predictions(3): Ocean Acidification

- ~10 billion tons/year of CO_2 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



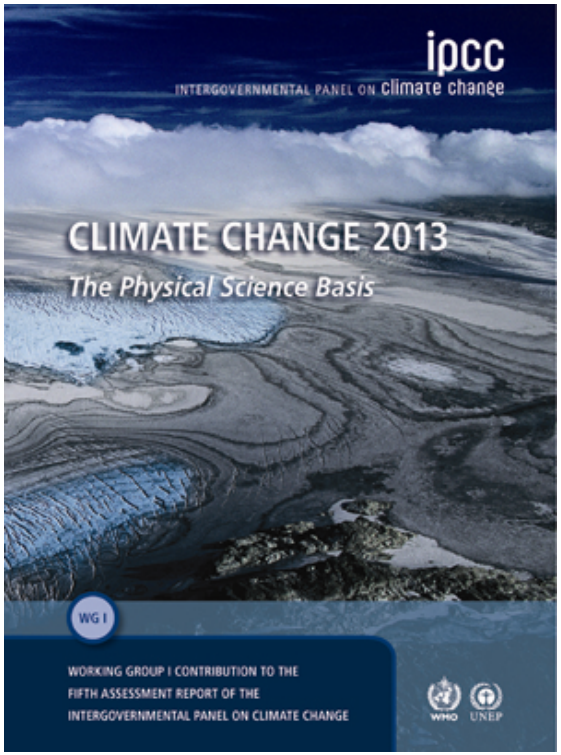
W. Bauer
Oct. 2013

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

ipcc Report 2013

W. Bauer
Oct. 2013

Headline Statements from the Summary for Policy makers:



- "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased."
- "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century."

Disinformation

W. Bauer
Oct. 2013

- NIPCC (Nongovernmental International Panel on Climate Change)
- Warming "modest and cause no net harm"

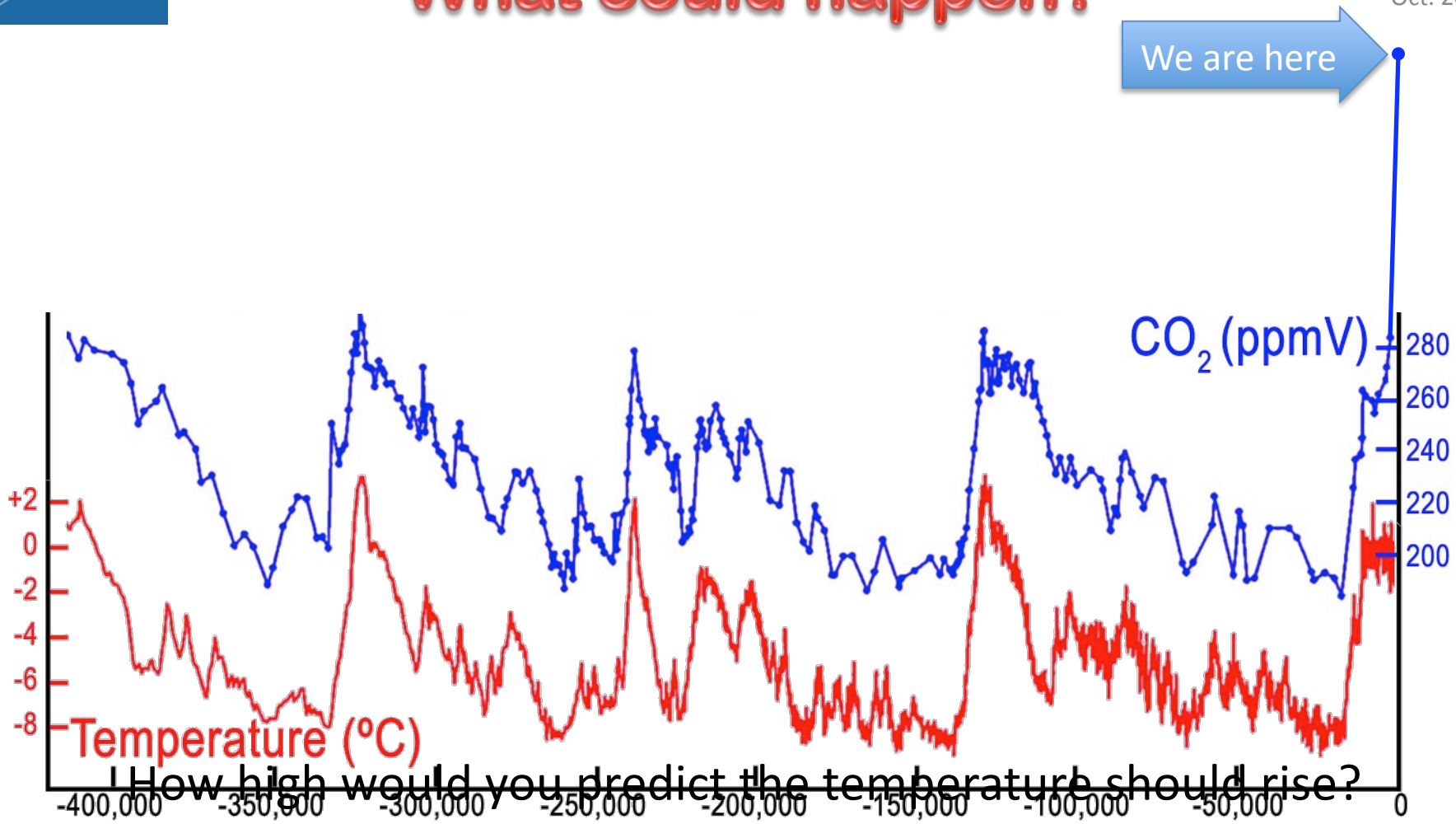
"The NIPCC has no standing whatsoever. It is not a reviewed document, it is not open for review at any point and it contains demonstrable garbage and falsehoods. In contrast the IPCC process is rigorous, open and there are 2 major reviews. This is irresponsible journalism."

Kevin Trenberth, National Center for Atmospheric Research

More detail:
http://mediamatters.org/blog/2013/09/18/
fox-equates-faux-un-climate-report-with-the-rea/195947

What could happen?

W. Bauer
Oct. 2013



How high would you predict the temperature should rise?

If system responds linearly, then: **+13 °C (~23 F)**

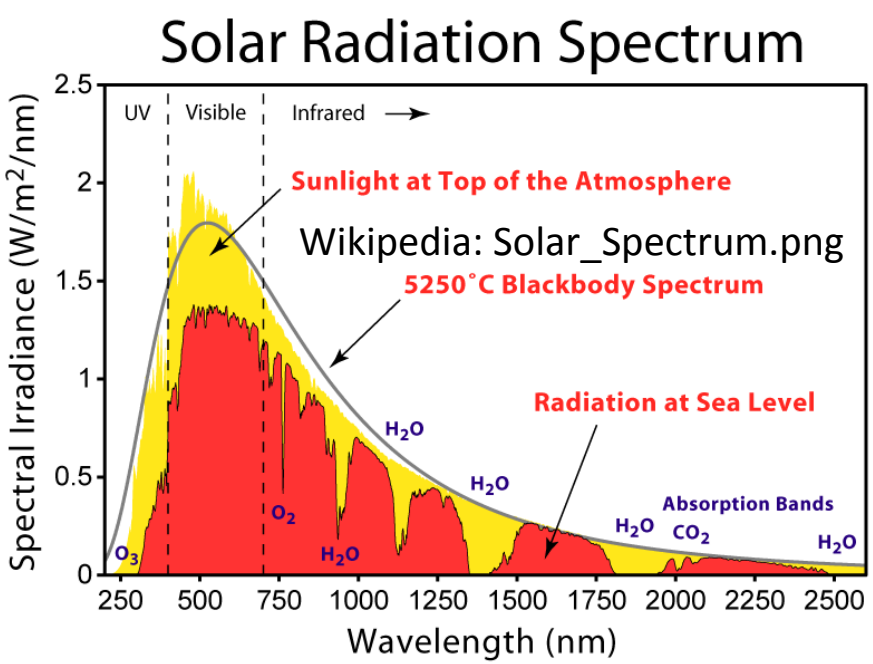
PART 3:

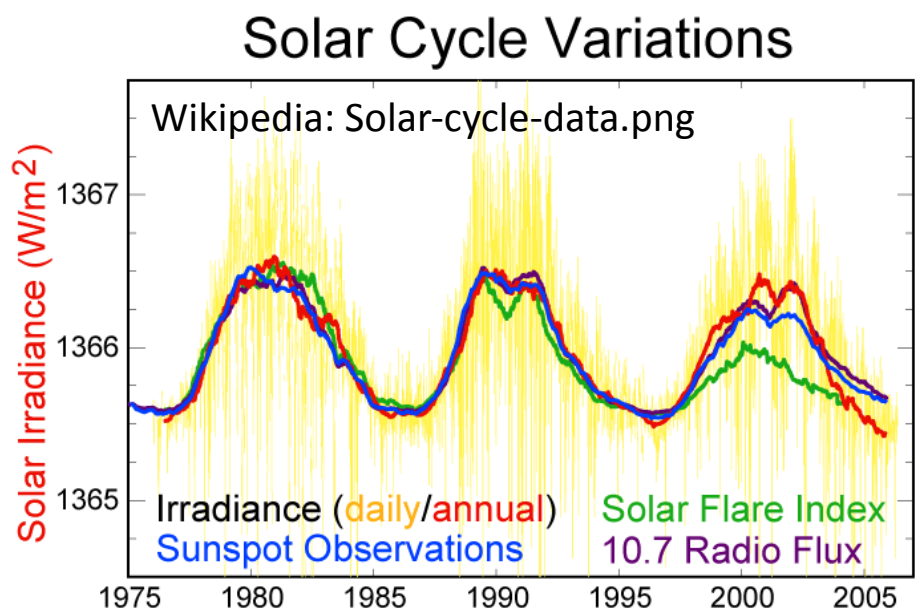
Alternatives

Power from the Sun

W. Bauer
Oct. 2013

- Solar "constant" = 1.366 kW/m^2
  (1.41 kW/m^2 in Jan., 1.31 kW/m^2 in July)
- Average radiation hitting any point on the ground
  200 W/m^2 (= 55% of 1.366 kW/m^2/4)
- Total: **~100,000 TW** (> 5,000x humanity's demand)

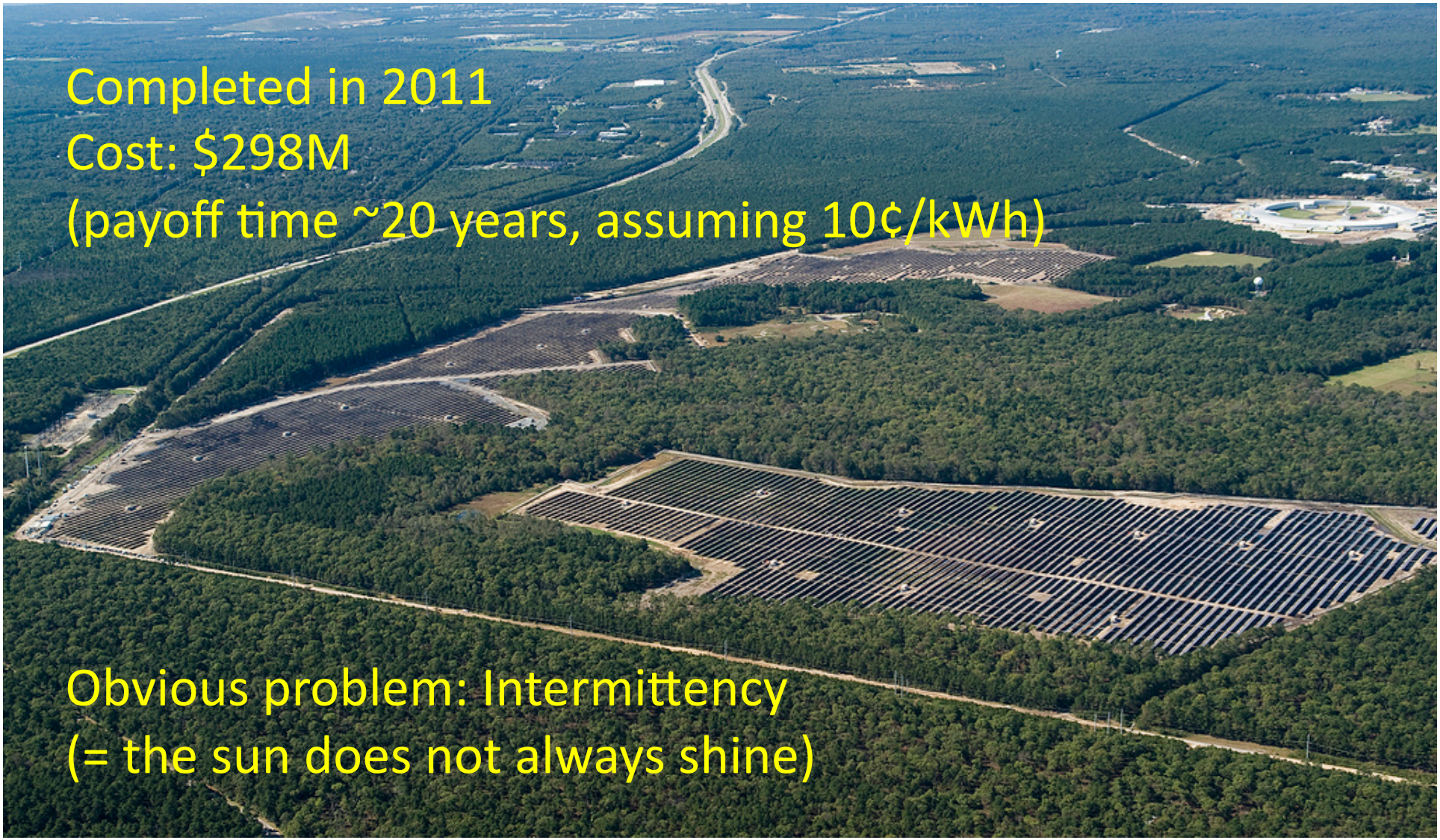


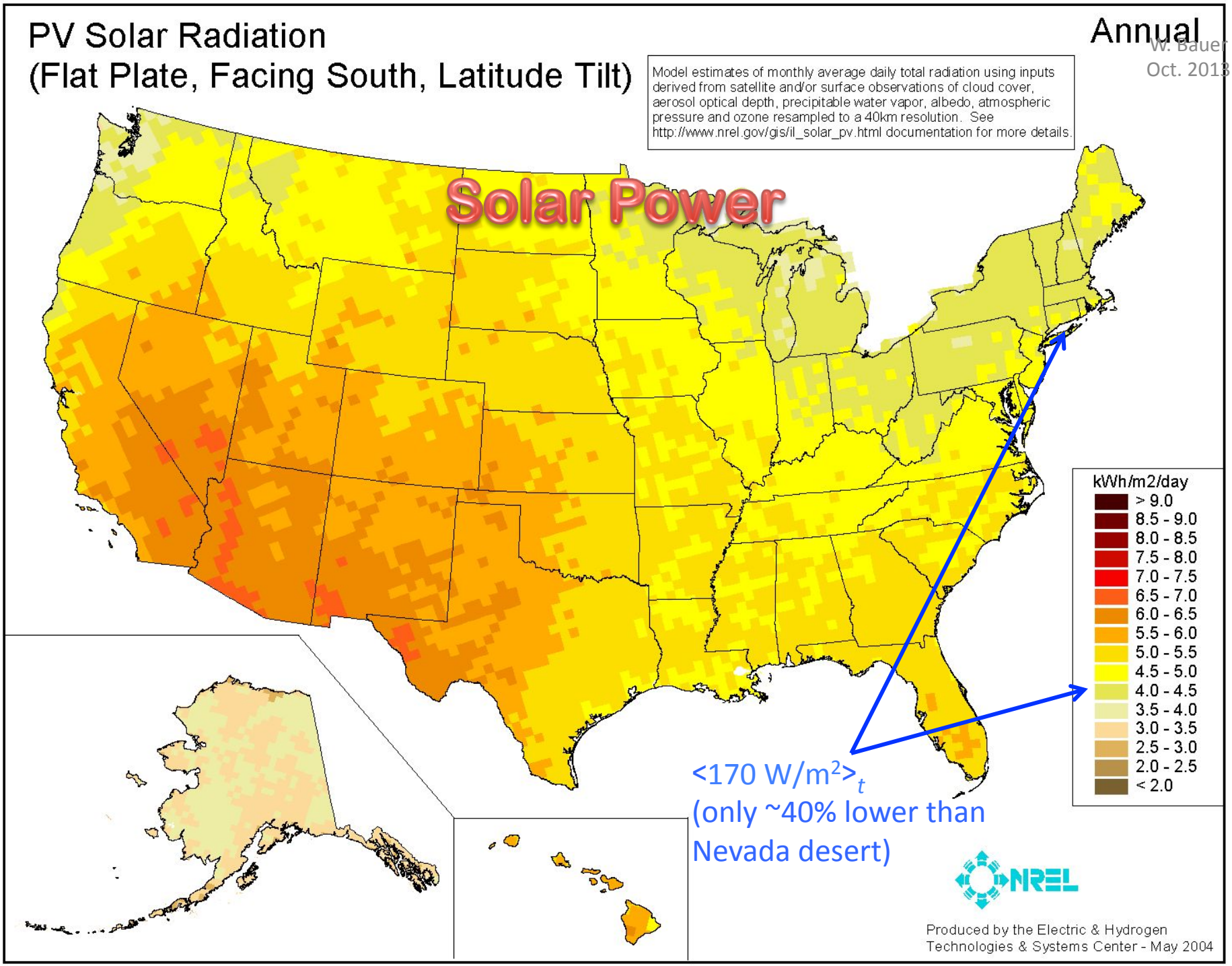


Power from the Sun: Photo-Voltaic

W. Bauer
Oct. 2013

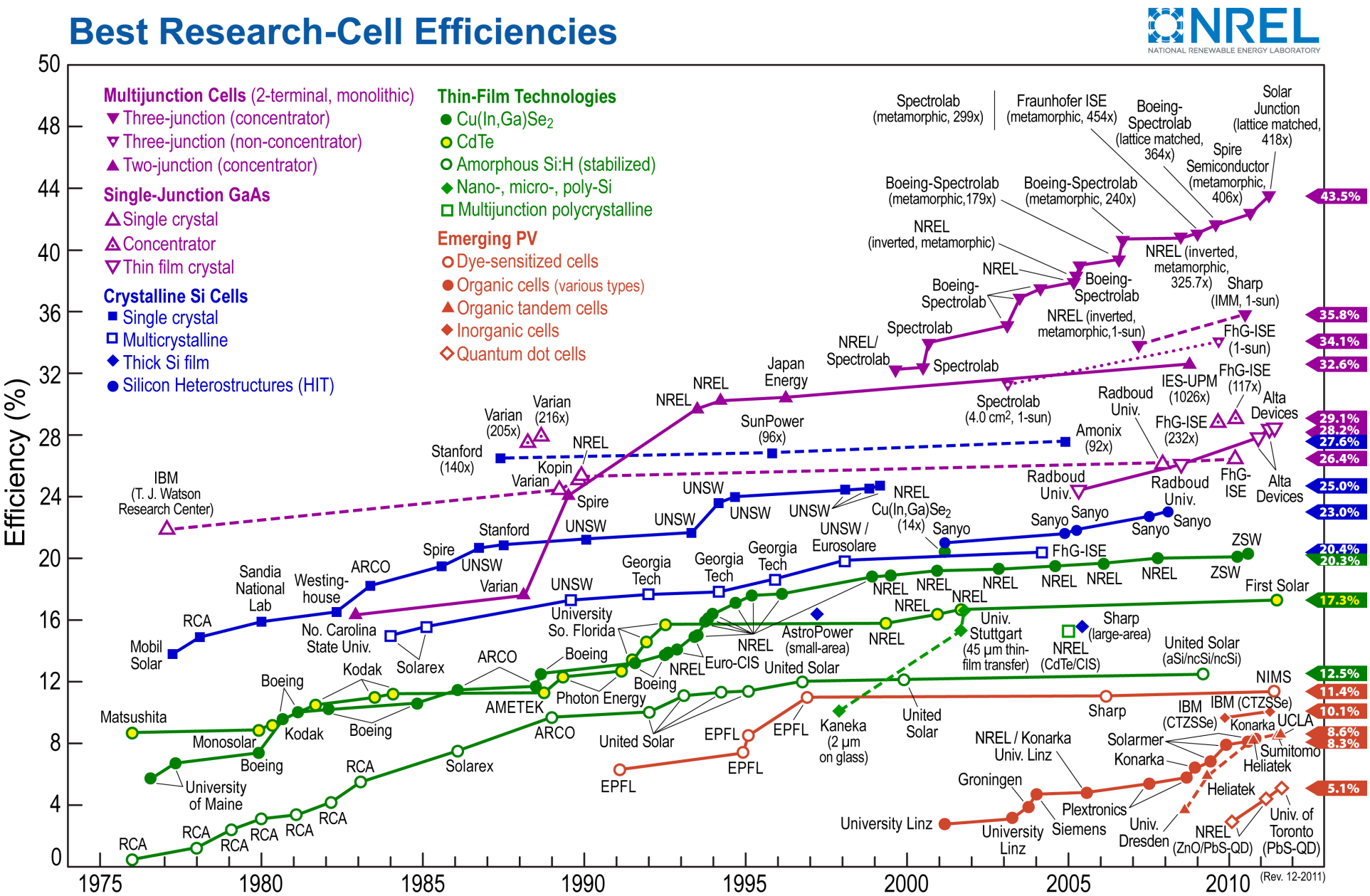
32 MW (peak) Brookhaven solar farm (BP Solar, MetLife, LIPA, DOE)




PV Solar Radiation
(Flat Plate, Facing South, Latitude Tilt)
Annual
W. Bauer
Oct. 2013
Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_solar_pv.html documentation for more details.
Solar Power
kWh/m2/day
> 9.0
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2.0
<170 W/m²>t
(only ~40% lower than
Nevada desert)
NREL
Produced by the Electric & Hydrogen
Technologies & Systems Center - May 2004

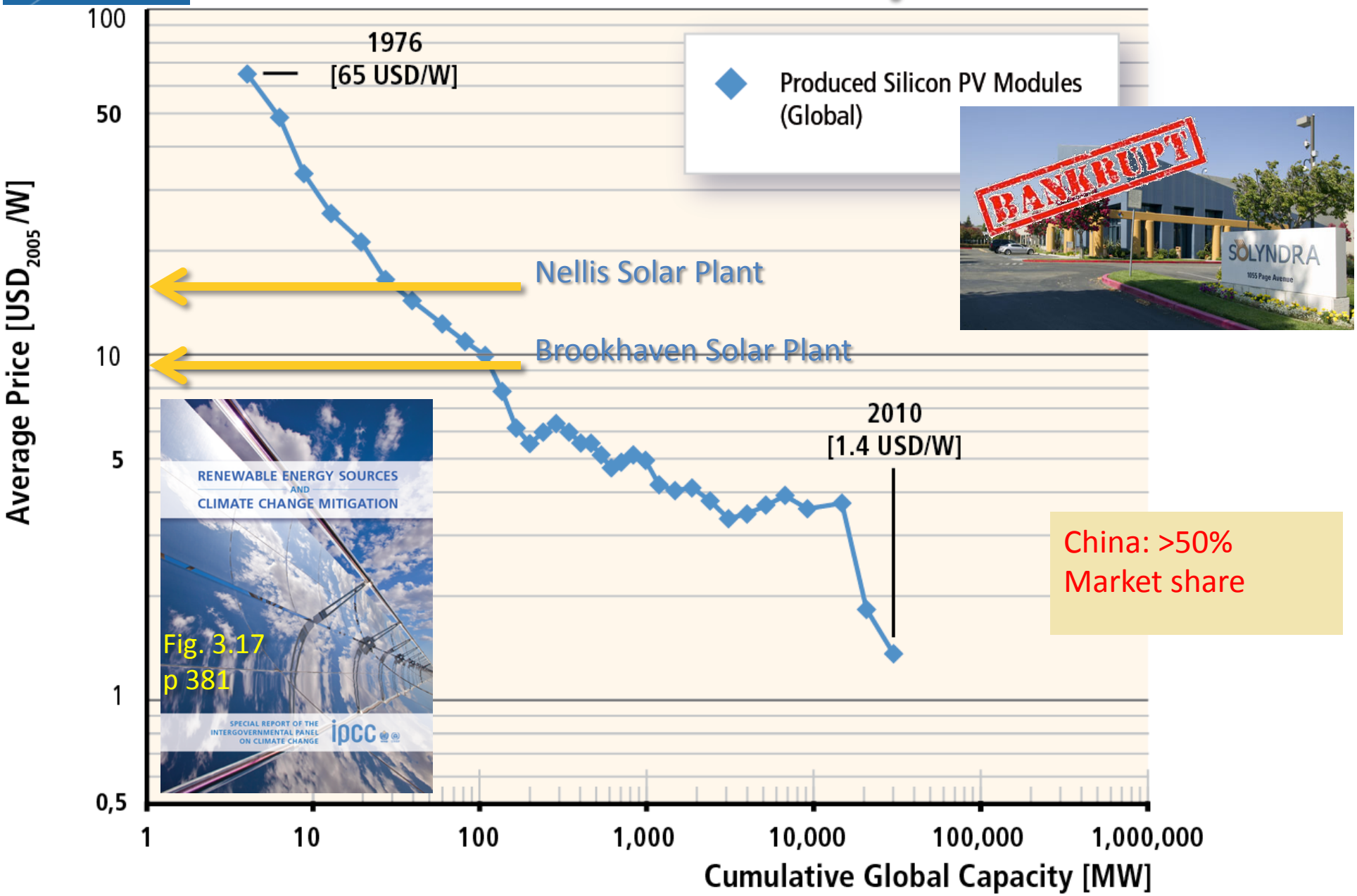
PV solar… getting more efficient

W. Bauer
Oct. 2013



… and less expensive

W. Bauer
Oct. 2013

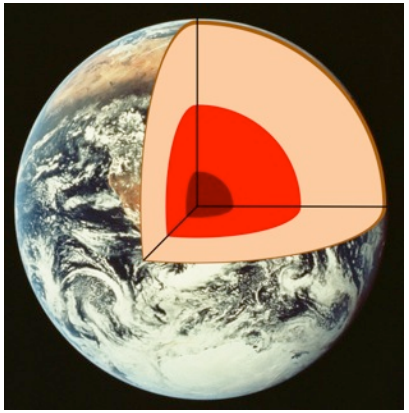


Power from the Sun: Solar-Thermal

W. Bauer
Oct. 2013

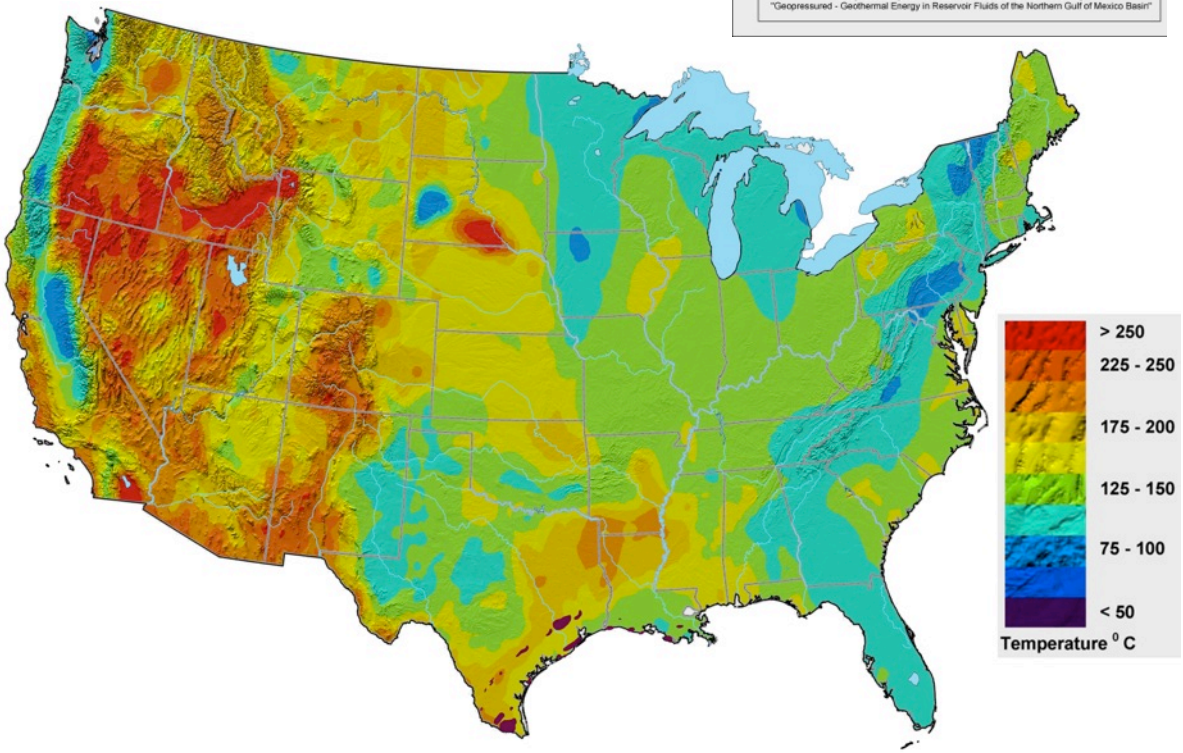
Power from the Earth

W. Bauer
Oct. 2013



Earth's thermal energy ~ 10^{31} J
Heat flow density: 0.1 W/m^2
Total heat flow: 44 TW

FIGURE 18.32 Nesjavellir Geothermal Power Station in Southwest Iceland, which generates 120 MW of electrical power.



Enhanced Geothermal

W. Bauer
Oct. 2013

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

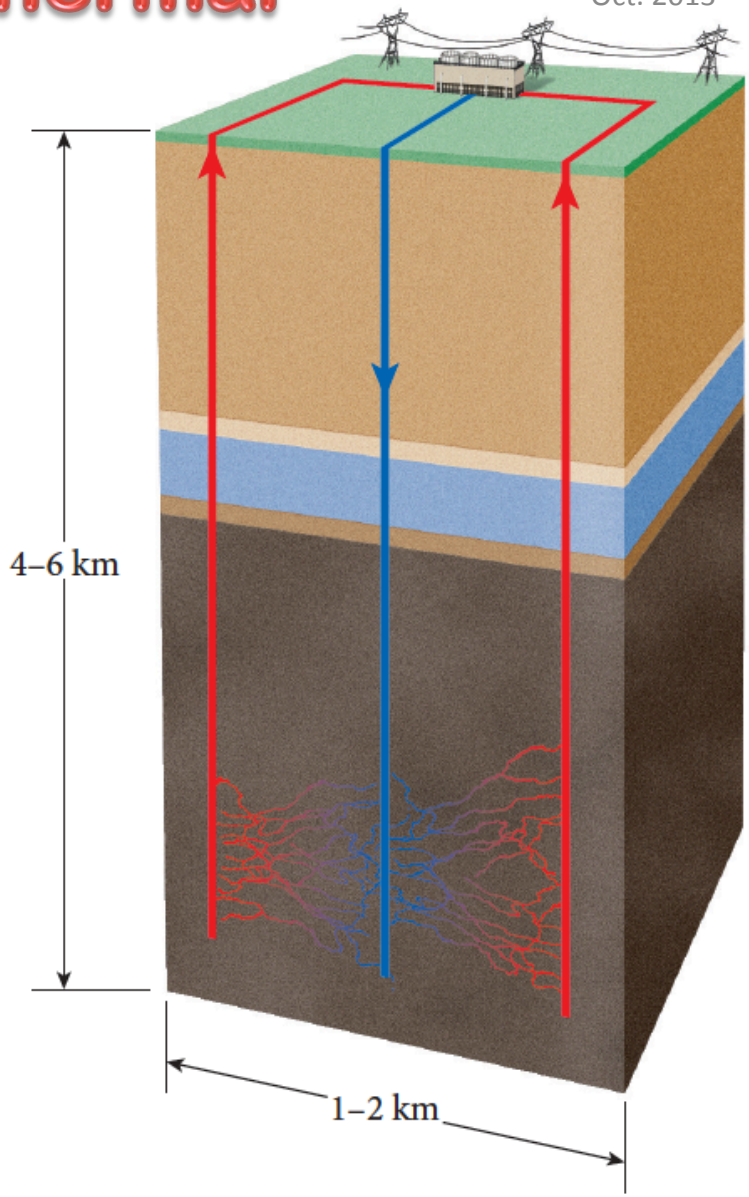


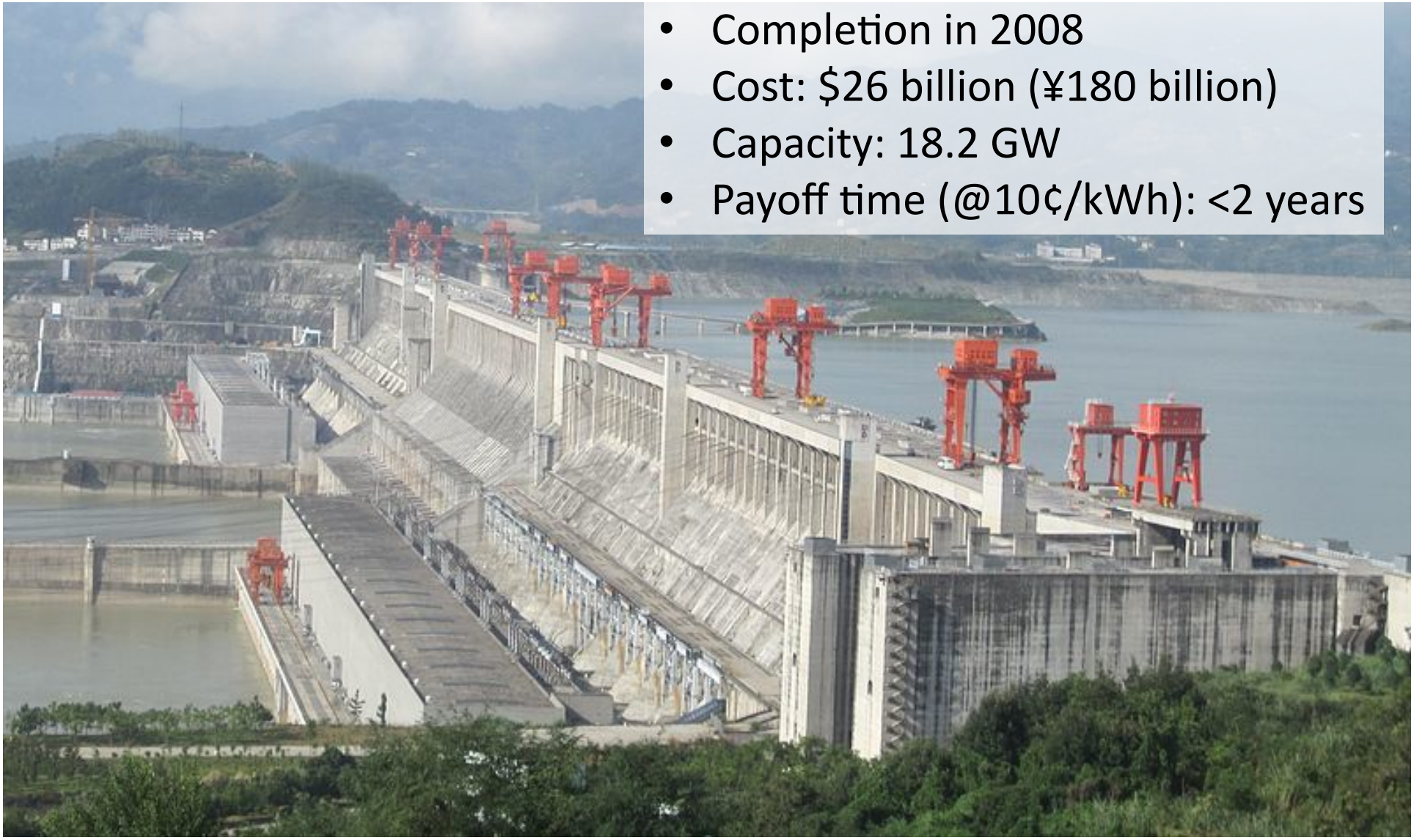
FIGURE 18.33 Diagram of an enhanced geothermal system.

Hydro

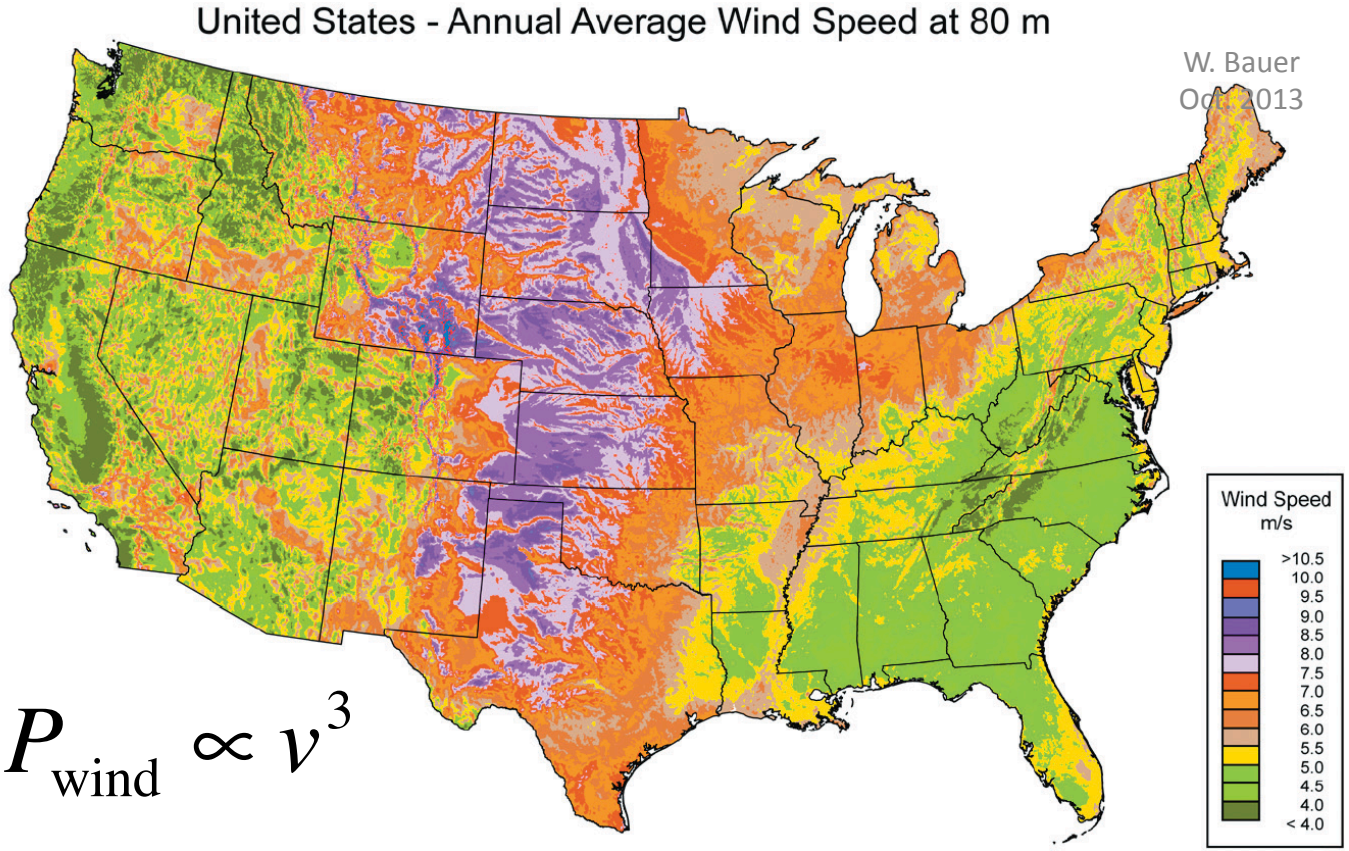
W. Bauer
Oct. 2013

Example: Three Gorges Dam

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



Wind



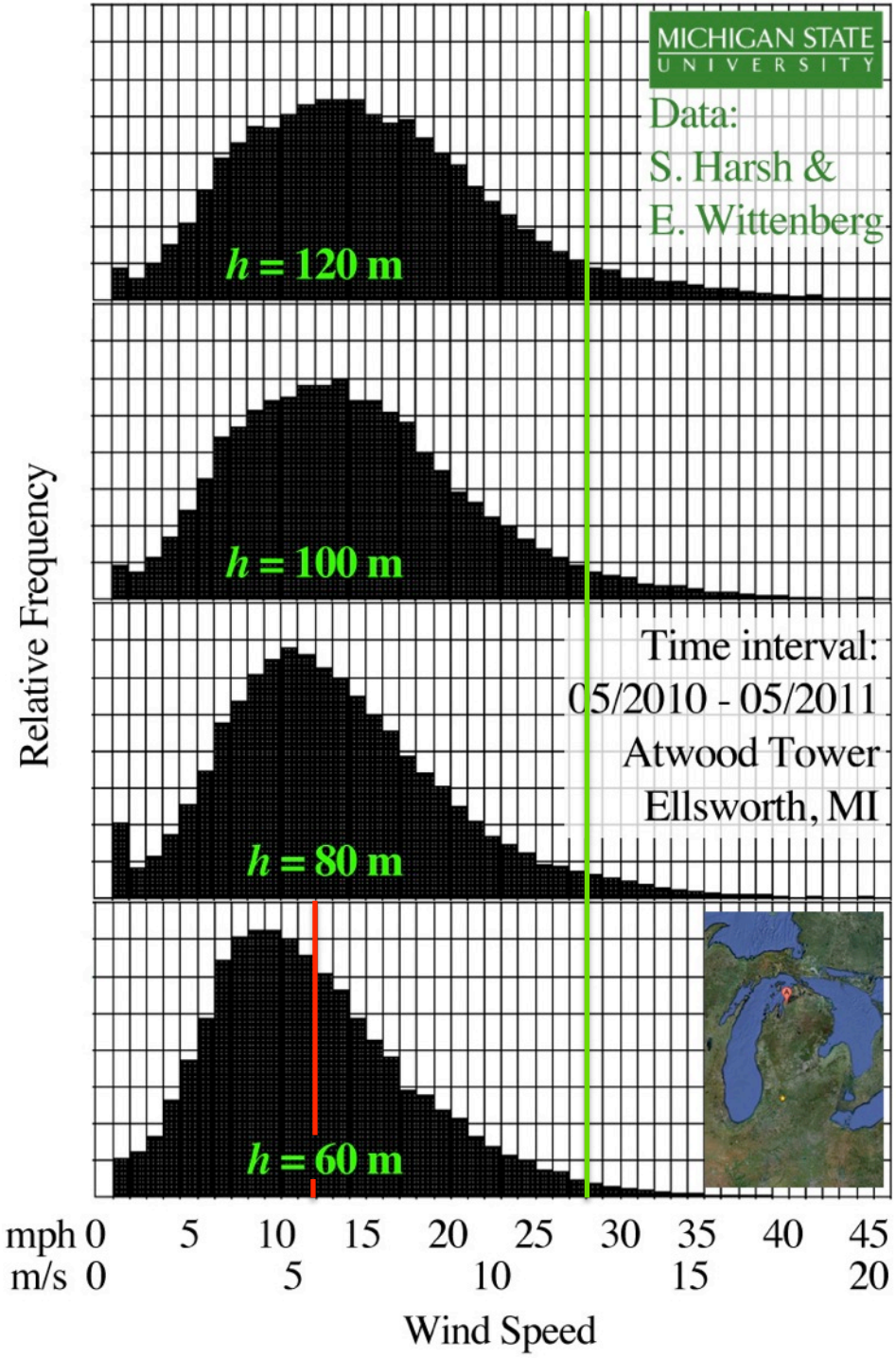
$$P_{\text{wind}} \propto v^3$$

Wind

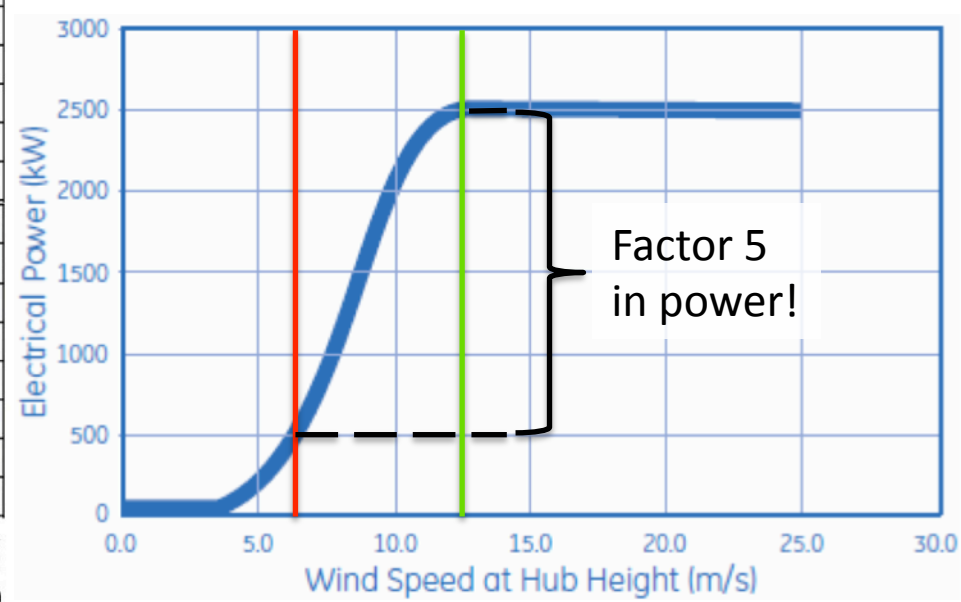
W. Bauer
Oct. 2013

W. Bauer
Oct. 2013

Wind Speed



- Wind speed increases with altitude
  - More power from taller towers
- Broad distribution
  - Intermittency

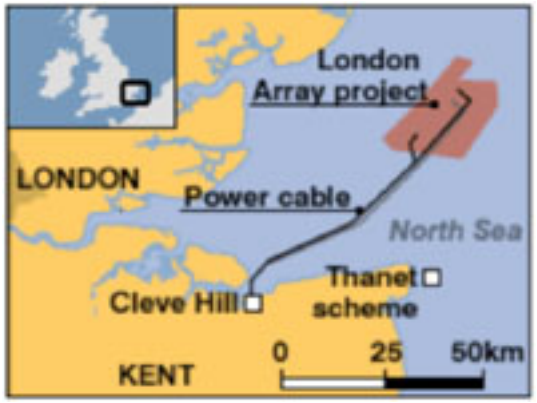


Bottom line: Wind

W. Bauer
Oct. 2013

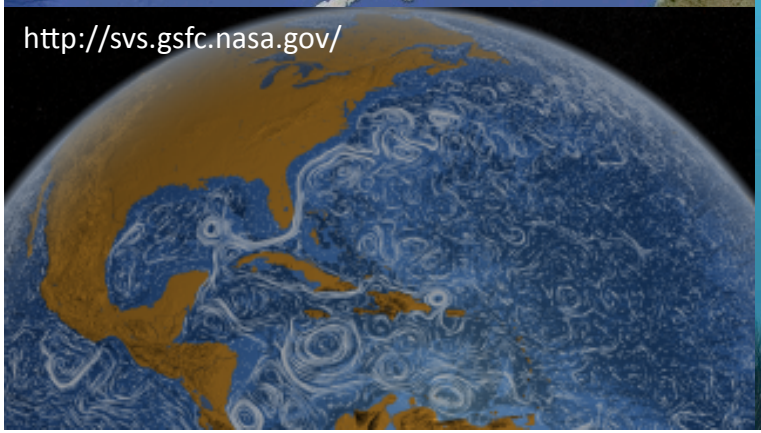
Most efficient: Offshore wind farms

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



Ocean Currents

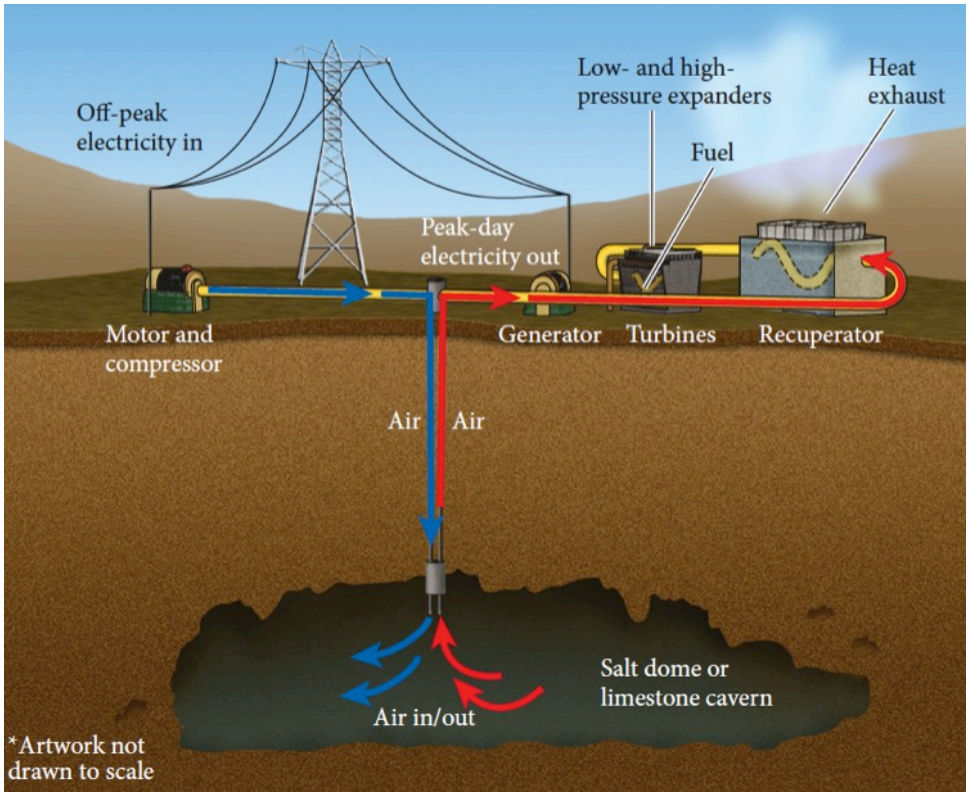
W. Bauer
Oct. 2013



- Sound of Islay, Orkney Islands, UK
- HS1000 sub-sea turbine
- 1 MW
- $11M
- (Almost) no intermittency
- Payoff time ~12 years (@10¢/kWh):

Energy Storage

W. Bauer
Oct. 2013



- Intermittent power sources need macroscopic energy storage
  - Pump-storage hydro
  - Compressed air caverns
  - Molten salt (high latent heat)

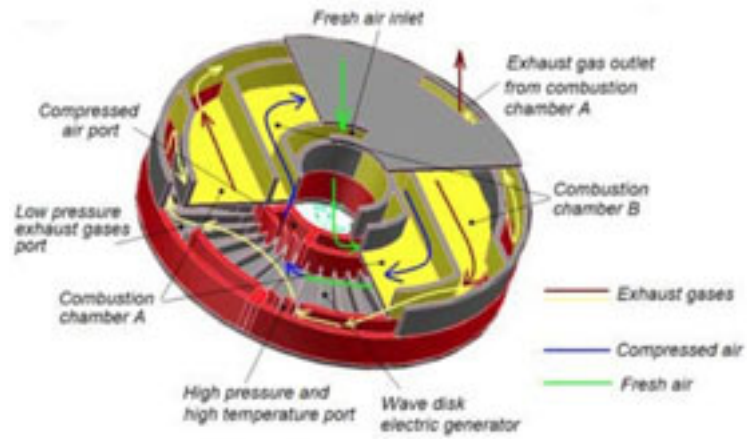
Really BIG Plans: DESERTEC

W. Bauer
Oct. 2013

Transportation

W. Bauer
Oct. 2013

- Public transport: Bus & train(!)
- More efficient engines
  (e.g. Norbert Müller's wave disk)
- Alternative fuels:
  - Ethanol (from sugar cane)
  - Methane
  - Hydrogen
- Hybrids with
  regenerative brakes
- Hybrid-electric
  (e.g. Chevy Volt)
- All-electric



Corn-Based Bio-Ethanol: Big Problems

- 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)

Best Deal?

W. Bauer
Oct. 2013

	MJ/L	kWh/gal	$/gal	$/kWh
Diesel	38.6	40.5	$3.649	0.090
Regular	34.8	36.5	$3.459	0.095
Premium	34.8	36.5	$3.659	0.100
E85	25.2	26.5	$3.099	0.117

E85 = 85% ethanol (23.5 MJ/L)
+ 15% regular gasoline

Cellulosic Bio-Ethanol

W. Bauer
Oct. 2013

- 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")

Transportation

W. Bauer
Oct. 2013

More than 13,000 yellow cabs in NYC transport ~250 million passengers/year!

2007 (Bloomberg): Switch to hybrids!

"My hybrid saves me more than $20 in gas each day"

Progress!
(Remember: ***E* = $**)

Time Square, NYC. Photo: Jessica Bauer

Transportation

W. Bauer
Oct. 2013

- Shanghai *CAPABUS*
  - Powered by 5 kF (!) super-capacitors, with regenerative brakes
  - Recharges quickly every 3-5 miles at bus stops
  - Saves estimated **$200,000** in fuel cost over lifetime (***E* = $**)

Don’t forget efficiency!

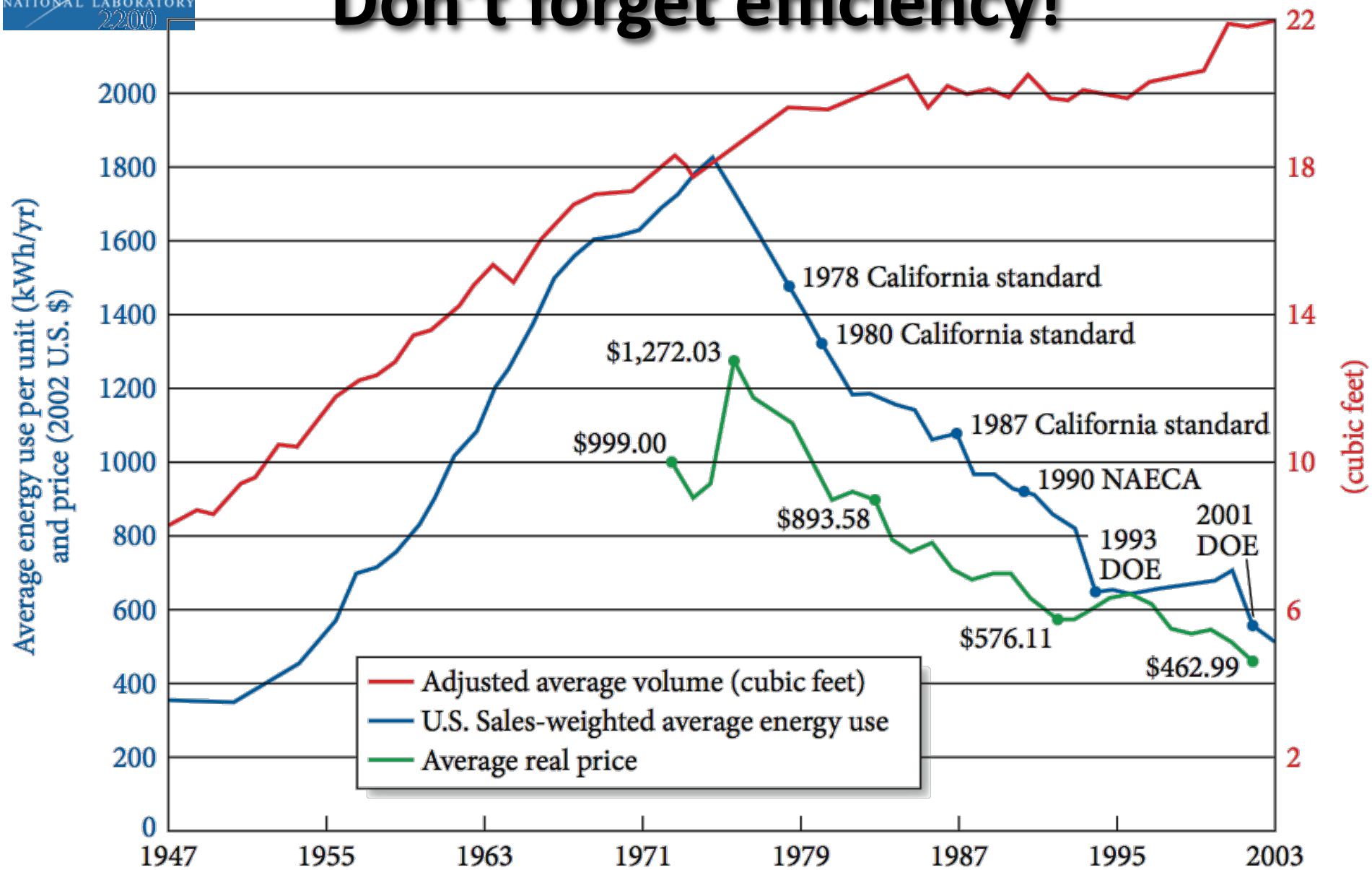


FIGURE 20.13 Average U.S. refrigerator volume (red line), price (green line), and energy use (blue line) from 1947 to 2003. (Original figure: Steve Chu)

Efficiency: Lighting

W. Bauer
Oct. 2013

LEDs: 130-170 lm/W (record as of April 2012: 254 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

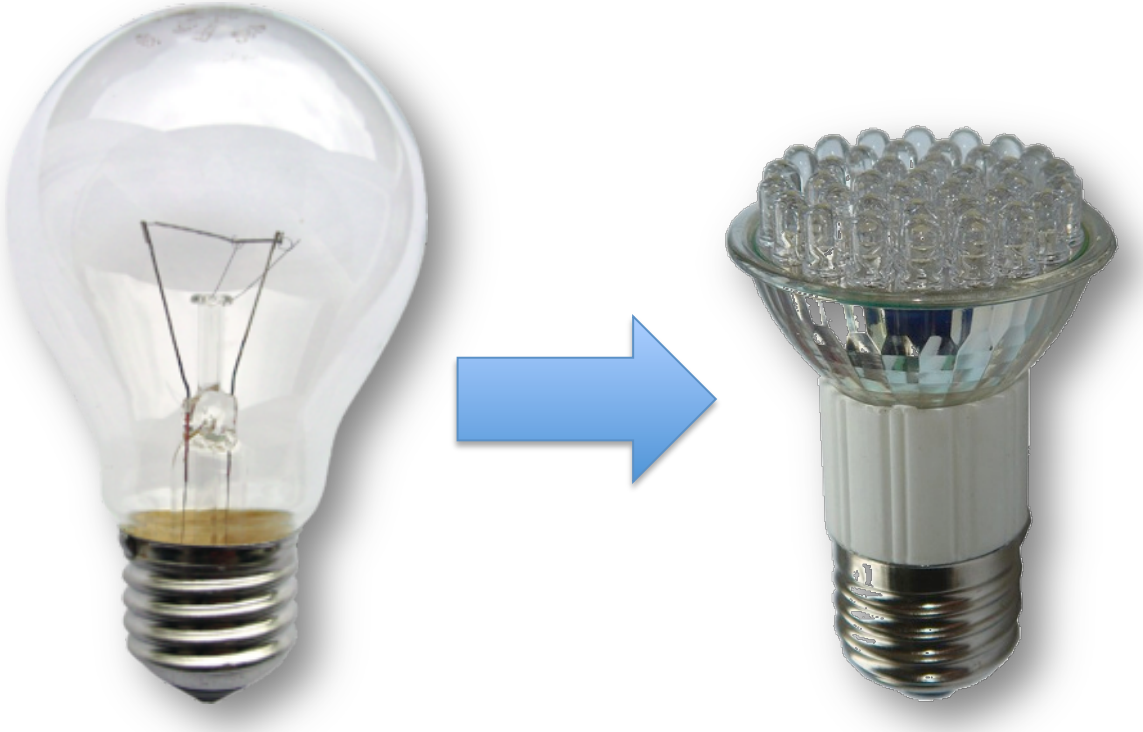
* http://www.cree.com/news-and-events/cree-news/press-releases/2012/april/120412-254-lumen-per-watt

Reducing Demand = Saving Money

W. Bauer
Oct. 2013

"A ~~penny~~ kWh saved is a ~~penny~~ kWh earned"

Benjamin Franklin (Jan.17, 1706 –Apr.17, 1790)



= up to $20 savings in electricity per year for a light left on overnight

W. Bauer
Oct. 2013

PART 4:

Biogas Power Plant

W. Bauer
Oct. 2013

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"**

W. Bauer
Oct. 2013

Raw material: Corn (whole plant)

W. Bauer
Oct. 2013

Biomass Consumption / Day

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

Mixer

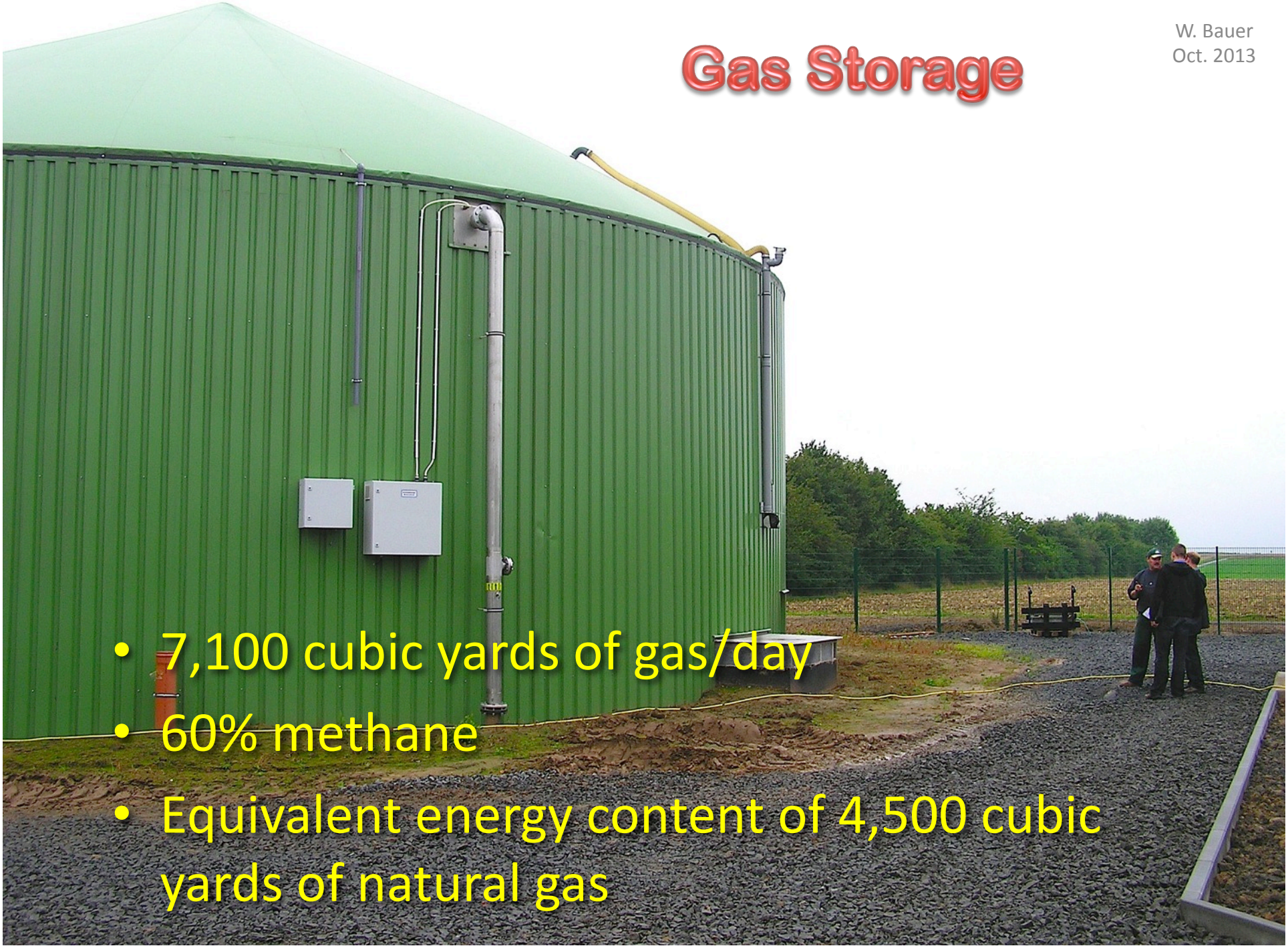
W. Bauer
Oct. 2013

Fermenter

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

W. Bauer
Oct. 2013

Gas Storage



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

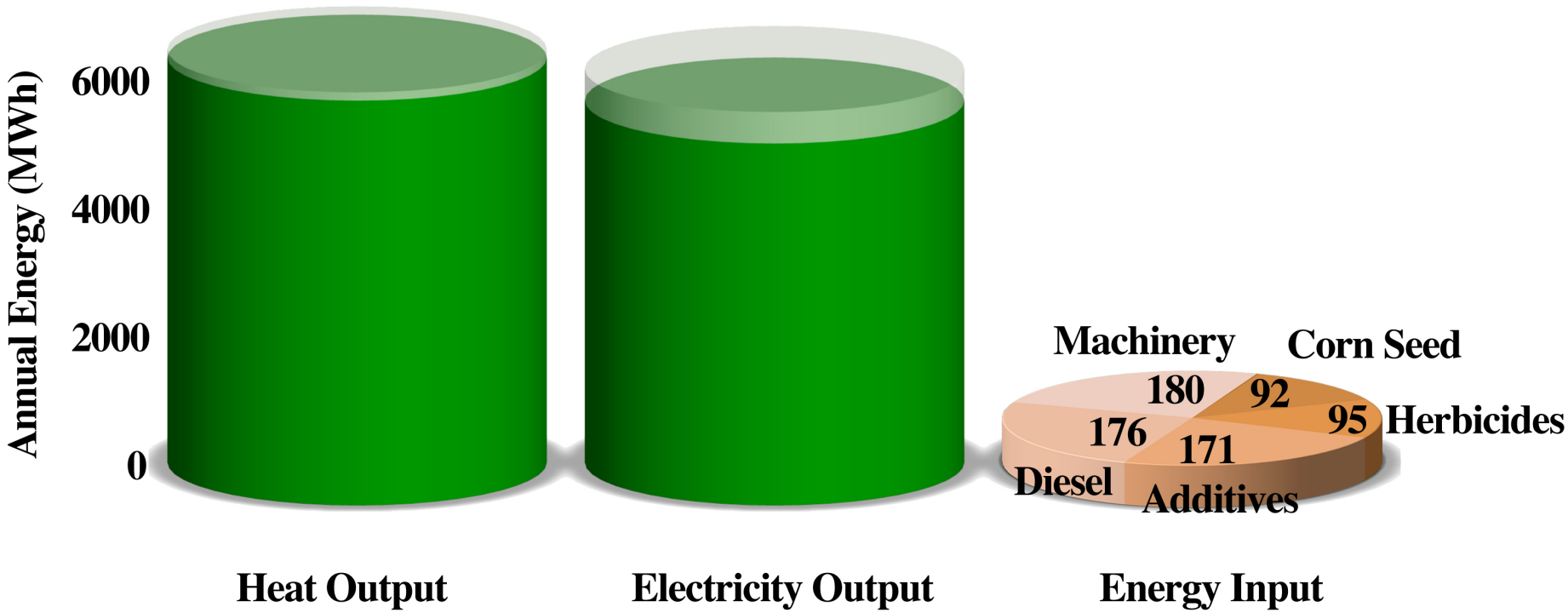
Generators (82% efficient)

W. Bauer
Oct. 2013

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

Energy Balance

W. Bauer
Oct. 2013

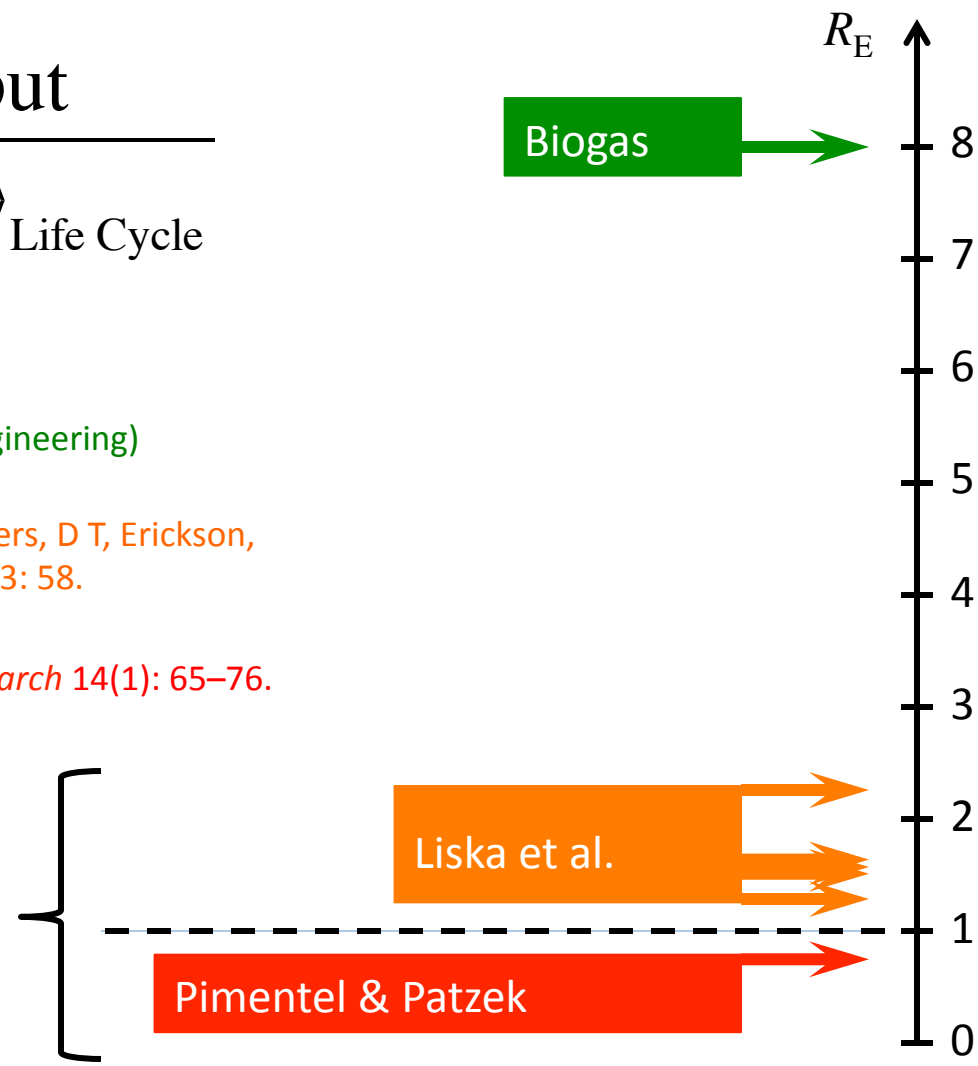


Factor **8** more electricity output than total energy input!
(comparison bioethanol: energy-out/energy-in [0.75,2.2])

Net Energy Ratio

W. Bauer
Oct. 2013

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



Bauer, W, (2013, to be published, J. Energy & Power Engineering)

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.

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

Bio-Ethanol from Corn

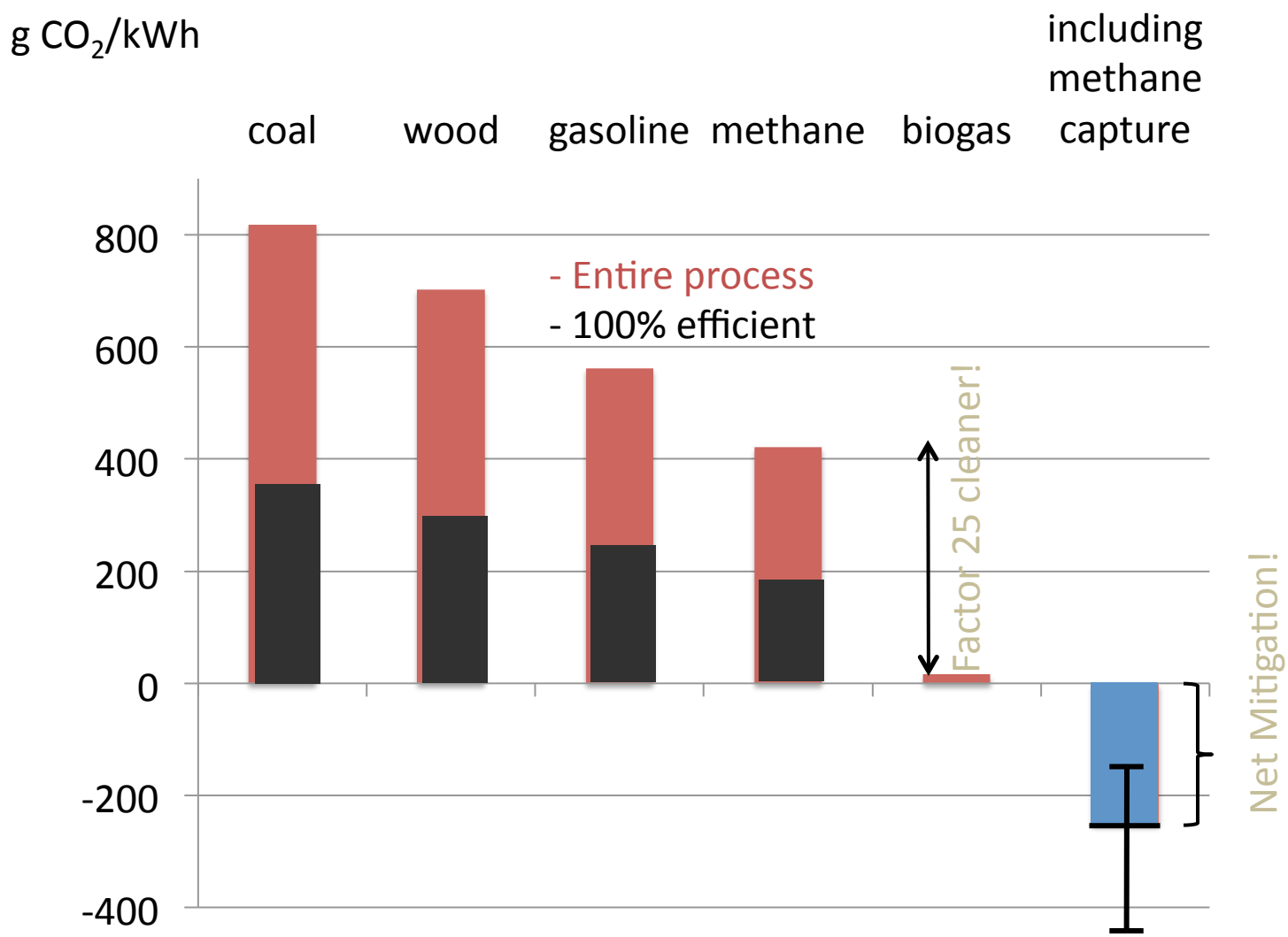
MW Biogas Power Plant: Bottom Line

W. Bauer
Oct. 2013

- Basic principle: grow corn, shred it, store in silo, then ferment in an anaerobic digester
- 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 co-generated thermal energy
- Payoff time (@10¢/kWh): 3-4 years
- NO INTERMITTENCY (can buffer wind/sun energy production with leverage factor 3-10)

Greenhouse Gas Balance

W. Bauer
Oct. 2013

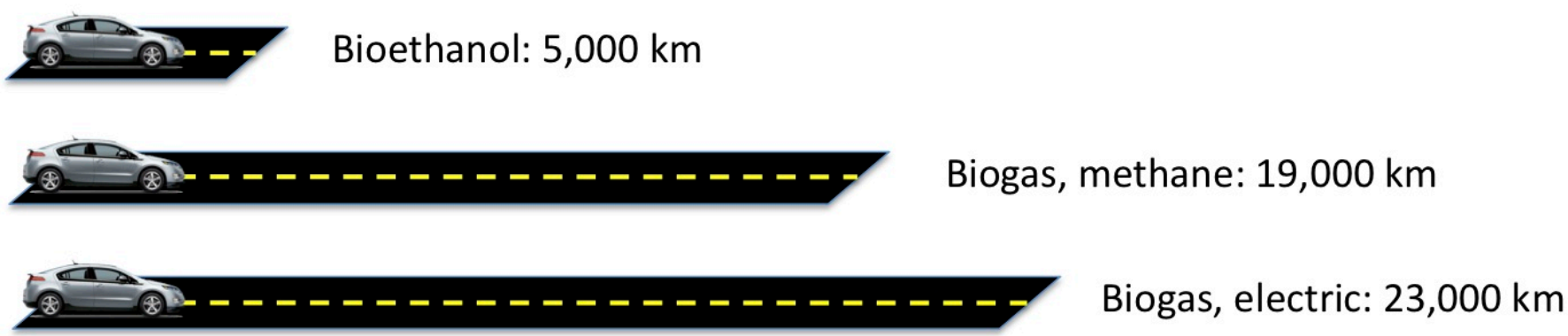


Methane is ~25 times more powerful greenhouse gas than CO_2
- our process prevents methane from cow dung to escape

Transportation Fuel

W. Bauer
Oct. 2013

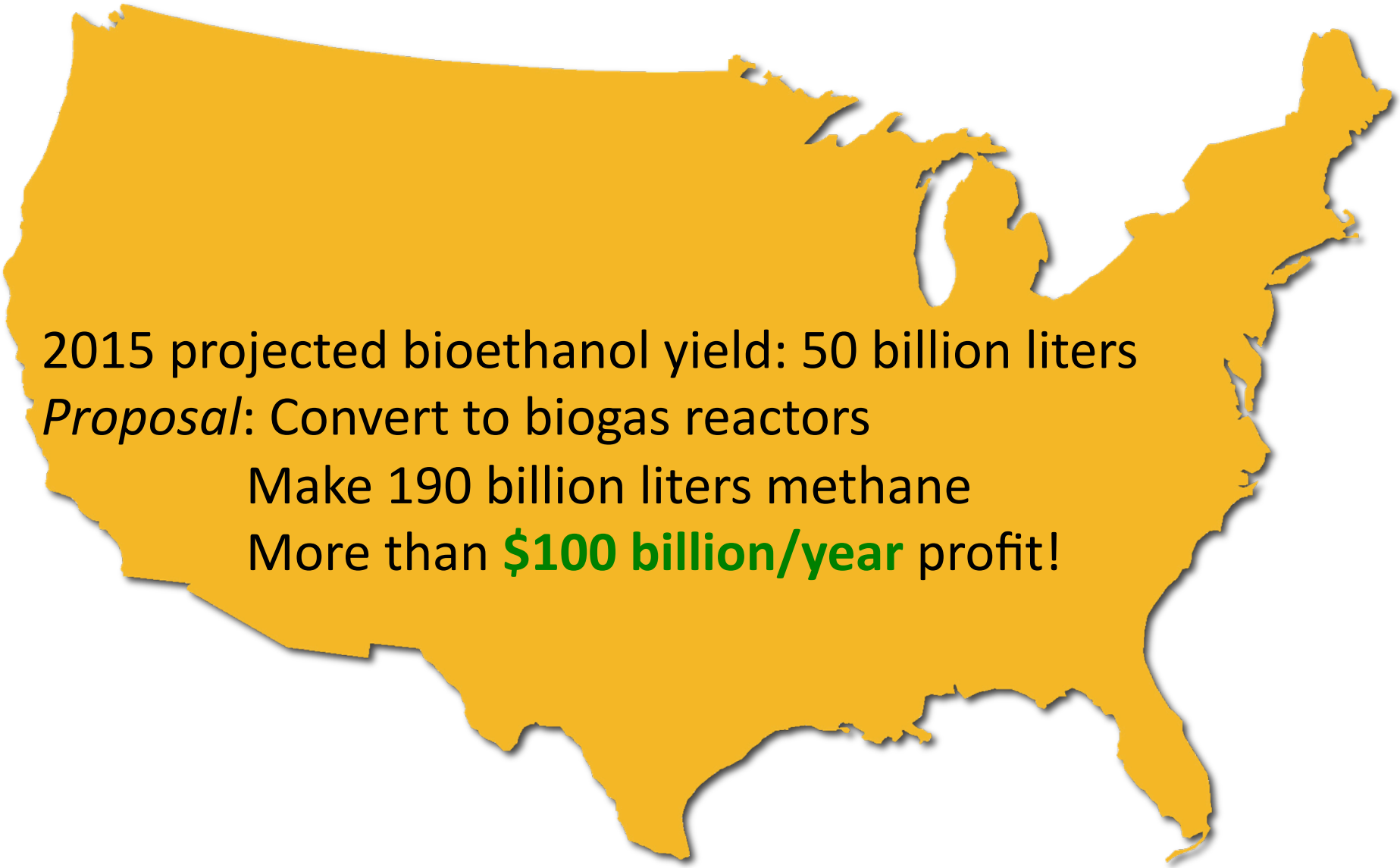
- Could produce 0.68 M liter of ethanol / year
  - Industry standard output from our corn yield on 150 ha
- Are producing 2.6 M liter of (liquid) CH_4 / year
- Factor of **3.8** better yield!
  (heat of combustion per liter almost identical for ethanol and methane, ~ 2/3 of gasoline)



Driving distance per hectare (numbers for Chevy Volt)

US Economic Impact

W. Bauer
Oct. 2013



2015 projected bioethanol yield: 50 billion liters

Proposal: Convert to biogas reactors

Make 190 billion liters methane

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

MSU Anaerobic Digester

W. Bauer
Oct. 2013

- Completed, Sep. 2013
- Research on better bacteria, plants, & processes

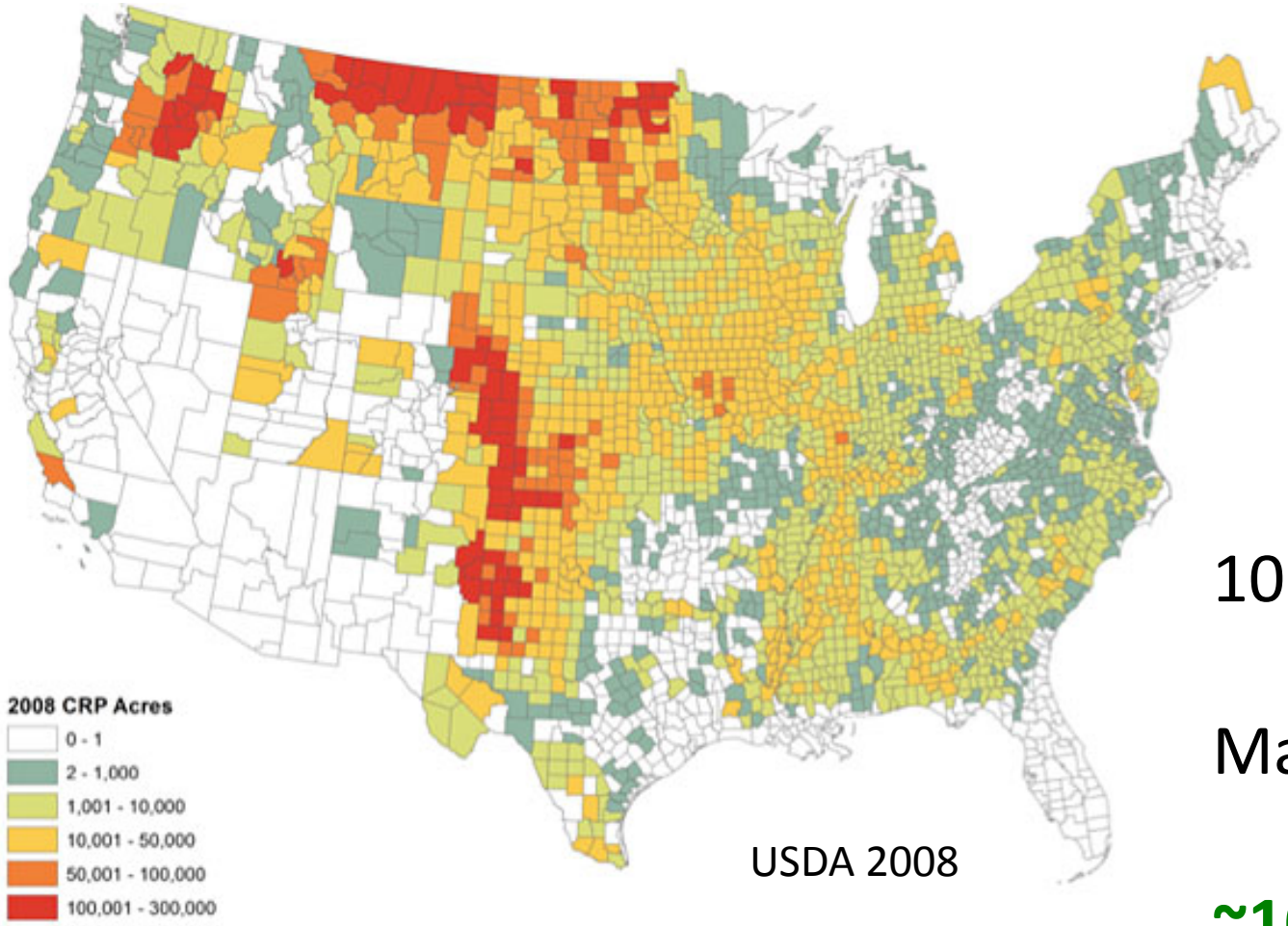
Biogas Cleaning

W. Bauer
Oct. 2013

- Remove CO_2 and HS with water spray jets
- Pipeline grade CH_4
- Consumes ~ 25% of biogas energy content
  - Need to heat water and liquefy methane
  - Latent heat ~ 1/10 of heat of combustion for methane
- Transportation fuel for < $2/gallon

Food vs. Fuel?
Conservation Reserve Program

W. Bauer
Oct. 2013



USDA 2008

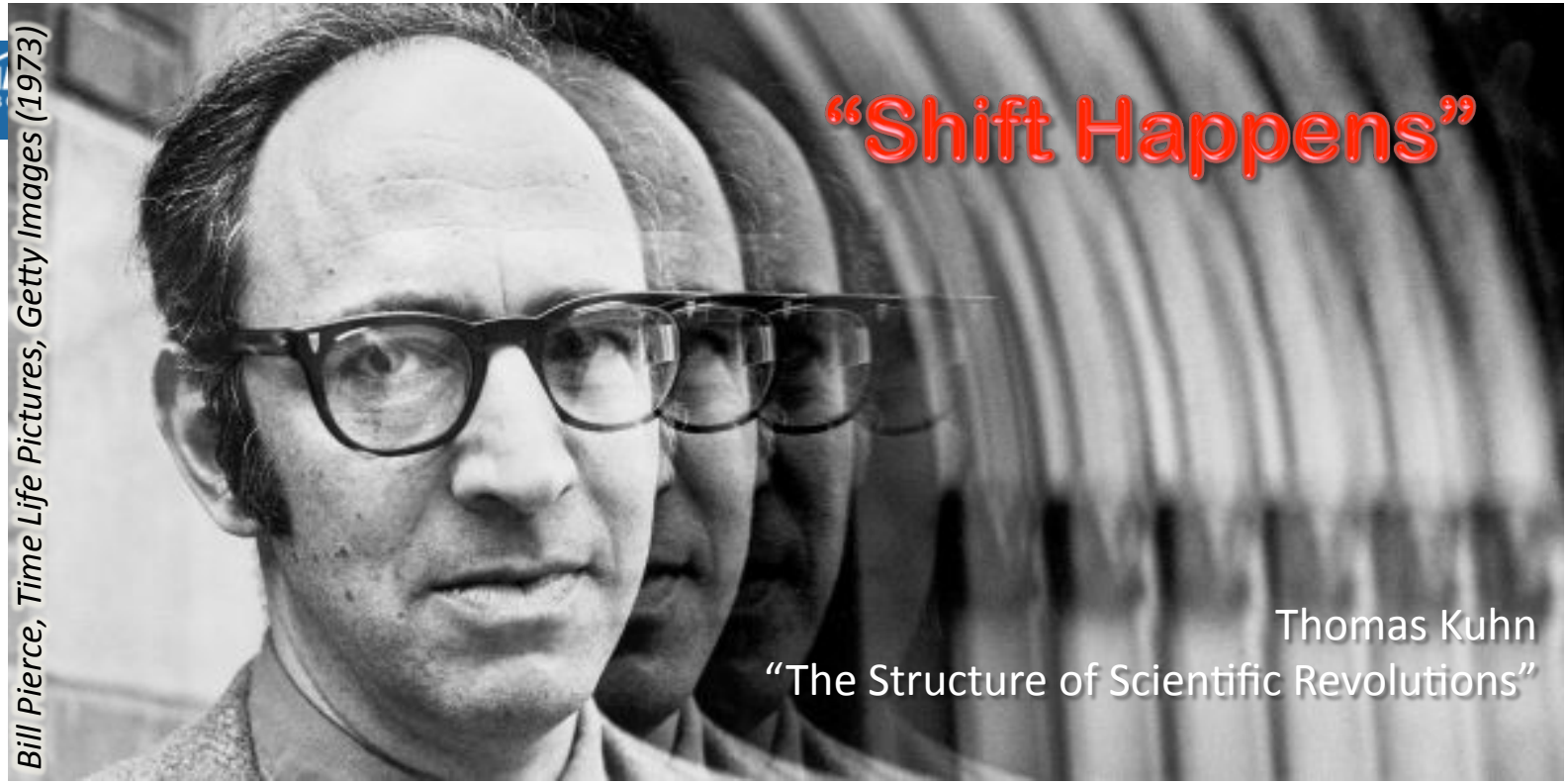
10 M hectare

Marginal land(?)

~100 GW potential

Summary:

Paradigm Shift



Bill Pierce, Time Life Pictures, Getty Images (1973)

- Scientist are in the business of solving interesting puzzles, not overthrowing paradigms
- Current paradigms dictate which puzzles are considered interesting
- Paradigms are shifted by new research results … *in scale-invariant steps, anywhere from evolution to revolution*
- Is it time for a new energy paradigm?

Previous Paradigm Shifts

W. Bauer
Oct. 2013

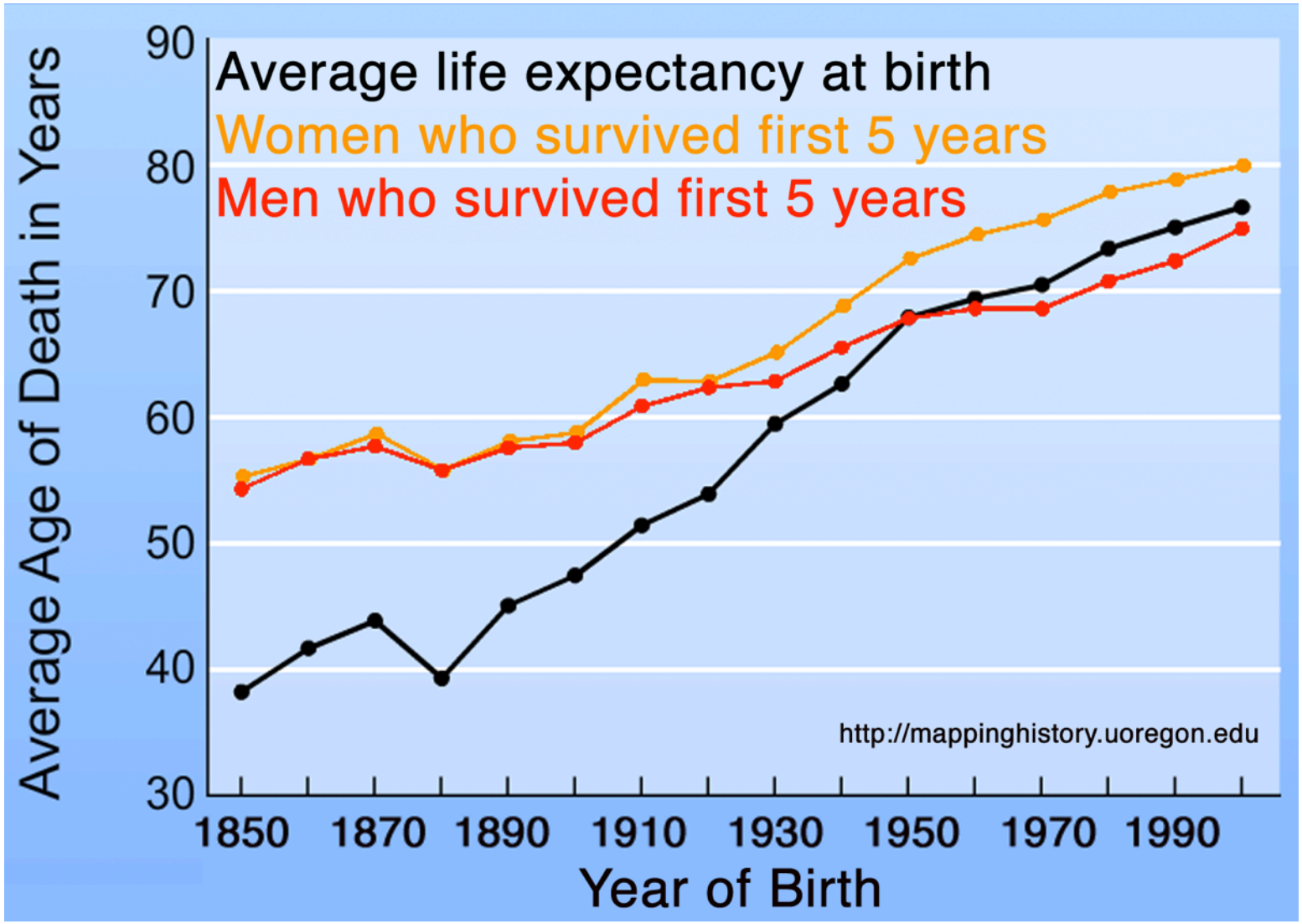
- "Outhouse to indoor plumbing" transition

  - Last 2 centuries … (even going on now in some parts of World)
  - Giant grid of millions of miles of pipes, connection every building to water treatment plants

- Was it worth the effort and expense?

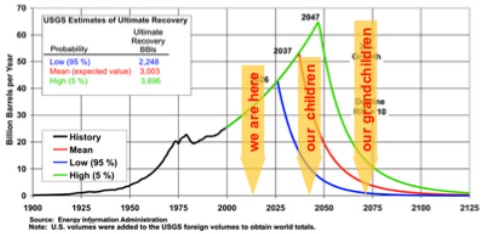
Life Expectancy

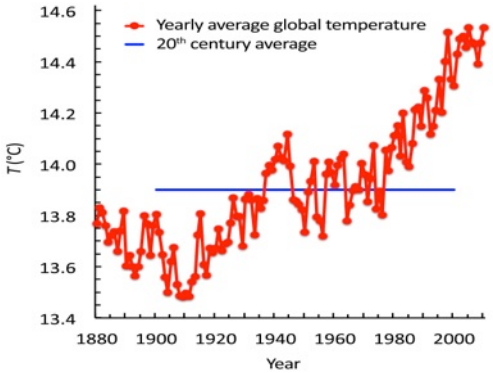
W. Bauer
Oct. 2013



Summary

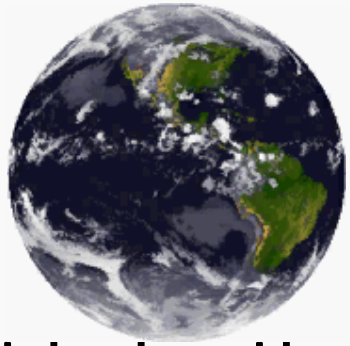
W. Bauer
Oct. 2013



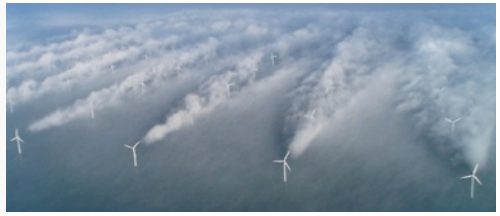


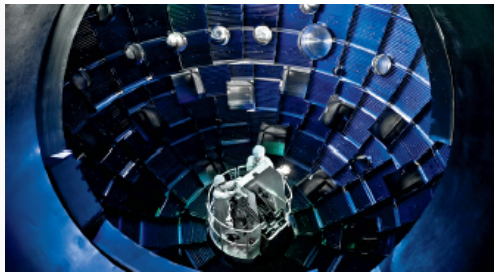
Biggest Opportunity of our Time:

- Replace ~ 14 TW of fossil fuel-based power
- Installation cost ~ $5/W
- ~**$70 trillion** economic growth opportunity!



… and it helps the planet!



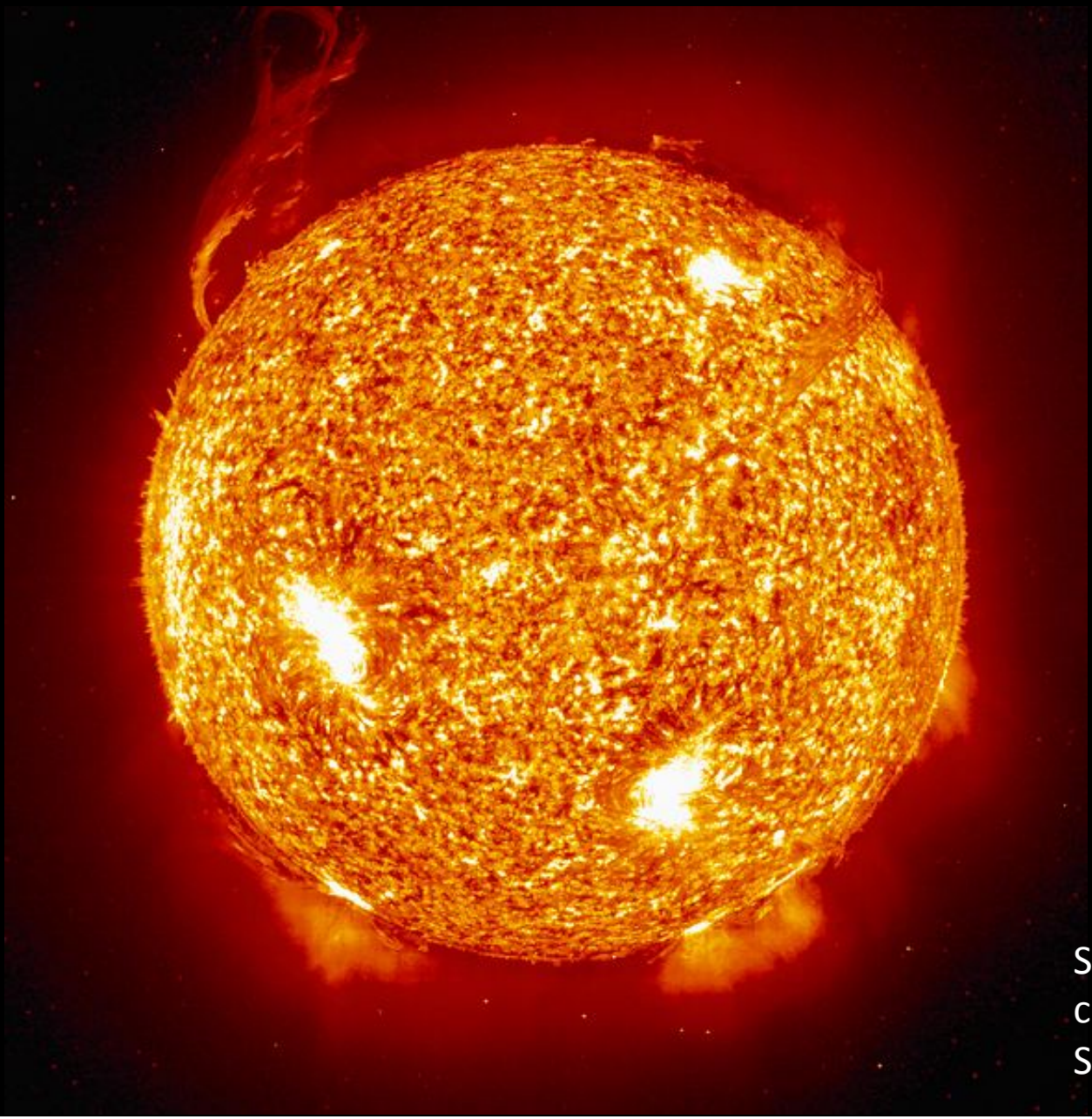


PART 5:

How Nuclear Physicists Can Help

Nuclear Power

W. Bauer
Oct. 2013

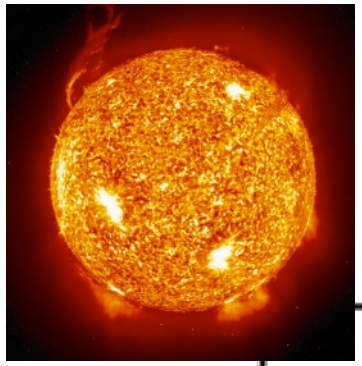


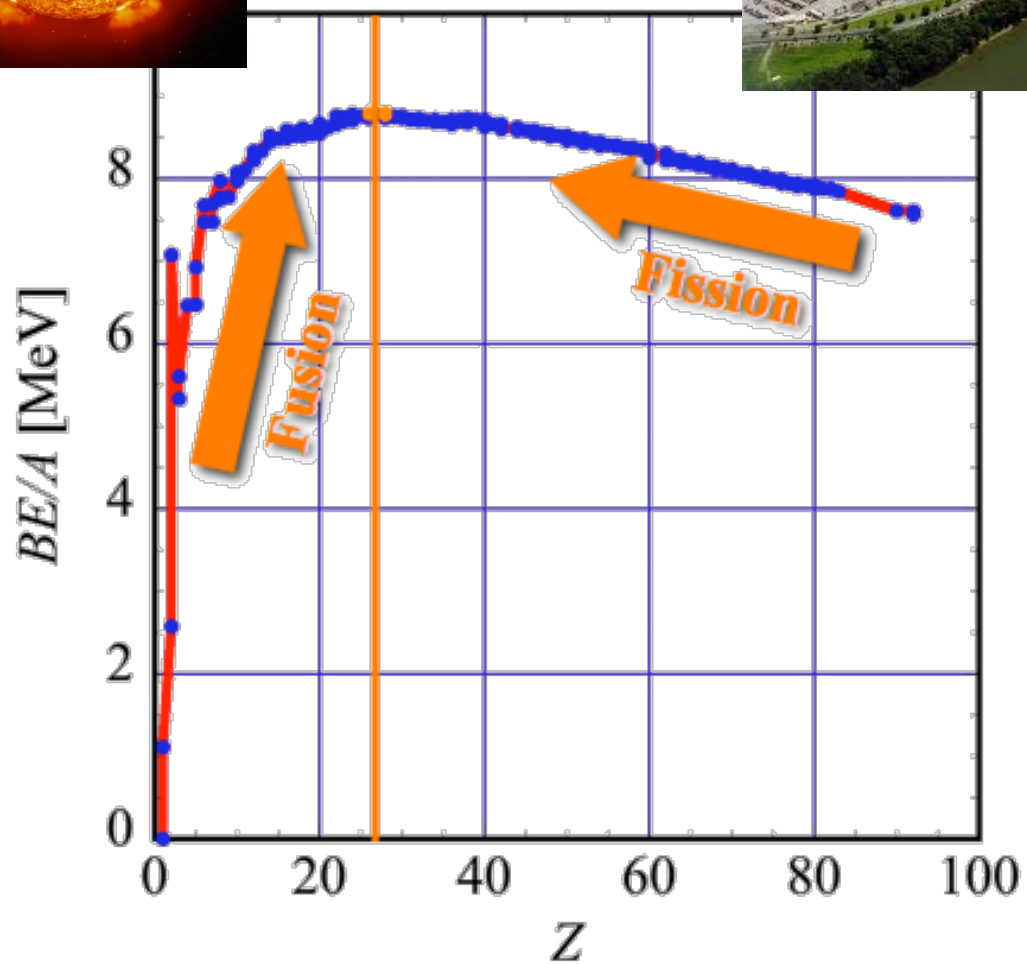
Sun at 30.4 nm
credit:
SOHO, NASA

Nuclear Power

W. Bauer
Oct. 2013

- Back to $E = mc^2$
- Nucleus made of Z protons and N neutrons
- $M_{\text{nucleus}} < Zm_p + Nm_n$
- Binding energy!





Nuclear Power

W. Bauer
Oct. 2013

- Typical chemical reaction

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

  - Heat of combustion: 802 kJ/mol
  - $\Delta E/mc^2 = 802\ \text{kJ}/[(0.08\ \text{kg})(3\cdot 10^8\ \text{m/s})^2] = 10^{-10}$

- Typical nuclear fission reaction

$$n + {}^{235}_{92}\text{U} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3n$$

  - $\Delta E/mc^2 = 173.3\ \text{MeV}/219{,}882\ \text{MeV} = 8\cdot 10^{-4}$

Ratio ~10^7

Wikipedia

~

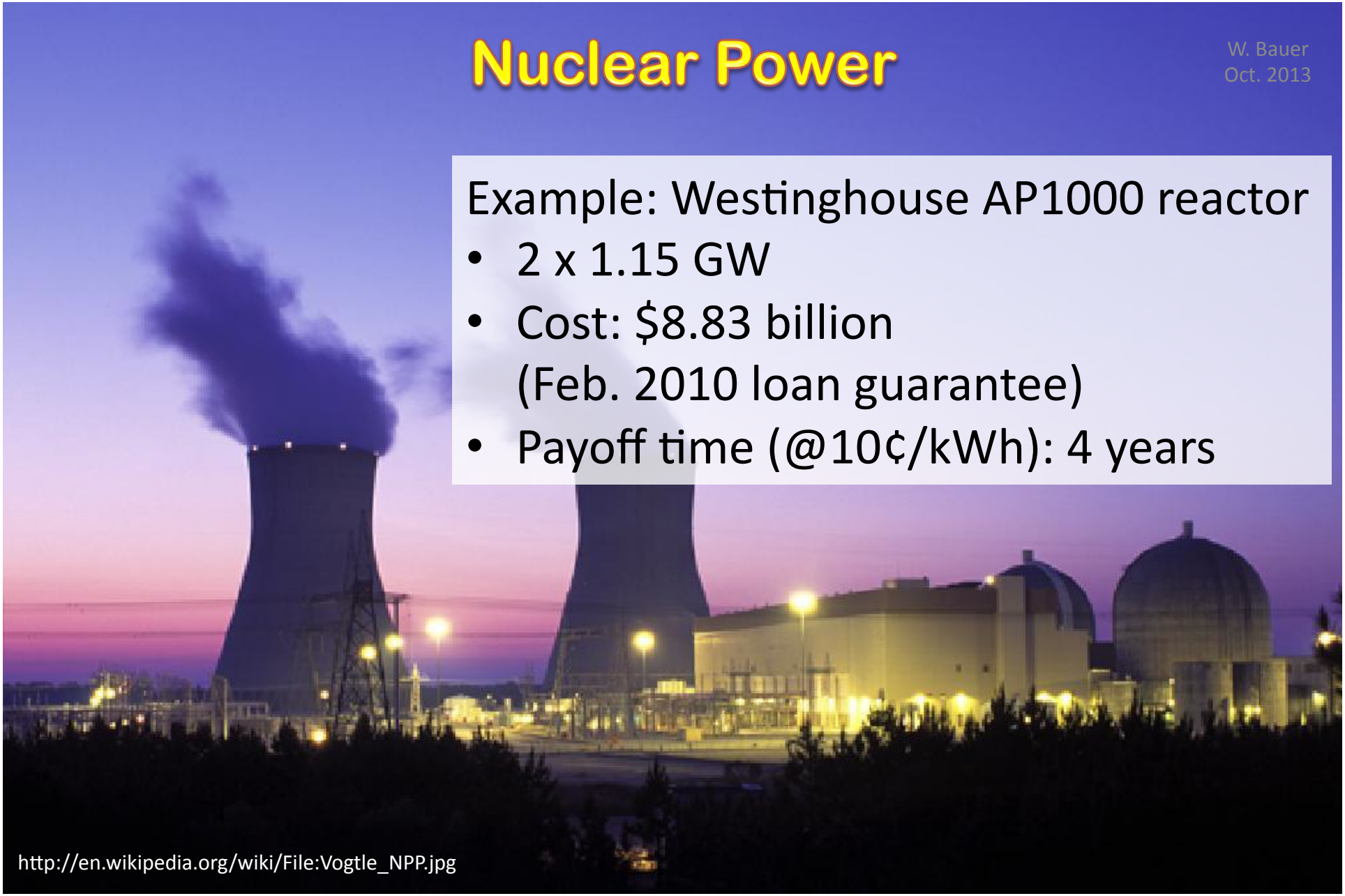
Wikipedia

Nuclear Power

W. Bauer
Oct. 2013

Example: Westinghouse AP1000 reactor

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



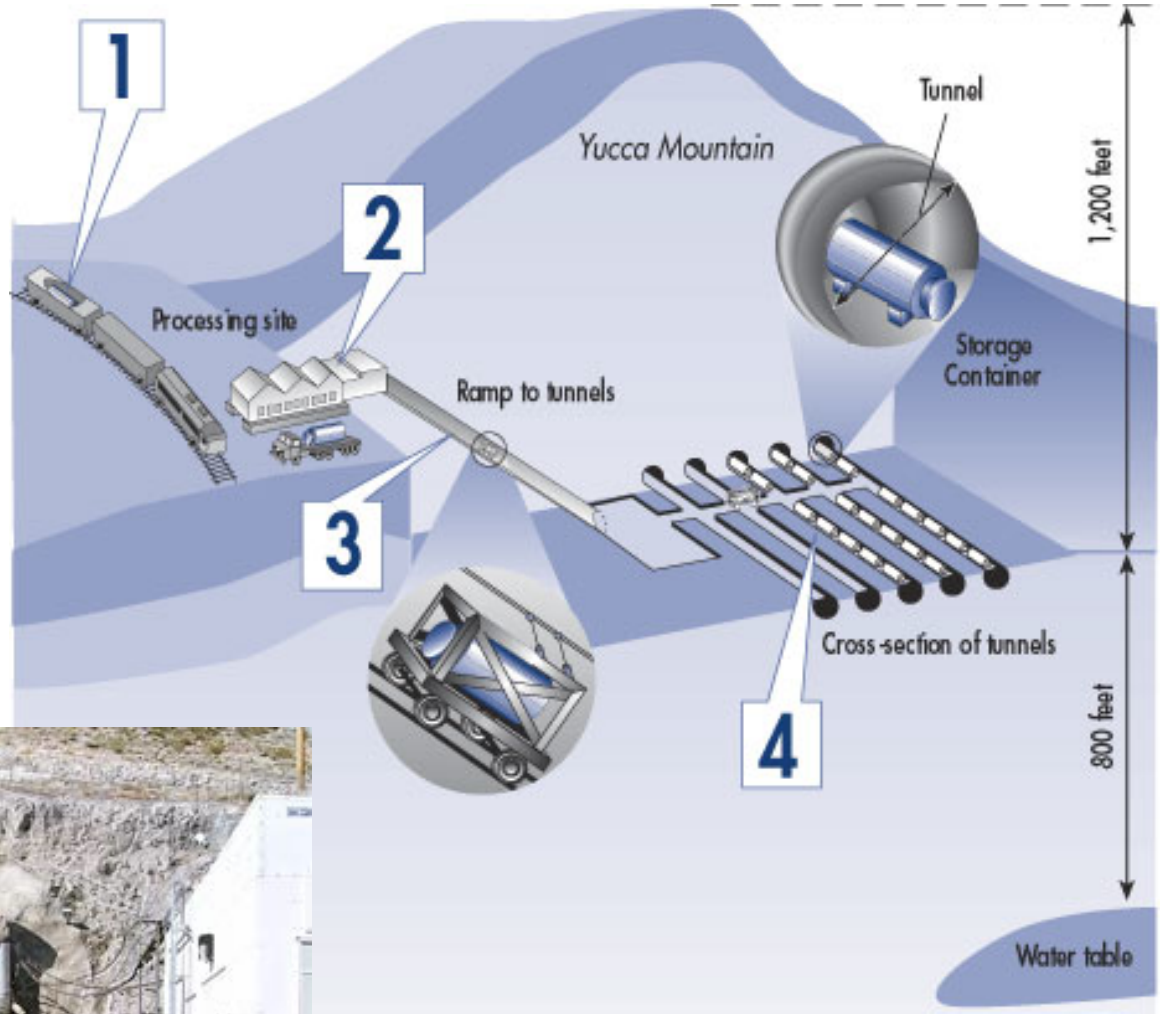
http://en.wikipedia.org/wiki/File:Vogtle_NPP.jpg

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

Problems with Nuclear Fission

W. Bauer
Oct. 2013

- Really big waste storage problems



Problems with Nuclear Fission

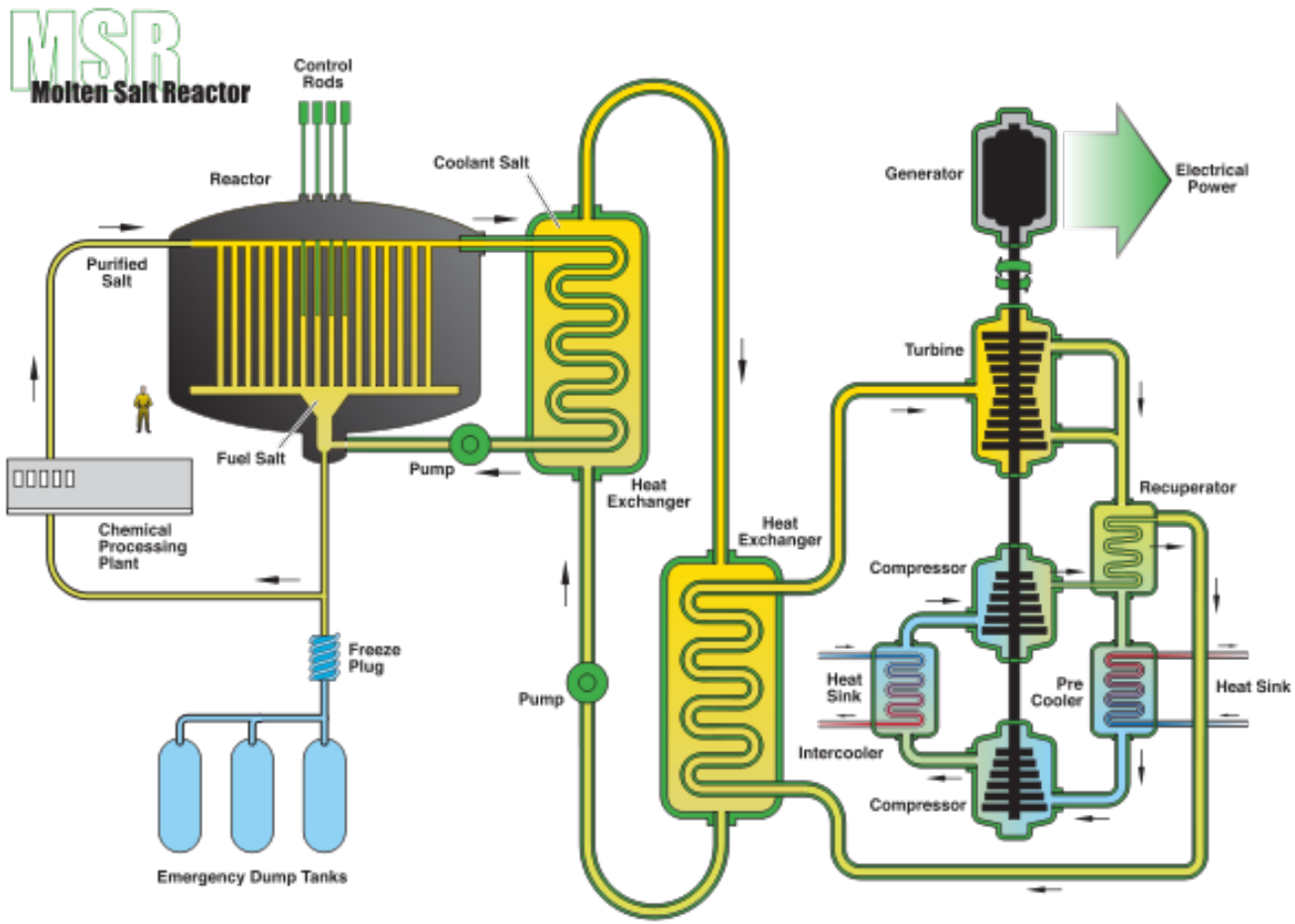
W. Bauer
Oct. 2013

- Potential for really big accidents

Better Nuclear Fission

W. Bauer
Oct. 2013

- Better reactor design
  - Generation IV reactors
  - Subcritical Accelerator-Driven System (?)
  - Molten salt reactor (?)
- Less waste
  - Breeder (?)
- Better fuel
  - Thorium (?)



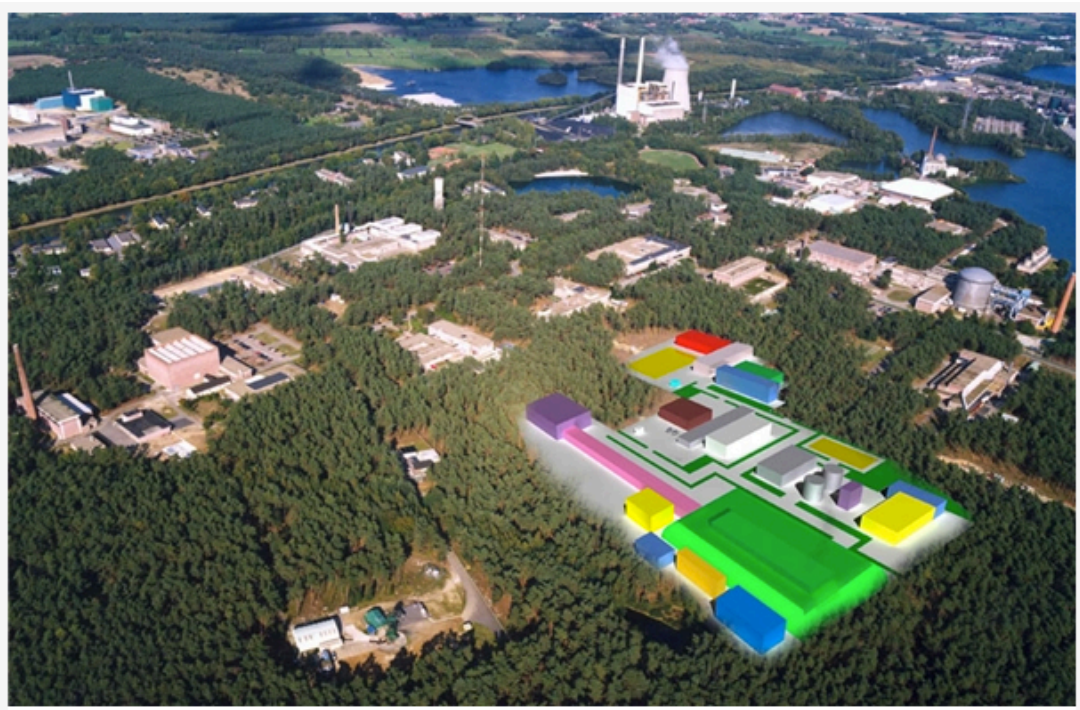
US Department of Energy Nuclear Energy Research Advisory Committee

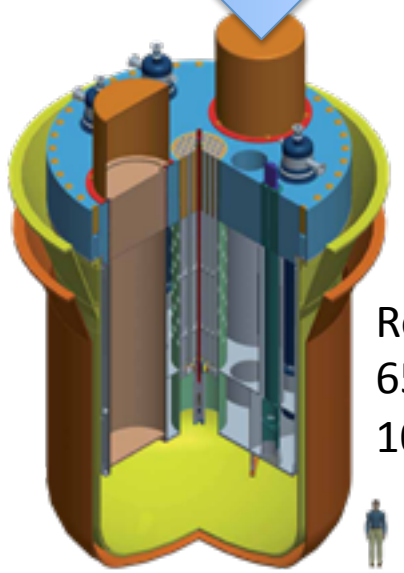
Accelerator-Driven System (ADS)

W. Bauer
Oct. 2013

- Example: MYRRHA reactor (Belgium)
  - MOX fuel
  - M€960
  - To be operational in 2023

600 MeV, 4 mA, proton





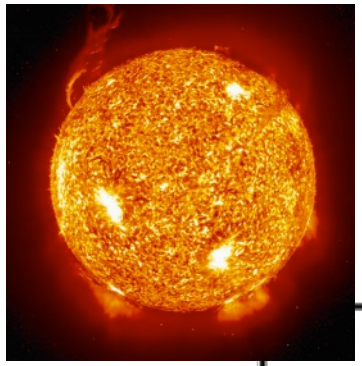
Reactor
65 MWth subcr.
100 MWth crit.

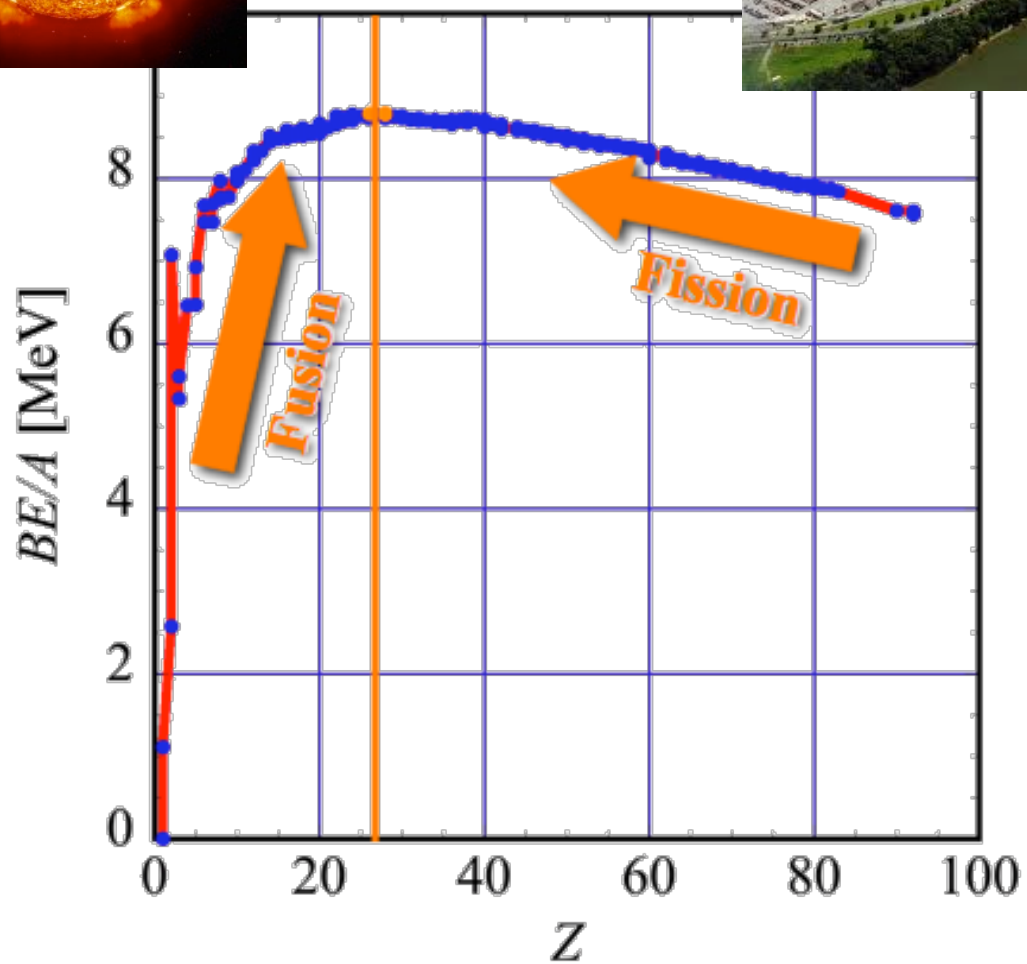
http://myrrha.sckcen.be/

Nuclear Power

W. Bauer
Oct. 2013

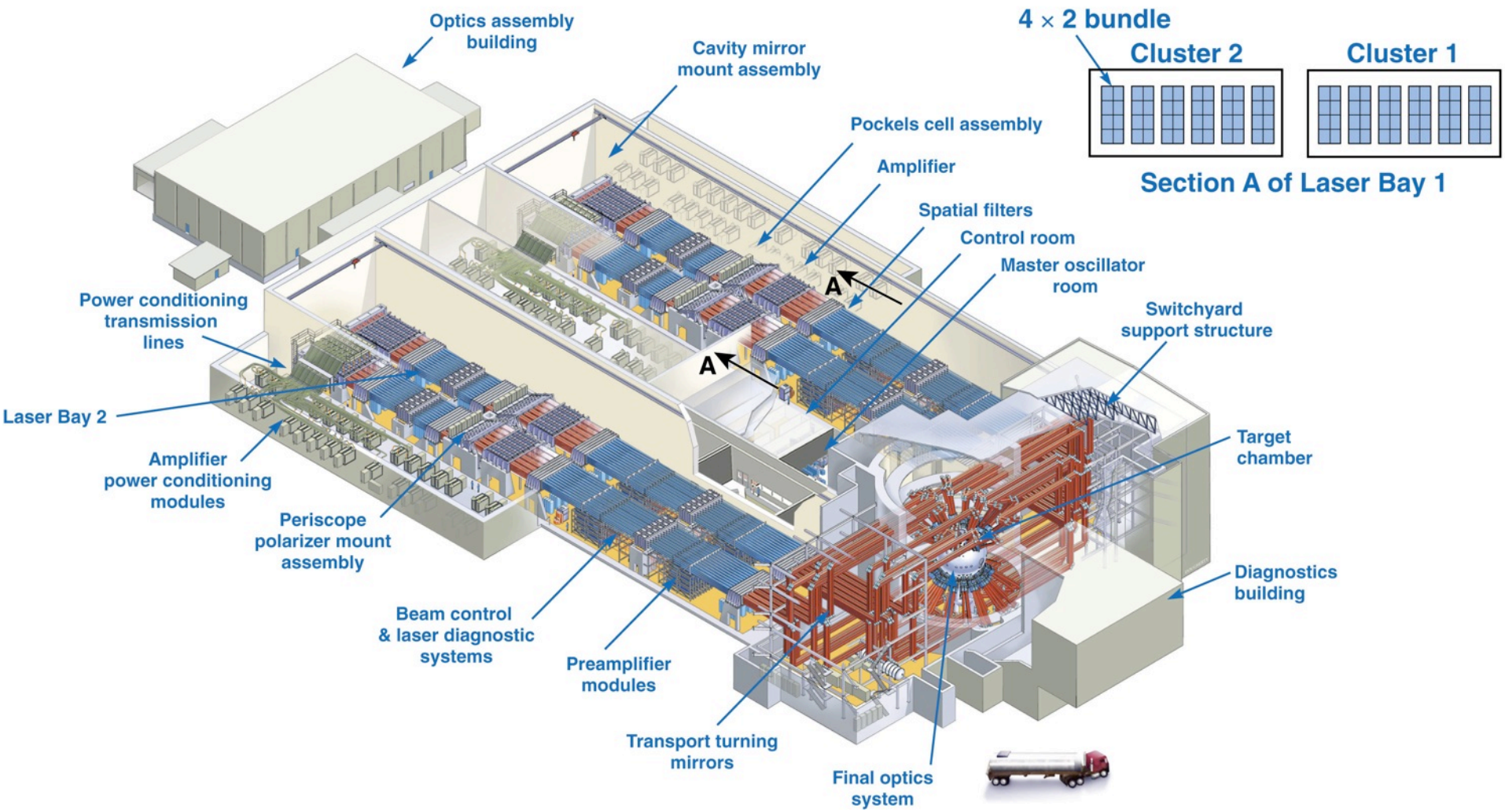
- Back to $E = mc^2$
- Nucleus made of Z protons and N neutrons
- $M_{\text{nucleus}} < Zm_p + Nm_n$
- Binding energy!

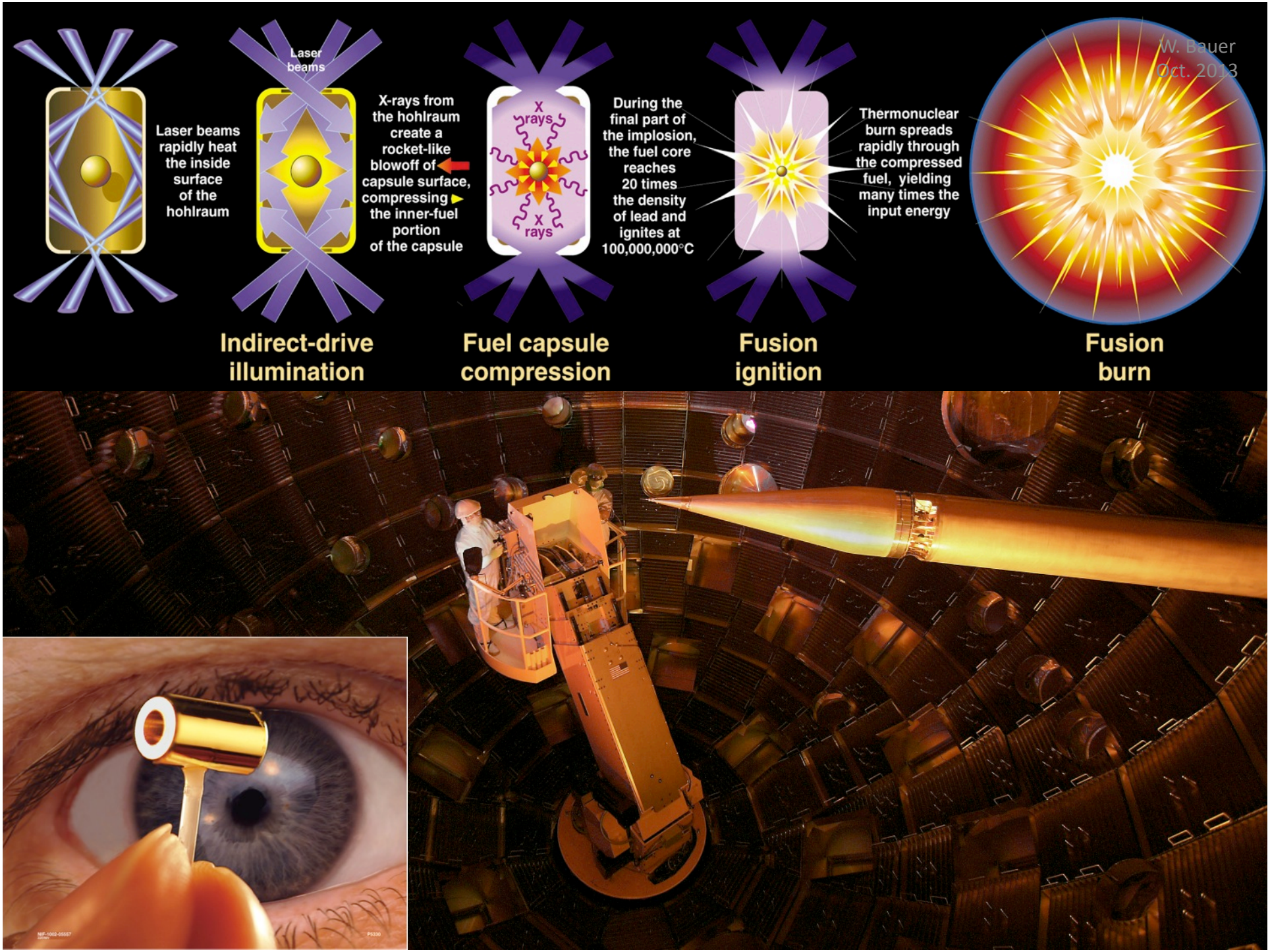




NIF

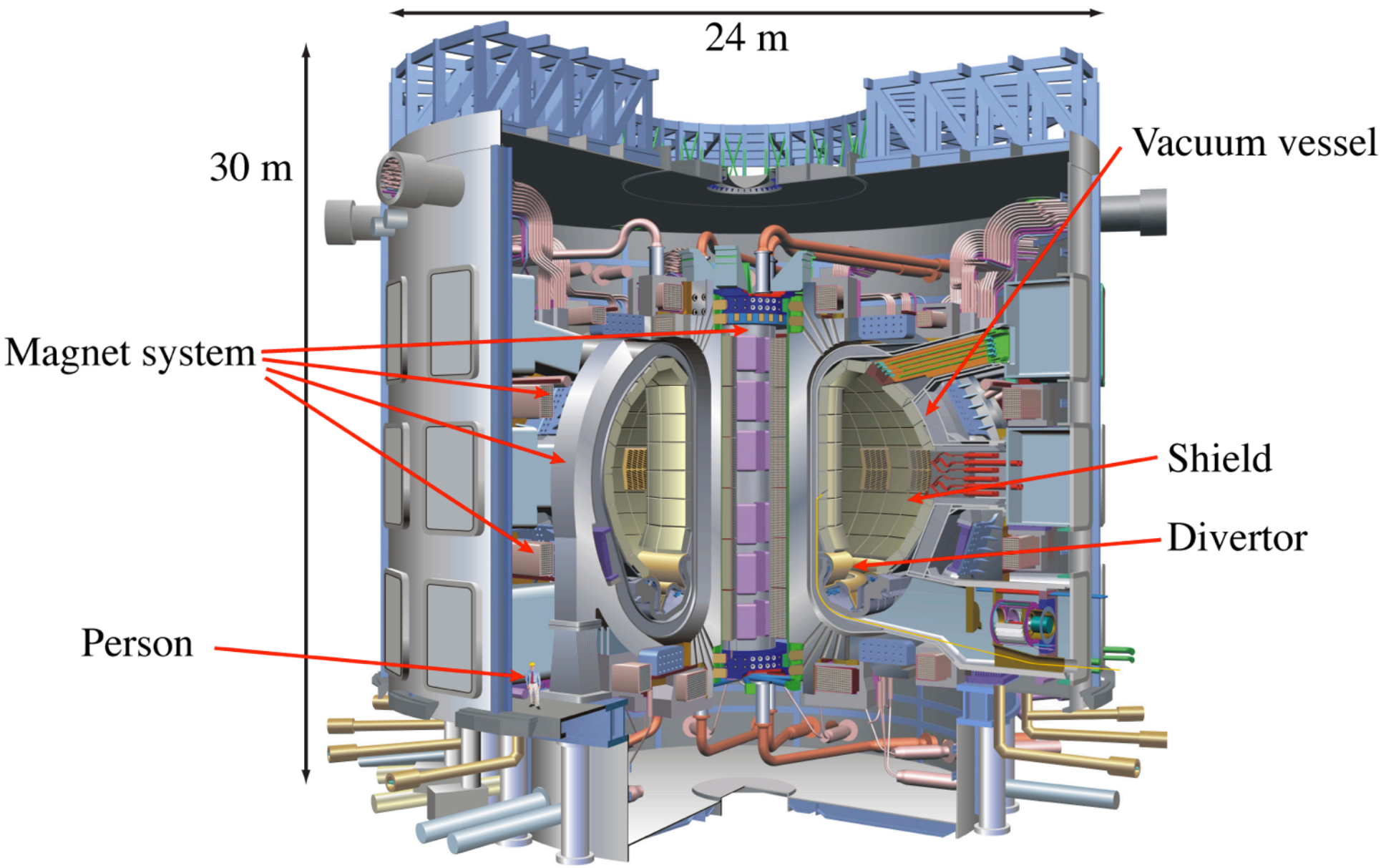
W. Bauer
Oct. 2013

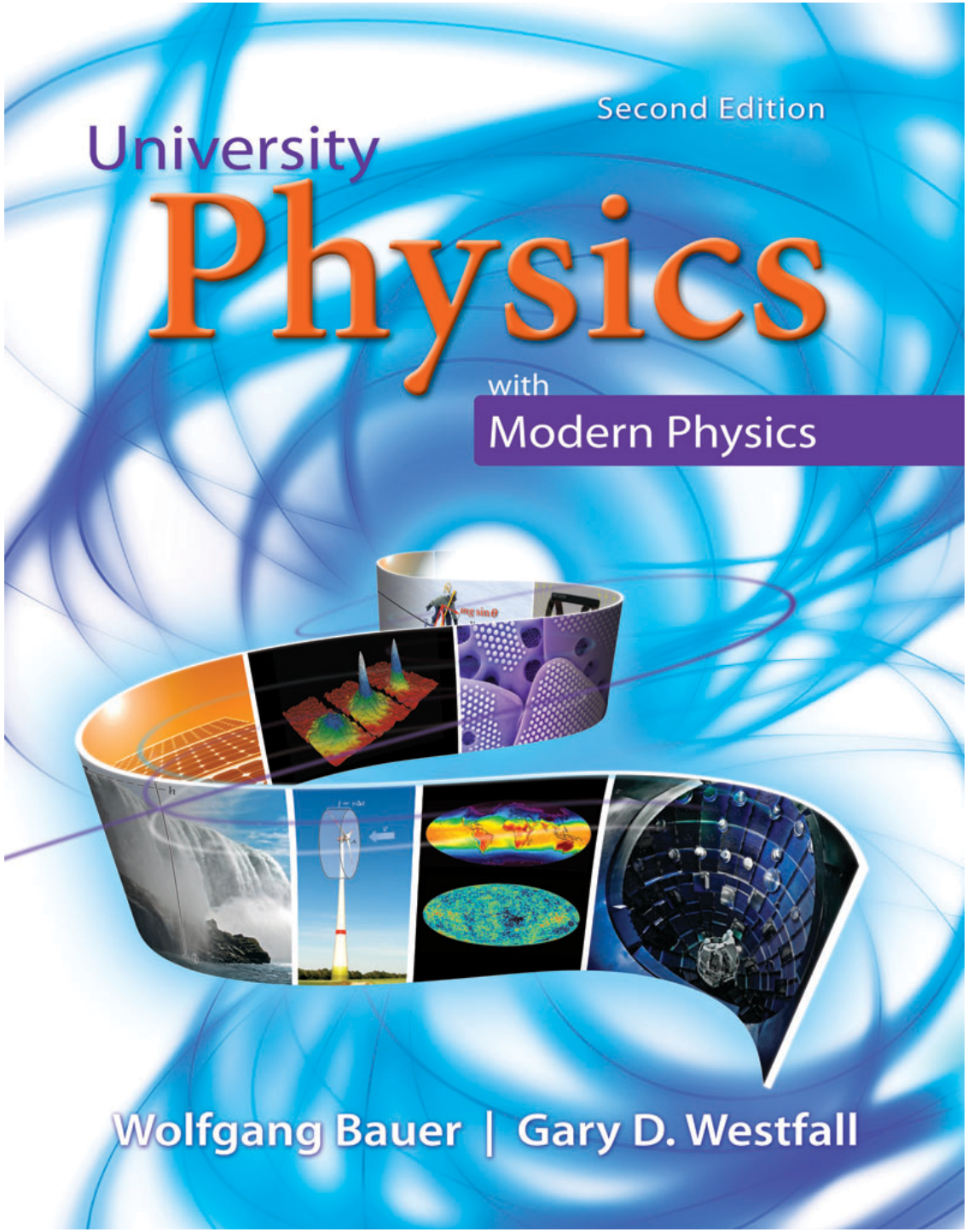



W. Bauer
Oct. 2013
Laser beams rapidly heat the inside surface of the hohlraum
Laser beams
X-rays from the hohlraum create a rocket-like blowoff of capsule surface, compressing the inner-fuel portion of the capsule
X rays
X rays
During the final part of the implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy
Indirect-drive illumination
Fuel capsule compression
Fusion ignition
Fusion burn

ITER

W. Bauer
Oct. 2013



BROOKHAVEN NATIONAL LABORATORY

W. Bauer
Oct. 2013