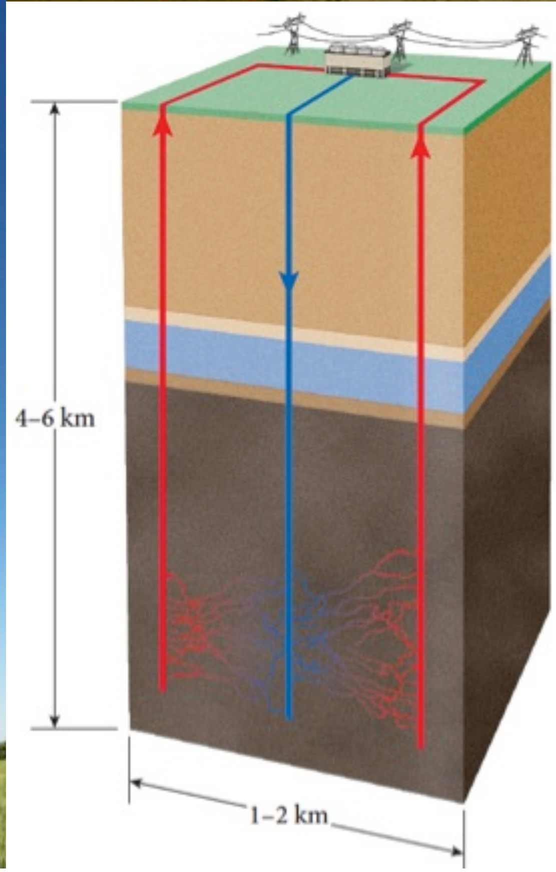
Bio-fuels: What works?



Wolfgang Bauer
Michigan State University

Preamble: Fearlessness

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PHYSICAL REVIEW B VOLUME 38, NUMBER 13 1 NOVEMBER 1988

Simulation of vacancies in a two-dimensional Ising antiferromagnet

W. Bauer and S. E. Koonin
W. K. Kellogg Radiation Laboratory 106-38, California Institute of Technology, Pasadena, California 91125
(Received 28 March 1988)

We present simulations of one- and two-vacancy states in a two-dimensional square-lattice Ising antiferromagnet. We find that the energy of the single-vacancy ground state scales as $J^{2/3}$, where J is the spin-spin coupling. The S- and P-wave states of two vacancies are bound, with binding energy $\mathcal{E} \propto J^{2/3}$ and J, respectively, while the D-wave state is unbound.

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Steven E. Koonin is chief scientist for BP, London, UK. He is a theoretical physicist from the California Institute of Technology, Pasadena, CA, USA, where he also served as provost from 1995 to 2004. E-mail: Steven.Koonin@uk.bp.com

EDITORIAL

Getting Serious About Biofuels

ALTHOUGH RUDOLF DIESEL IMAGINED THAT HIS EPONYMOUS ENGINE WOULD BE FUELED BY VEGETABLE oils, the widespread availability of inexpensive petroleum during the 20th century determined otherwise. The world is now seriously revisiting Diesel's vision, driven by surging global oil demand, the geographical concentration of known petroleum reserves, the increasing costs of finding and producing new reserves, and growing concerns about atmospheric greenhouse gas (GHG) concentrations.

Liquid hydrocarbons are well suited for transport uses because of their high energy density and handling convenience. Although fossil fuels will be required and available for many decades, producing supplementary fuels from biomass can simultaneously address three important societal concerns without requiring substantial modification of existing vehicles or of the fuel distribution infrastructure: security of supply (biofuels can be produced locally in sustainable systems), lower net GHG emissions (biofuels recycle carbon dioxide that was extracted from the atmosphere in producing biomass), and support for agriculture.

The 2% of today's transportation fuels derived from biomass and blended with fossil fuels are produced either by the fermentation to ethanol of food-derived carbohydrates (such as cane sugar or cornstarch) or by the processing of plant oils to produce biodiesel. Unfortunately, current practices based on food production models do not maximize energy or GHG benefits (because they use fossil fuels) and are not economically competitive with fossil fuels at today's energy prices.* Nevertheless, many nations (including the United States, European Union, and India) are expecting that some 5% of their road fuels will be bioderived within the next 5 years.

Credible studies show that with plausible technology developments, biofuels could supply some 30% of global demand in an environmentally responsible manner without affecting food production. To realize that goal, so-called advanced biofuels must be developed from dedicated energy crops, separately and distinctly from food. This is a multidisciplinary task in which biologists, agronomists, chemical engineers, fuel specialists, and social scientists must work to integrate and optimize several currently disjoint activities.

There are major technological challenges in realizing these goals. Genetic improvement of energy crops such as switchgrass, poplar, and jatropha has barely begun. It will be important to increase the yield and environmental range of energy crops while reducing agricultural inputs. Plant development, chemical composition, tolerance of biotic and abiotic stresses, and nutrient requirements are important traits to be manipulated. The combination of modern breeding and transgenic techniques should result in achievements greater than those of the Green Revolution in food crops, and in far less time.

The cost of biomass transport determines the supply area of a biofuels processing facility and thus its scale and economics. But unlike most food crops, there is no need to keep biomass intact. That means that in-field densification, pelletization, drying, and pyrolysis are among the technology opportunities to reduce transport costs. Fuel production from the lignocellulosic component of biomass will be a very important improvement. Its particular challenges of chemical recalcitrance and utilization of the constituent sugars to produce optimal fuel molecules and co-products are not intractable to current biotechnology. Similarly, process integration comparable to that of a modern petroleum refinery is a plausible chemical engineering goal.

Intertwined with the technology of large-scale biofuels production are the social and policy issues. The balances between natural vegetation and cultivation, arable and marginal land use, mechanized agriculture and employment opportunities, and food and energy crops will be important matters of discussion in many different forums. Whatever the outcomes, technologies will have to be sufficiently robust to accommodate a diversity of needs around the globe.

There is substantial technology "headroom" for advanced biofuels to enhance energy security, reduce GHG emissions, and provide economical transport. It exists largely because the world's scientific and engineering skills have not yet been focused coherently on the challenges involved. It is now time to do that through a coordination of government, university, and industrial R&D efforts, facilitated by responsible public policies. In the jargon of the petroleum industry, the "size of the prize" is too large to ignore.

—Steven E. Koonin

10.1126/science.1124886

*Brazil is a singular counterexample, where favorable agricultural conditions and a flexible processing infrastructure allow the majority of the country's road transport to be powered economically with cane-derived ethanol.

- 'biofuels could supply some 30% of global demand [of transportation fuels] … without affecting food production'
- 'major technical challenges'
- 'cost of biomass transport'
- 'the "size of the prize" is too large to ignore'

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$E = \$$

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

E = $

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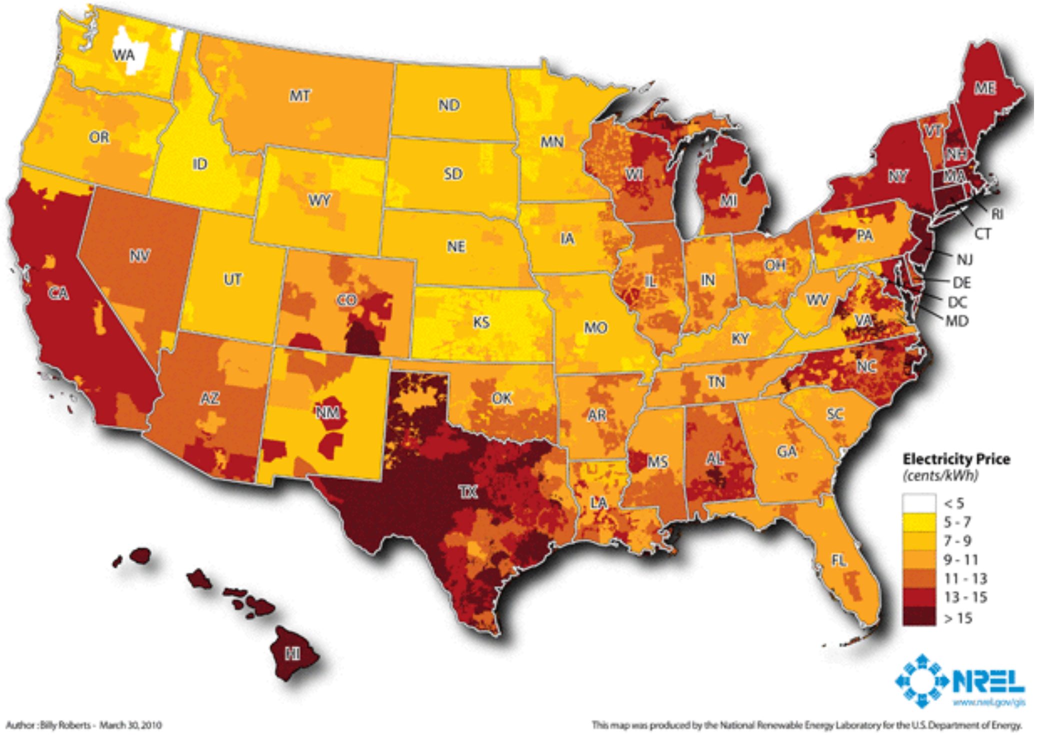

- Electricity
  1 kWh ~ $0.1
- Gasoline (1 gal ~ $4, 35 MJ/L = 36.6 kWh/ gallon)
  1 kWh ~ $0.1
- 2% Milk (122 Cal/cup = 2.28 kWh/gallon, 1 gal ~ $4)
  1 kWh ~$1.75
- Big Mac meal w large fries & coke (1350 Cal = 1.57 kWh, ~$6)
  1 kWh ~ $3.8

Energy Use & Prosperity

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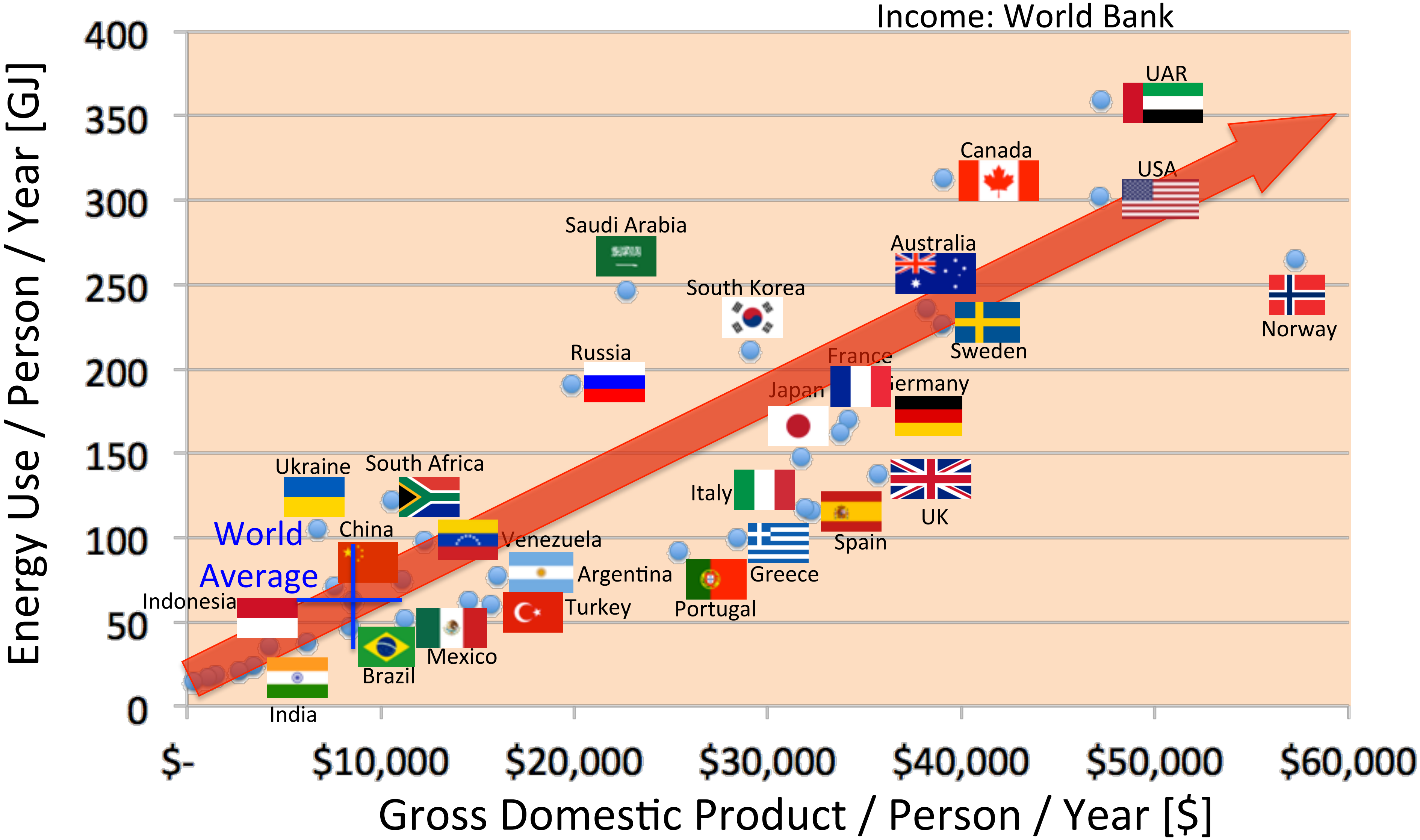
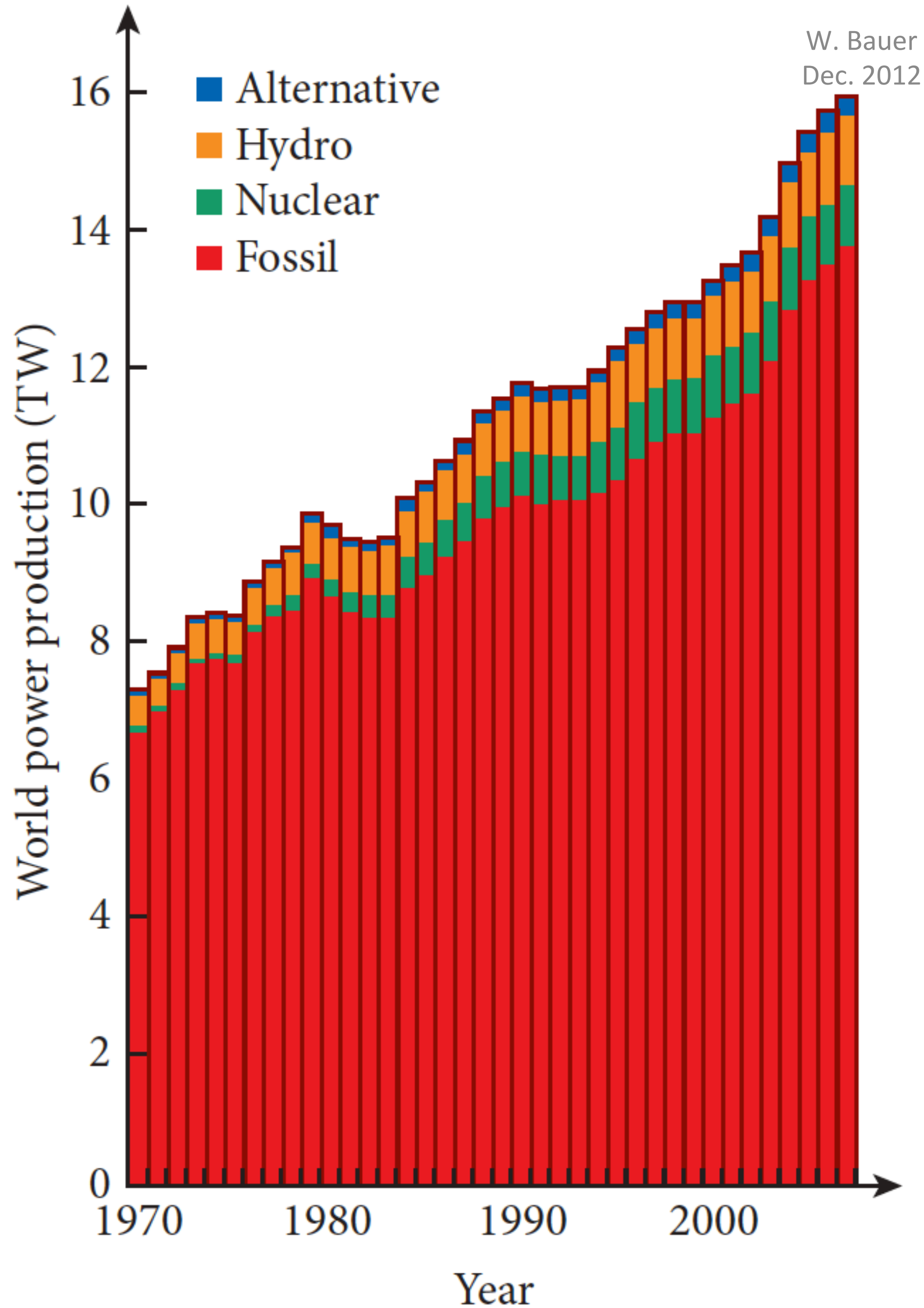


World Power Consumption

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



US Power Consumption ~ 4 TW

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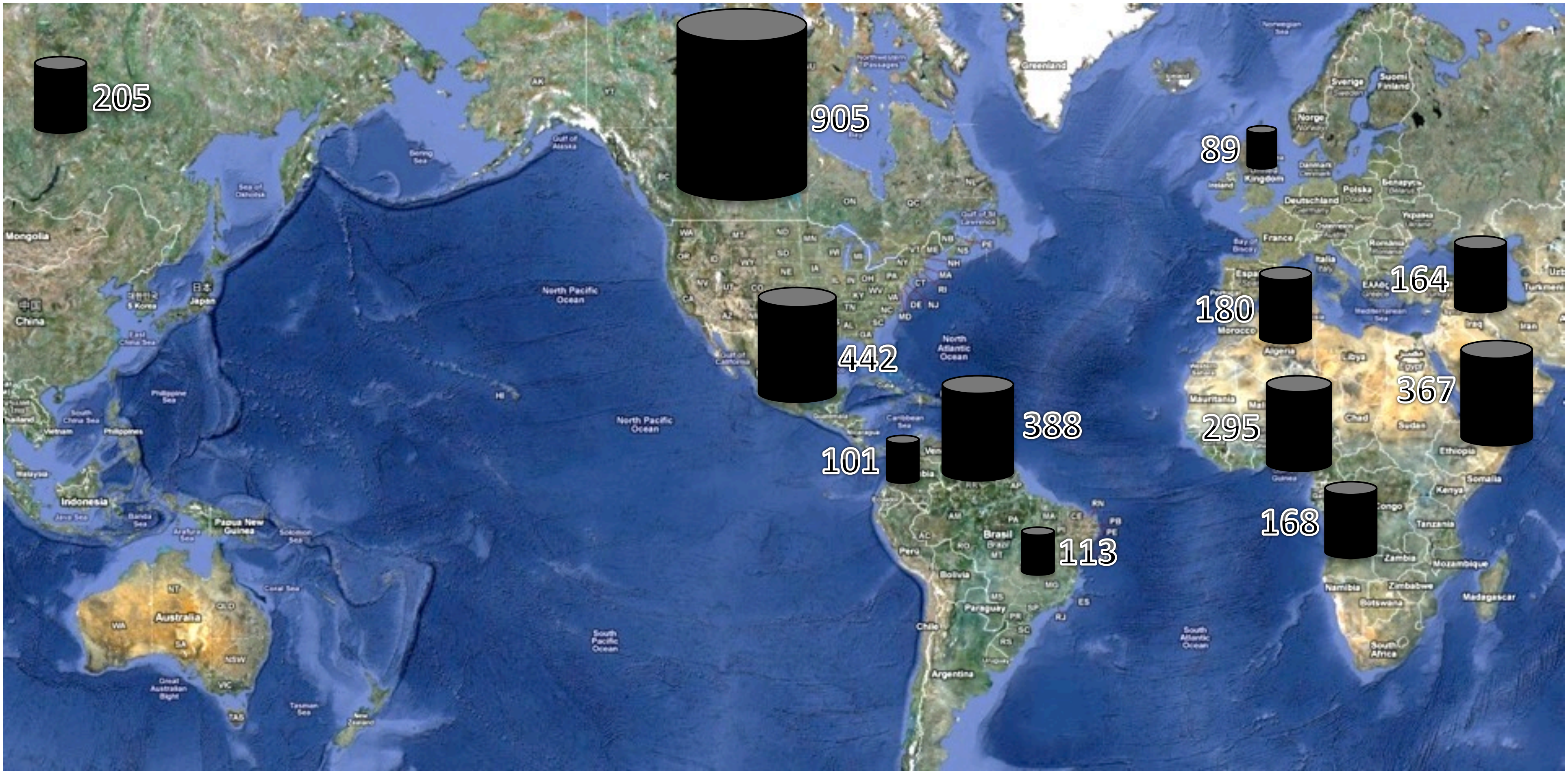
Where do fossil fuels come from?

- **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**
  - Almost 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

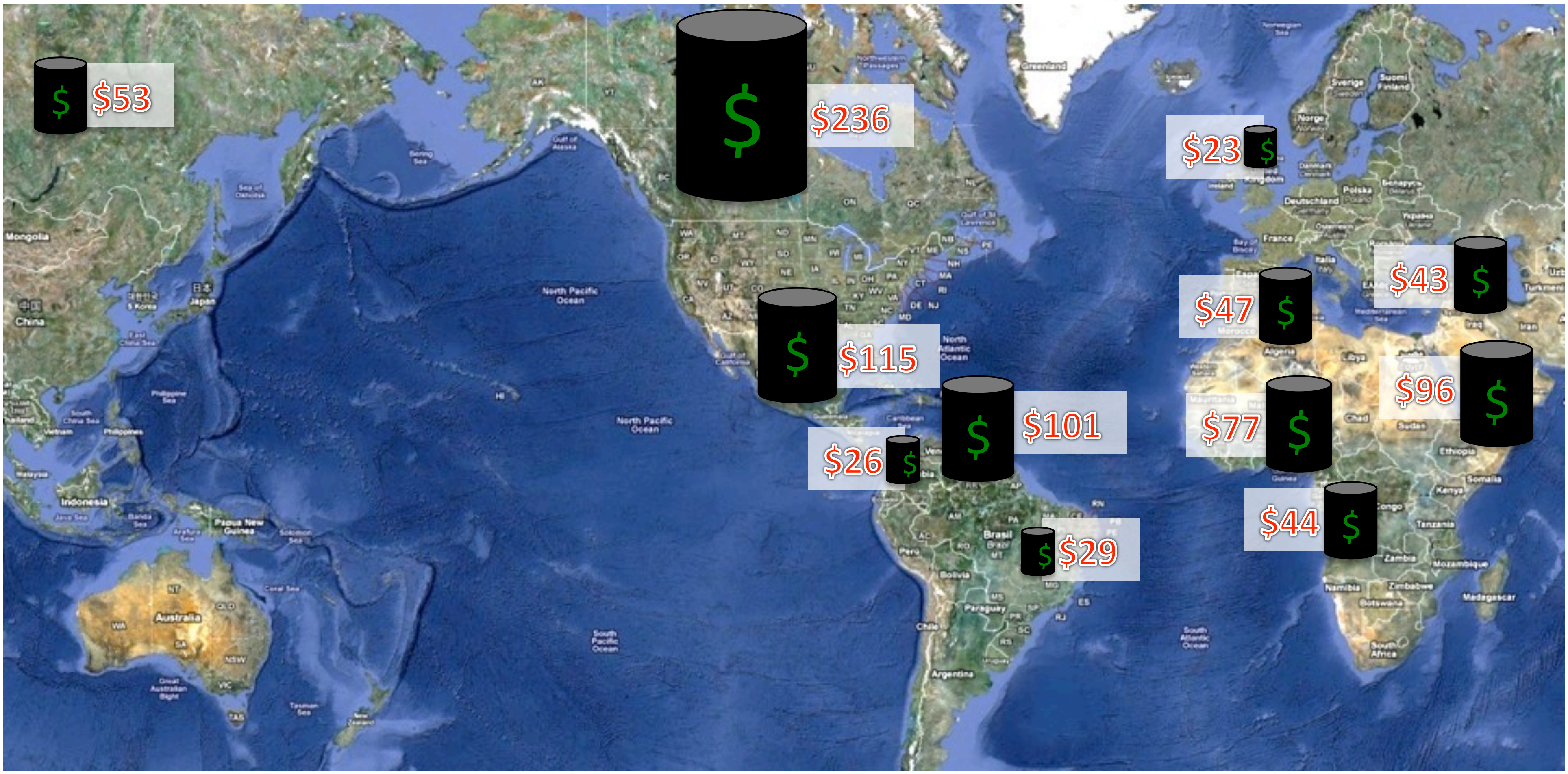
(by country, in million barrels)



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!

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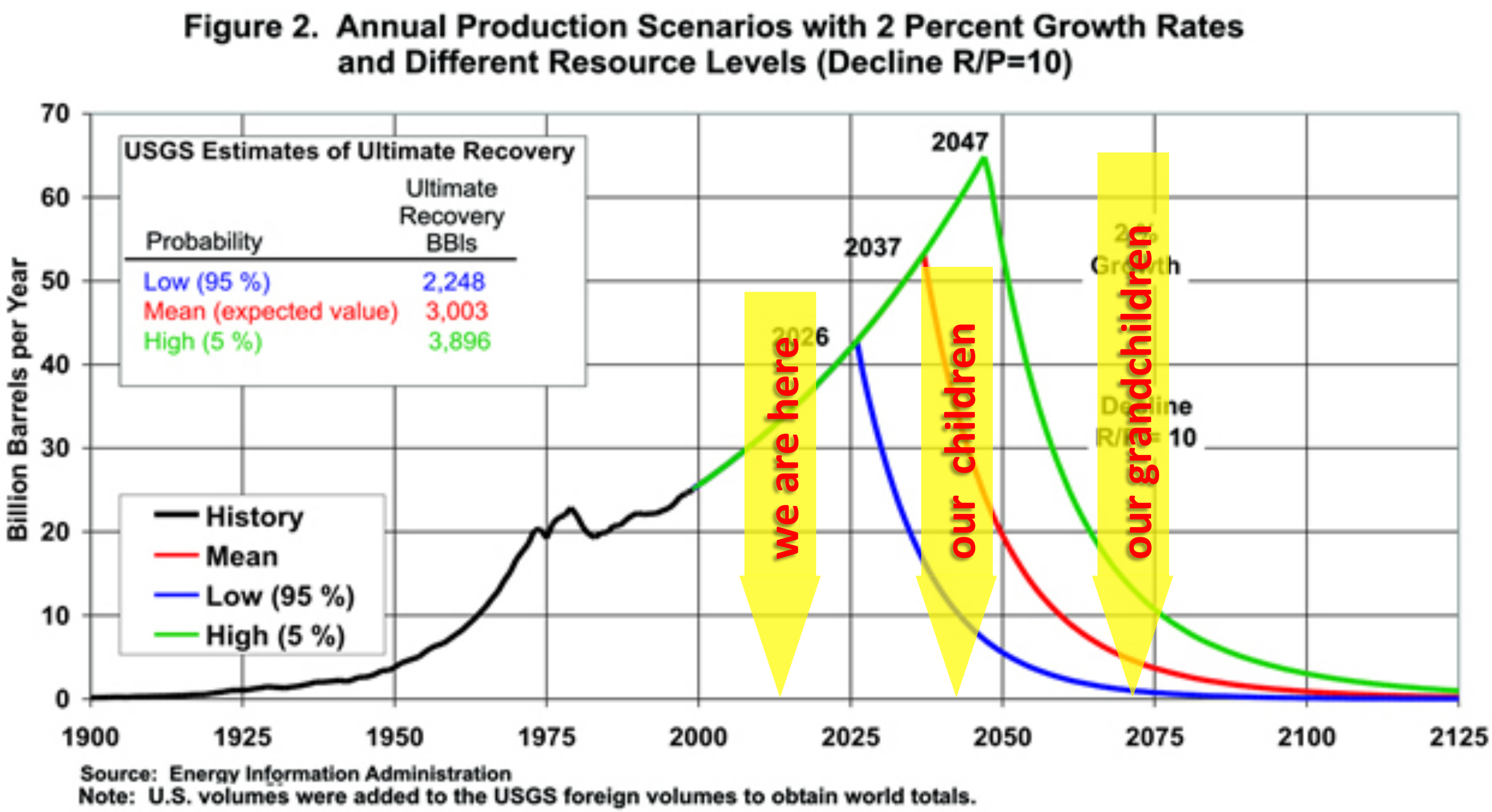

http://www.eia.doe.gov/
S.E. Koonin, BP


Drilling for oil gets more expensive and dangerous
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http://gcaptain.com/wp-content/uploads/2011/01/Deepwater-Horizon-oil-rig-explosion.jpg

Atmosphere

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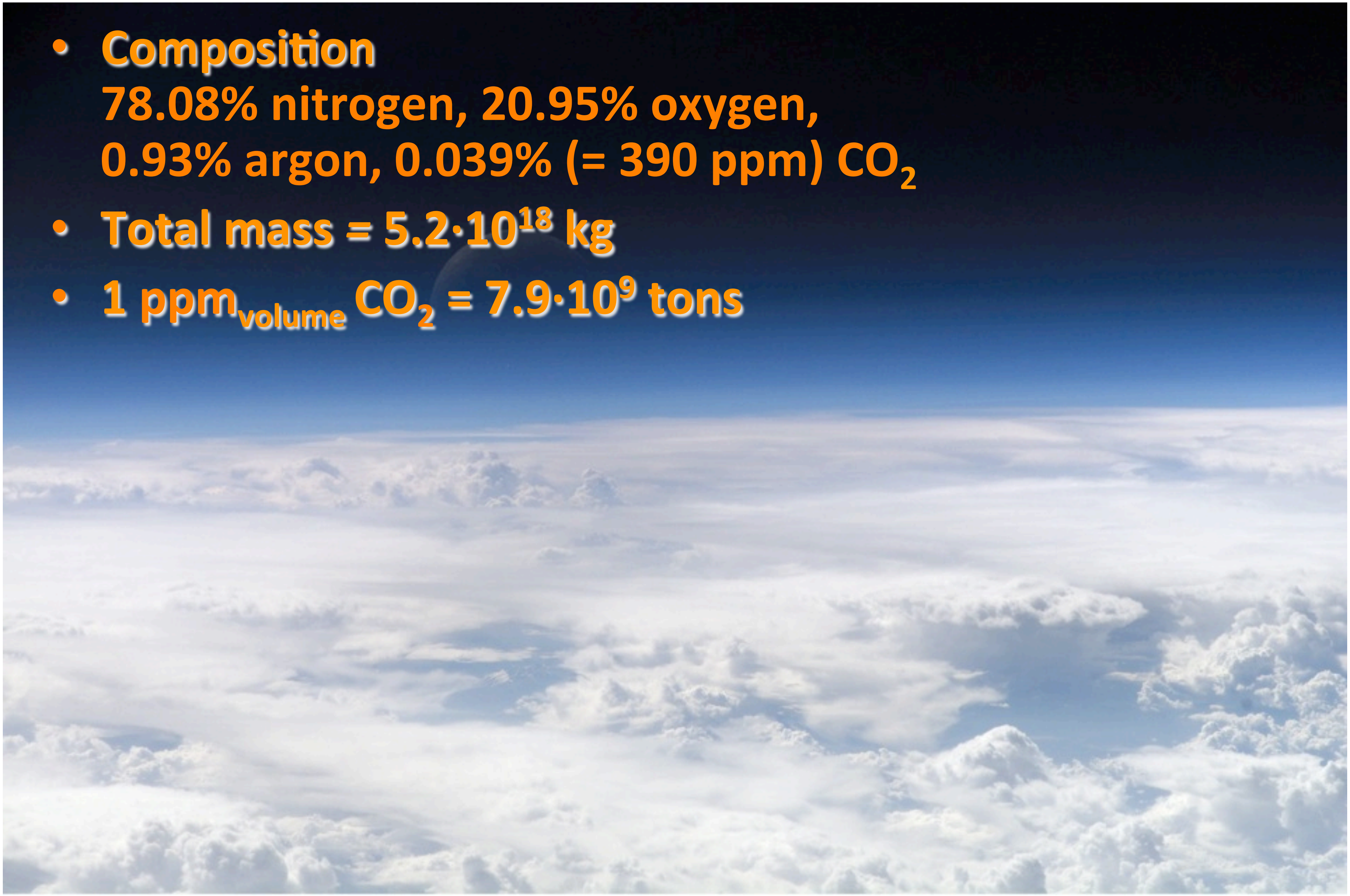
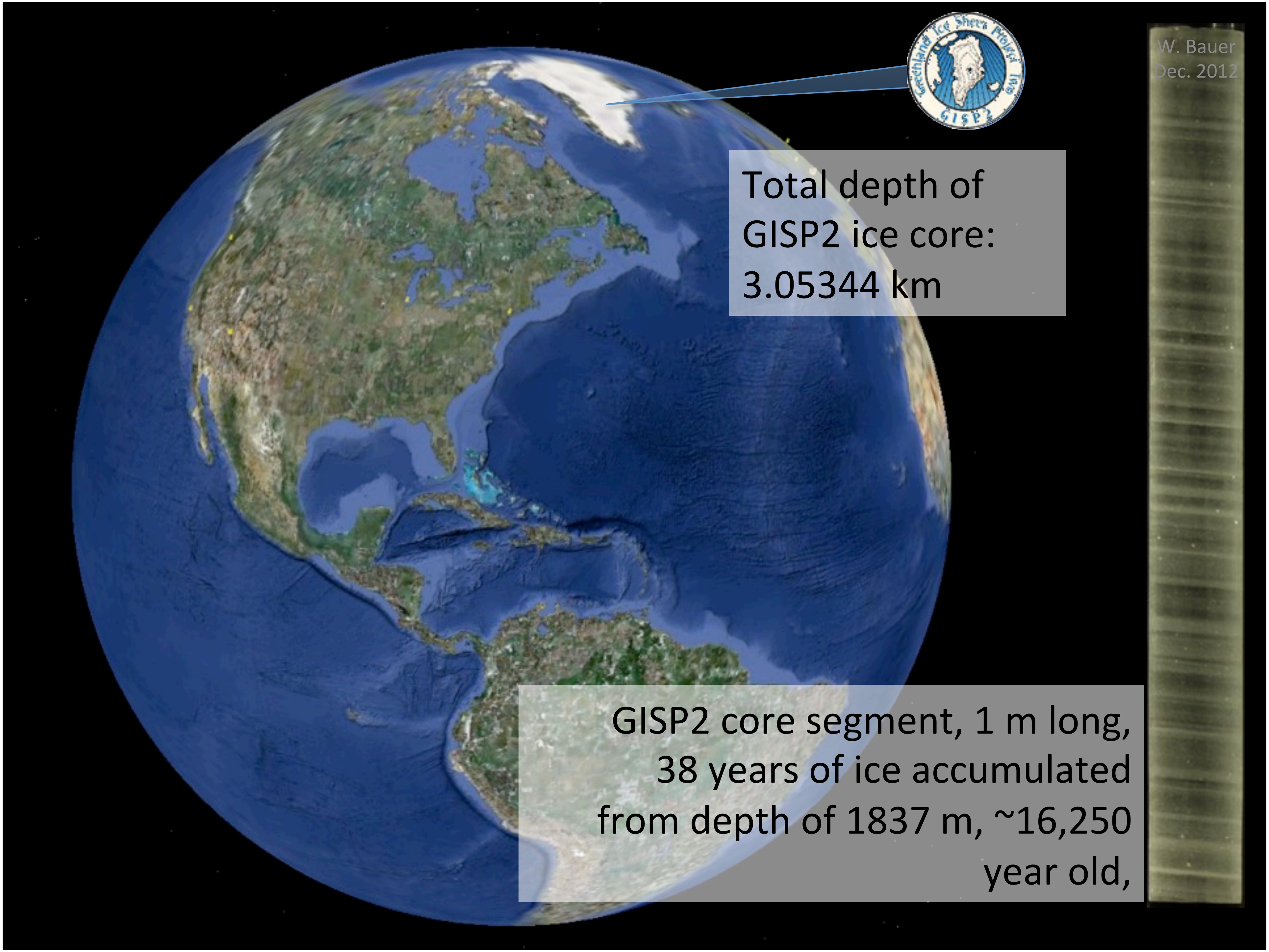


- **Composition**
  78.08% nitrogen, 20.95% oxygen,
  0.93% argon, 0.039% (= 390 ppm) CO_2
- **Total mass = $5.2 \cdot 10^{18}$ kg**
- **1 ppm_{volume} CO_2 = $7.9 \cdot 10^{9}$ tons**

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


Greenland Ice Sheet Project Two
GISP2
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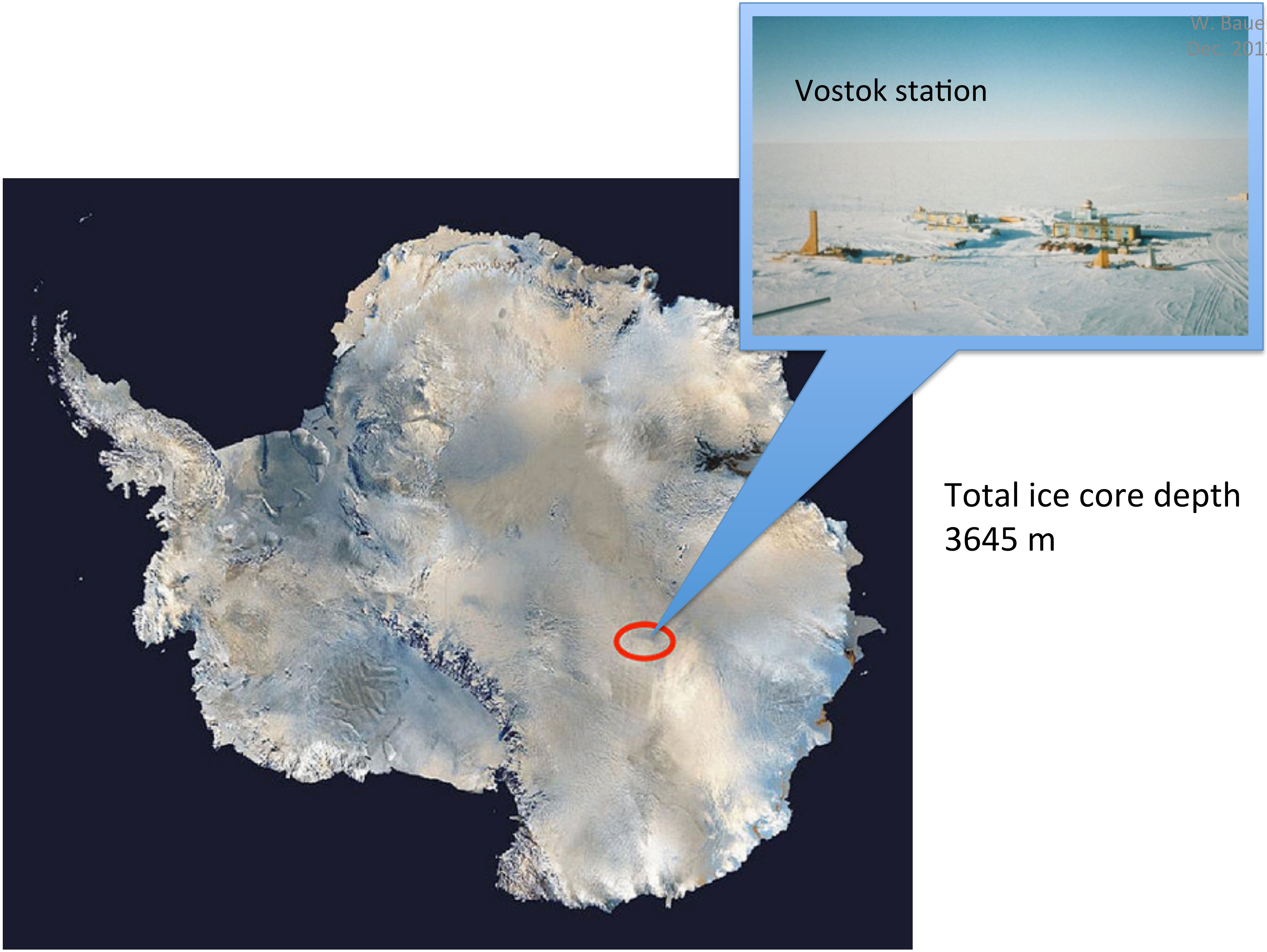
Total depth of
GISP2 ice core:
3.05344 km
GISP2 core segment, 1 m long,
38 years of ice accumulated
from depth of 1837 m, ~16,250
year old,



Total ice core depth
3645 m

CO_2 and Surface Temperature

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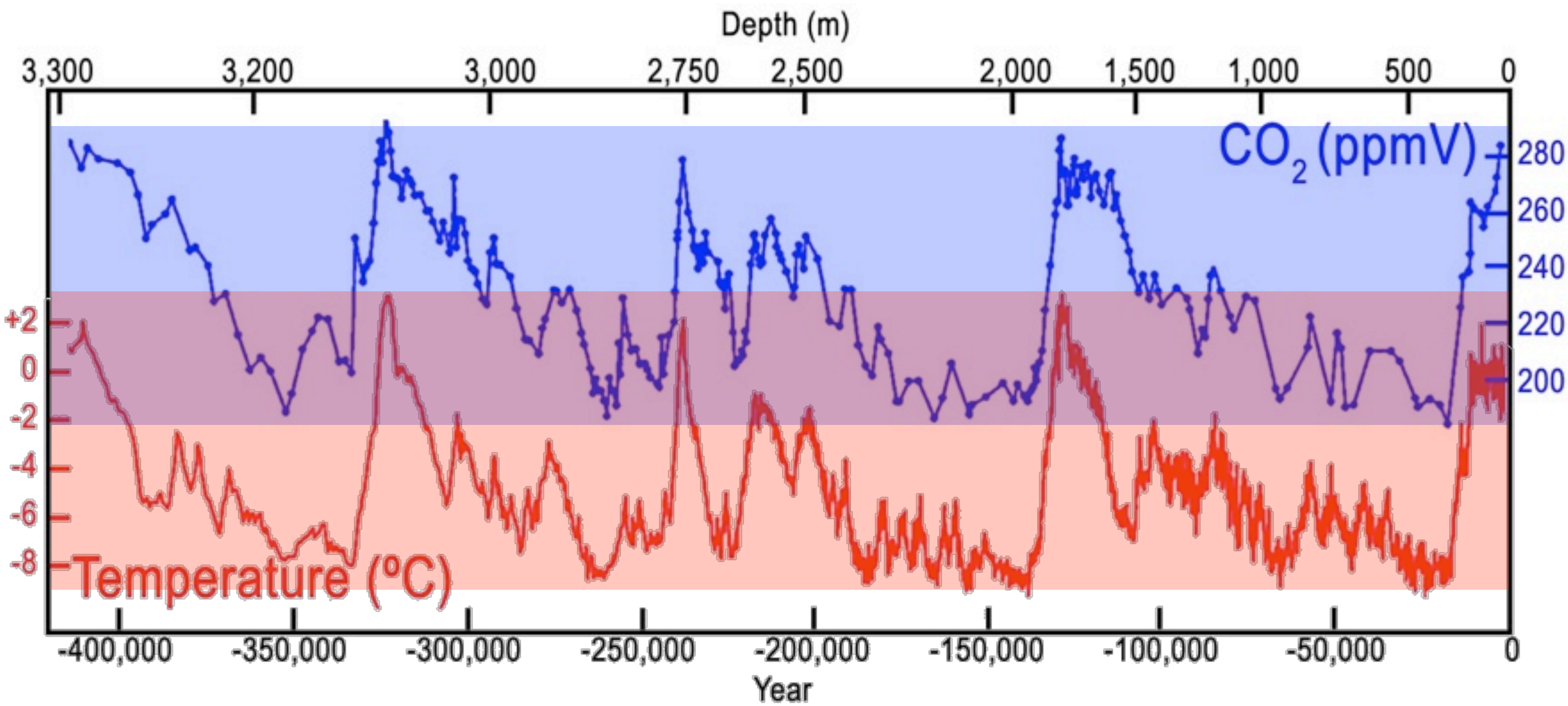

CO_2 in a range between 190 and 290 ppmV during last ~ half million years

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**

How big is the problem?

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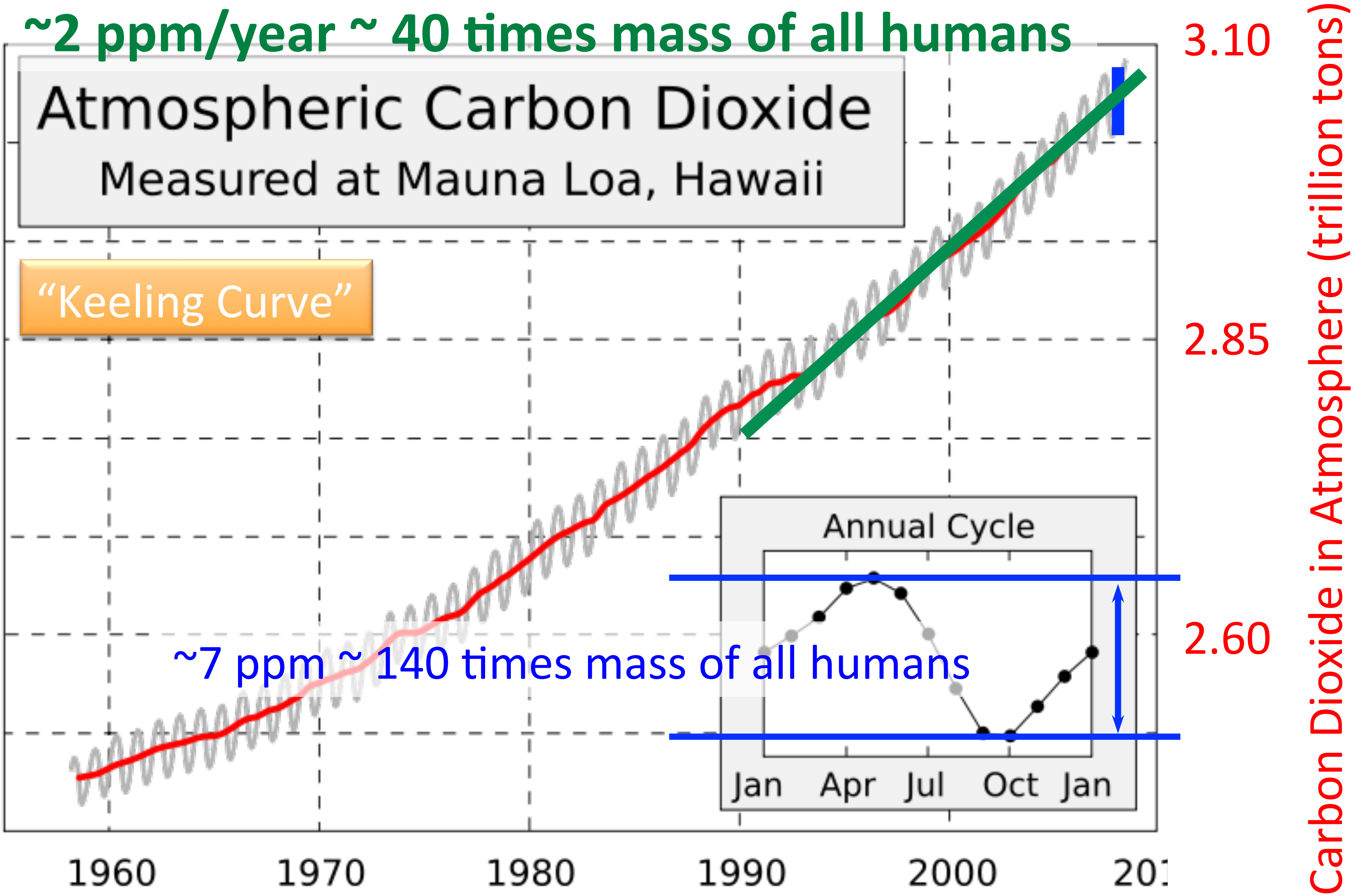

Global Temperature

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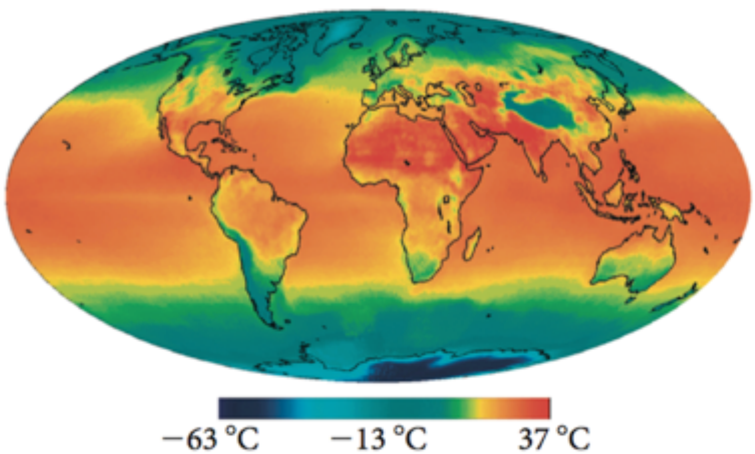
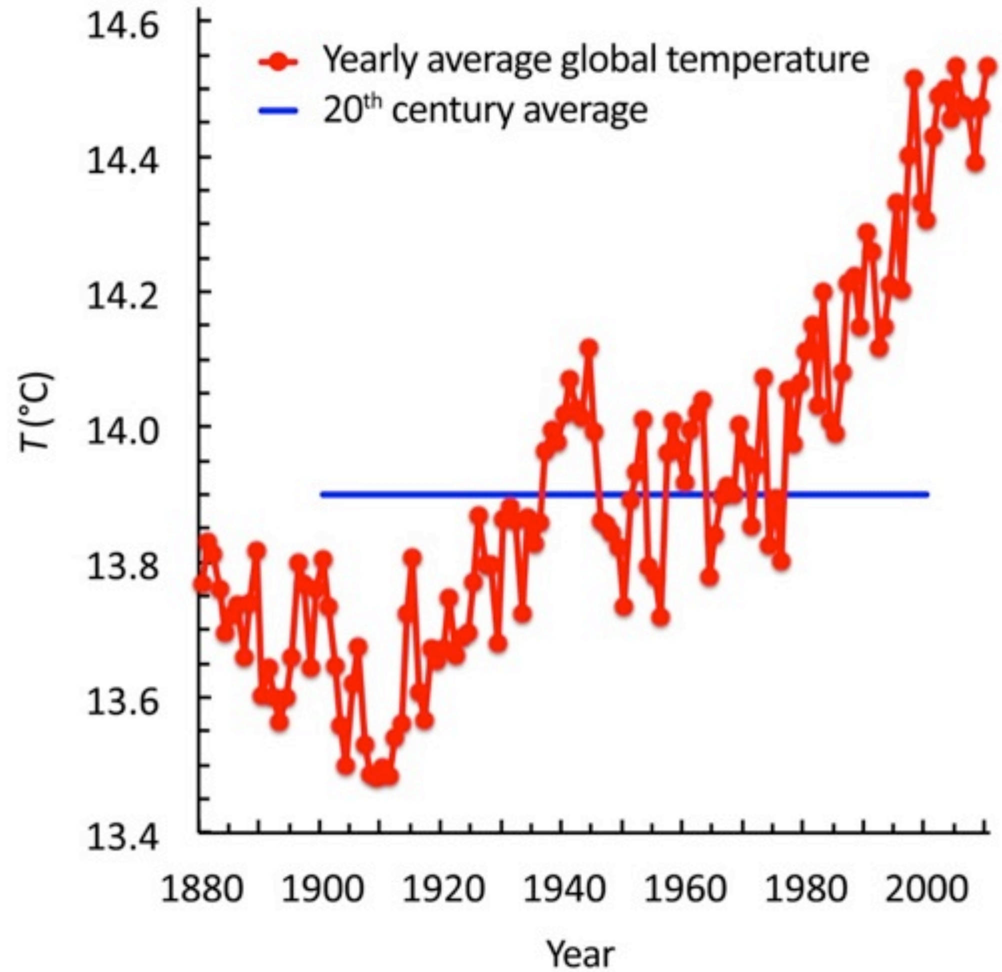
- Careful averaging needed (over *space* and *time*)



June 1992



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

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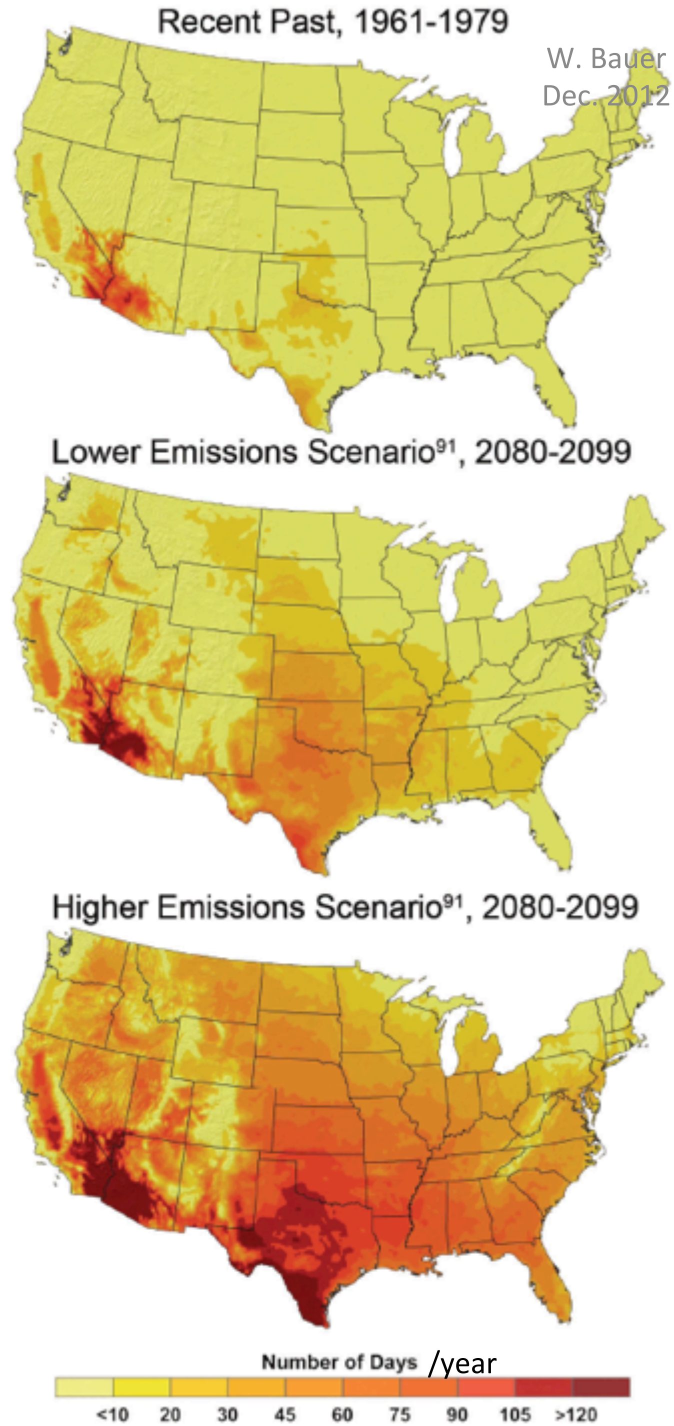

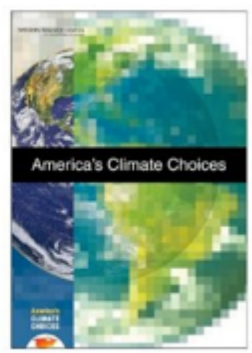

"America's Climate Choices", NRC Report

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

Predictions(2): Sea Level Rise

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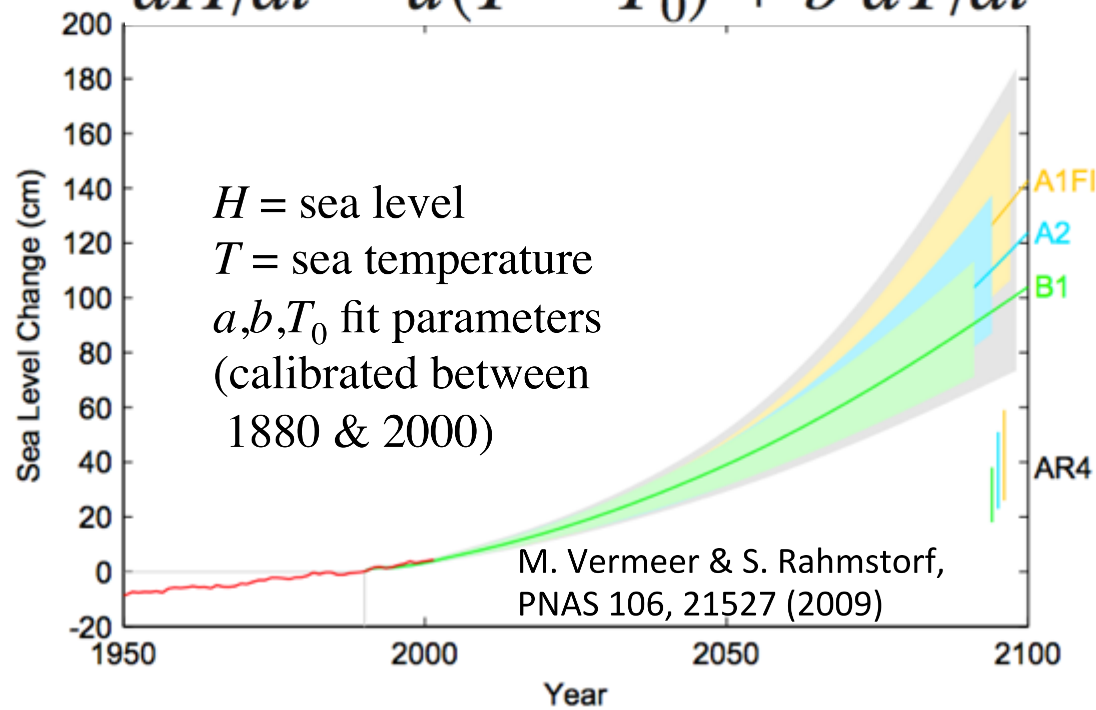
Earth surface area = 510M km^2,
361M km^2 covered by oceans
40-50M km^2 covered by ice

Message:
do not buy beachfront property!

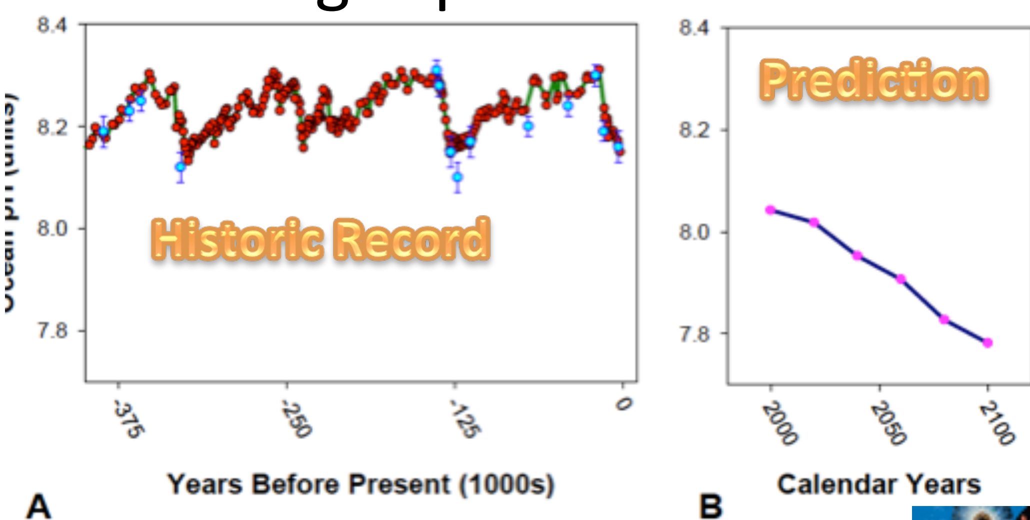
Ice source	Ice Volume	Sea rise
Greenland	2.8M km^3	7.2 m
Antarctic	30M km^3	76 m
North Pole	5-25M km^3	0
Total	**33M km^3**	**83 m**

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



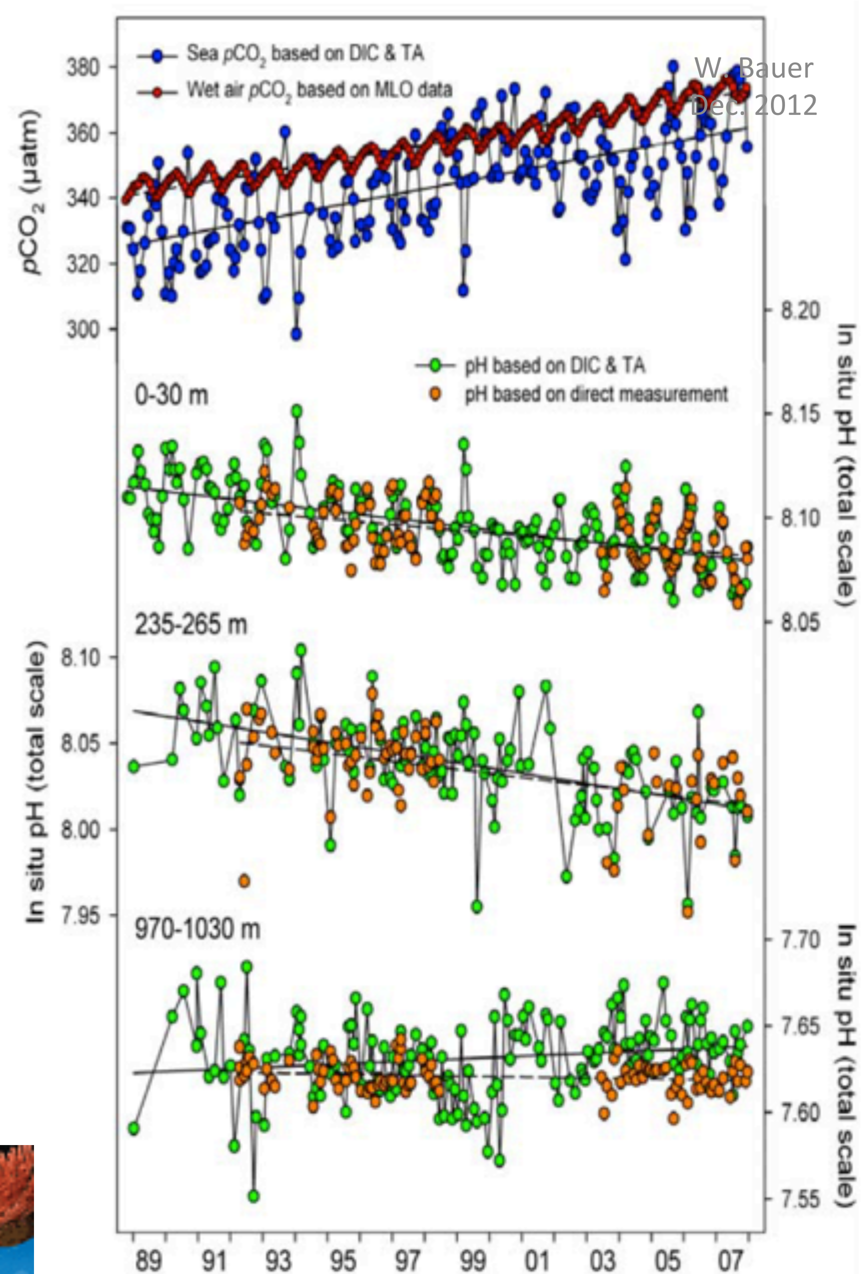
Predictions(3): Ocean Acidification

- ~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



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

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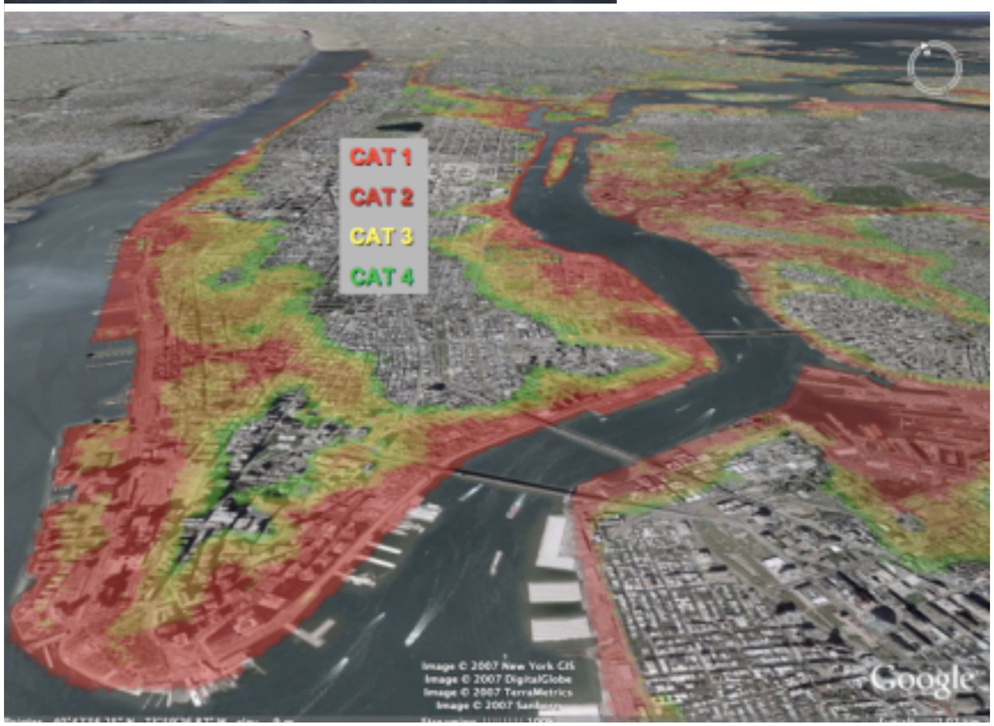
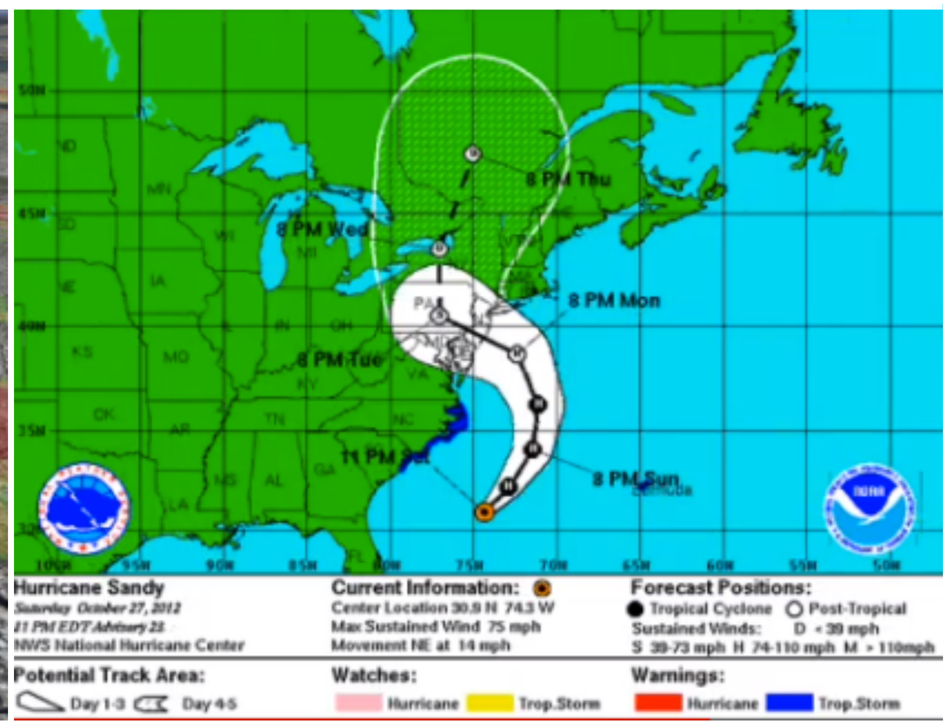
"Our climate is changing. And while the increase in extreme weather we have experienced in New York City and around the world may or may not be the result of it, the risk that it may be — given the devastation it is wreaking — should be enough to compel all elected leaders to take immediate action."

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





What could happen?

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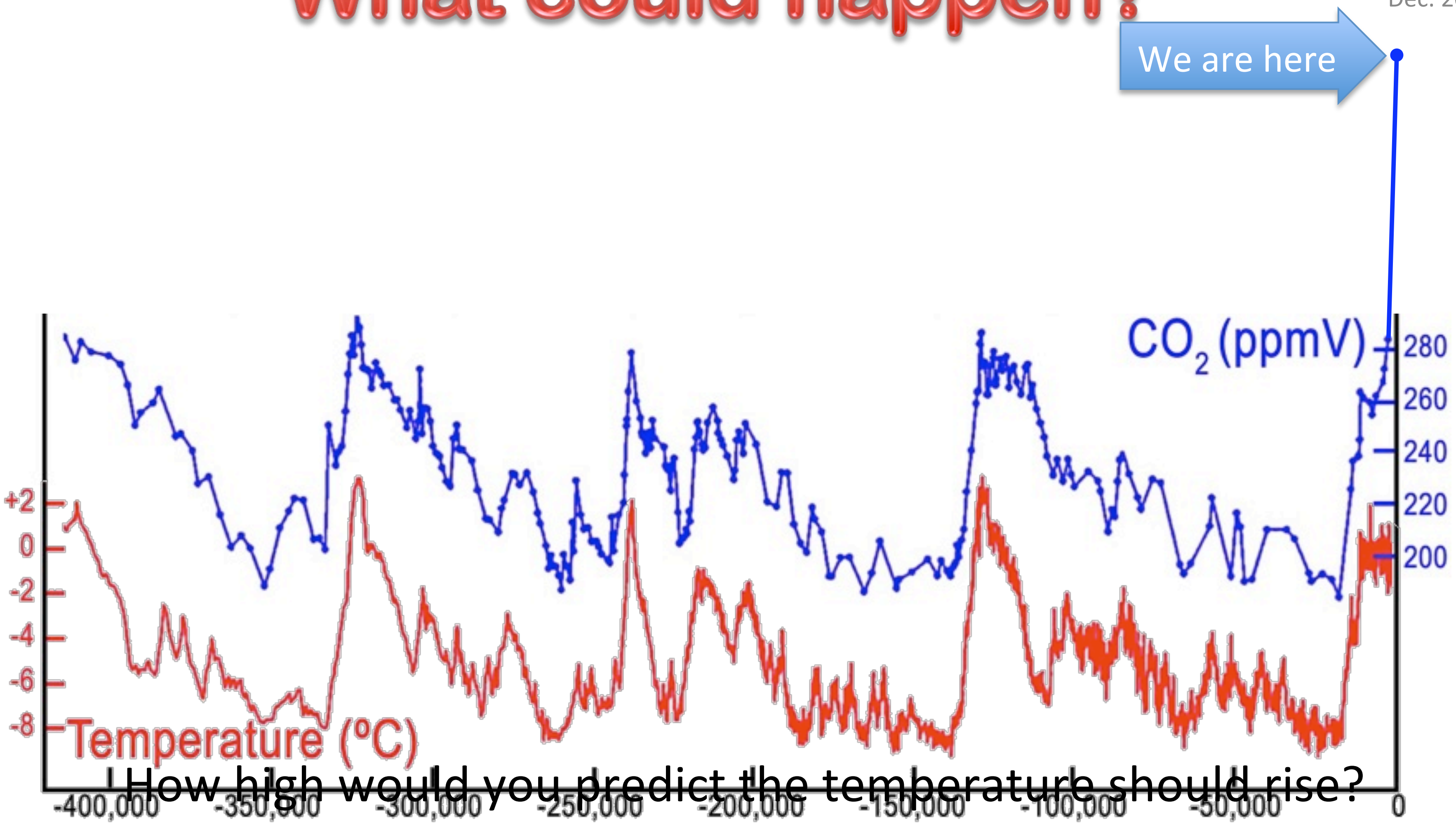

How high would you predict the temperature should rise?

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

Power from the Sun

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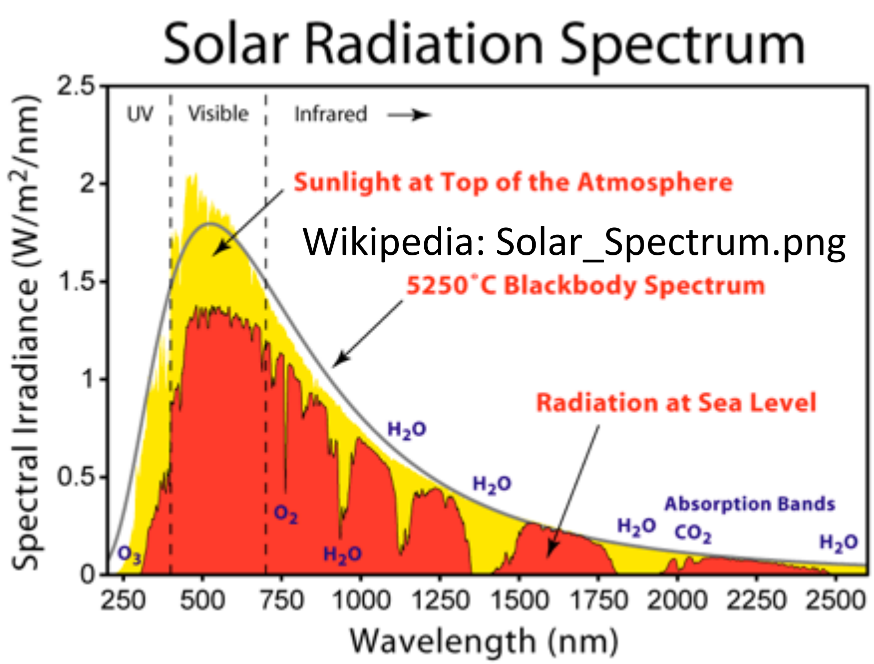
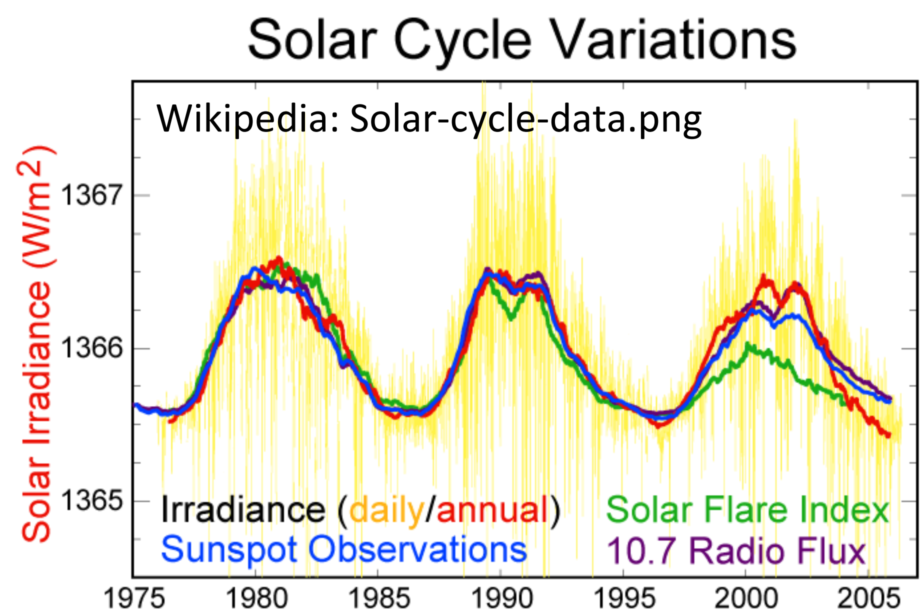
- Solar "constant" = 1.366 kW/m^2
(1.41 kW/m^2 in Jan., 1.31 kW/m^2 in July)
- Average radiation hitting any point on the ground **200 W/m^2** (= 55% of 1.366 kW/m^2/4)
- Total: **~100,000 TW** (> 5,000x humanity's demand)





Power from the Sun: Photo-Voltaic

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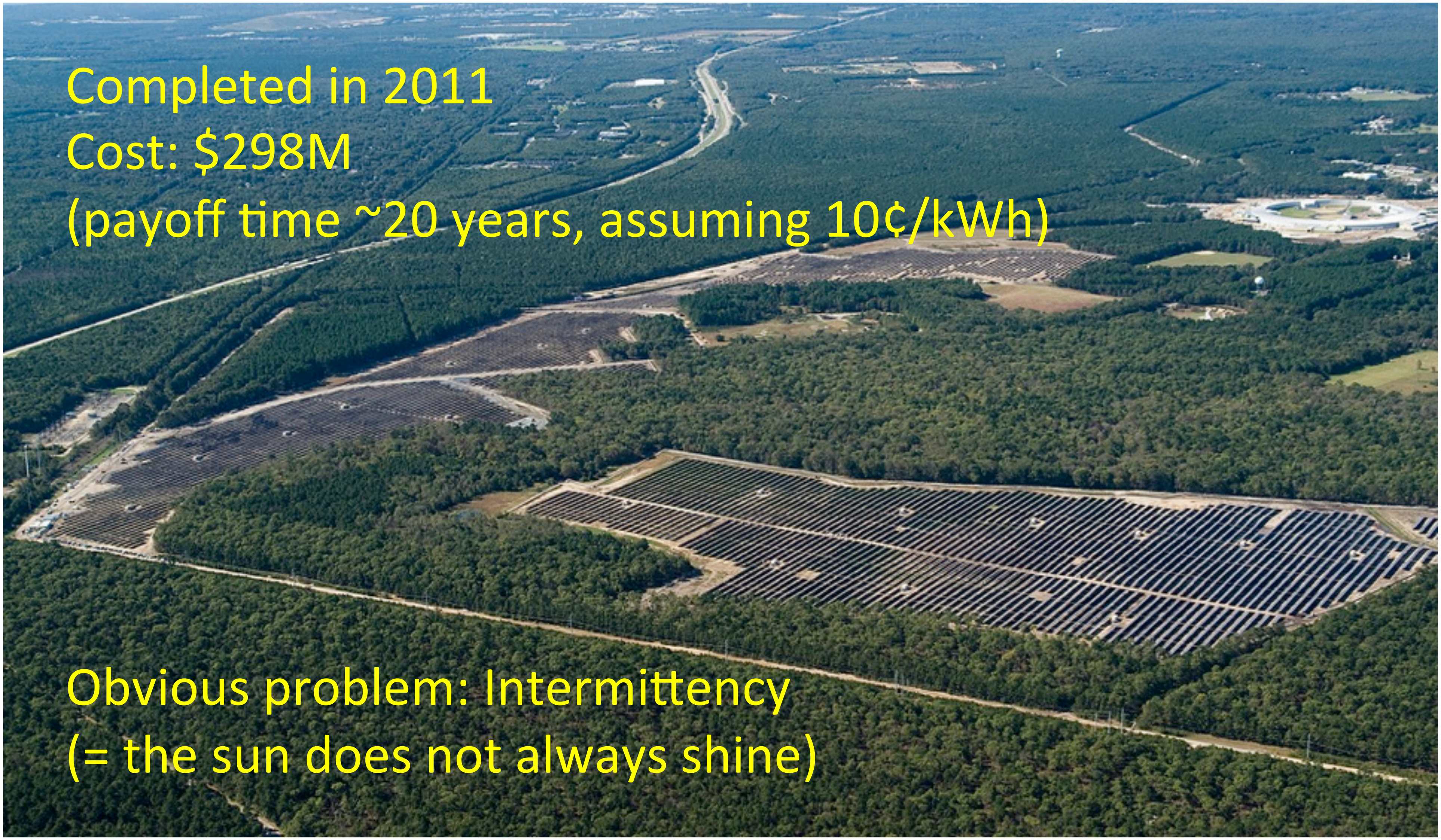
32 MW (peak) Brookhaven solar farm (BP Solar, MetLife, LIPA, DOE)



Power from the Sun: Solar-Thermal

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Power from the Earth

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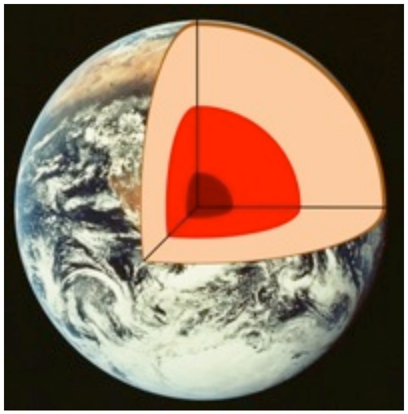
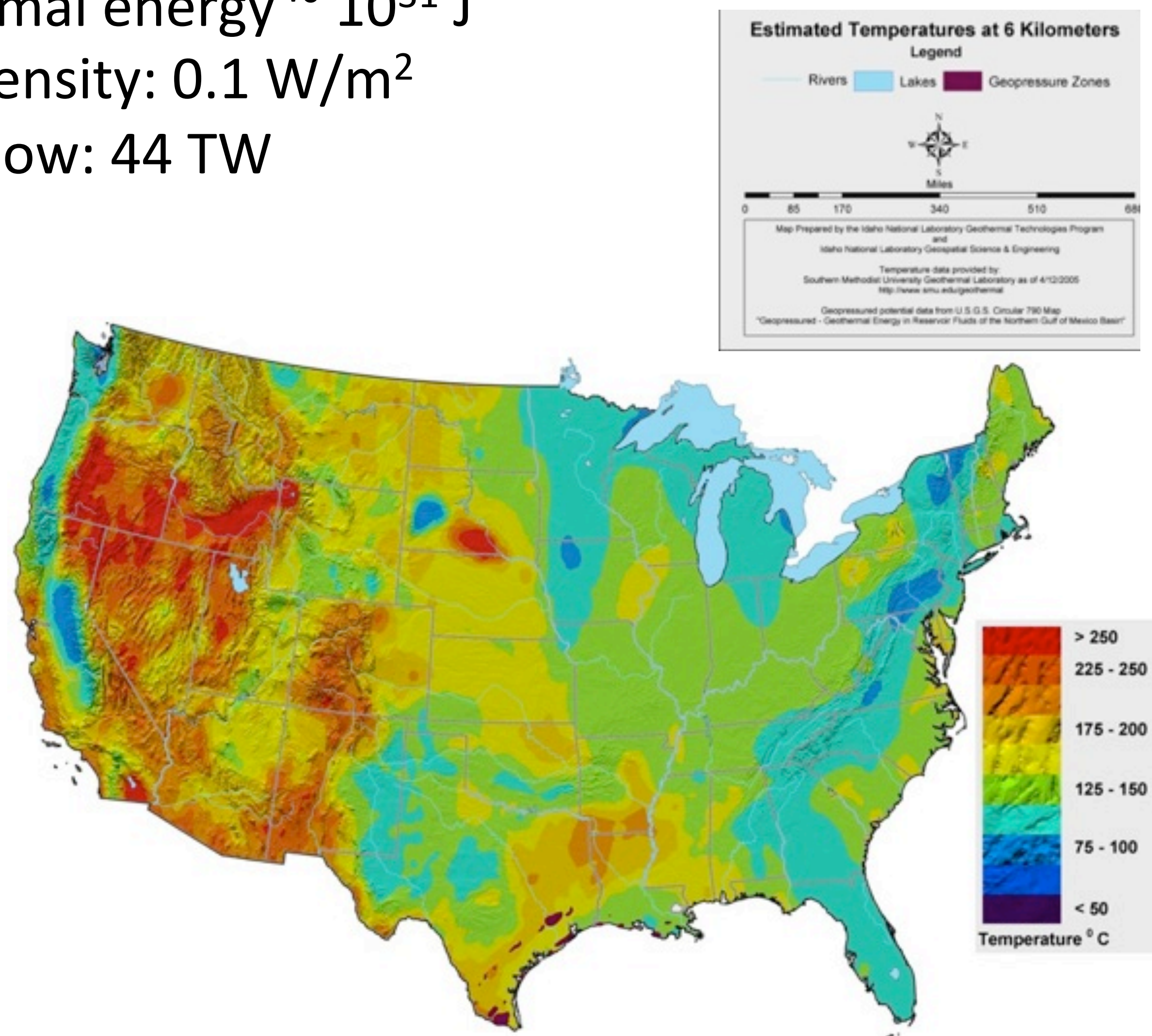


Earth's thermal energy ~ 10^{31} J
Heat flow density: 0.1 W/m^2
Total heat flow: 44 TW

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



Enhanced Geothermal

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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

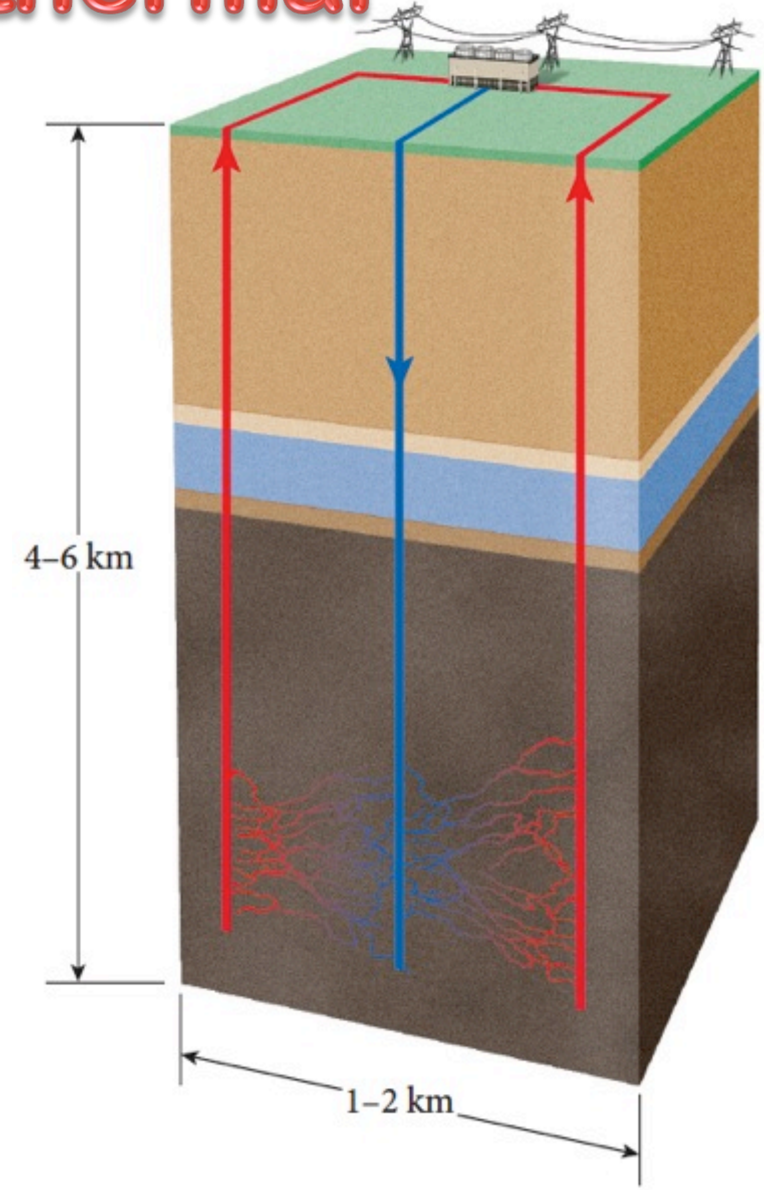

FIGURE 18.33 Diagram of an enhanced geothermal system.

Hydro

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Example: Three Gorges Dam

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

Wind

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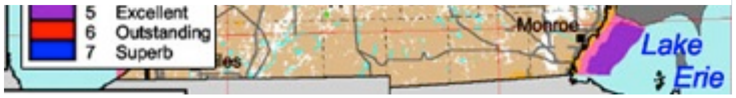

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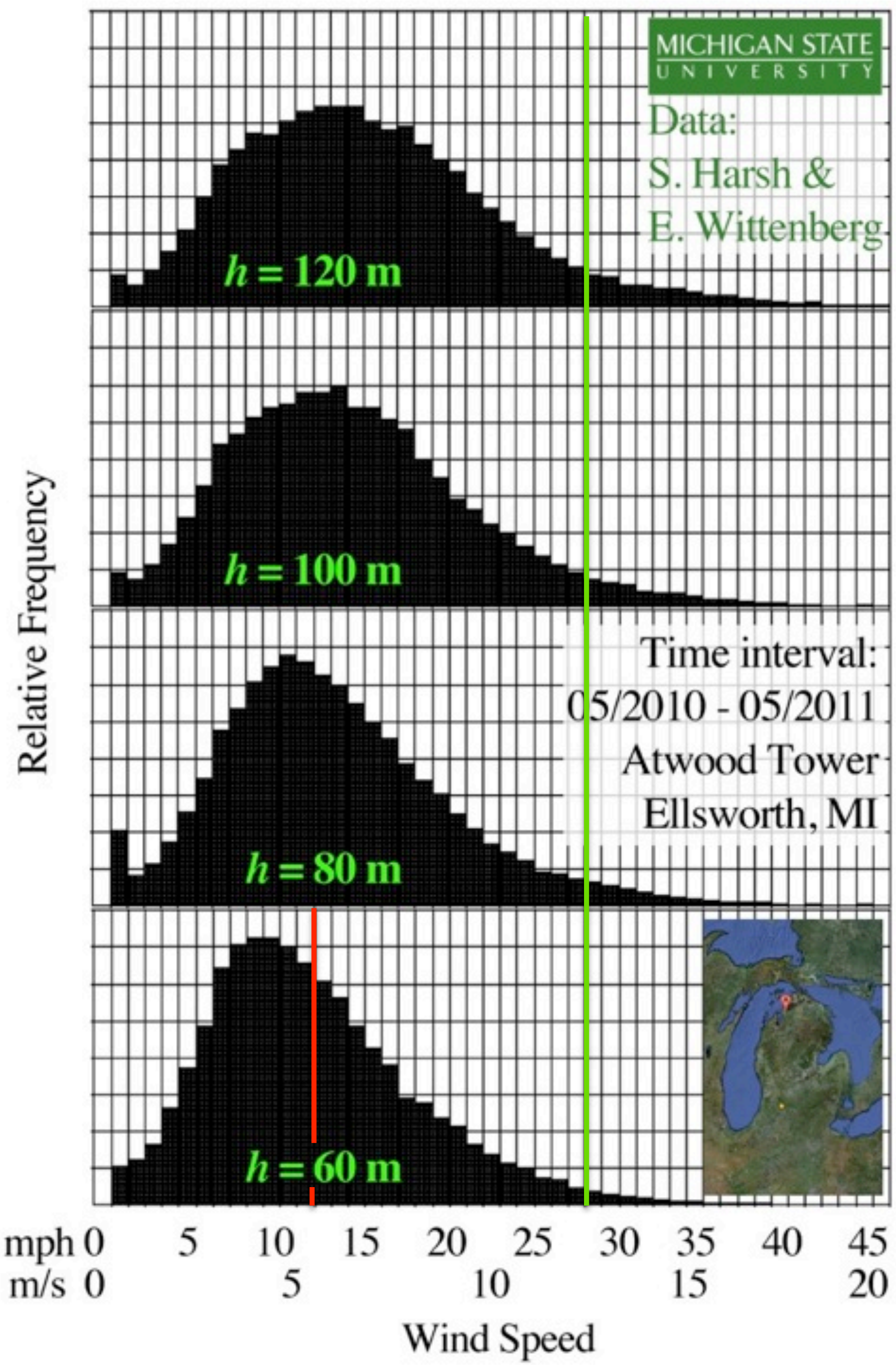
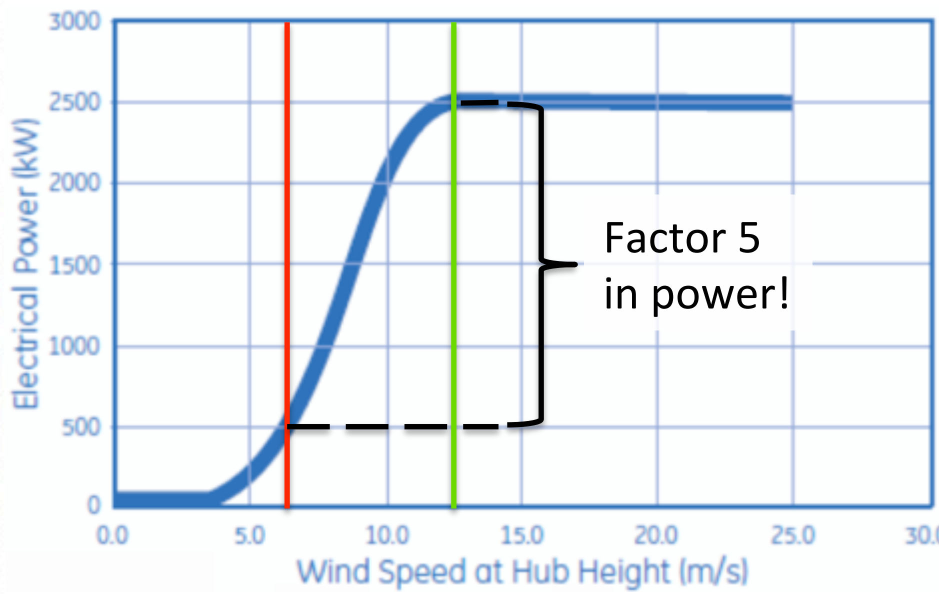
Wind Speed



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



Bottom line: Wind

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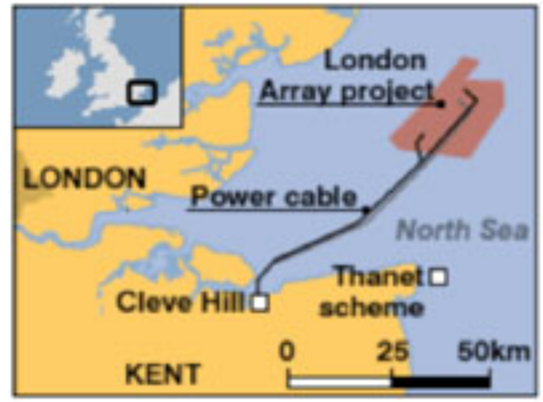
Most efficient: Offshore wind farms

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



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

Ocean Currents

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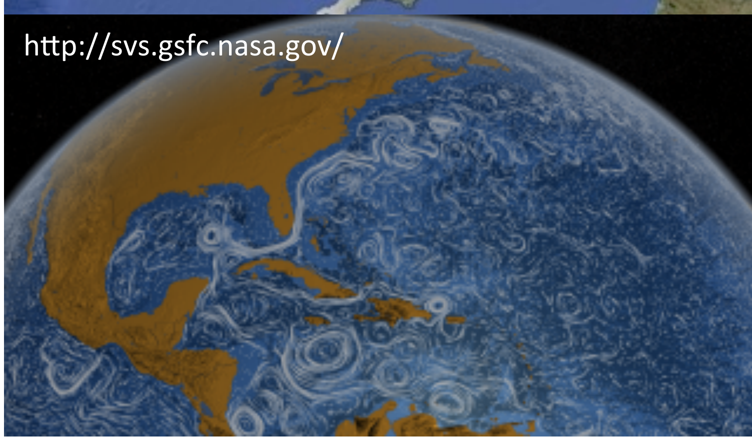

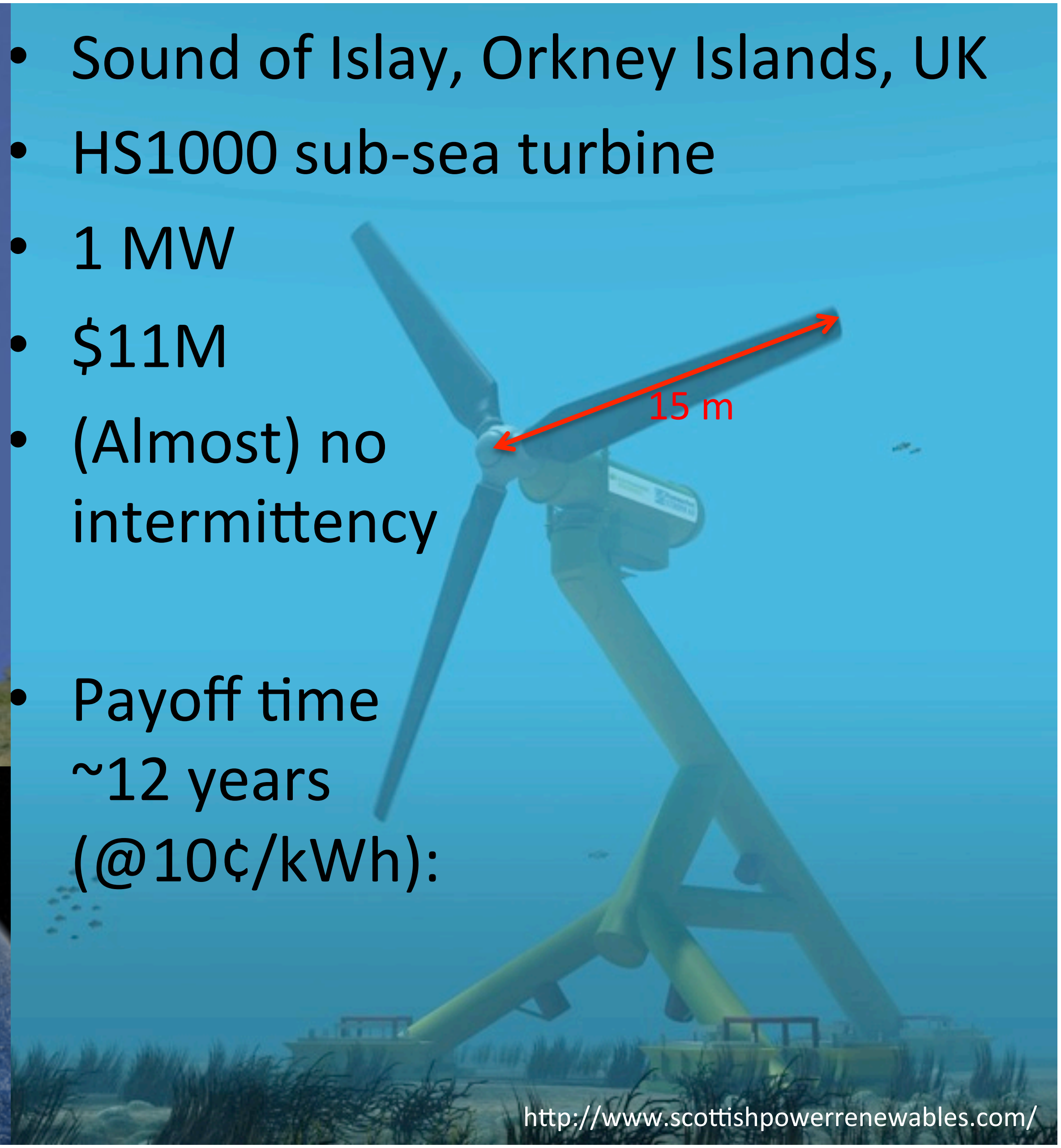

- Sound of Islay, Orkney Islands, UK
- HS1000 sub-sea turbine
- 1 MW
- $11M
- (Almost) no intermittency
- Payoff time ~12 years (@10¢/kWh):

Energy Storage

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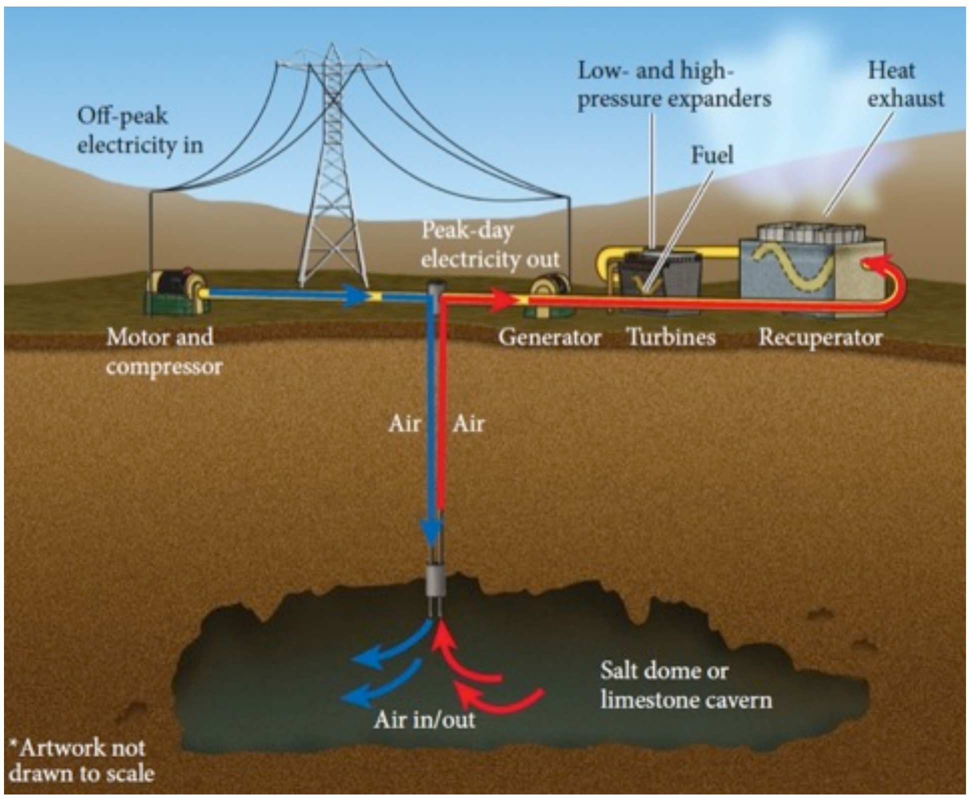

- Intermittent power sources need macroscopic energy storage
  - Pump-storage hydro
  - Compressed air caverns
  - Molten salt (high latent heat)

Really BIG Plans: DESERTEC

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Transportation

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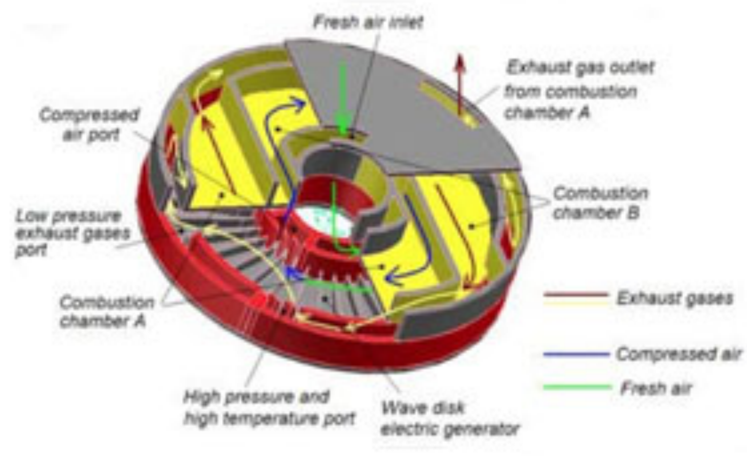
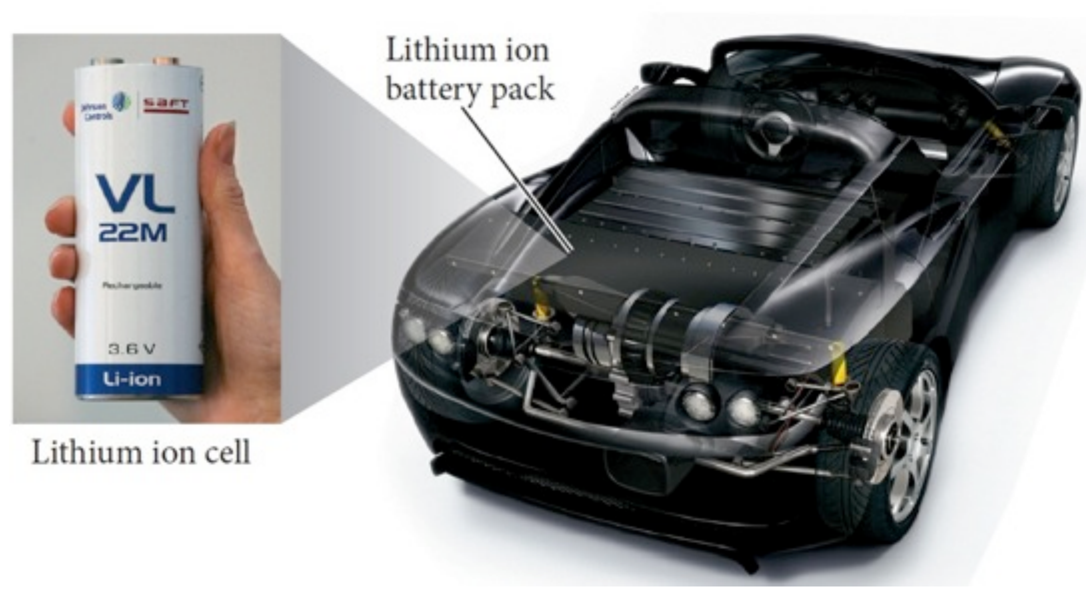
- Public transport: Bus & train(!)
- More efficient engines
  (e.g. Norbert Müller's wave disk)



- 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

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- 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?

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	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/kg)
+ 15% regular gasoline

Cellulosic Bio-Ethanol

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- 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

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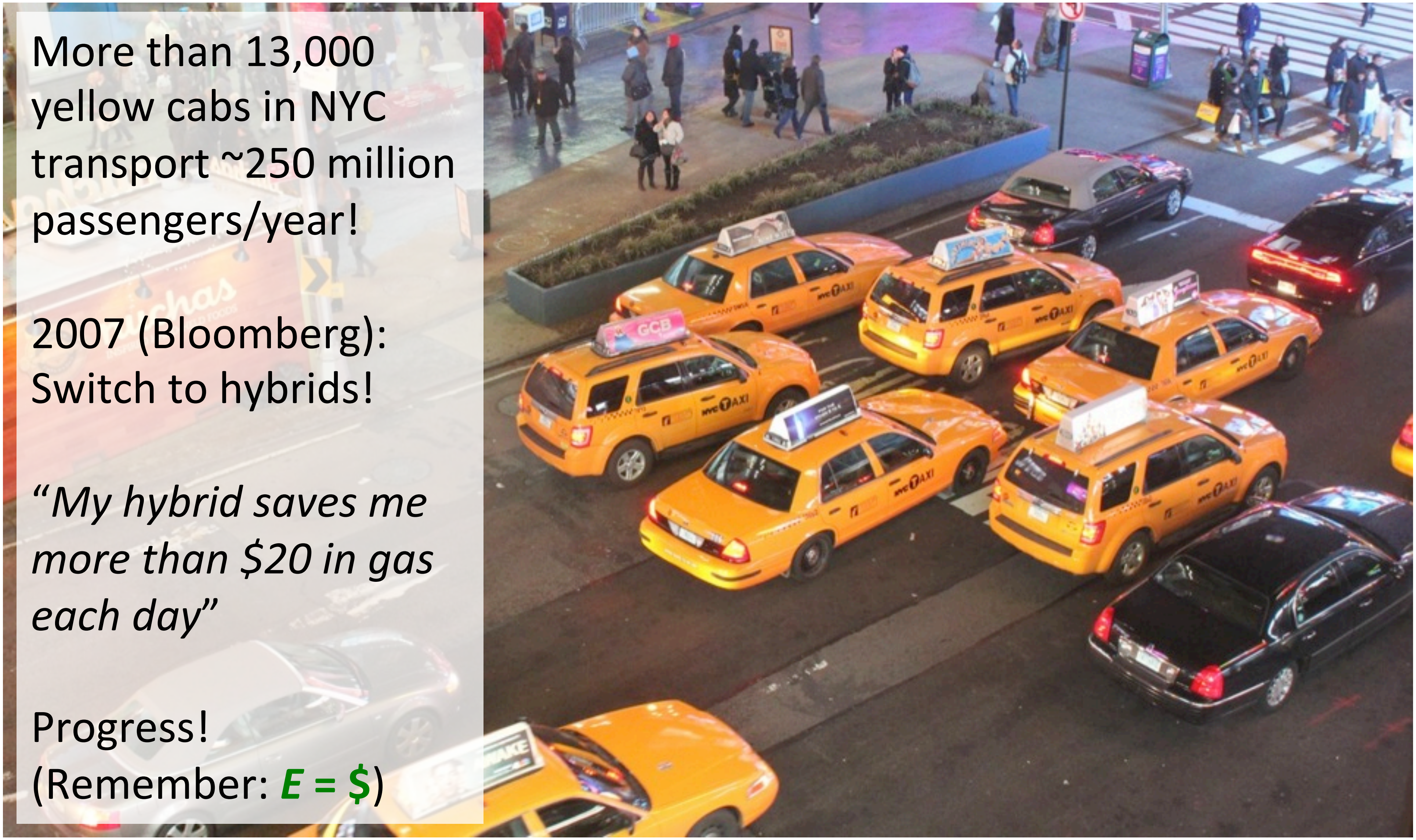
More than 13,000 yellow cabs in NYC transport ~250 million passengers/year!

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

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- 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* = $**)

1 MW Biogas Power Plant

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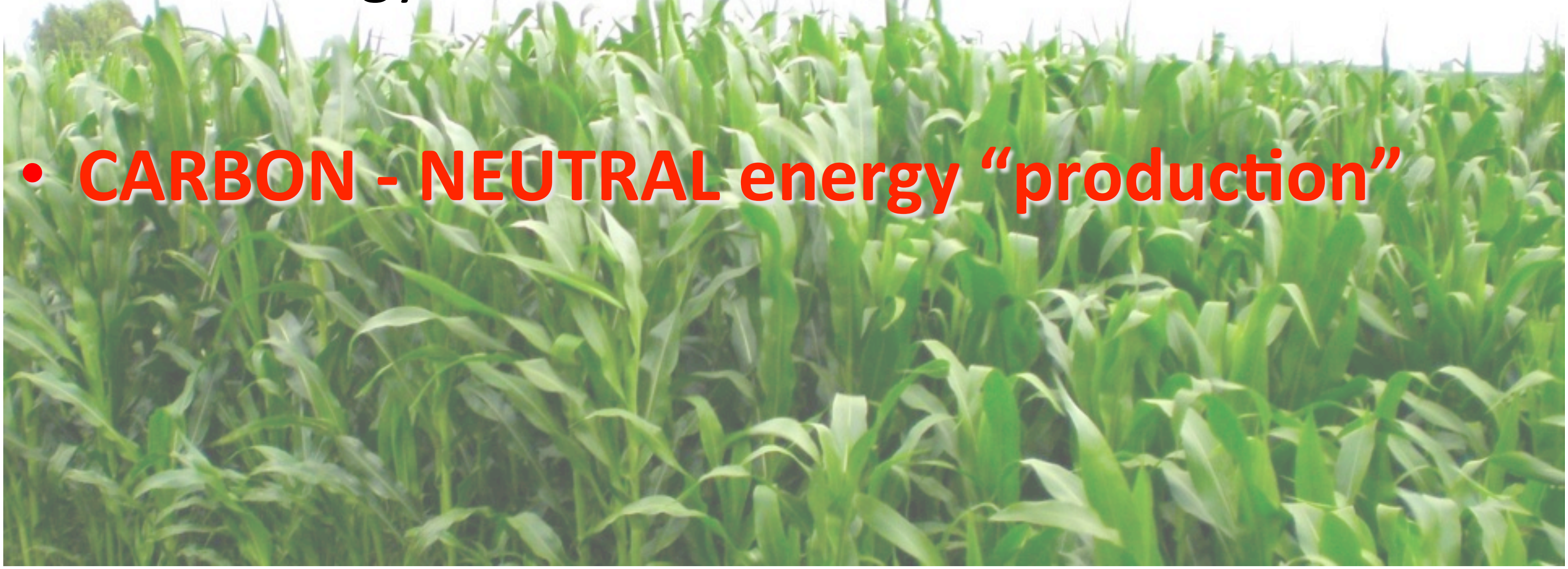
Sept. 2012

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”**

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Energy Crop: Corn (whole plant)

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Biomass Consumption / Day

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

Mixer

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Fermenter

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

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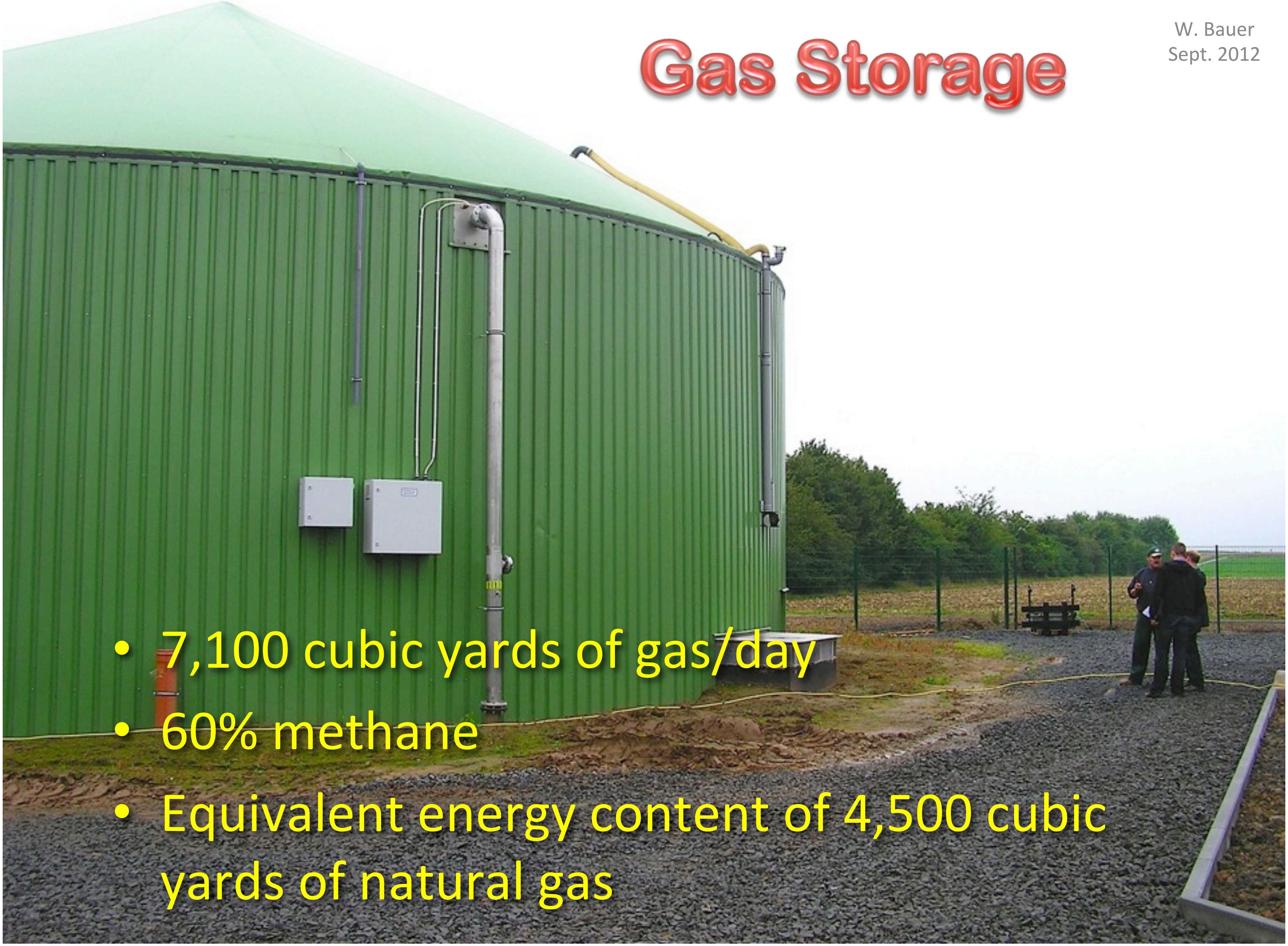
Gas Storage



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

Generators (82% efficient)

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

MW Biogas Power Plant

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- 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)

Energy Balance

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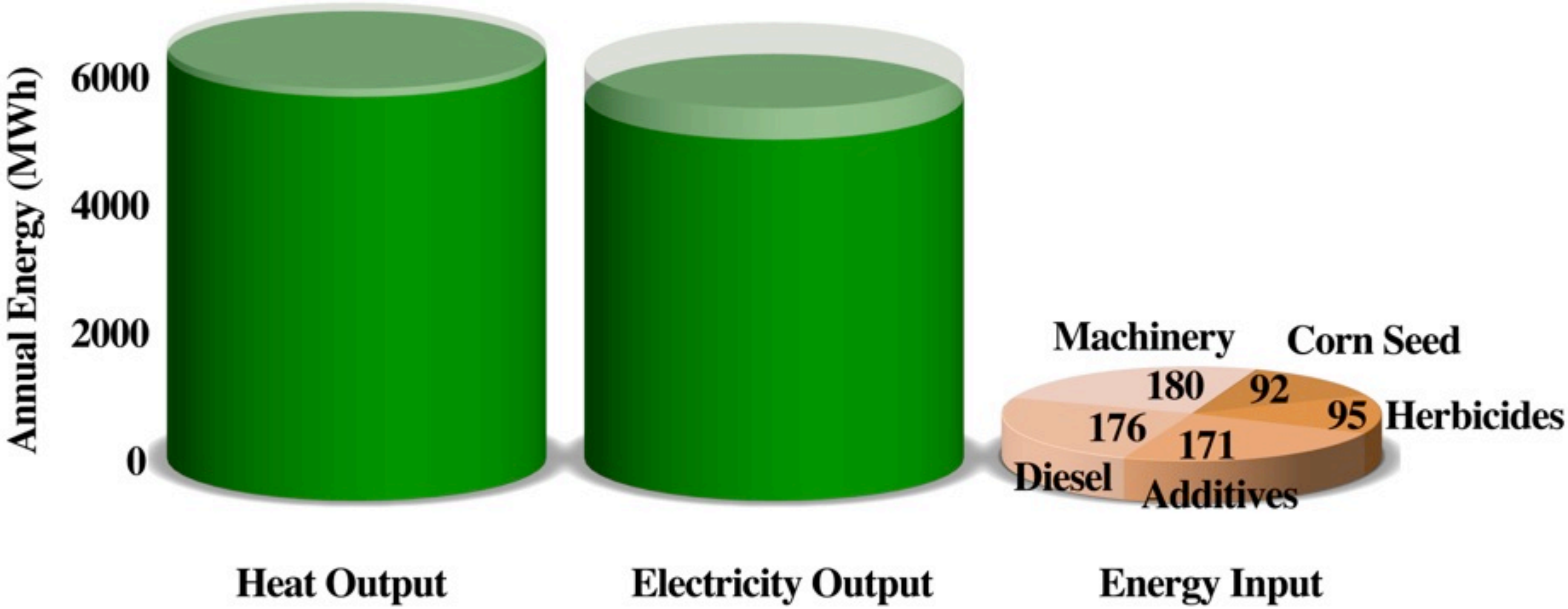

Net Energy Ratio

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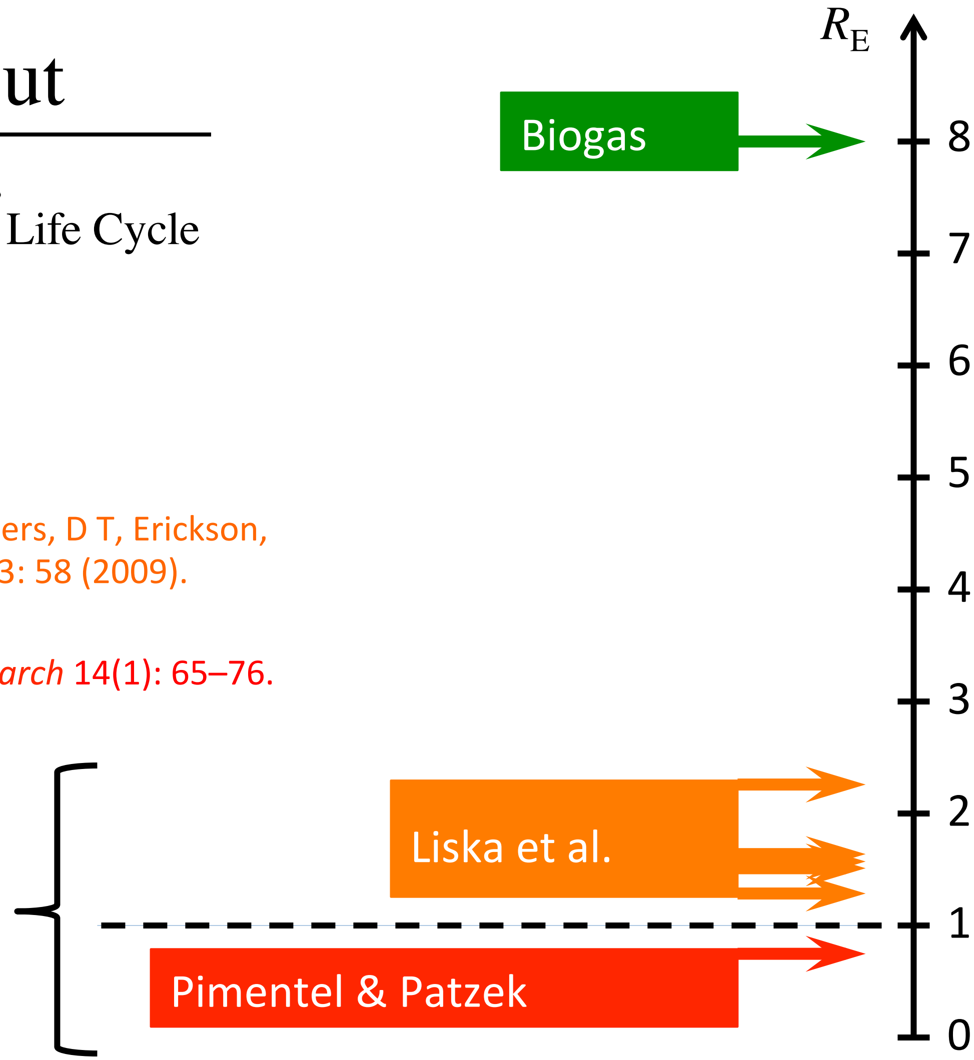
$$R_E = \frac{\text{Net Energy Output}}{\langle \text{Fossil Energy Input} \rangle_{\text{Life Cycle}}}$$

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



Transportation Fuel

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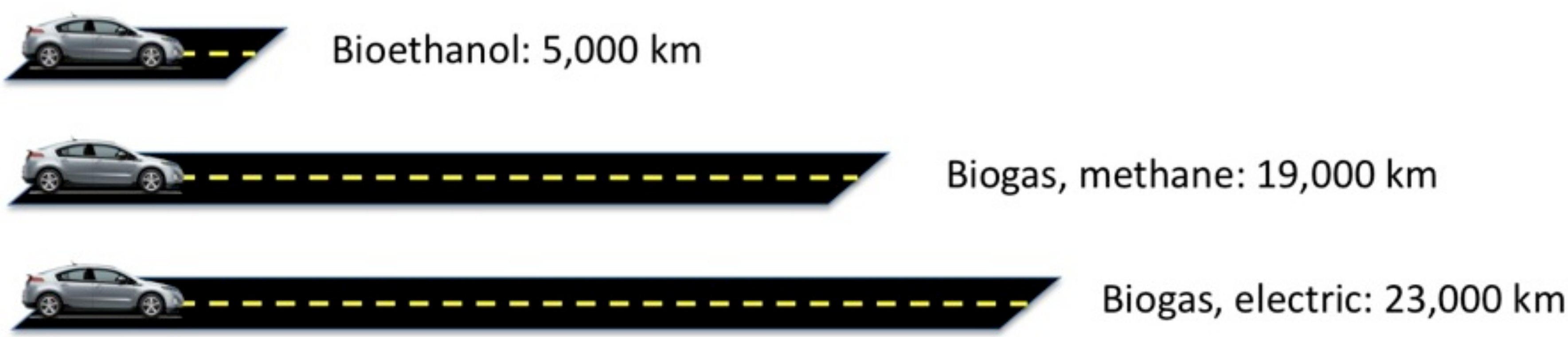
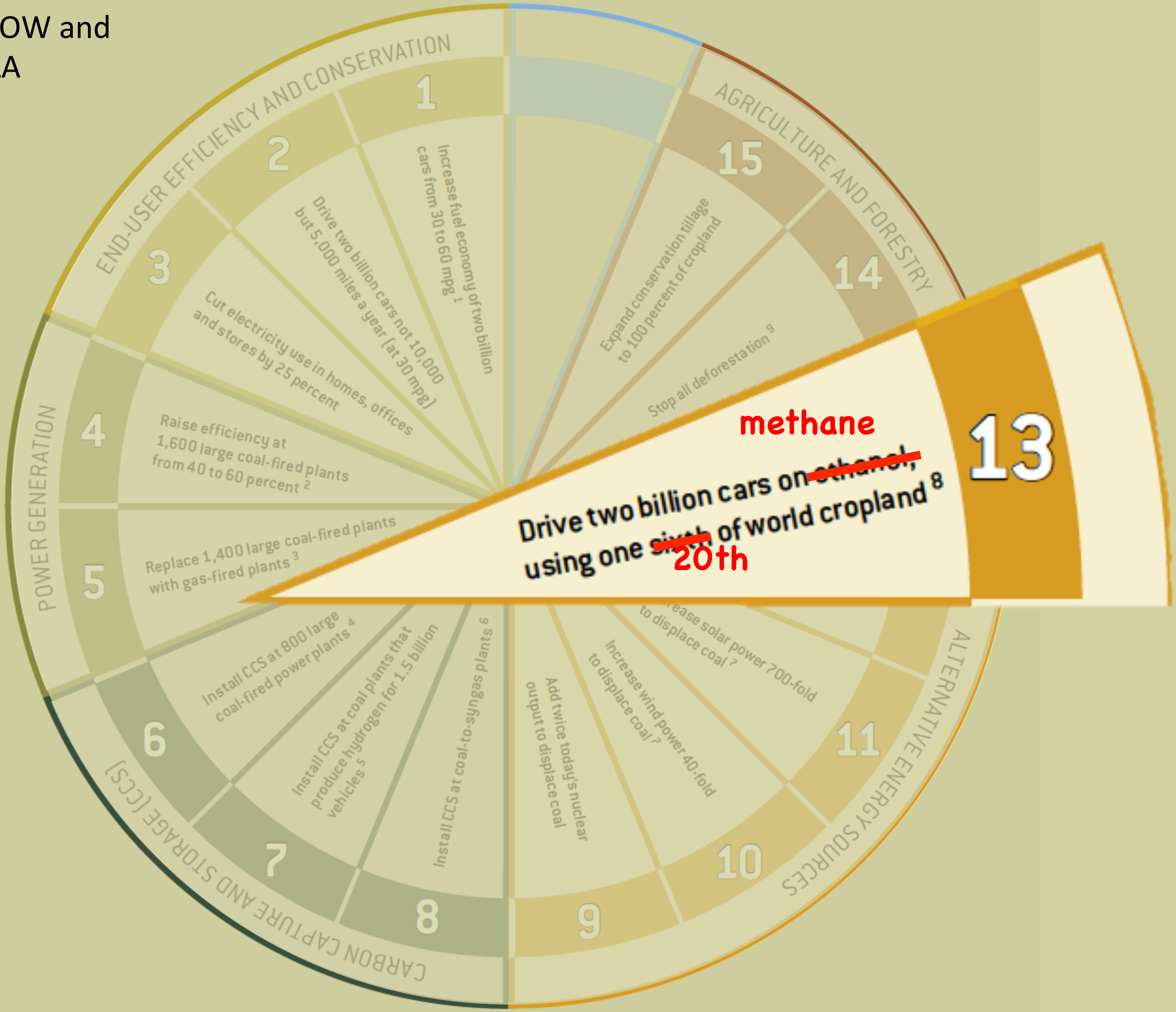
- Could produce 0.68 M liter of ethanol / year
  - Industry standard output from our corn yield on 150 ha
- Are producing 2.6 M liter of (liquid) CH_4 / year
- Factor of **3.8** better yield!
  (heat of combustion per liter almost identical for ethanol and methane, ~ 2/3 of gasoline)



Driving distance per hectare (numbers for Chevy Volt)

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



Potential US Economic Impact

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2015 projected bioethanol yield: 50 billion liters

Proposal: Convert to biogas reactors

Make 190 billion liters methane

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

Getting Serious About Biofuels

Greenhouse Gas Balance

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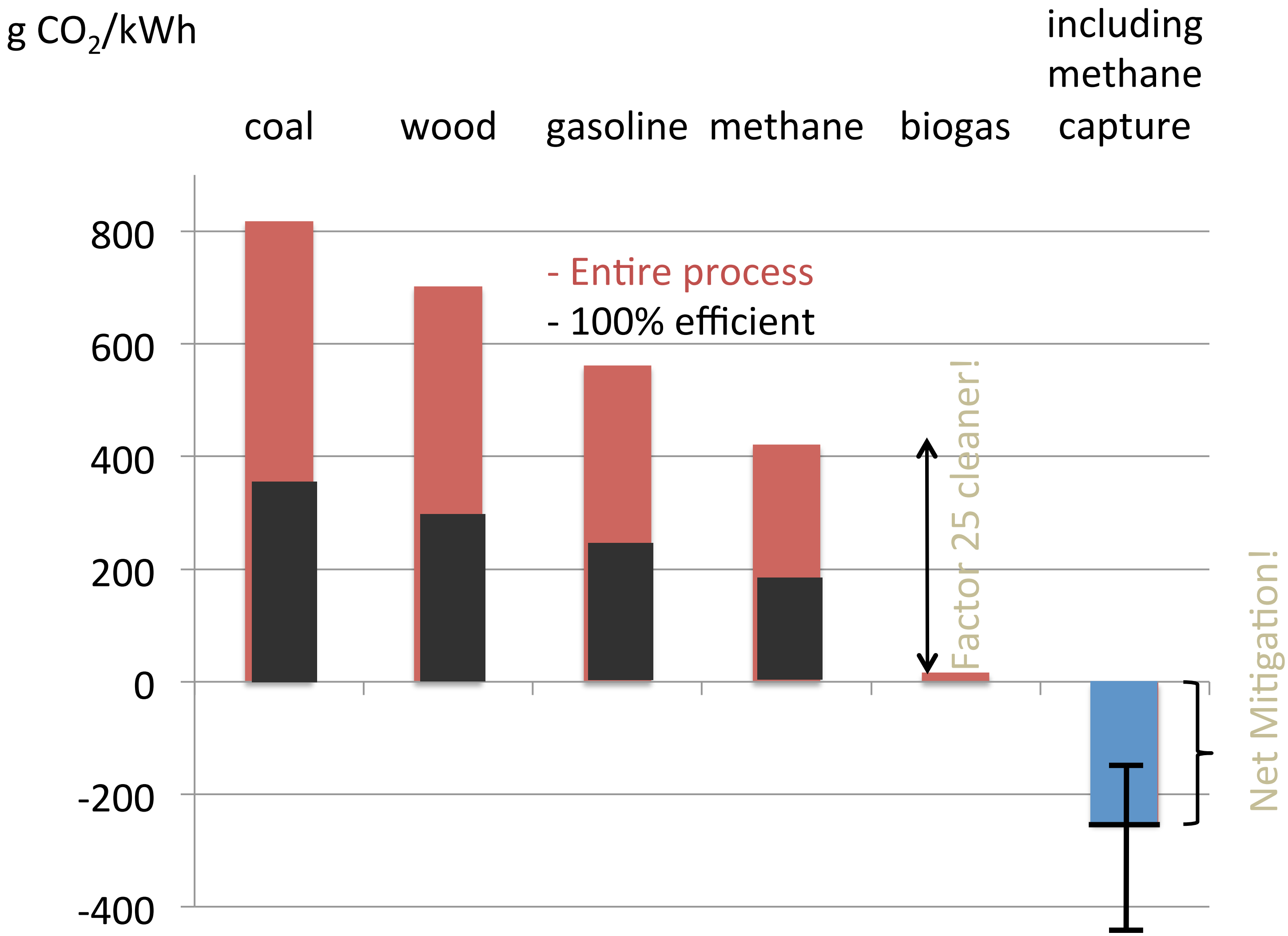

Methane is ~25 times more powerful greenhouse gas than CO_2
- our process prevents methane from cow dung to escape

MSU Anaerobic Digester

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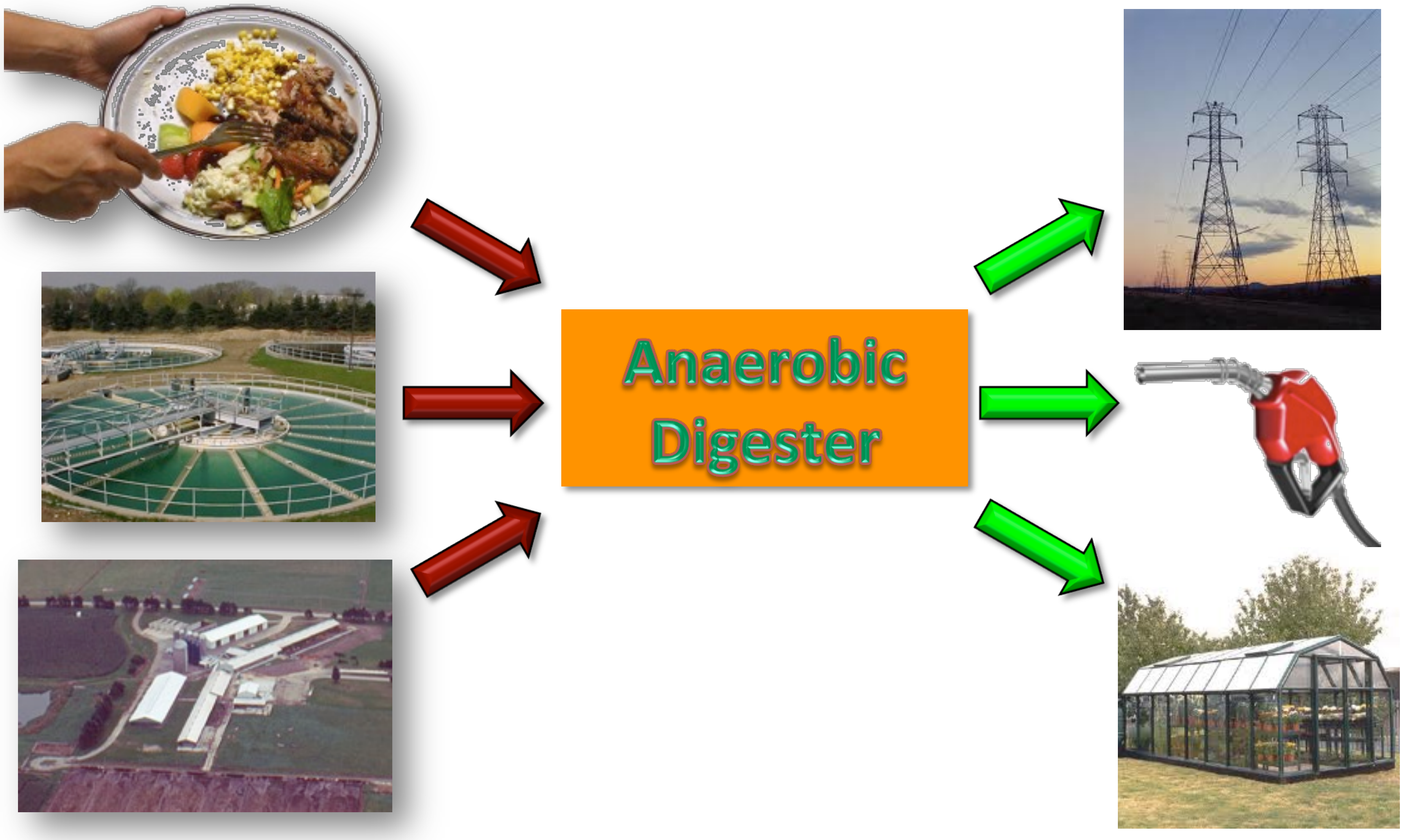
- Approved by MSU Board of Trustees, Jan. 2012
- Research on better bacteria, plants, & processes



Food vs. Fuel?

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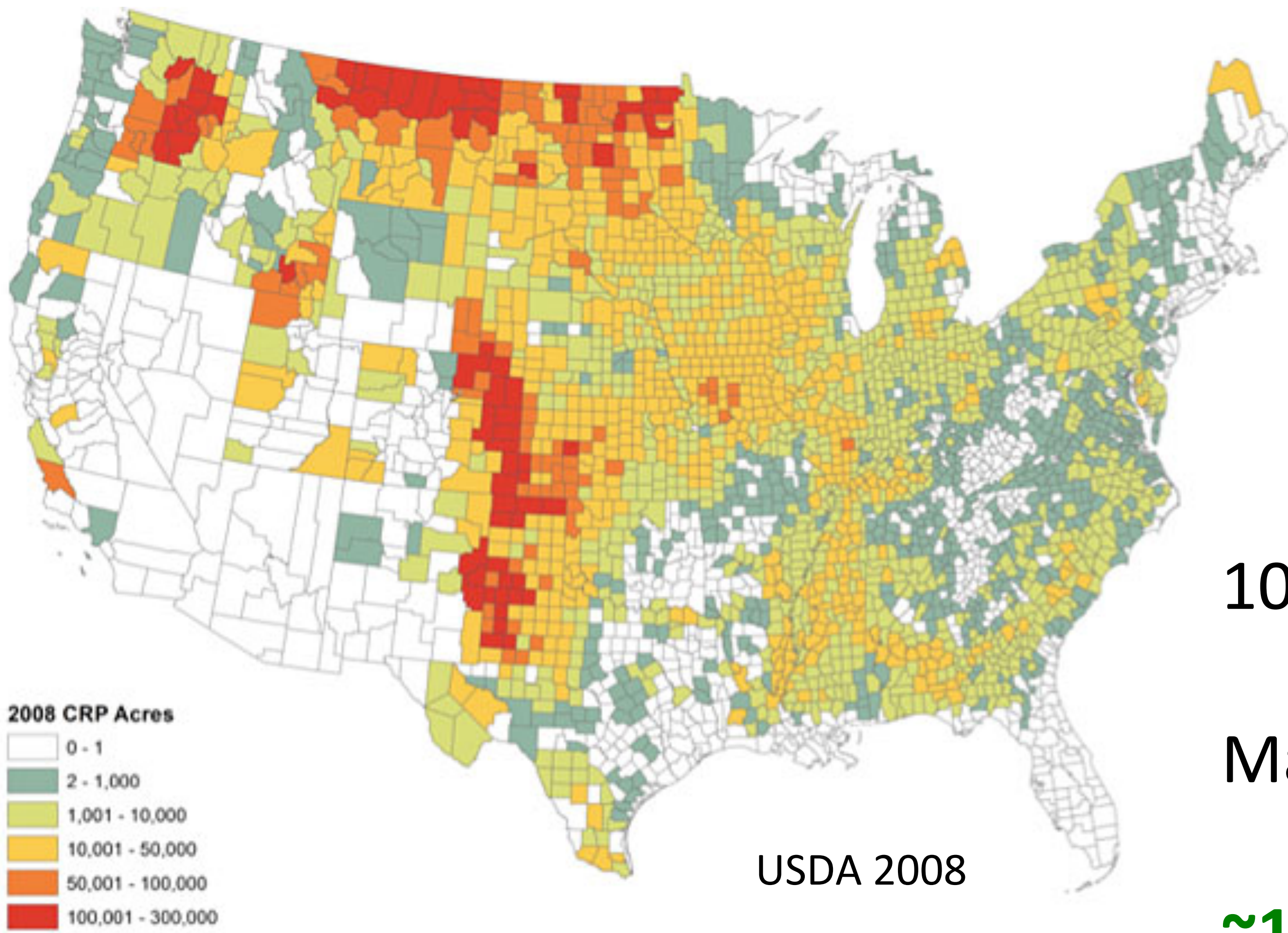
Conservation Reserve Program



USDA 2008

10 M hectare

Marginal land(?)

~100 GW potential

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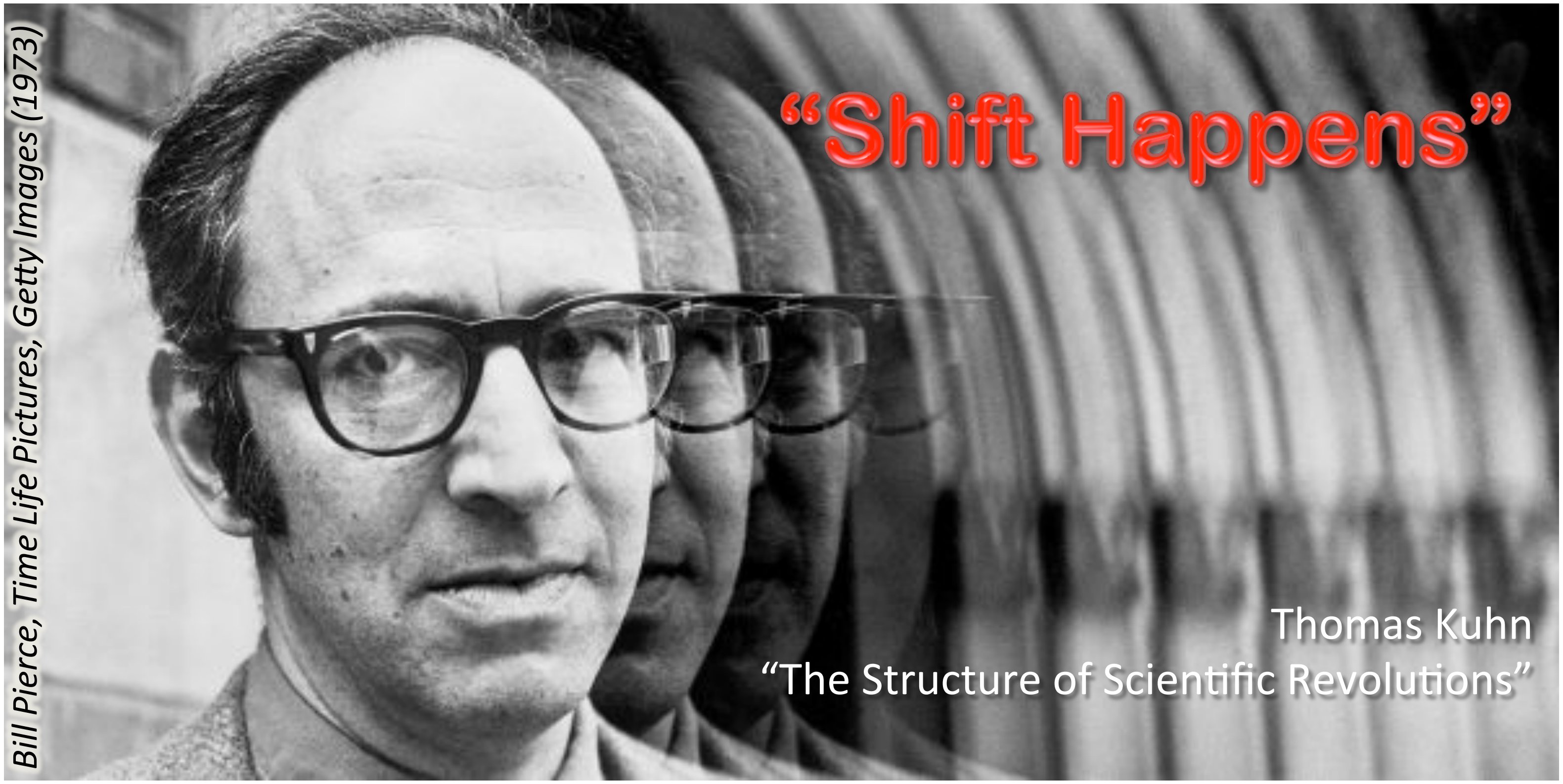
Summary:

Paradigm Shift



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- 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

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- "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

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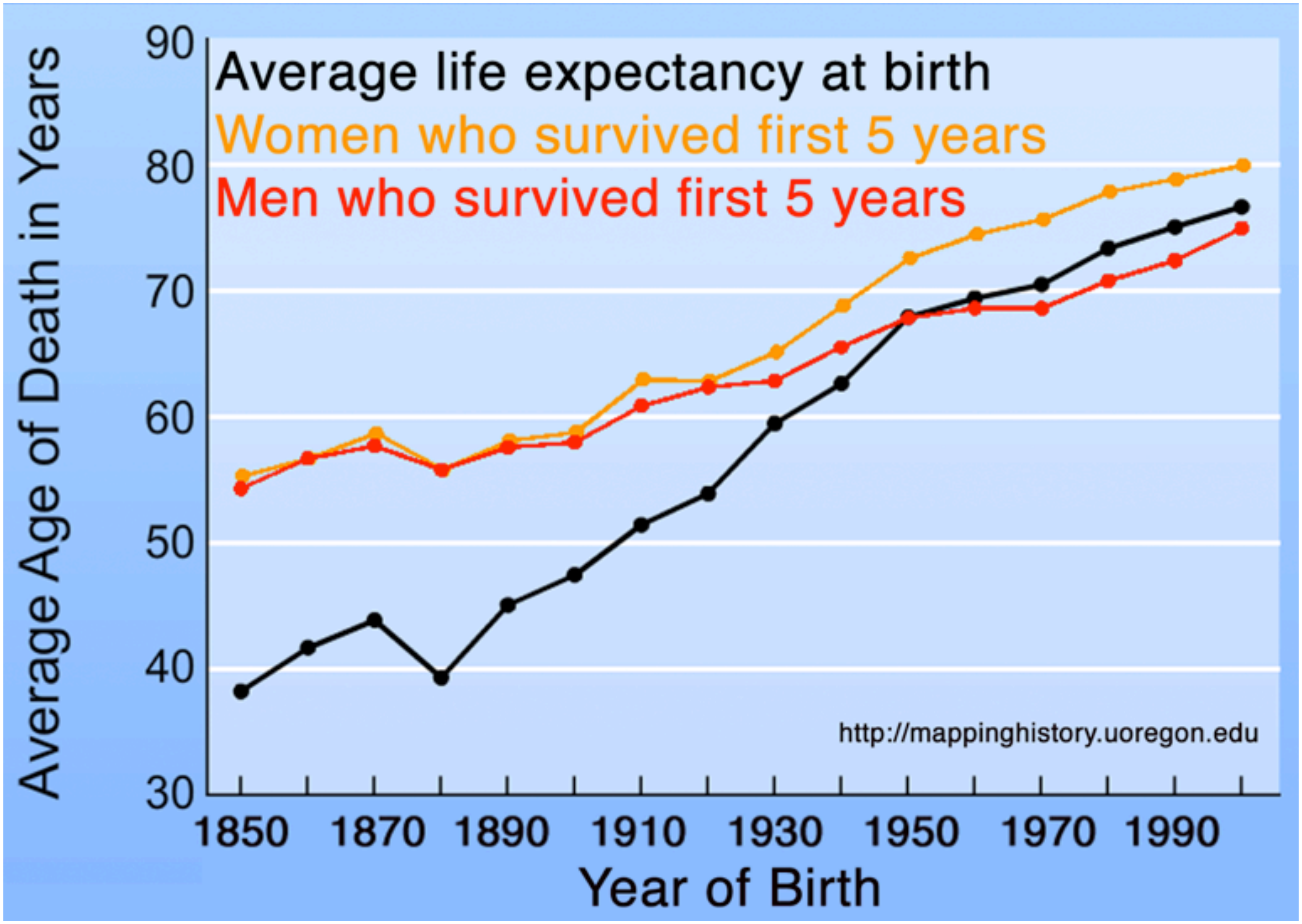

Summary

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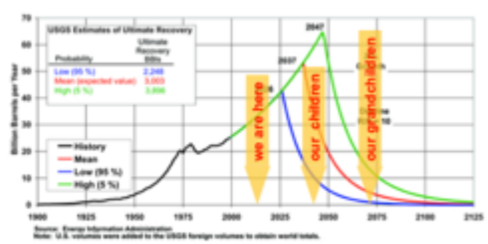

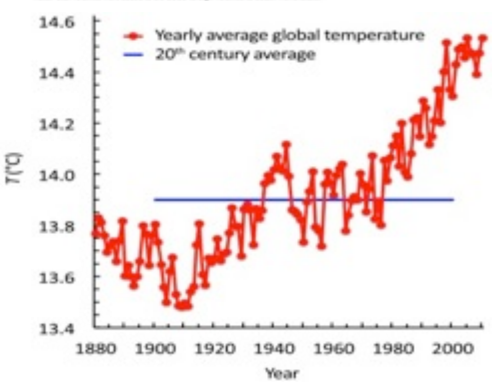

Biggest Opportunity of our Time:

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

… and it helps the planet!