Energy for You, Me, and 7 Billion Other People

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Center for Sustainable Energy at Notre Dame

Humanity's Top Ten Problems for next 50 years

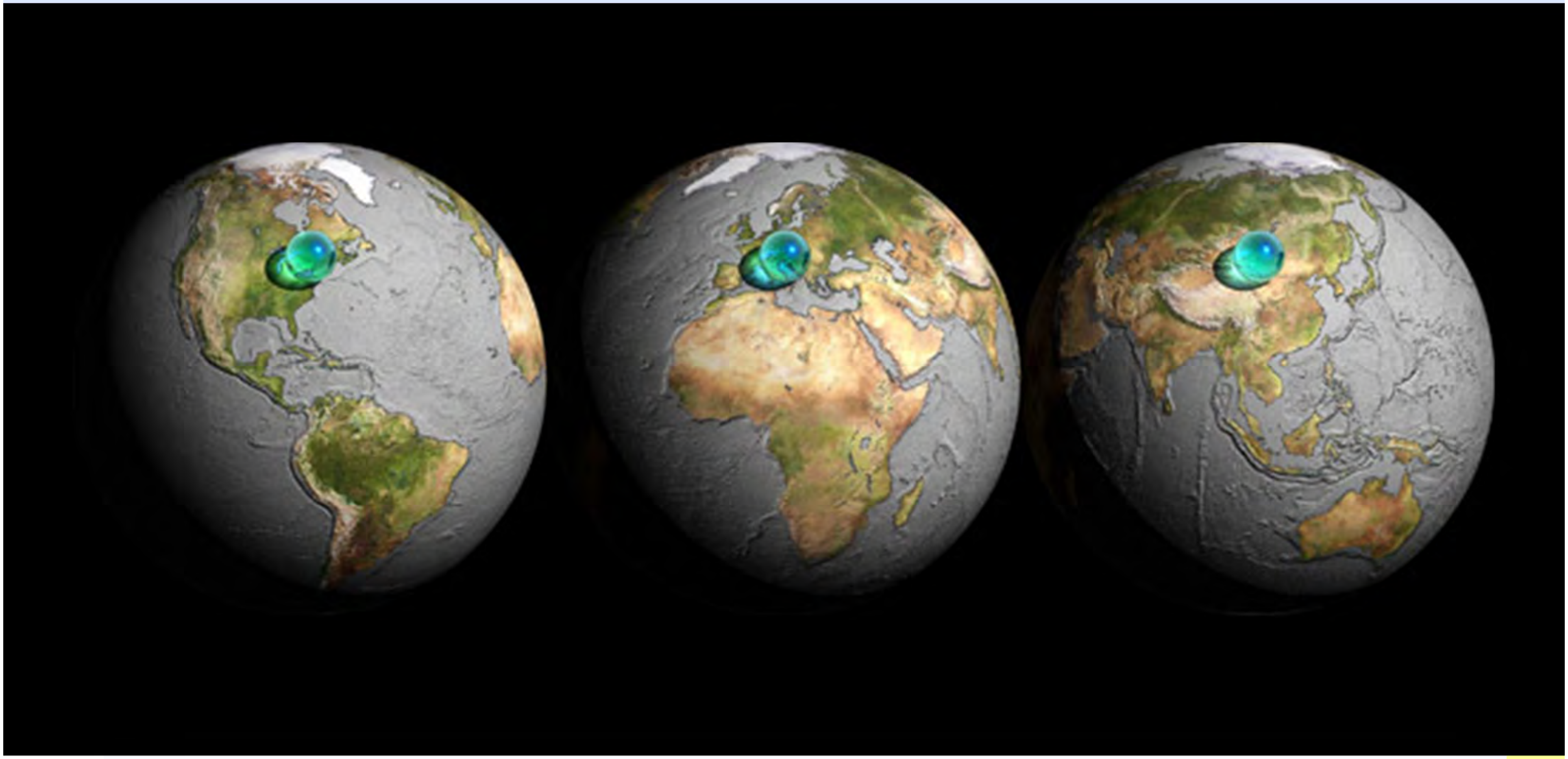
1. ***ENERGY***
2. *WATER*
3. *FOOD*
4. *ENVIRONMENT*
5. *POVERTY*
6. *TERRORISM & WAR*
7. *DISEASE*
8. *EDUCATION*
9. *DEMOCRACY*
10. *POPULATION*

List developed by Nobel Laureate, Richard Smalley, while surveying colleagues from 2002-2003

~~**2006**~~	~~**~ 6.5**~~	~~**Billion People**~~
2012	**~ 7.1**	**Billion People**
2050	**~ 10**	**Billion People**

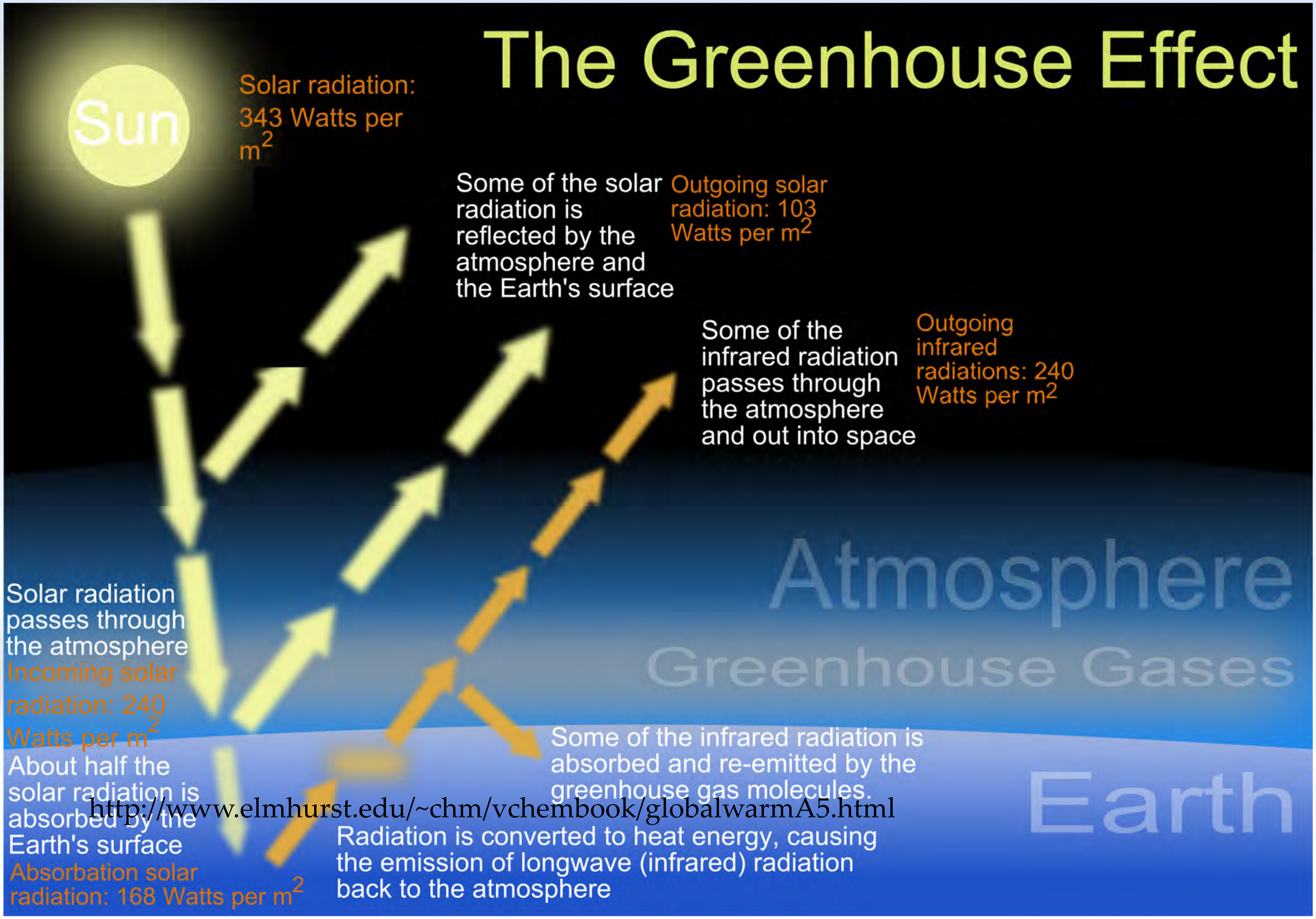
http://www.agci.org/library/presentations/about/presentation_details.php?recordID=16950

Earth's key natural resources: water and air



Volume of Earth: 1.1×10^{12} km^3
Volume of water: 1.4×10^9 km^3
Volume of atmosphere: 4.2×10^9 km^3

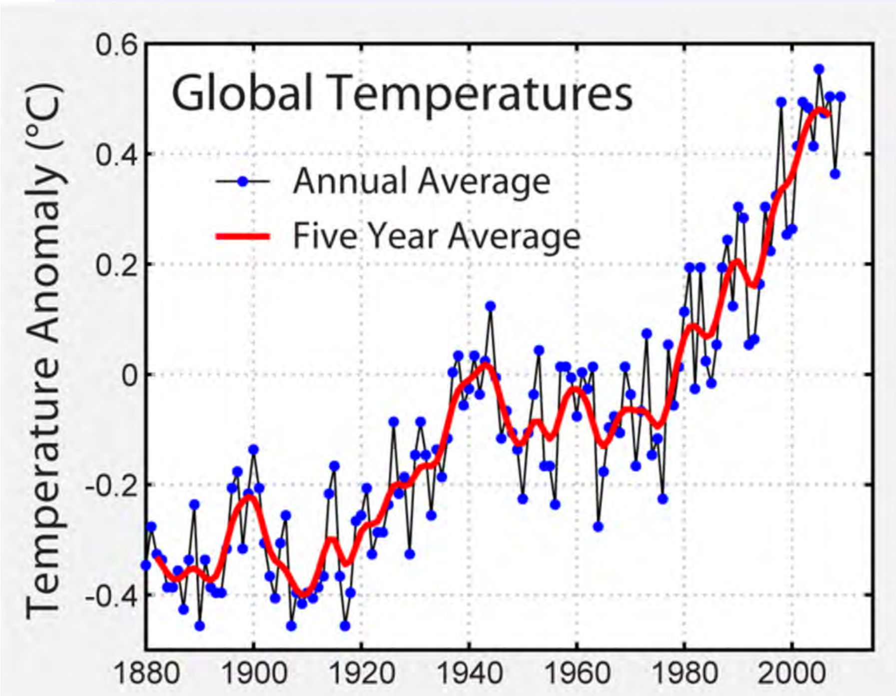
Photo & caption info: ADAM NIEMAN / SCIENCE PHOTO LIBRARY

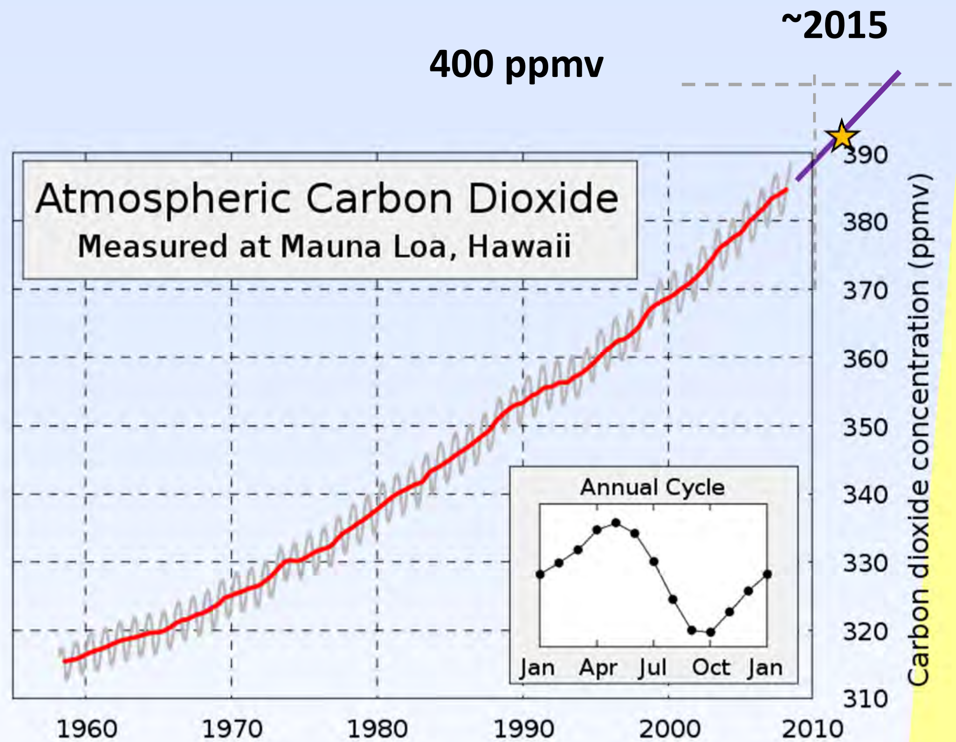


http://www.elmhurst.edu/~chm/vchembook/globalwarmA5.html

On watch: global temperatures, atmospheric CO_2

Global average temperatures from NASA's *Goddard Institute for Space Studies* (Columbia University). Data set follows methodology developed by J. Hansen.



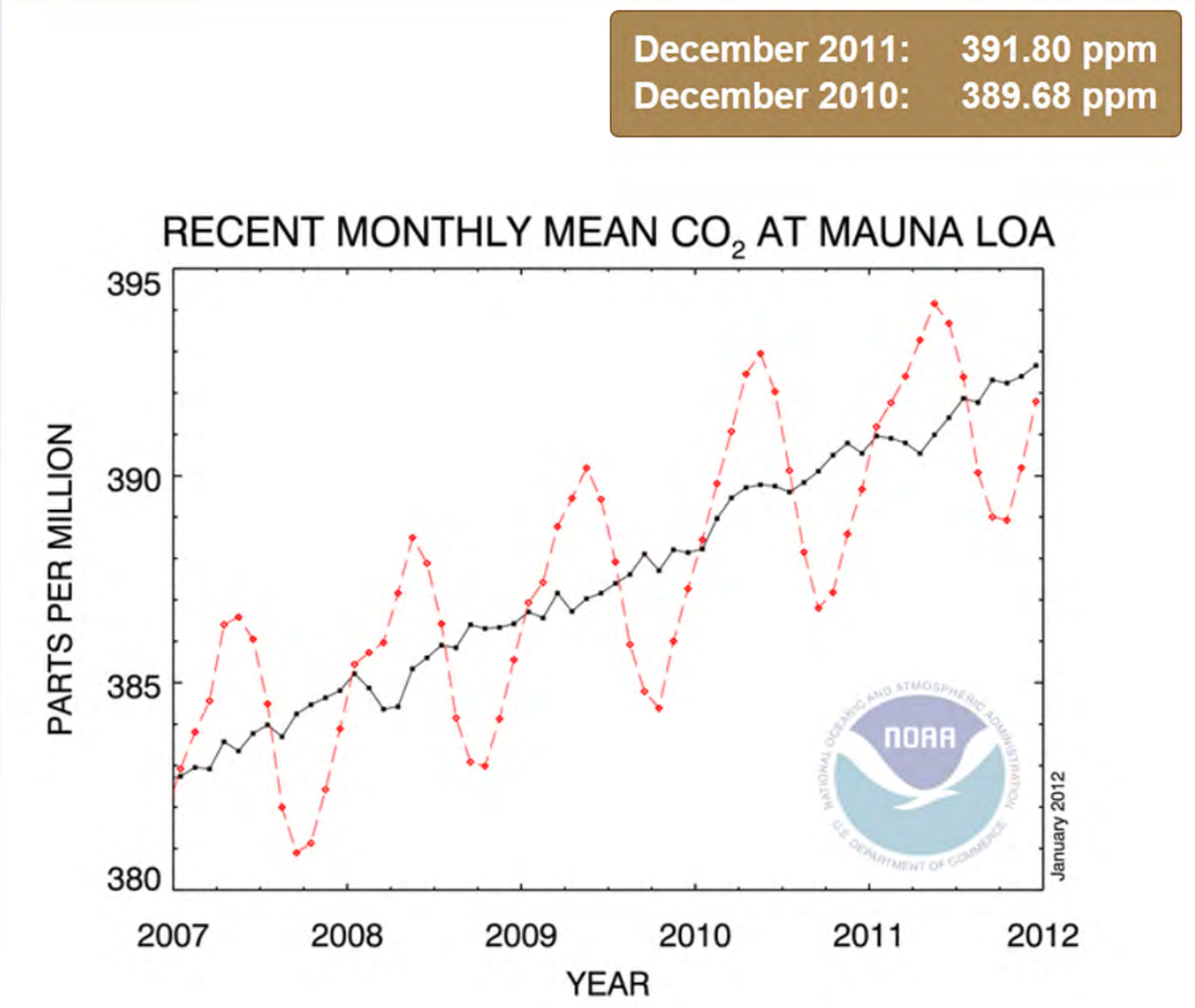


Keeling curve, data from Mauna Loa, Hawaii. (Charles David Keeling)

- All 2011 measurements show CO_2 > 390 ppmv

Hansen, J., et al. (2006) "*Global temperature change*", PNAS 103: 14288-14293.

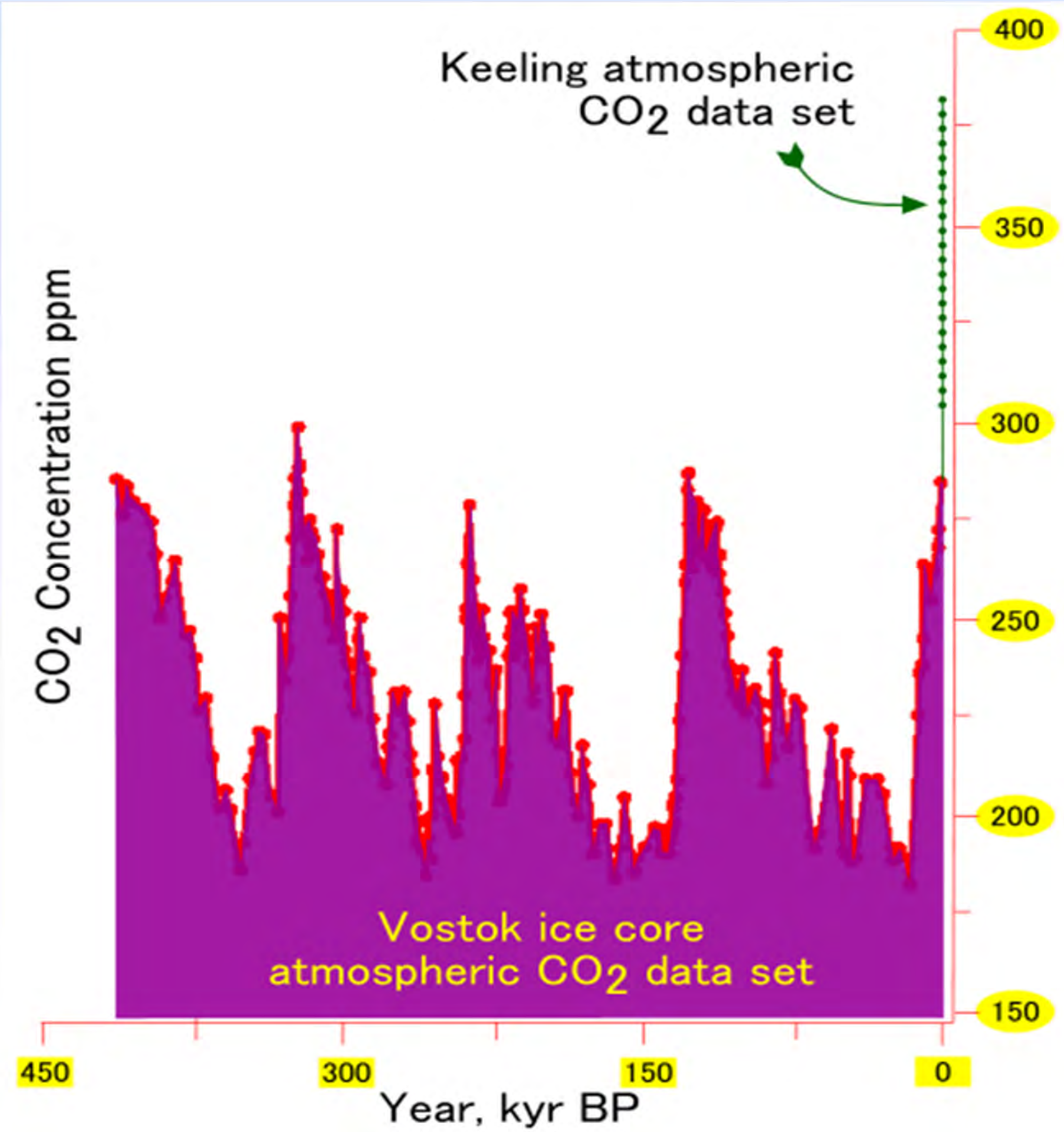
On watch: global temperatures, atmospheric CO_2



http://www.esrl.noaa.gov/gmd/ccgg/trends/

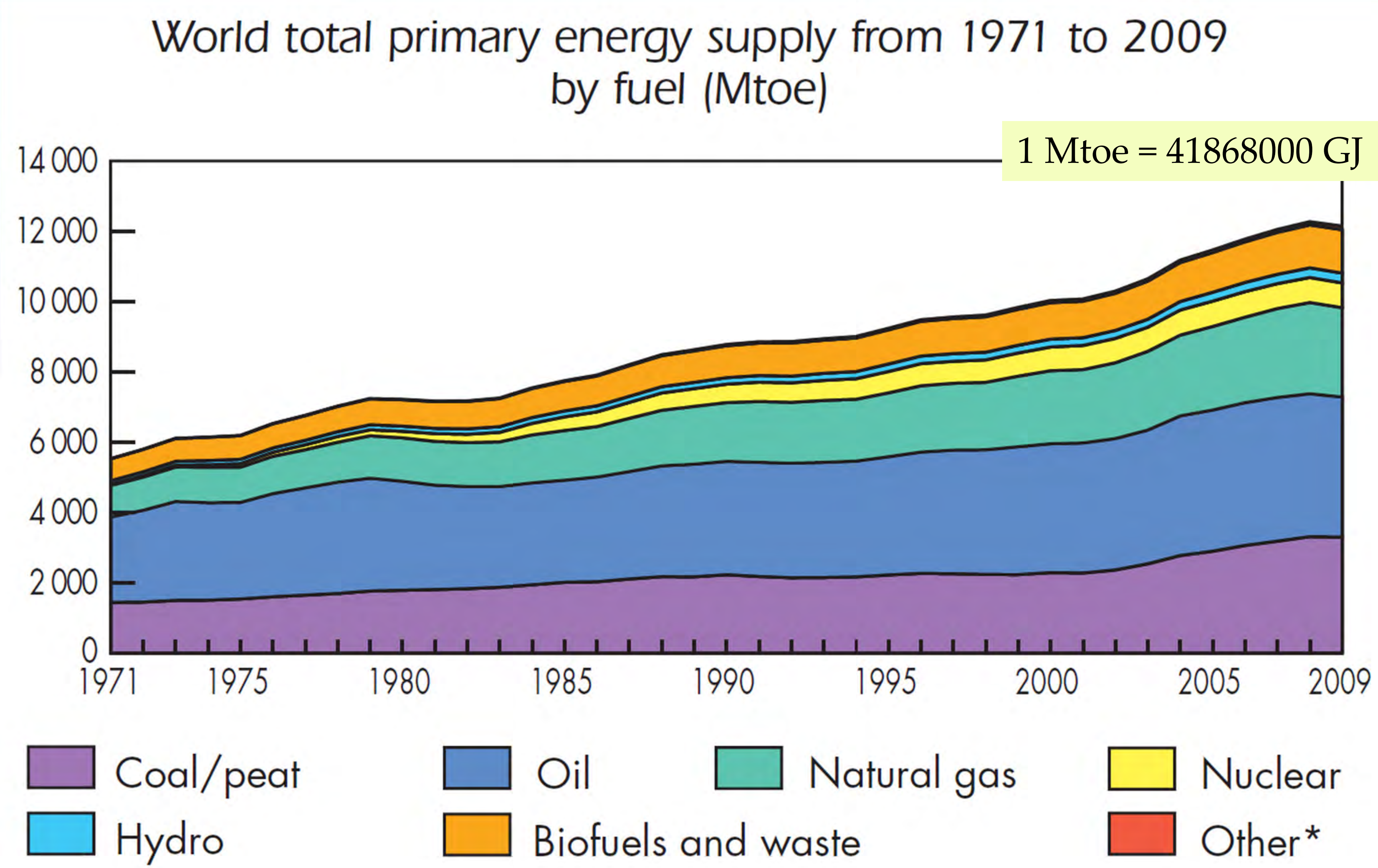
.... energizing Ohio for the 21st Century

420,000+ years of atmospheric CO_2 levels



from N. Lewis, Cal Tech

Energy for People (forms of energy)



http://www.iea.org/textbase/nppdf/free/2011/key_world_energy_stats.pdf

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A Power and Energy Primer

Dealing with **energy** and **power** in:

1 kW·hr = 3.6 x 10^6 J

	Standard International Units	Everyday Life*
Energy	Joule	kW·hr
Power	Watts (1 W = 1 J/sec)	Watts

Energy is the amount of total work that can be completed (by a force).
Power is the *rate* at which the energy is converted (dE/dt).

A toaster is a good benchmark for power → typically at the 1,000 W (1 kW) power level.

Leave a toaster on for an hour continuously → 1 kW·hr. Same as a 100 W bulb left on for 10 hrs. Cost is about $0.12/ kW·hr, but leave one on for a year?

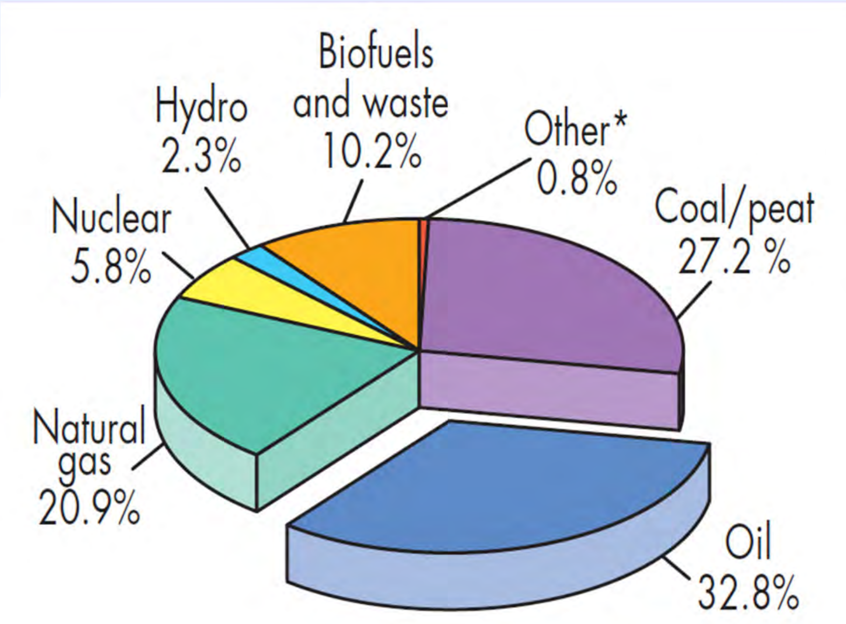
How much energy is used to light this room for 10 hours?

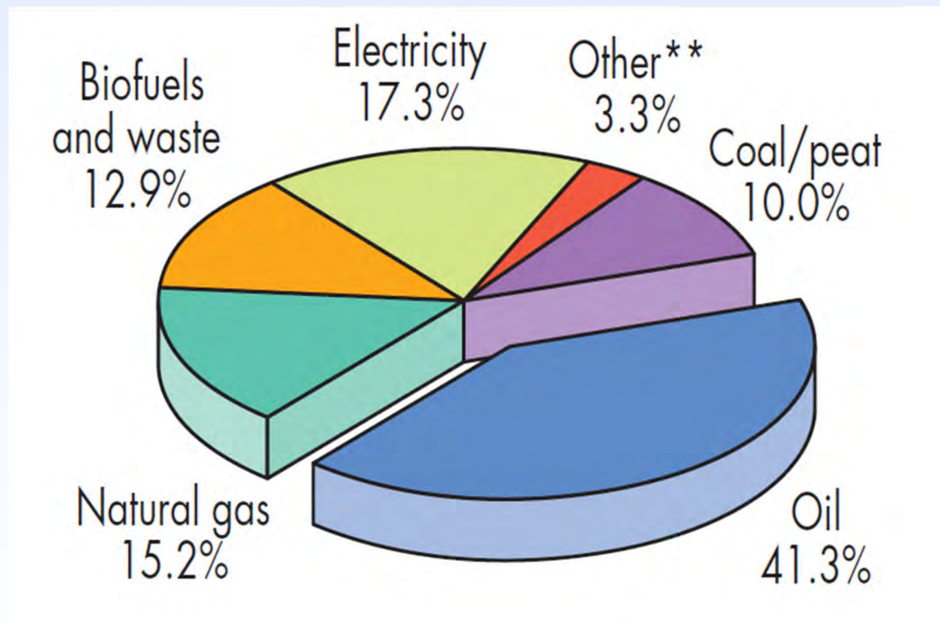
* Average cat generates ~5 W of heat during sleep, and ~24 W walking briskly

Energy for People: *2009*

Primary energy is the raw fuel used as the input to a system.

Final energy consumed refers to the form of the energy prior to it's ultimate use.



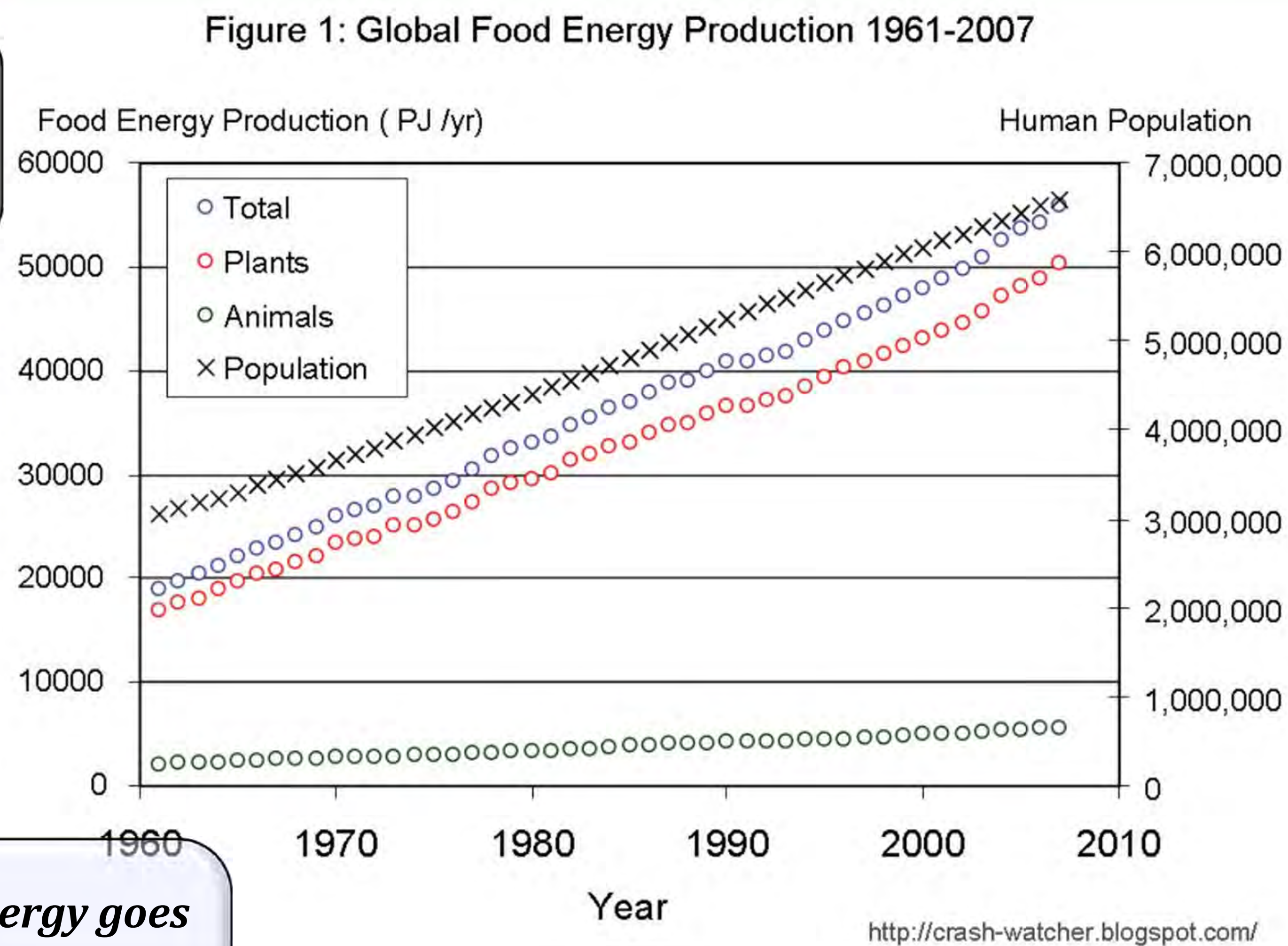


Fossil fuels sum to ~81% of our primary energy.

http://www.iea.org/textbase/nppdf/free/2011/key_world_energy_stats.pdf

Energy for people (food)

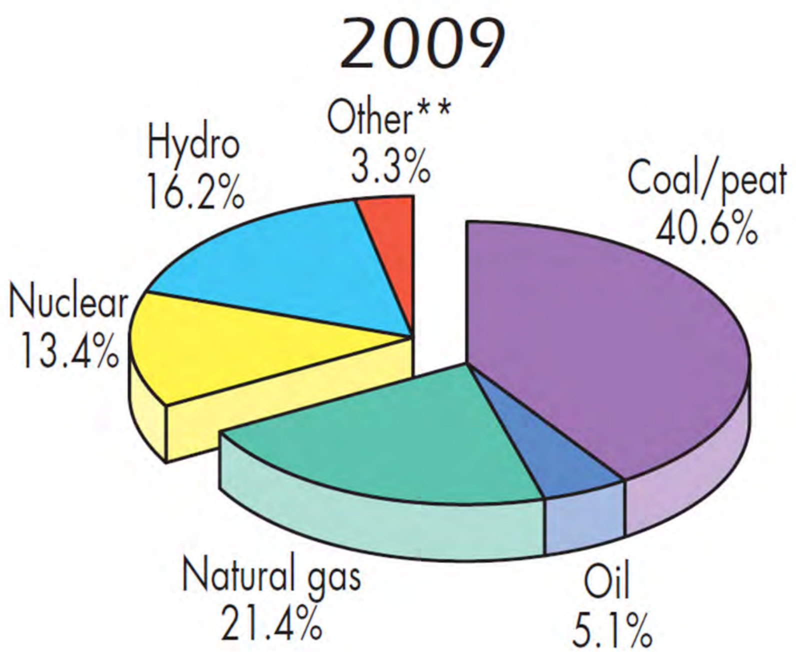
60 EJ represents ~ 12% of the annual global primary energy supply.



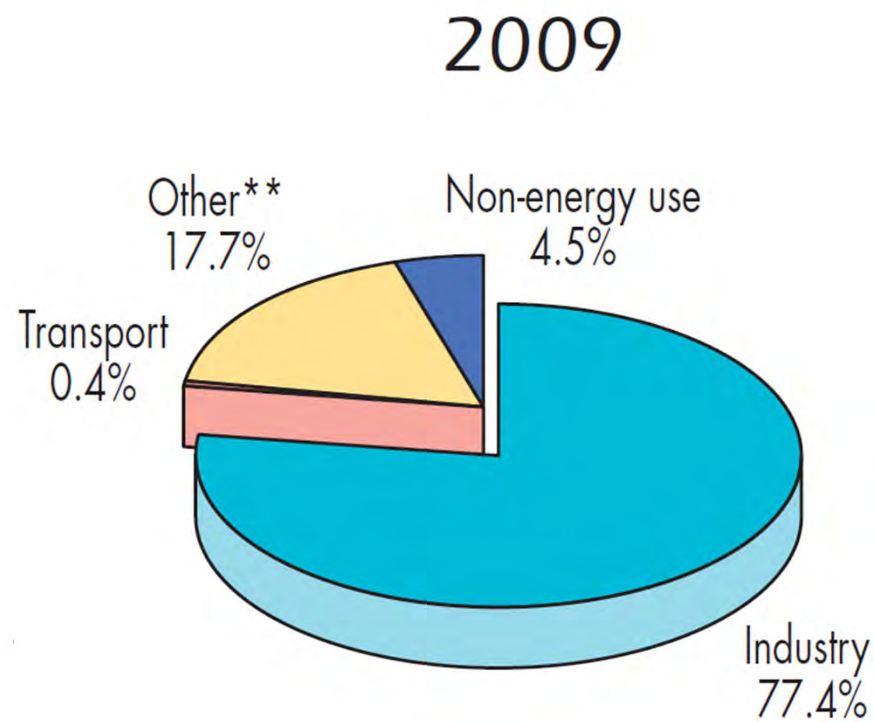
How much primary energy goes toward food?

The rest would be photosynthesis…

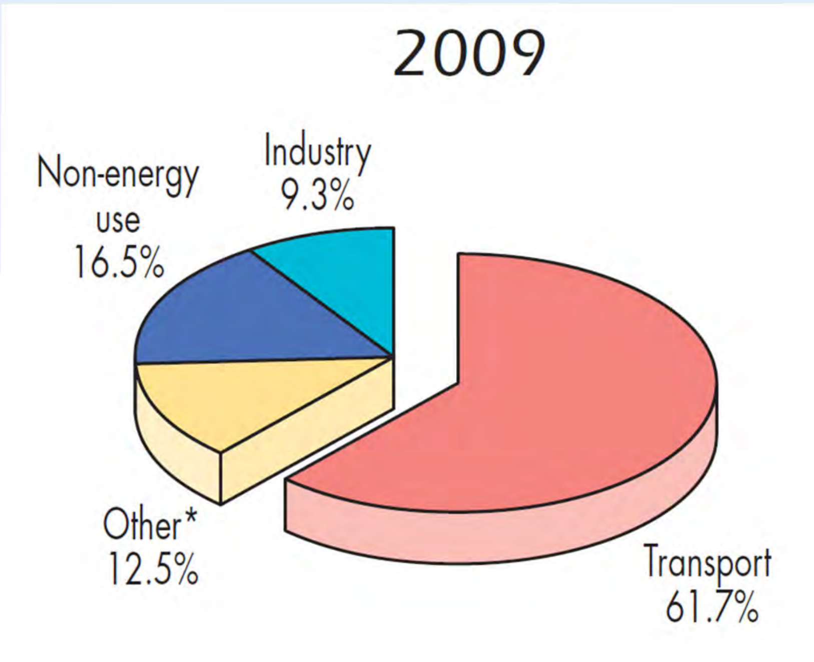
Fuels for global electricity generation:



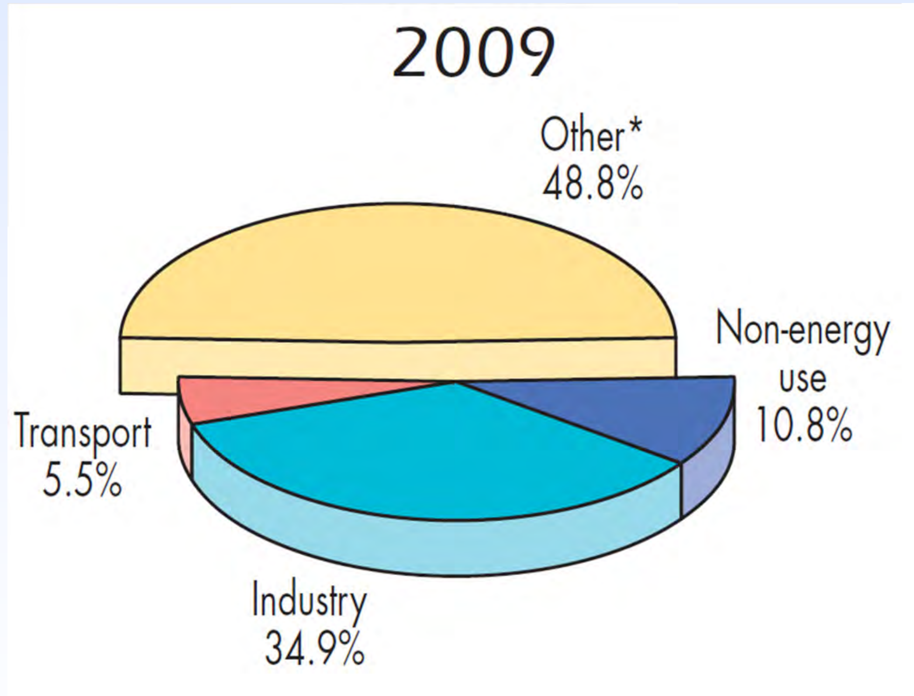
How is coal being used?



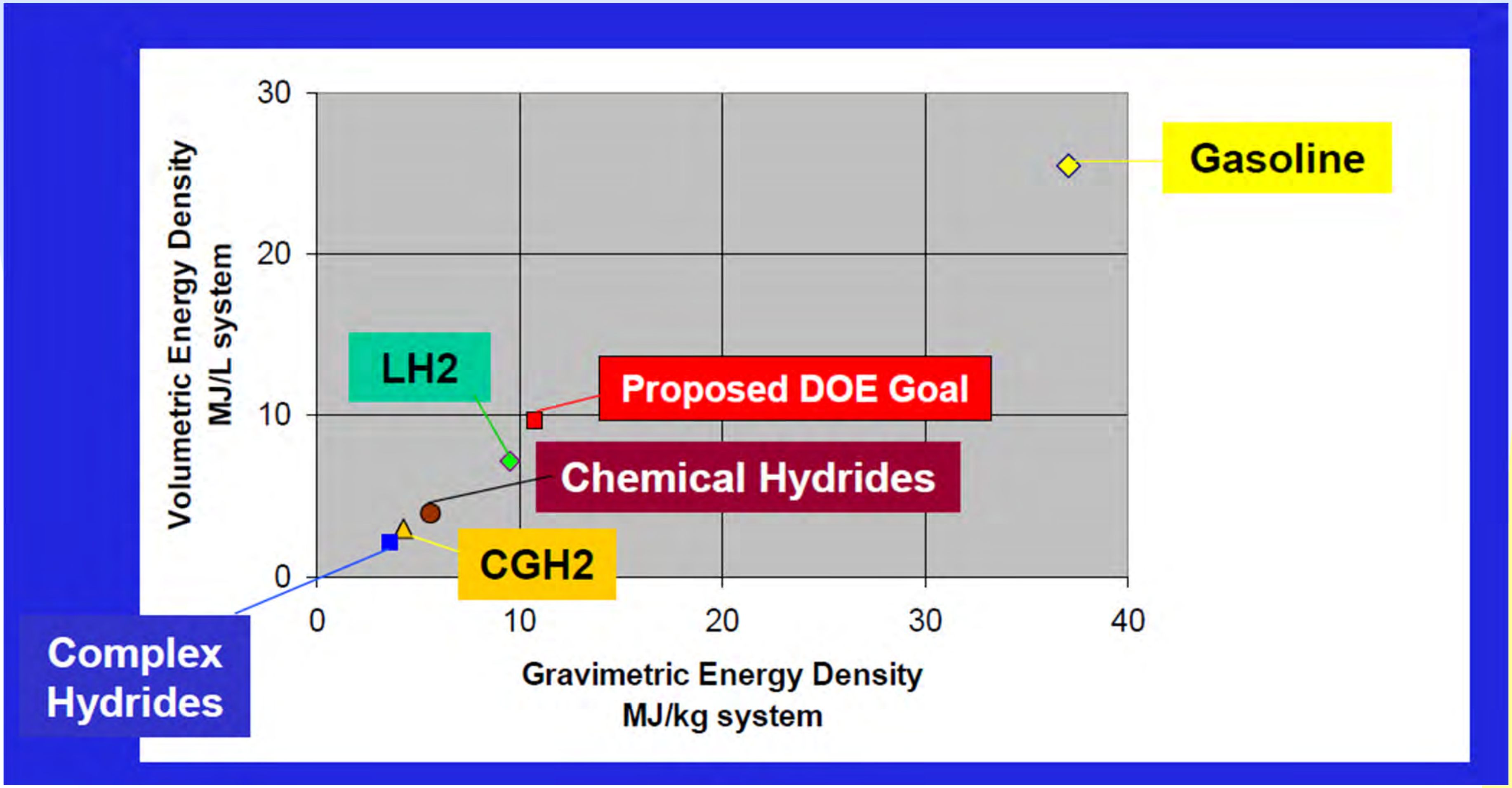
How is oil being used?



How is natural gas being used?



Transportation fuel energy density

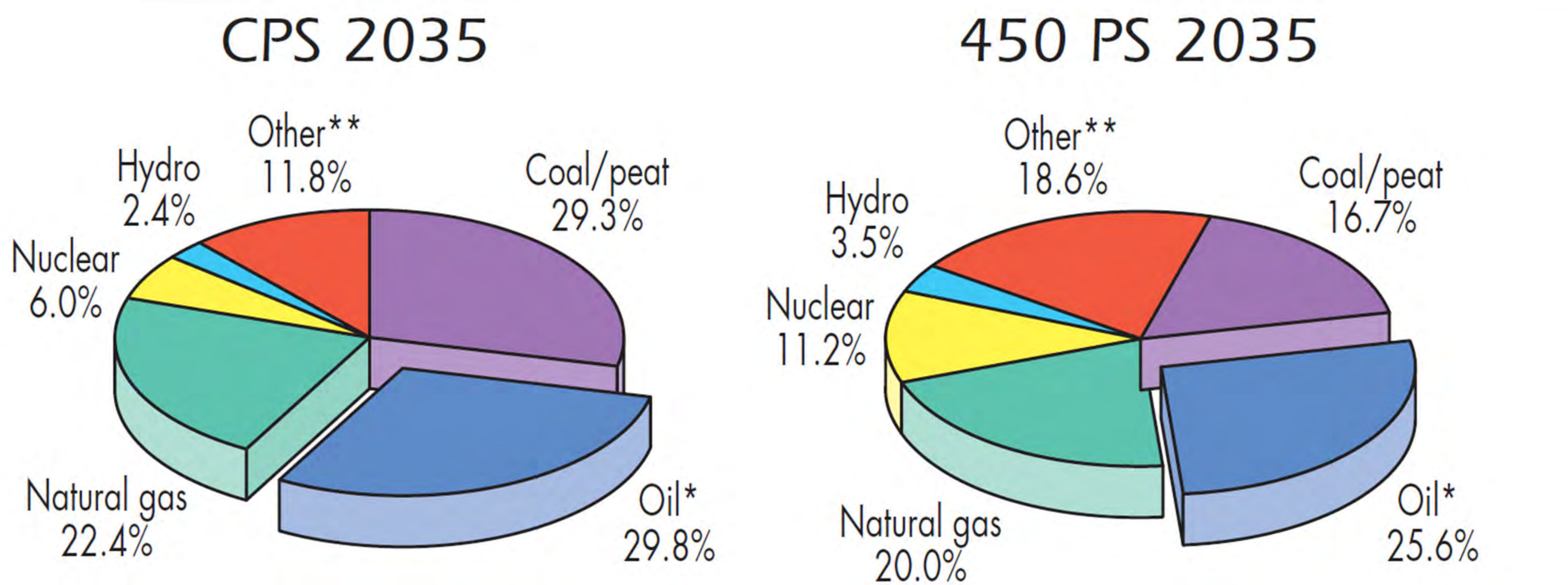


"Gasoline was great."

-- from R. Smalley's energy talk (2003)

Total primary energy in 2035

Current Policy Scenario vs.
450 Policy Scenario



http://www.iea.org/textbase/nppdf/free/2011/key_world_energy_stats.pdf

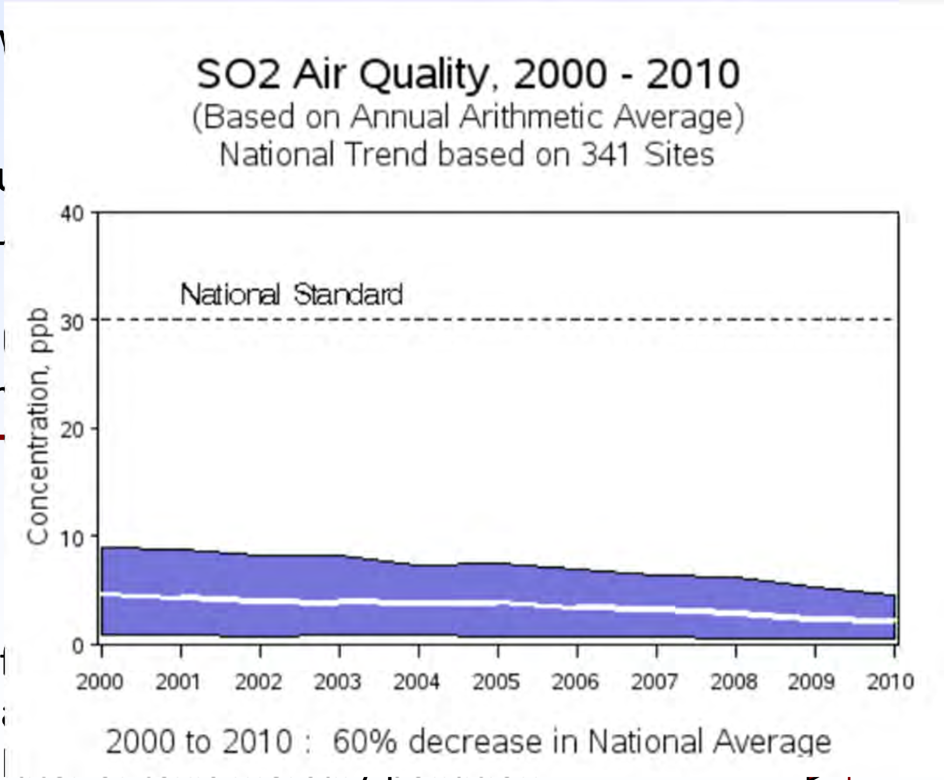
Need for clean energy

1 Mtoe = 41868000 GJ
1998 Global power use of 11.9 TW
2010 Global power use of 15.9 TW
2012 Global power ~16.5 TW
Present annual energy use ~ 0.5 ZJ

NATURE, VOL. 395, 29 OCTOBER 1998
Energy implications of future stabilization of Atmospheric CO_2 content
M. Hoffert et al.

Growth in energy consumption

- Grov ... verage ~1.6-1.7% per ... *at a rate of 2.0%**
- Inclu
- 28 T ... *re**
- Popu ... ries → increased C- ir



Health

Coal-fired power

- significant
- majority of
- ~4% of tota
- largest poll

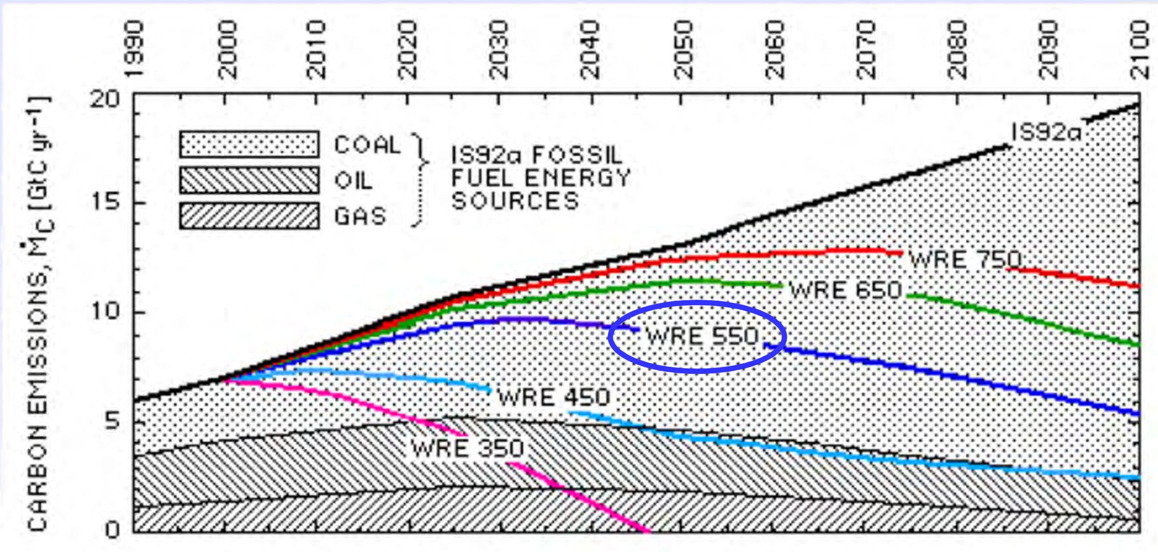
smog (ozone), soot → ecosystems, respiratory unhealthy lungs (incl.

velopmental toxin, affecting unborn children

All U.S. power plants: release over 41% of U.S. CO_2 in 2009

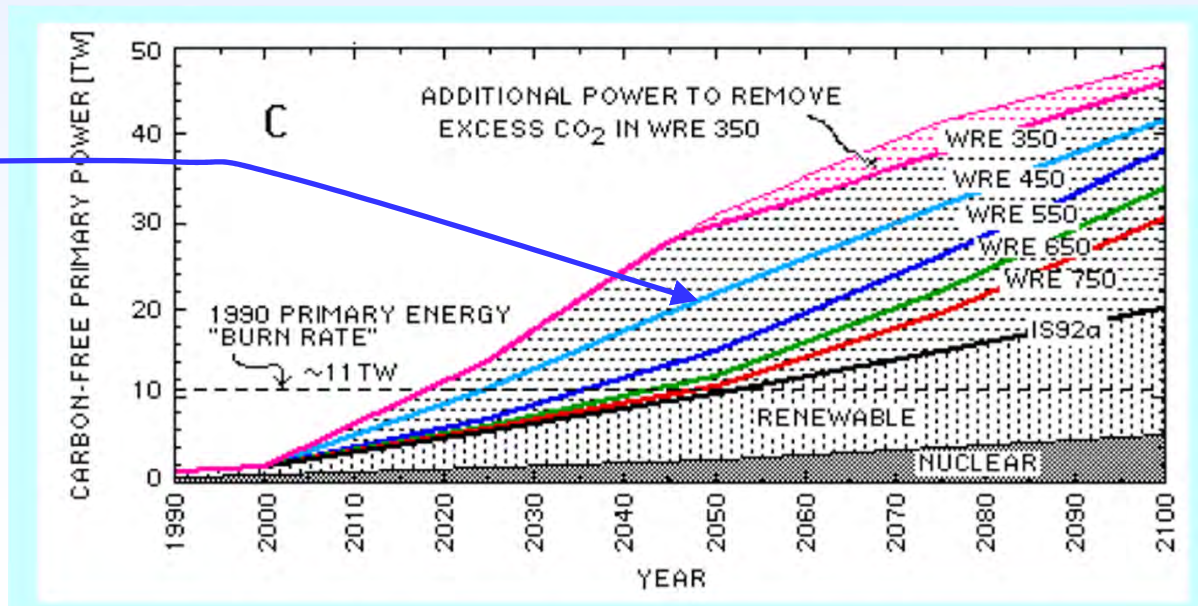
[Sources – U.S. DOE and U.S. EPA]

Earth's energy problem



Global power consumption is current ~15 TW; projected need by 2050 of ~30 TW.

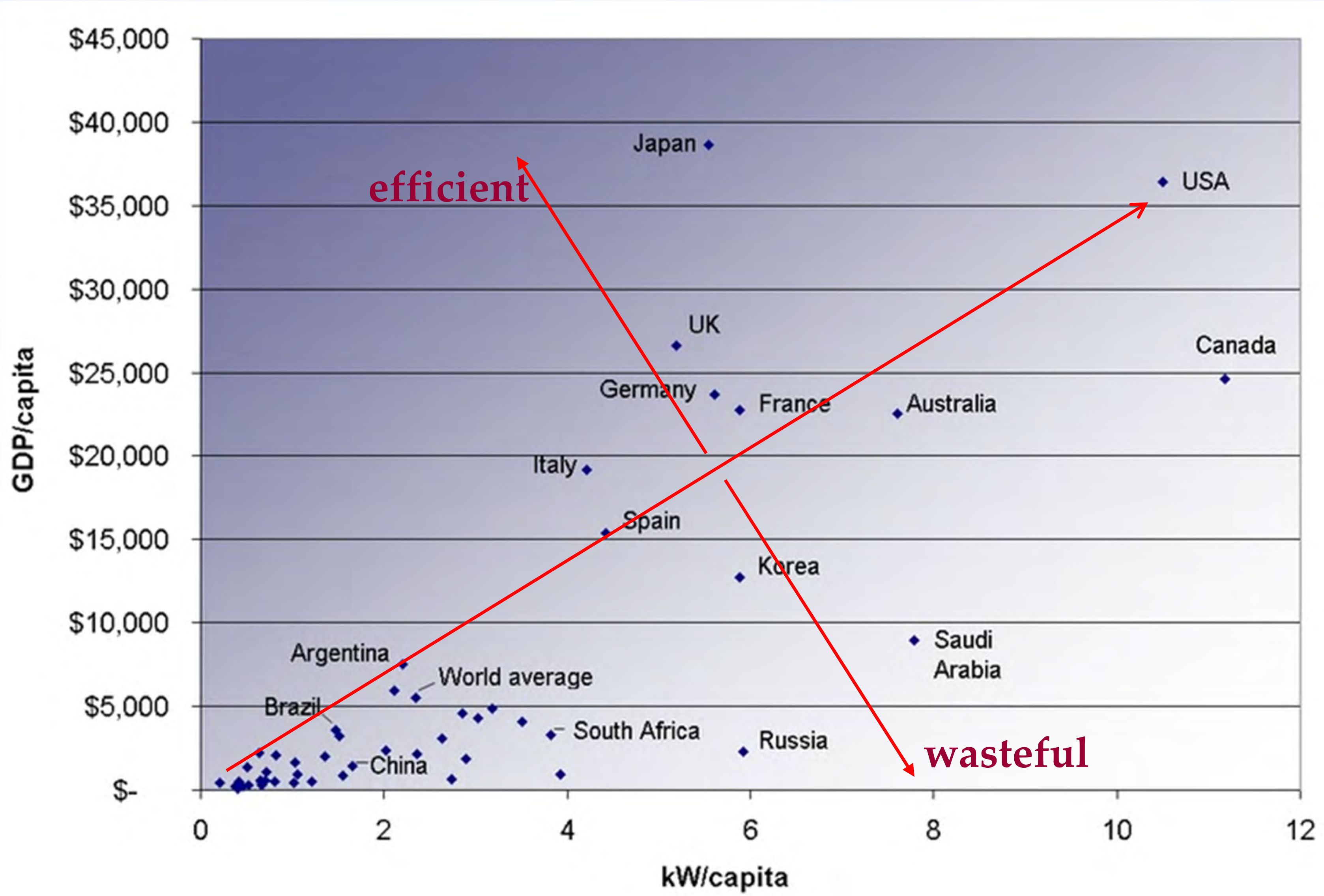
Carbon-free power required by 2050 to stabilize atmospheric CO_2 at 450 ppm ~15 TW



By 2100, carbon-free power requirement jumps to ~40 TW.

from M. I. Hoffert et. al., Nature, 1998, 395, 881

Energy Consumption and GDP



From: Wikimedia Commons

Earth's Energy use as of 2008 (burn rate)

2008 global energy consumption = 474 EJ (~5×10^{20} J) with ~85% derived from the combustion of fossil fuels. The average power consumption rate was 15 terawatts (1.5×10^{13} W), and the yearly energy consumption was 133 Petawatt•hr (133×10^{15} Wh).

Most of the world's energy resources are from the sun's rays hitting earth.

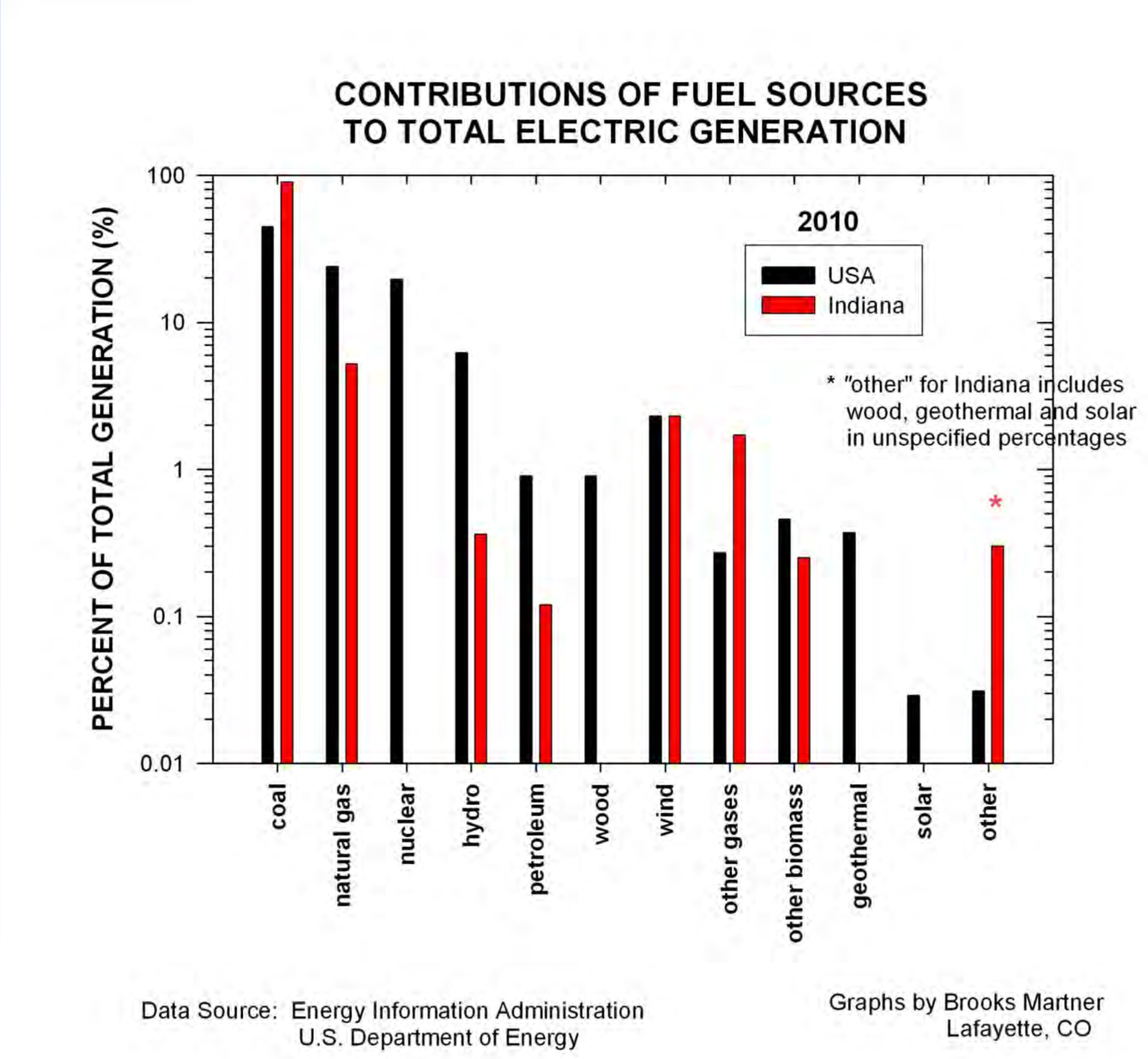
Tough Reality

The Good News

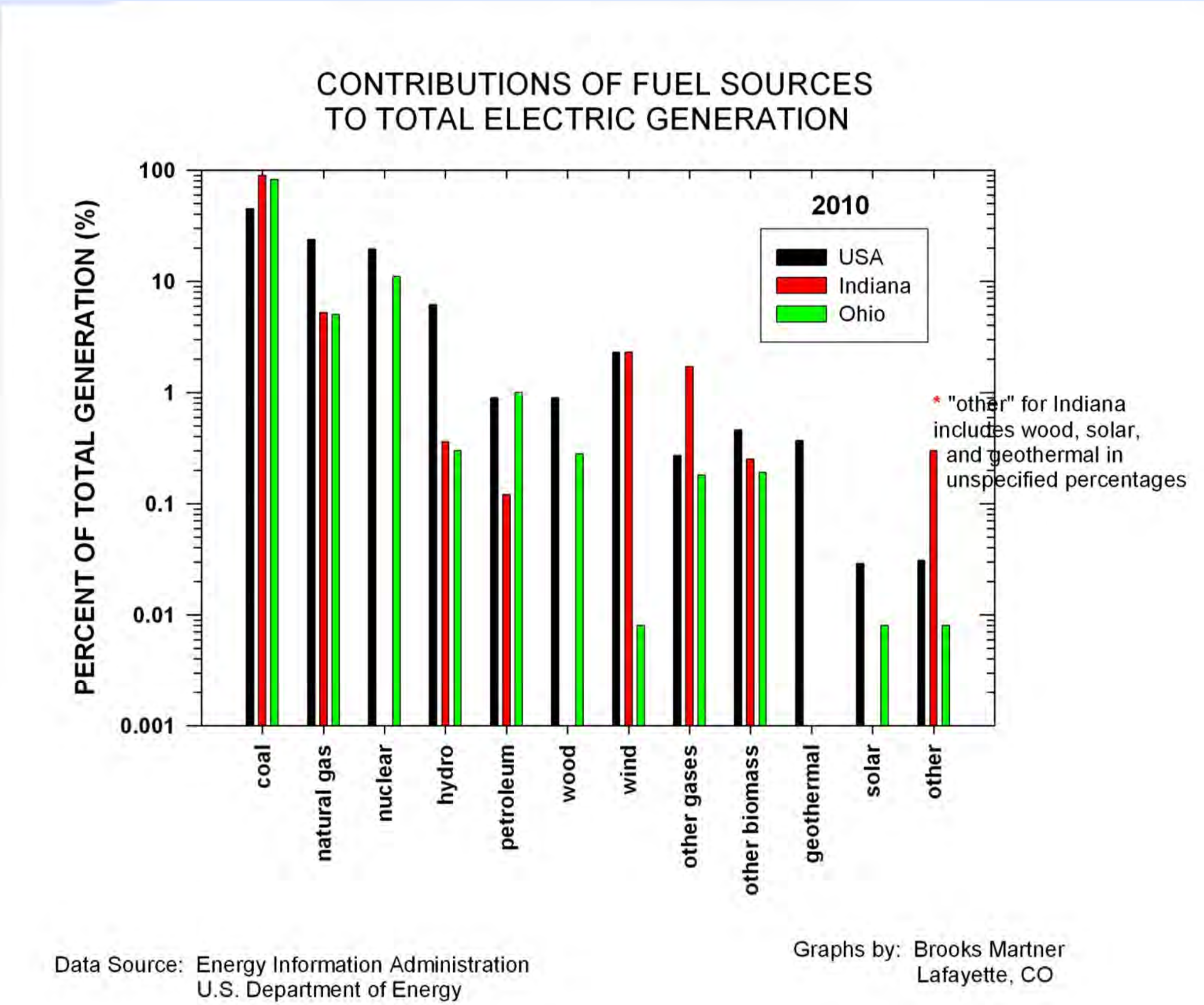
In 2009, world energy consumption decreased for the first time in 30 years (-1.1%) , a result of the financial and economic crisis (GDP drop by 0.6% in 2009). Coal posted a growing role in the world's energy consumption: in 2009, it accounted for 27% of the total. In 2010, world energy consumption increased by ~5%.

http://en.wikipedia.org/wiki/World_energy_resources_and_consumption

How Indiana's Electric Power Generation Stacks Up



Indiana vs. Ohio: How Electric Power Generation Stacks Up



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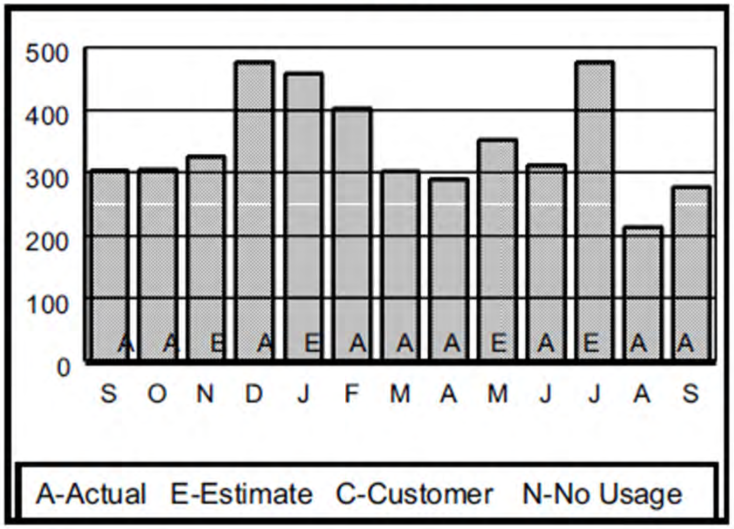
Household *electrical* energy consumption

According to [http://www.eia.doe.gov/cneaf/electricity/esr/table5.html], the average US home consumes 920 kW-hr/month, or about 11,000 kW-hr/year.

Usage Information

Usage Comparison



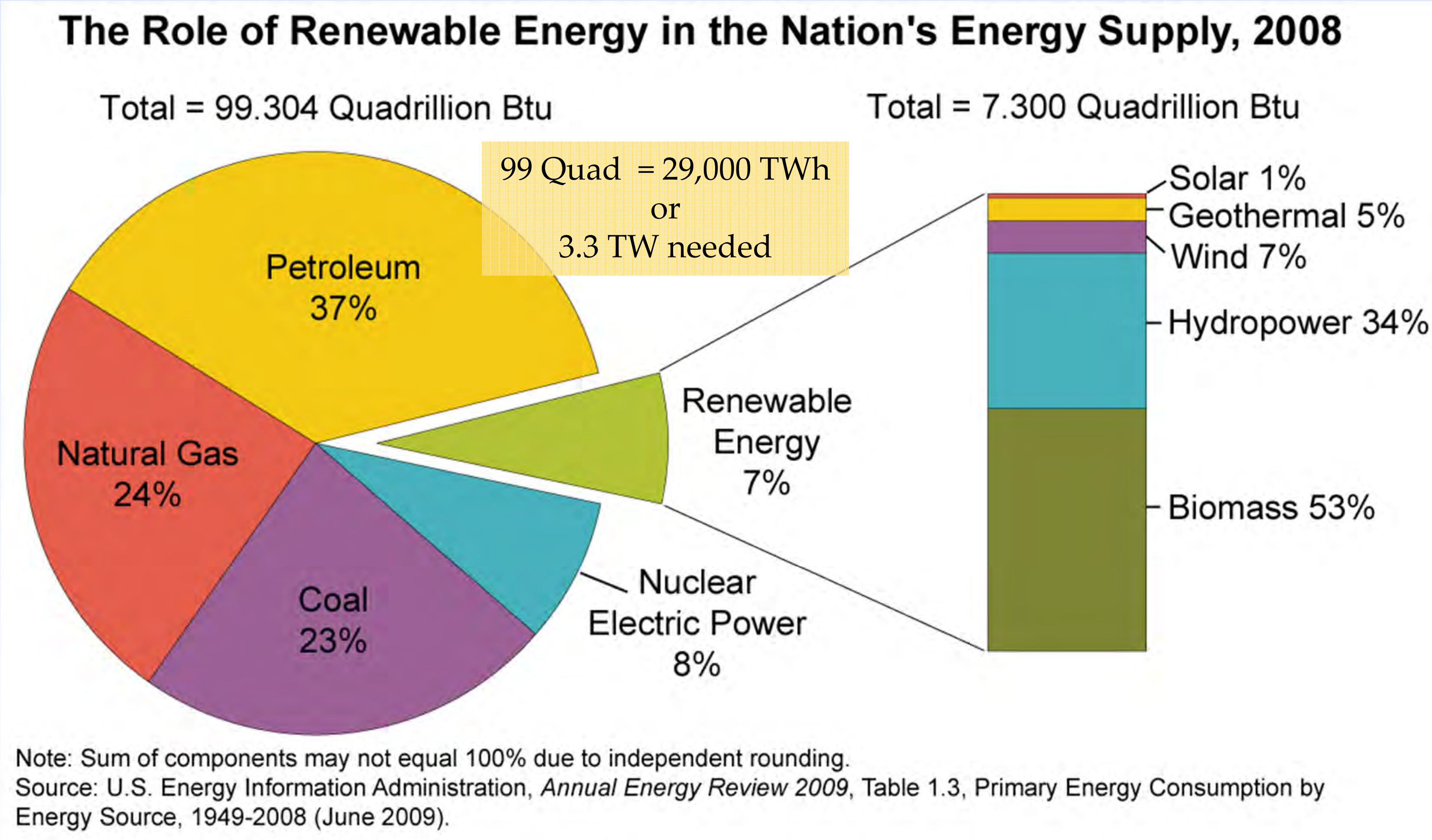
Historical Usage Information

Sep	10	303	Mar	11	302
Oct	10	304	Apr	11	289
Nov	10	326	May	11	352
Dec	10	476	Jun	11	312
Jan	11	458	Jul	11	476
Feb	11	402	Aug	11	213
			Sep	11	277

	Sep 10	Sep 11
Average Daily Use (KWH)	10	9
Average Daily Temperature	69	69
Days in Billing Period	30	30
Last 12 Months Use (KWH)		4,187
Average Monthly Use (KWH)		349

Average per-capita (total) energy consumption per day: World average is ~8 kW-hr/day; U.S. average is ~39 kW-hr/day.

How are We Doing so Far?



- In 2010, total worldwide energy consumption was 132,000 TWh, corresponding to an average annual power consumption rate of ~15.9 terawatts.
- Worldwide in 2010, 81% of energy use was fossil fuels, with another ~5% from nuclear and ~6% from hydroelectric.

Sources of renewable carbon-free energy

Potential Sources for Significant Carbon-Free Energy

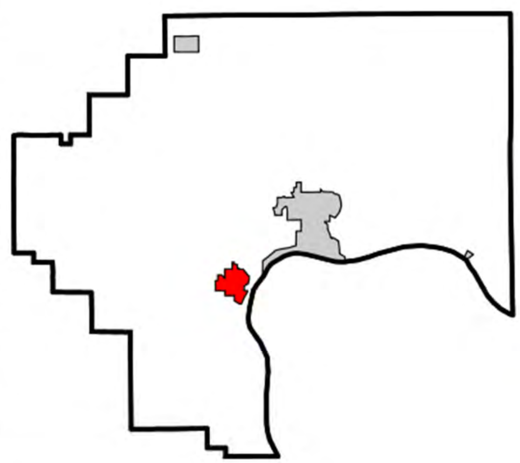
- Hydroelectric (technically feasible) 3.8 TW
  2.1 TW economically feasible, 0.9 TW in 2010
- Geothermal (installed capacity) 10.9 GW
- Tides/Waves 1 TW
- Wind 70 TW
- Solar (120,000 TW solar energy incident on Earth) 600 TW

* 50 TW – 1500 TW, depending upon land fraction, etc., and assuming today's typical solar-to-electricity conversion efficiency of 10%.

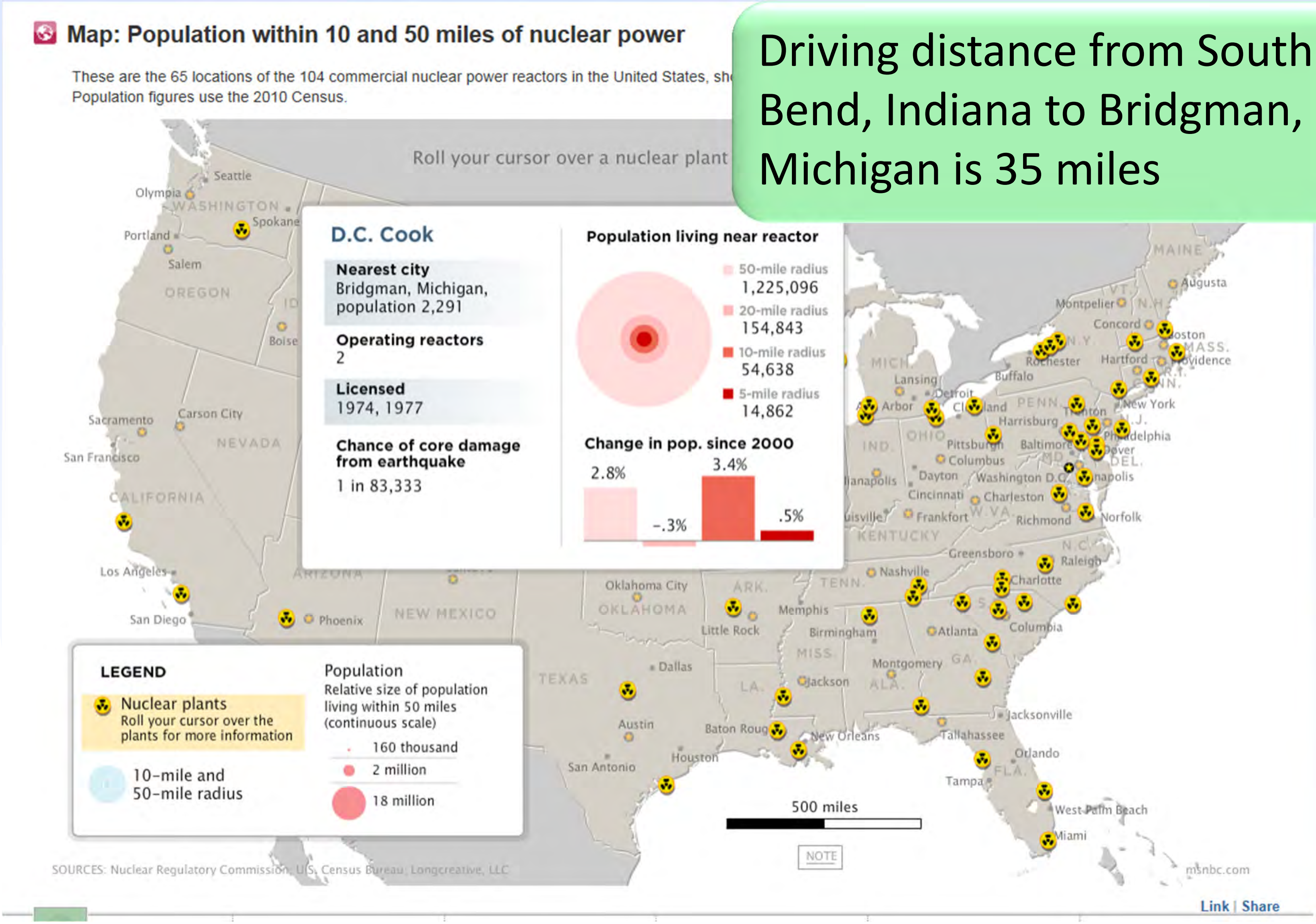
http://www.ieahydro.org/reports/Hydrofut.pdf
http://en.wikipedia.org/wiki/Geothermal_power
http://www.thecanadianencyclopedia.com/articles/tidal-energy
http://www.pnas.org/content/106/27/10933.full.pdf

What about … Nuclear Power?

Marble Hill Nuclear Facility
(~2.4 GW), near Hanover, IN



Nuclear never far away in the eastern half of US



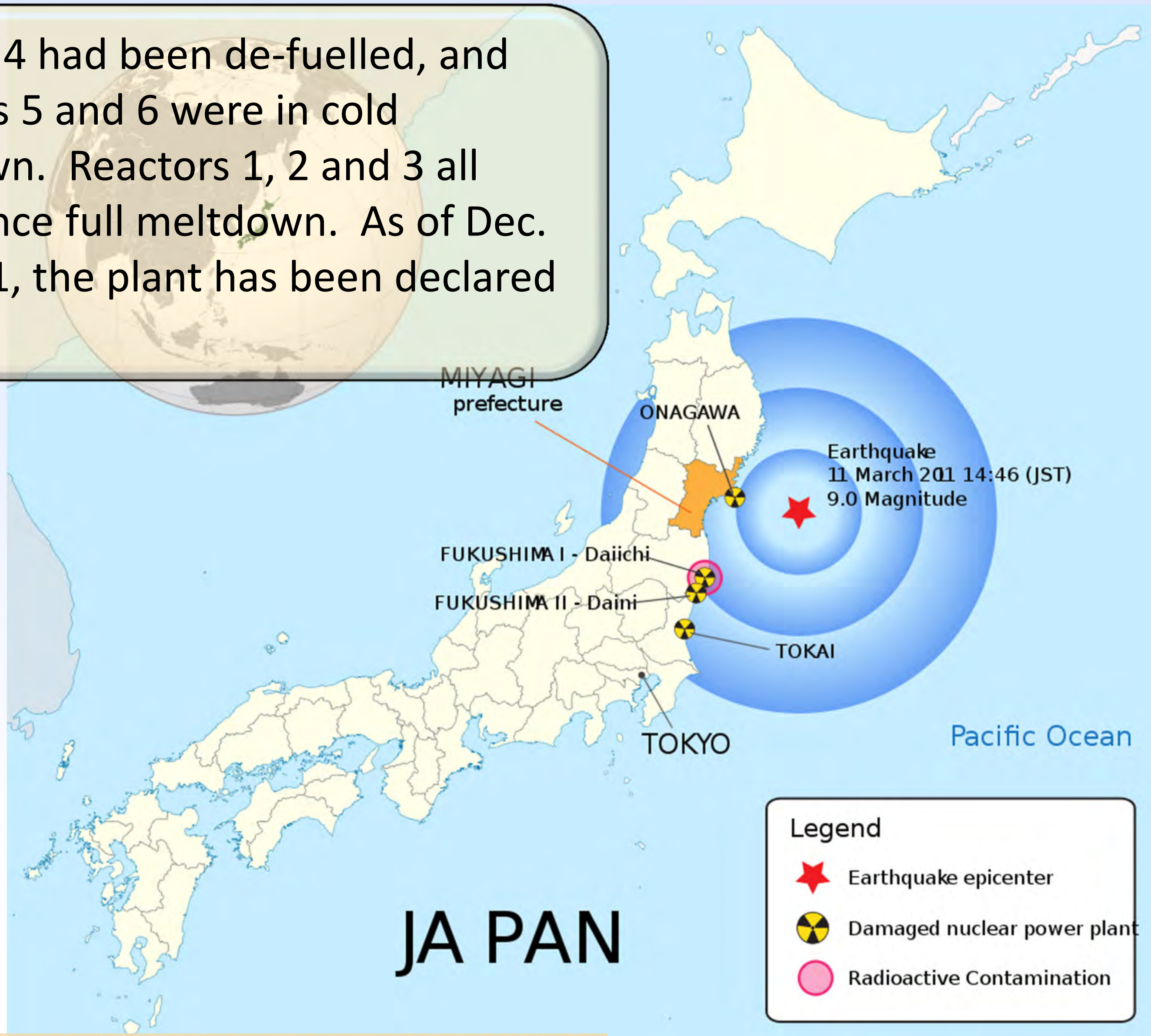
Driving distance from South Bend, Indiana to Bridgman, Michigan is 35 miles

Nuclear Power

- US generates ~30% (830 TWh) of total world nuclear energy (2009 IEA)
- Nuclear power provides ~6% of world energy, and ~14% of world electricity
- Differing views abound on many fronts:
  - Waste storage
  - Security concerns (nuclear weapons proliferation, terrorist interception of materials)
  - Economics of constructing nuclear power plants
  - Safety and acceptability of risk

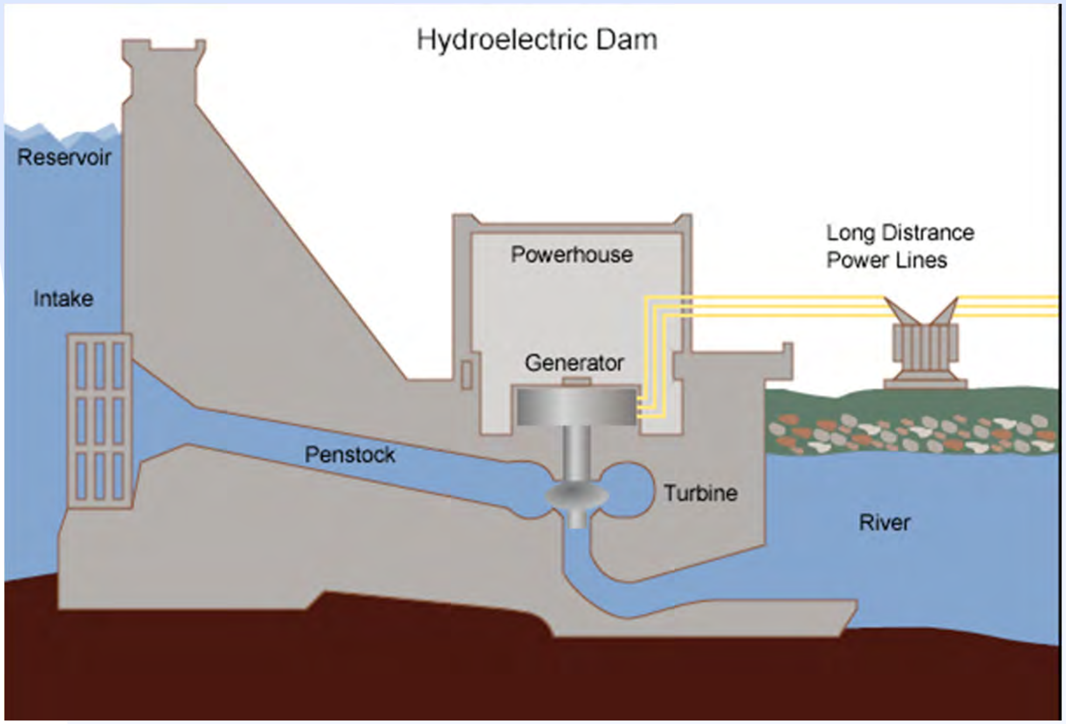
2011 Japan earthquake: Fukushima Daiichi nuclear disaster

Reactor 4 had been de-fuelled, and Reactors 5 and 6 were in cold shutdown. Reactors 1, 2 and 3 all experience full meltdown. As of Dec. 16, 2011, the plant has been declared stable.



http://en.wikipedia.org/wiki/Fukushima_Daiichi_nuclear_disaster
http://en.wikipedia.org/wiki/File:JAPAN_EARTHQUAKE_20110311.svg

Hydroelectric Power

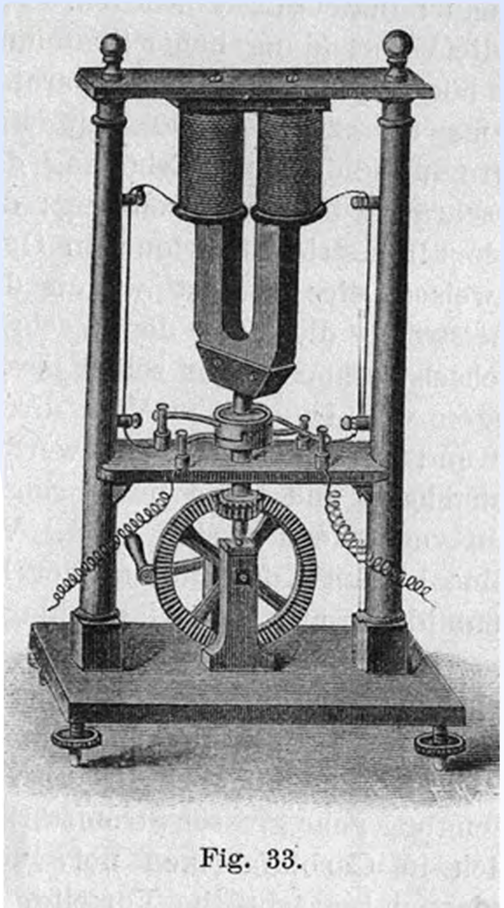


Power produced depends on factors such as the density of water ($\rho = 1000$ kg/m^3), the "hydraulic height" (h), the flow rate in cubic meters per second (r), the gravitational constant (g), and the efficiency factor (k):

$$P = \rho h r g k$$

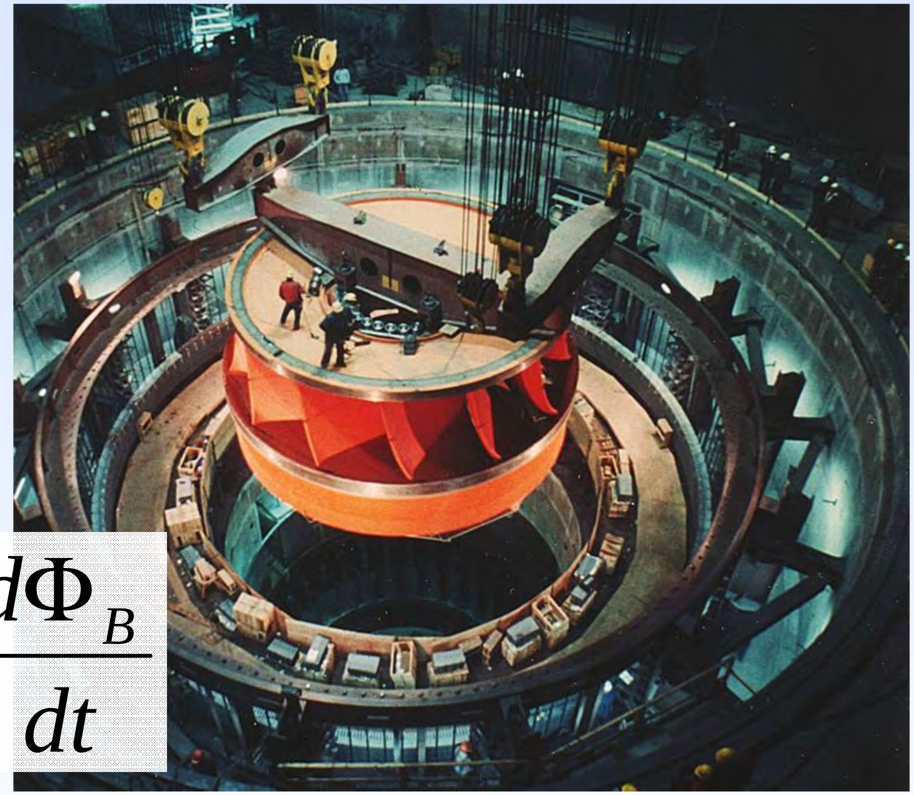
- eliminates cost of fuel;
- long-lived power production compared to fuel-fired plants;
- operates without CO_2 emissions;
- no nuclear waste
- sizeable hazard (dam failures among largest human-created disasters);
- siltation ultimately limits "economic" life;
- environmental impacts: spawning, downstream river environment, anaerobic decay of plant material – methane
- population relocation
- flow reduction (global warming)

Hydroelectric Power – Electromagnetic Induction



Pixii's dynamo (1832), built by **Hippolyte Pixii** (1808–1835), an instrument maker from Paris, France.

$$\varepsilon = -\frac{d\Phi_B}{dt}$$



750 MW water turbine being installed at Grand Coulee Dam (Columbia River).

ε is the electromotive force (volts); Φ_B is the magnetic flux (webers). 1 weber/m^2 = 1 tesla

electric motor ←→ electric generator

Hydroelectric Power – Big Players

Country	Annual Hydroelectric Energy Production(TWh)	Installed Capacity (GW)	Capacity Factor	Percent of all electricity
Norway	140.5	27.528	0.49	98.25[24]
Brazil	363.8	69.080	0.56	85.56
Venezuela	86.8	-	-	67.17
Canada	369.5	88.974	0.59	61.12
Sweden	65.5	16.209	0.46	44.34
Russia	167.0	45.000	0.42	17.64
China (2008)[25]	585.2	171.52	0.37	17.18
India	115.6	33.600	0.43	15.80
France	63.4	25.335	0.25	11.23
Japan	69.2	27.229	0.37	7.21
United States	250.6	79.511	0.42	5.74
Paraguay (2006)	64.0	-	-	

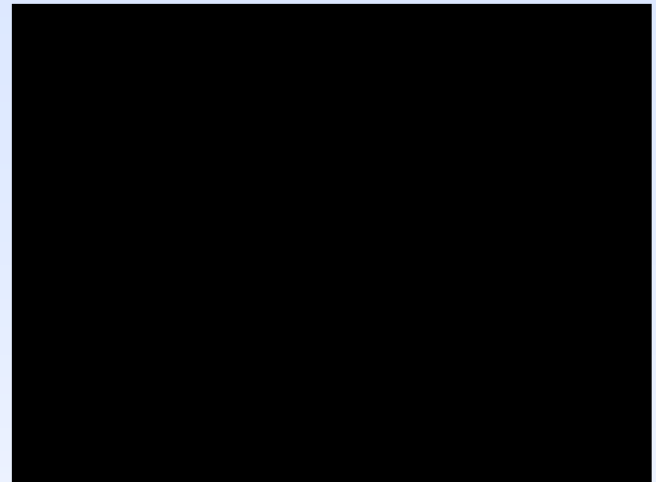
Potential capacity of 3.8 TW; ultimately driven by the Sun.

Reminder: We need 15 – 40 TW total CfP

Geothermal Power

What: thermal energy "in the Earth" from:

- original formation of the planet (hot springs, geysers)
- radioactive decay of minerals
- solar energy absorbed at the surface



Castle Geyser, Yellowstone NP

How much: 10.9 GW of geothermal power in 2010;
28 GW of direct thermal heating capacity.

Notes:

- Earth's heat content = 10^{31} J
- Thermal conduction to surface at rate of 44 TW (44×10^{12} J/s)
- Additional heat generated by radioactive decay, 30 TW
- Average thermal power at Earth's surface: ~ 0.1 W/m^2

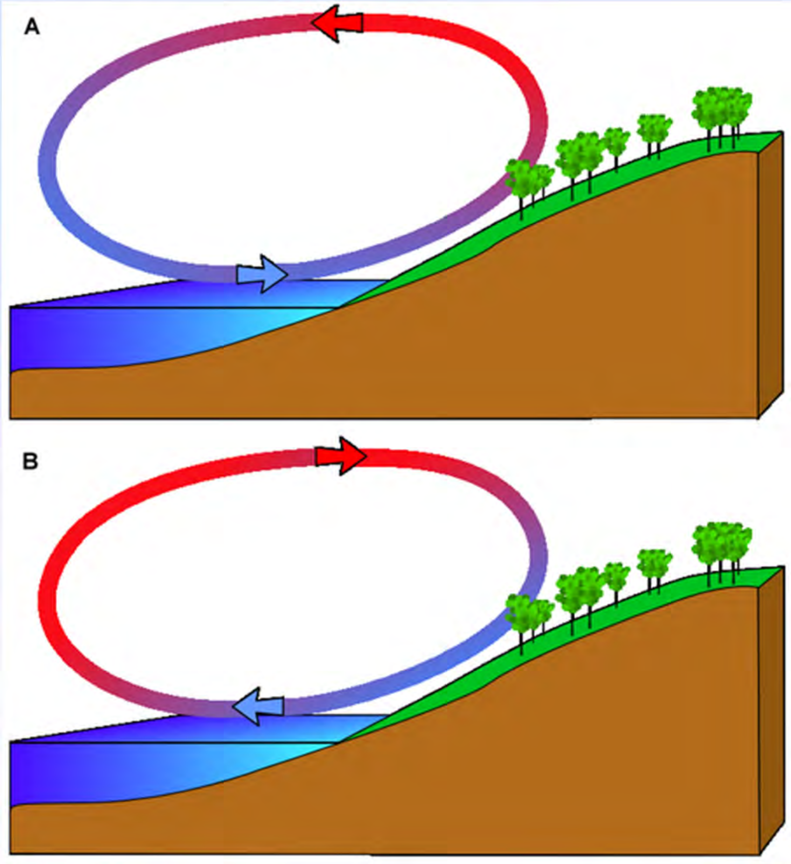
Origins of Wind

Pressure differentials in the atmosphere produce wind; local effects include variations in heating and cooling (e.g., land vs. a body of water).

Air motion (wind) alleviates these pressure differences. Air has mass, so wind carries kinetic energy that can be converted to electricity through the use of turbines (*electrical generators*).

The two dominant causes of wind in Earth's atmosphere are:

1. the differential solar heating between the equator and the poles, and
2. the rotation of the planet.



Land is often warmer than water (A) during the day, and cooler than water (B) at night.

Wind Power

"Humans have been using wind power for at least 5,500 years to propel sailboats and sailing ships, and architects have used wind-driven natural ventilation in buildings since similarly ancient times. Windmills have been used for irrigation pumping and for milling grain since the 7th century AD."

http://en.wikipedia.org/wiki/Wind_power

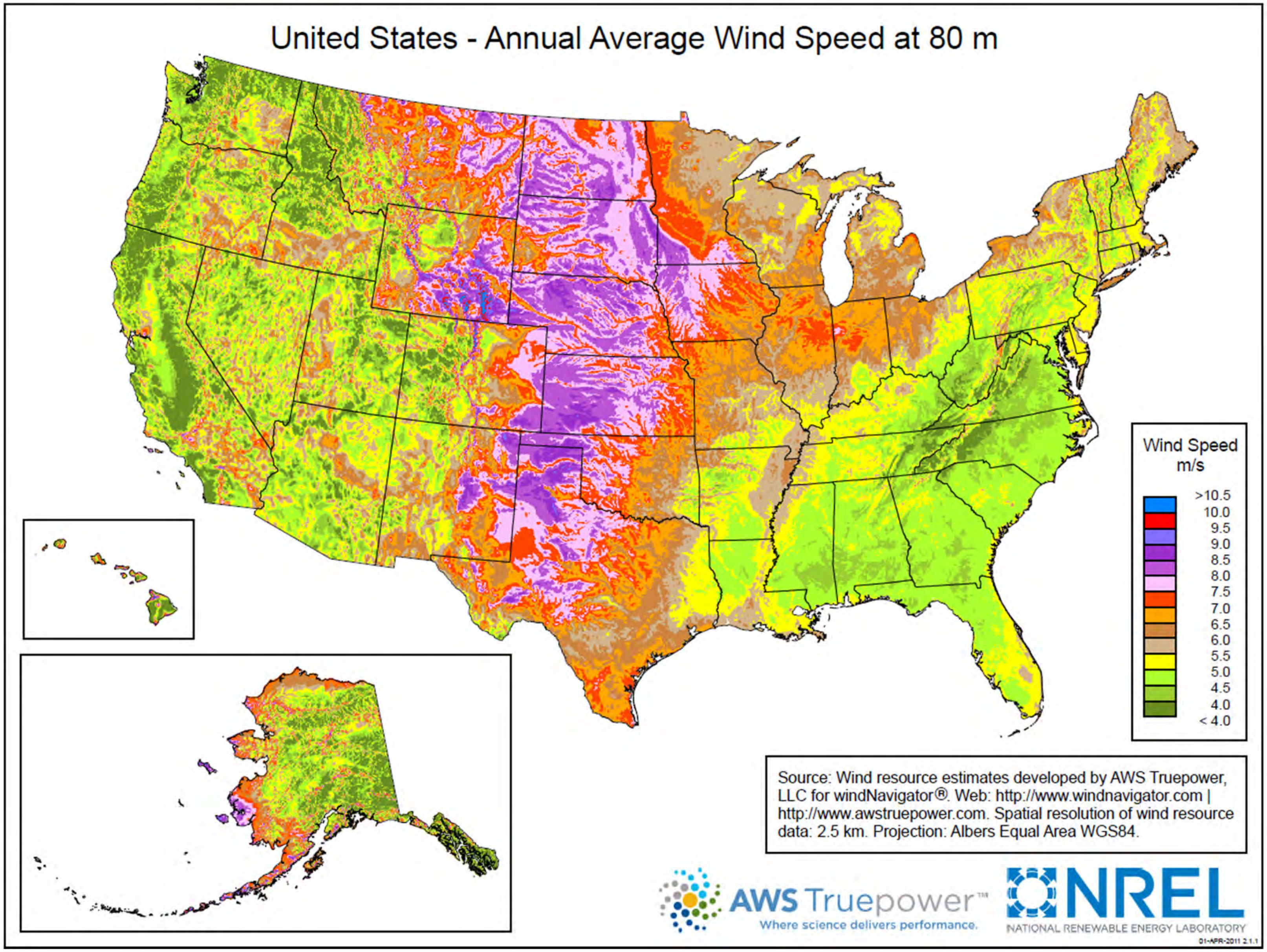
… growth in the forecasts can be attributed to the increasingly common use of very large turbines that rise to almost 100 meters.
Wind speeds are greater at higher elevations. Previous wind studies were based on the deployment of 50- to 80-meter turbines.

http://greeninc.blogs.nytimes.com/2009/07/16/

$$\boxed{E = A \cdot v \cdot t \cdot \rho \cdot \frac{1}{2} \cdot v^2}$$

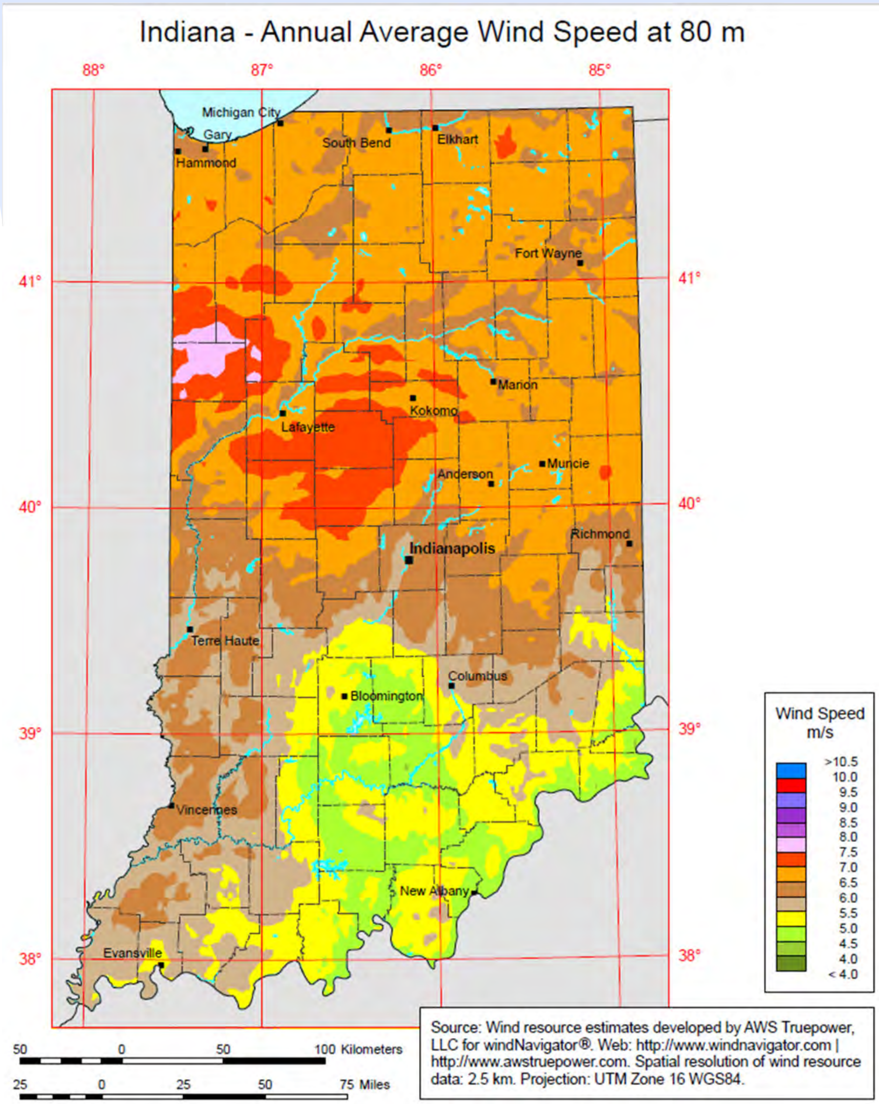
Global potential for wind-generated electricity
Xi Lu, Michael B. McElroya,, and Juha Kiviluomac
www.pnas.orgcgidoi10.1073pnas.0904101106

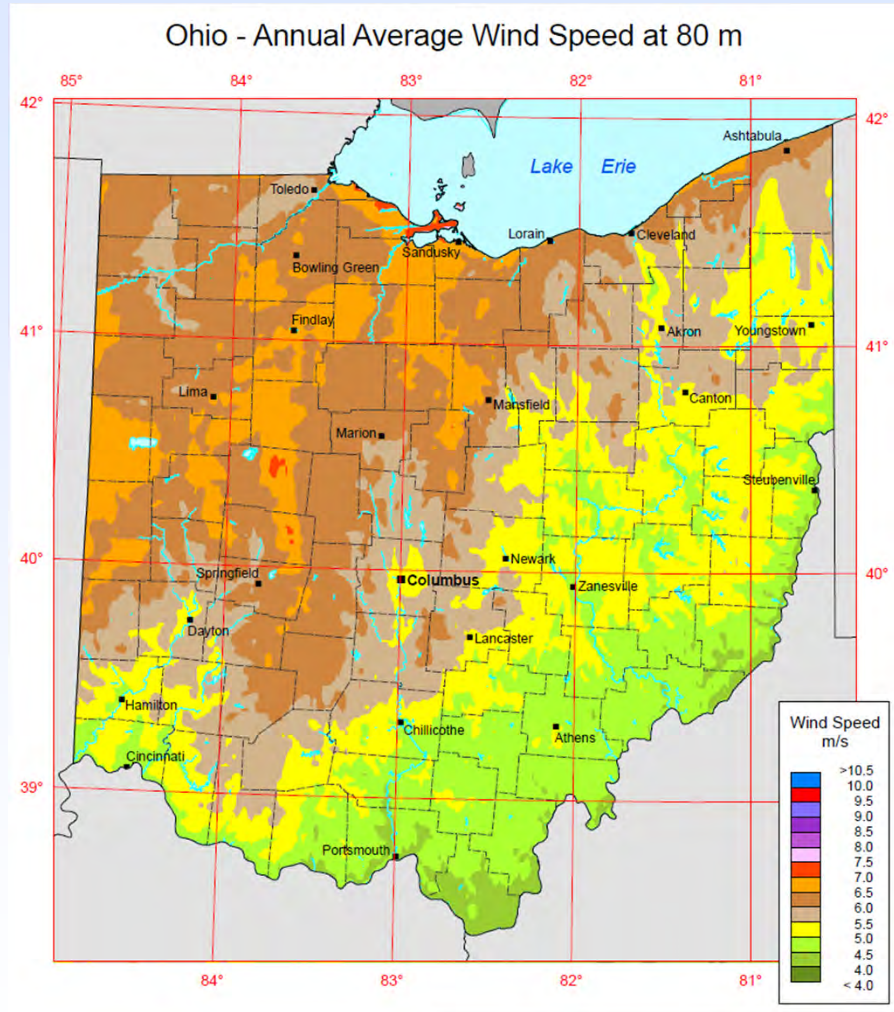
Wind Power



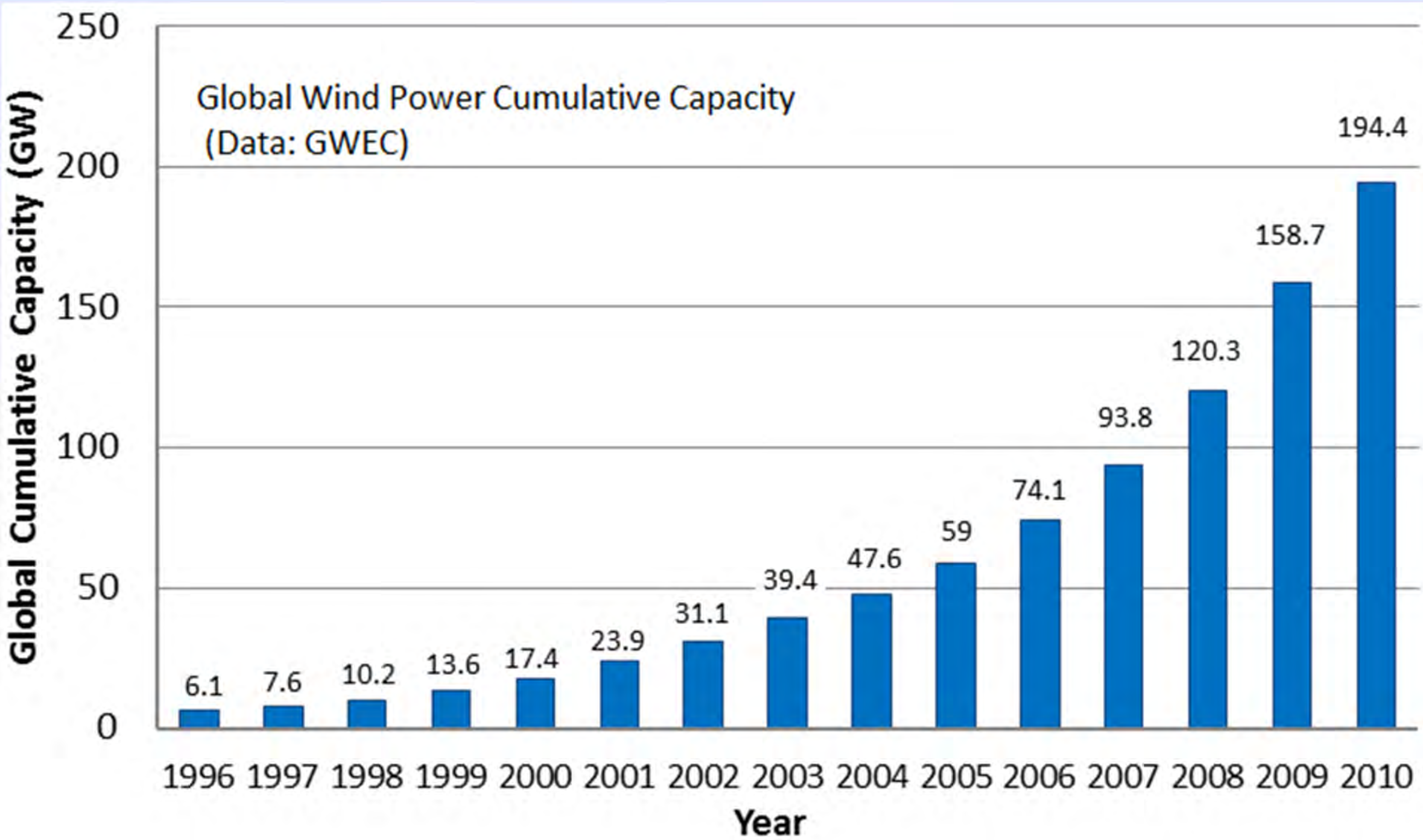
United States - Annual Average Wind Speed at 80 m
Wind Speed
m/s
>10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
< 4.0
Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.
AWS Truepower™
Where science delivers performance.
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

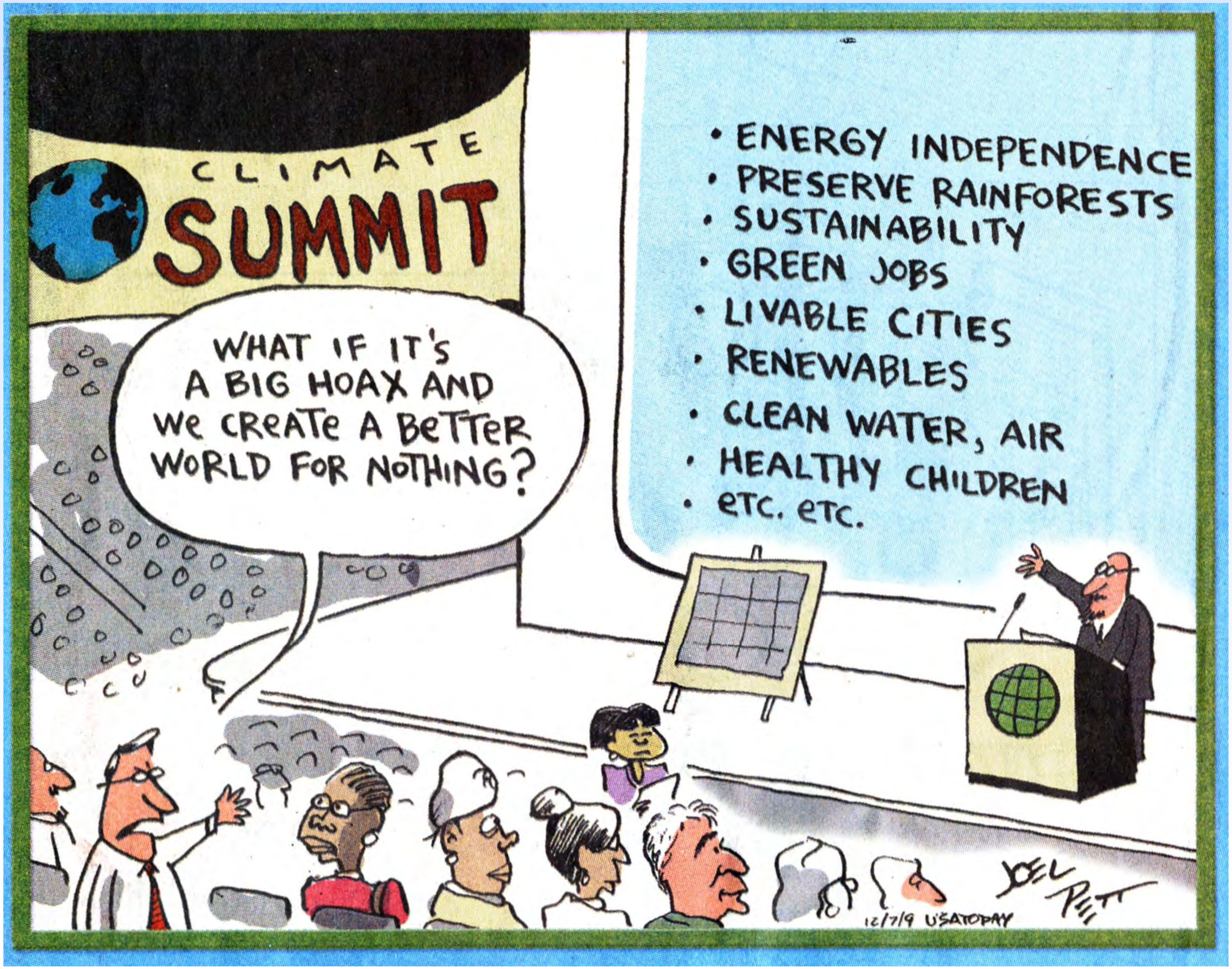
Indiana and Ohio Wind Power





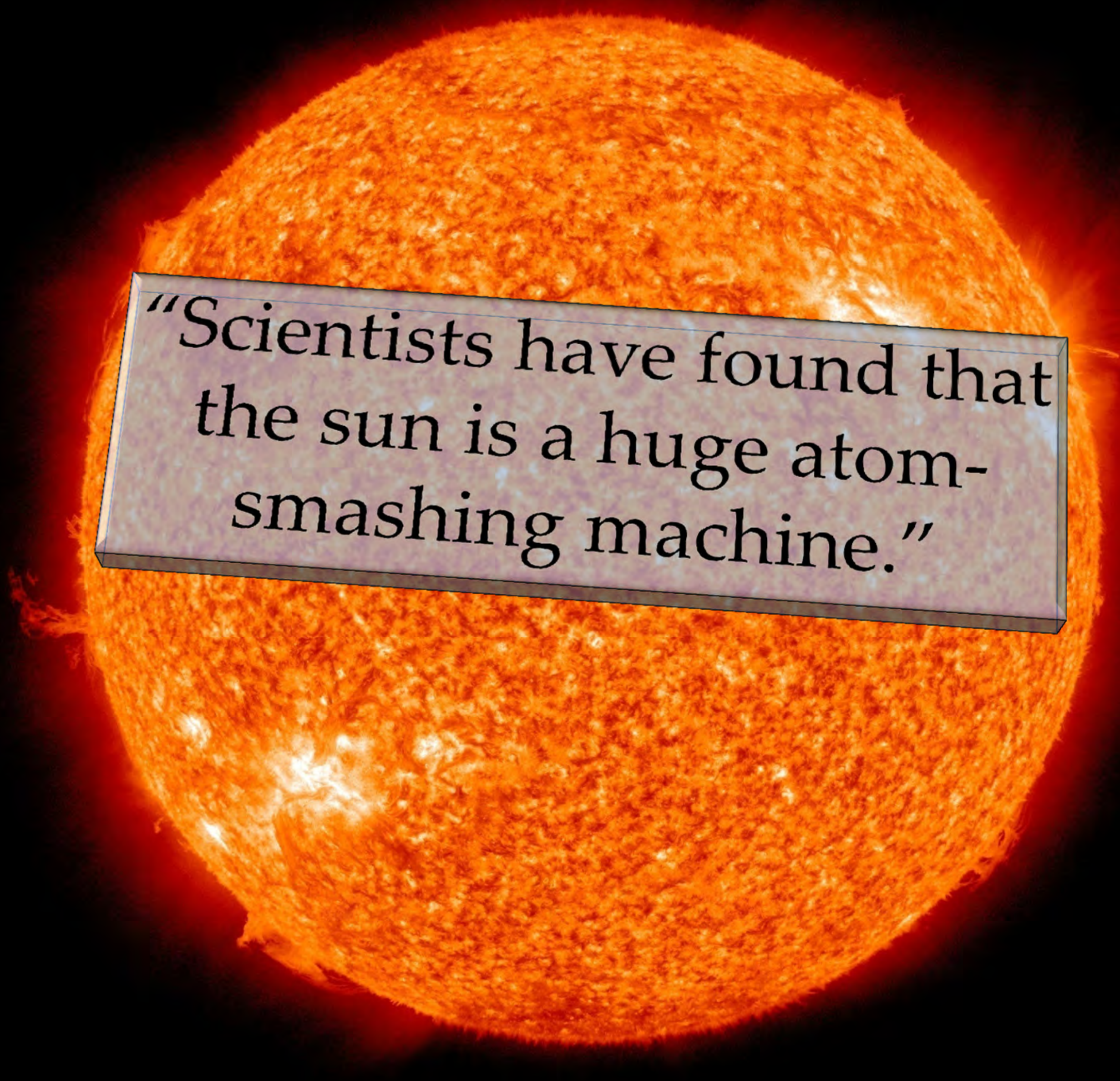
Global Wind Power





CLIMATE SUMMIT
WHAT IF IT'S A BIG HOAX AND WE CREATE A BETTER WORLD FOR NOTHING?
• ENERGY INDEPENDENCE
• PRESERVE RAINFORESTS
• SUSTAINABILITY
• GREEN JOBS
• LIVABLE CITIES
• RENEWABLES
• CLEAN WATER, AIR
• HEALTHY CHILDREN
• etc. etc.
JOEL PETT
12/7/9 USA TODAY

The Sun (worth revering)



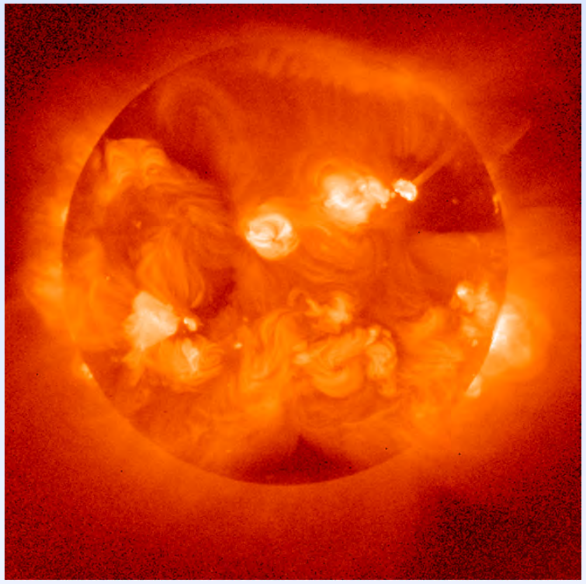
"Why Does the Sun Shine?"
by *They Might Be Giants*

The sun is a mass of
incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into
helium
At a temperature of millions
of degrees

Yo ho, it's hot, the sun is not
A place where we could live
But here on Earth there'd be
no life
Without the light it gives

We need its light
We need its heat
We need its energy
Without the sun, without a
doubt
There'd be no you and me

Earth’s Solar Resource



- Theoretical: 1.2×10^5 TW solar energy potential (1.76×10^5 TW striking Earth; 0.30 Global mean albedo)
- Energy in 1 hr of sunlight ↔ 14 TW for a year
- Practical: > Onshore electricity generation potential of ≈ 600 TW (10% conversion efficiency).
- *Photosynthesis*: 90 TW
- Cumulative installed PV (electricity) capacity:
    - 40 GW as of 2010 (2.5 GW in U.S., 17.3 GW in Germany, and > 3.5 GW in each of Italy, Spain, and Japan)
    - 68 GW as of 2011 (70% growth in a year)

Solar Radiation Spectrum

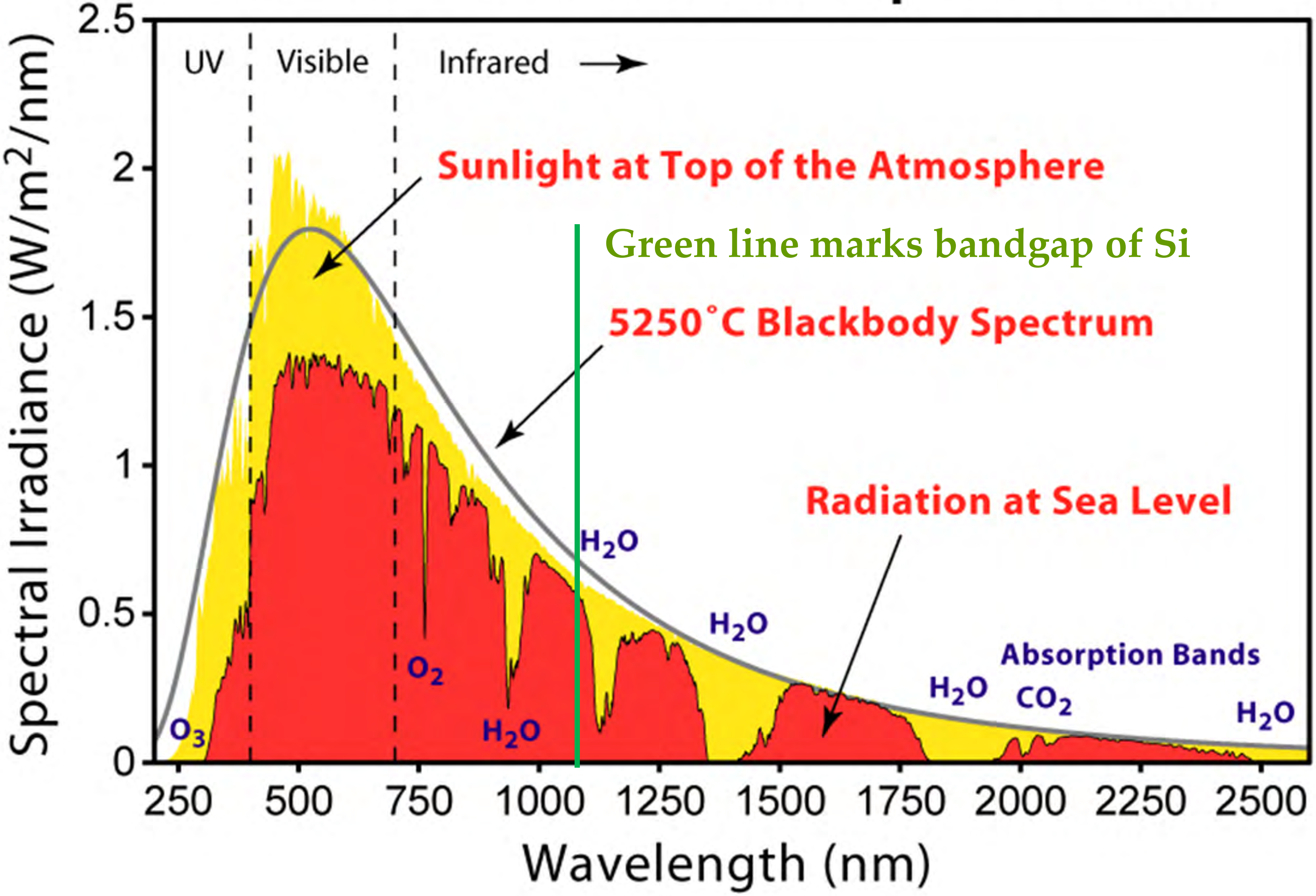


Image created by Robert A. Rohde / Global Warming Art

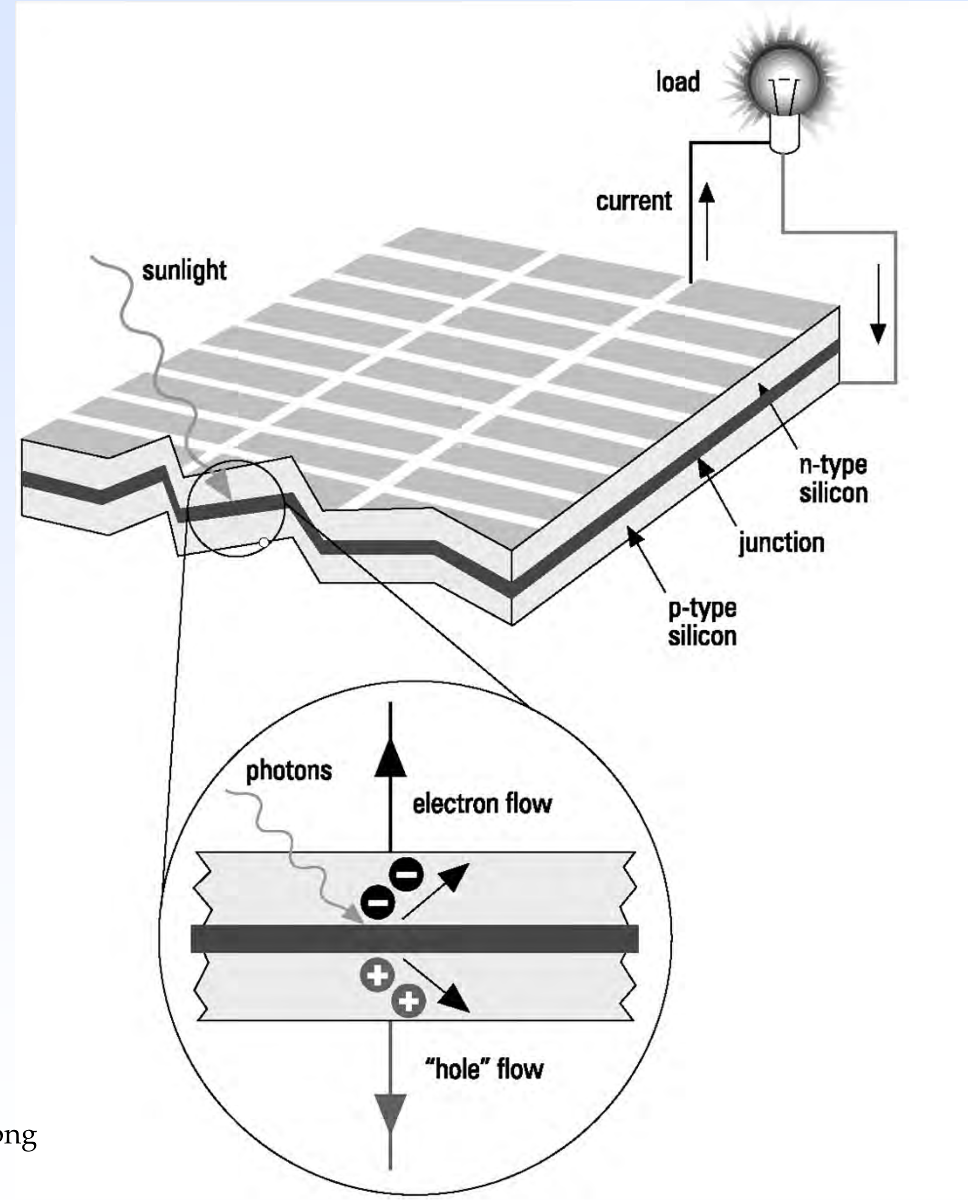
The Solar Resource in the US

PV covering area of square ~133 miles x 133 miles
can (easily) satisfy all of US's energy needs.

Basic silicon photovoltaic (solar) cell operation

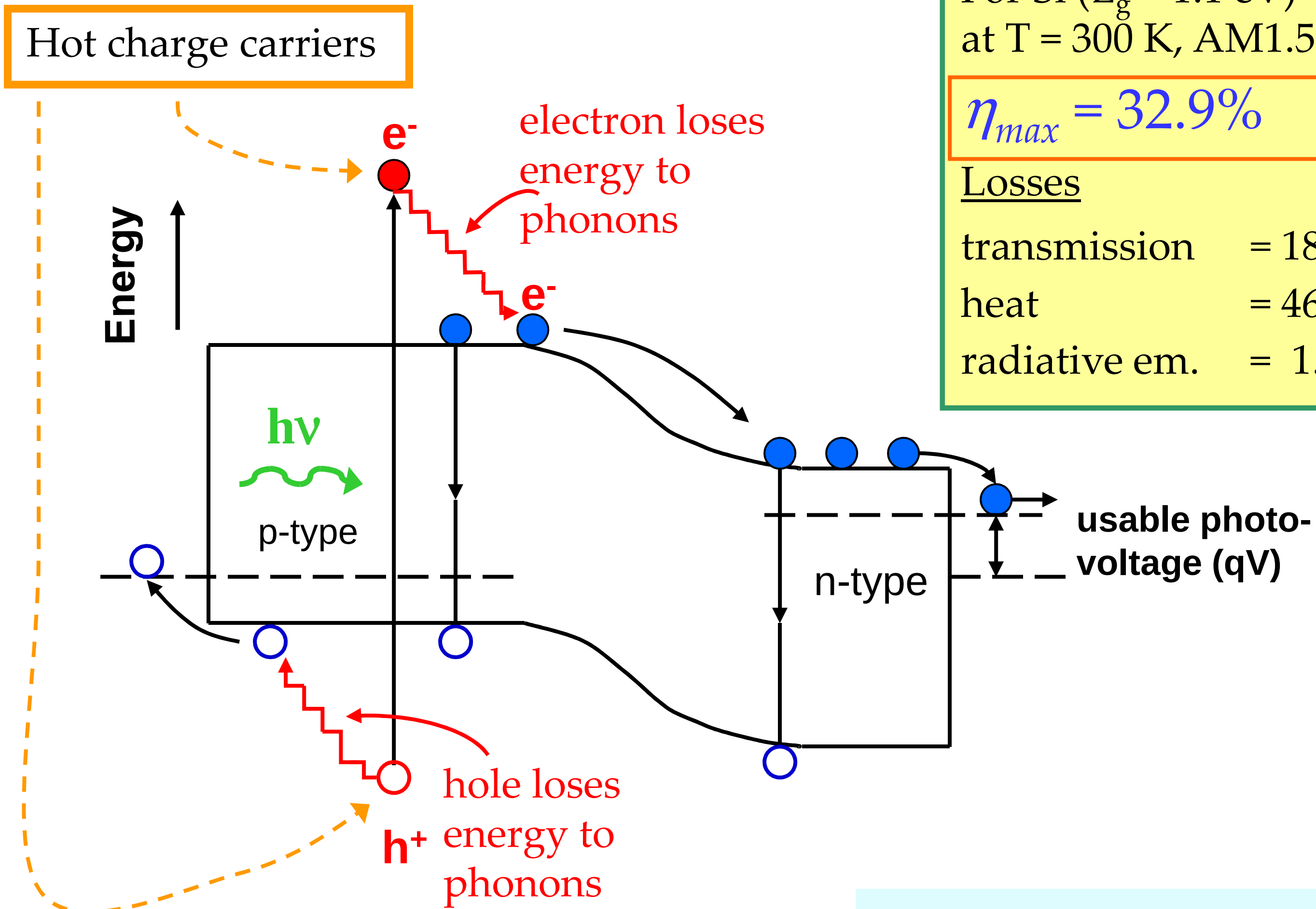
<u>Key functions of a solar cell</u>

- absorbs sunlight efficiently
- separates charge (electrons from "holes")
- creates an electrical current and voltage when illuminated
- acts like a battery under sunlight



http://www.emeraldinsight.com/fig/0870210205001.png

Conventional p-n junction photovoltaic cell



For Si (E_g = 1.1 eV)
at T = 300 K, AM1.5G

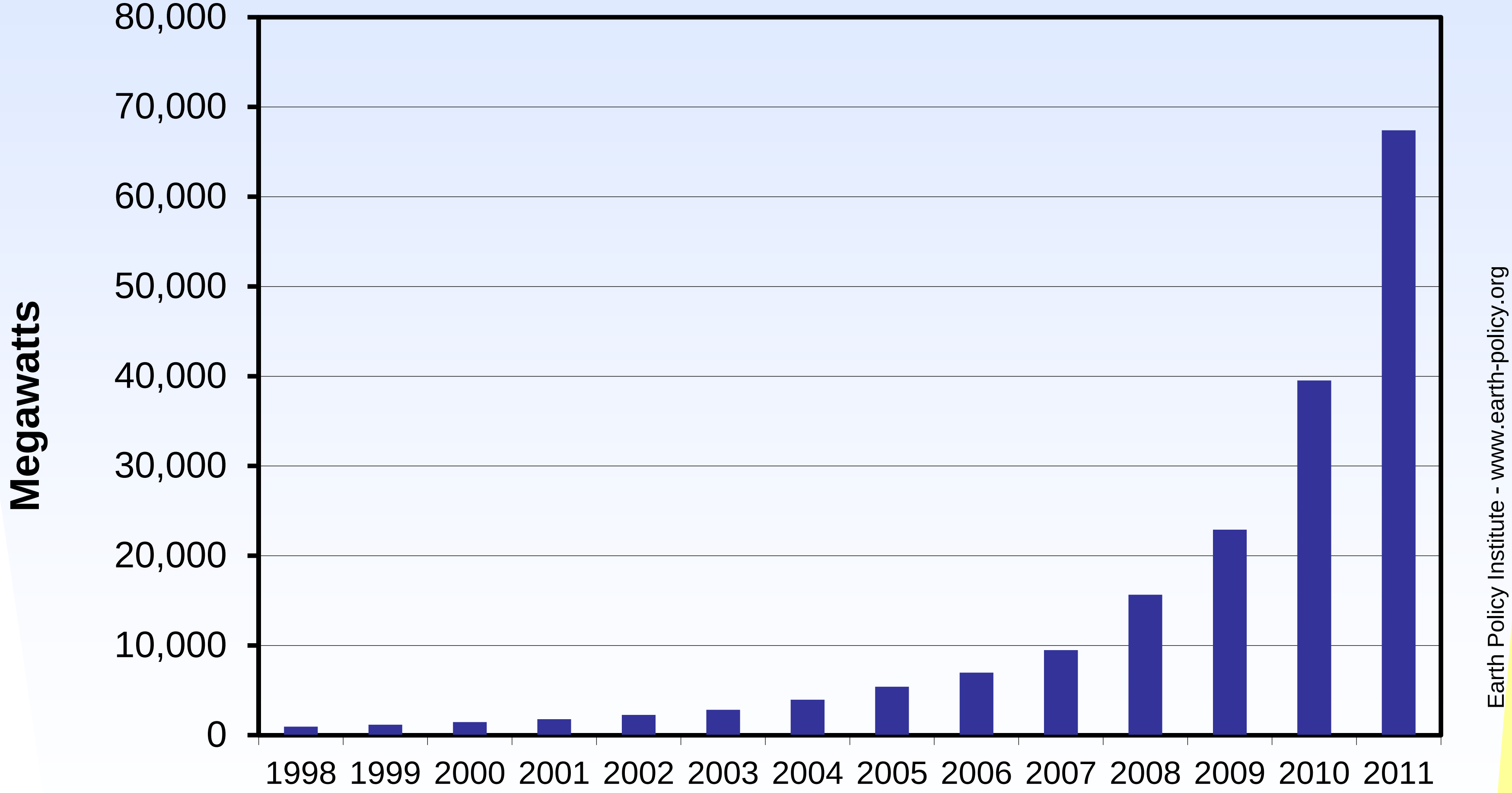
$\eta_{max} = 32.9\%$

<u>Losses</u>

transmission	= 18.7%
heat	= 46.8%
radiative em.	= 1.6%

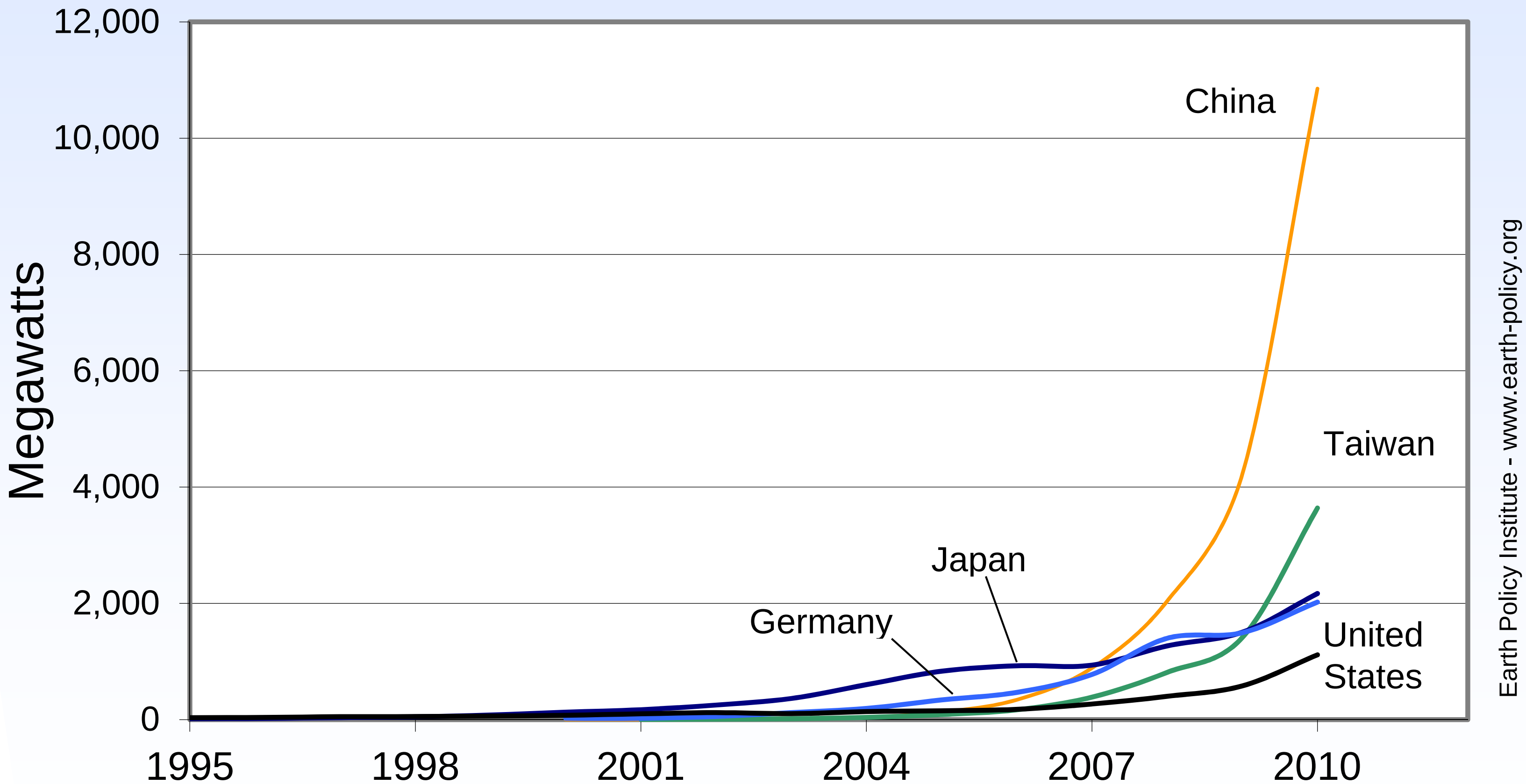
1 e^--h^+ pair/photon

World Cumulative Solar Photovoltaics Installations, 1998-2011



Source: EPI from EPIA

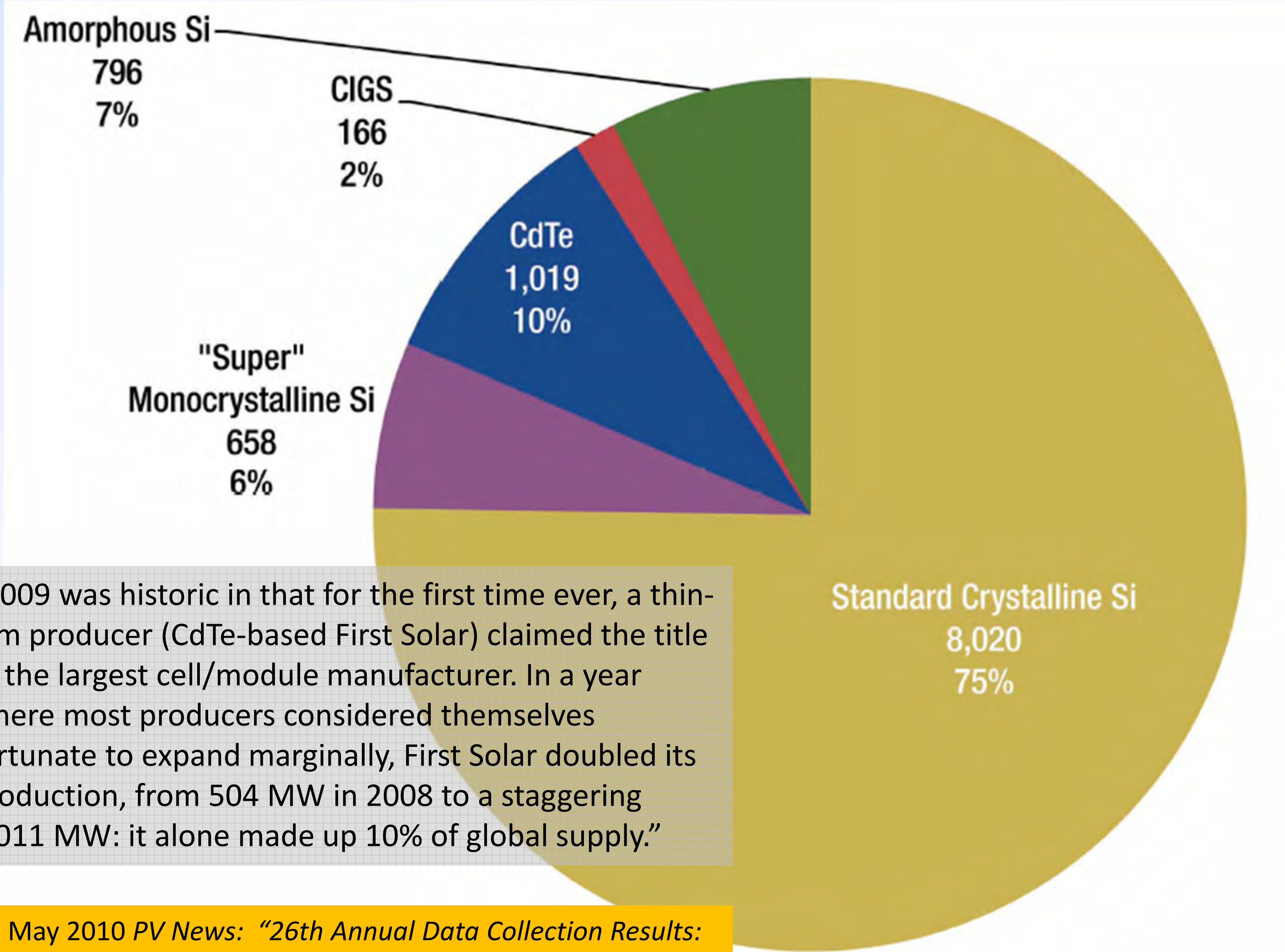
Annual Solar Photovoltaics Production in Selected Countries, 1995-2010



Source: EPI from Worldwatch; Prometheus Institute; Greentech Media

.... energizing Ohio for the 21st Century

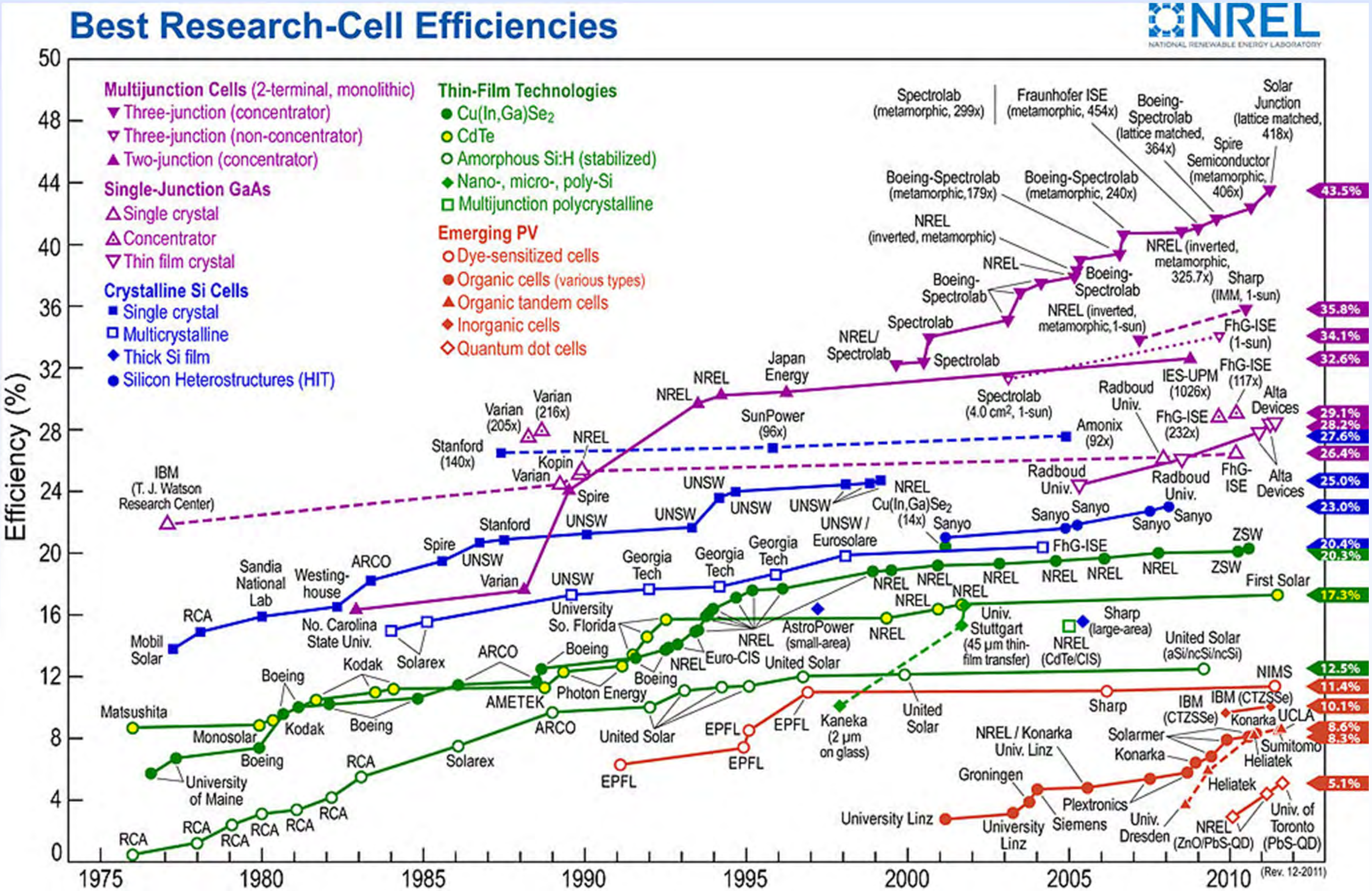
Commercial Photovoltaics as of 2010



"2009 was historic in that for the first time ever, a thin-film producer (CdTe-based First Solar) claimed the title of the largest cell/module manufacturer. In a year where most producers considered themselves fortunate to expand marginally, First Solar doubled its production, from 504 MW in 2008 to a staggering 1,011 MW: it alone made up 10% of global supply."

from May 2010 *PV News: "26th Annual Data Collection Results: Another Bumper Year for Manufacturing Masks Turmoil"*

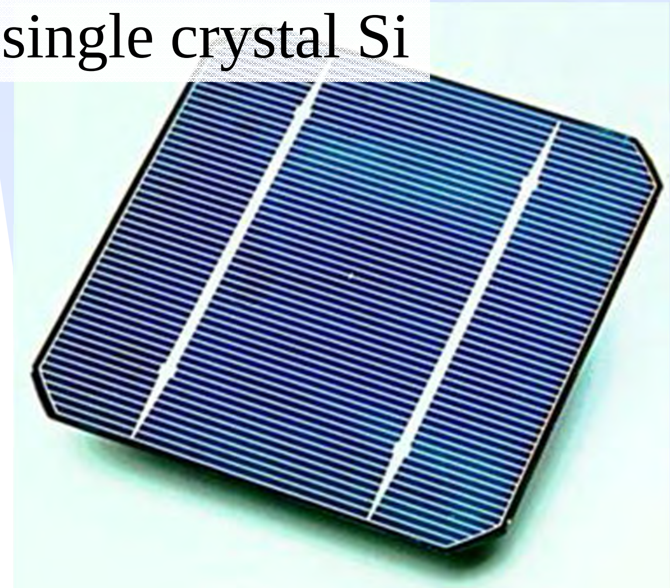
Trends in solar cell efficiencies

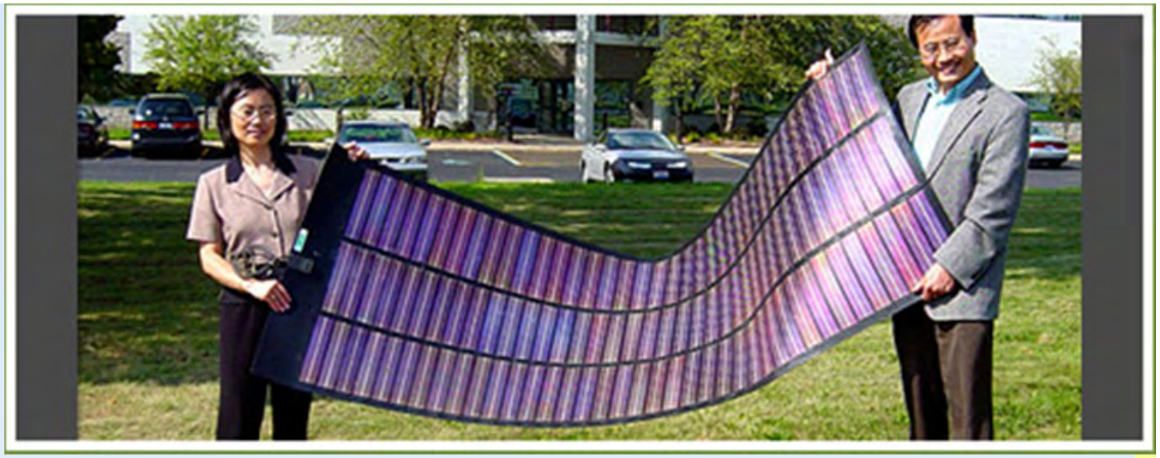


Many different solar cell technologies are being developed, for various applications (rooftops, solar power plants, satellites, backpacks or clothing, etc.).

1st gen.

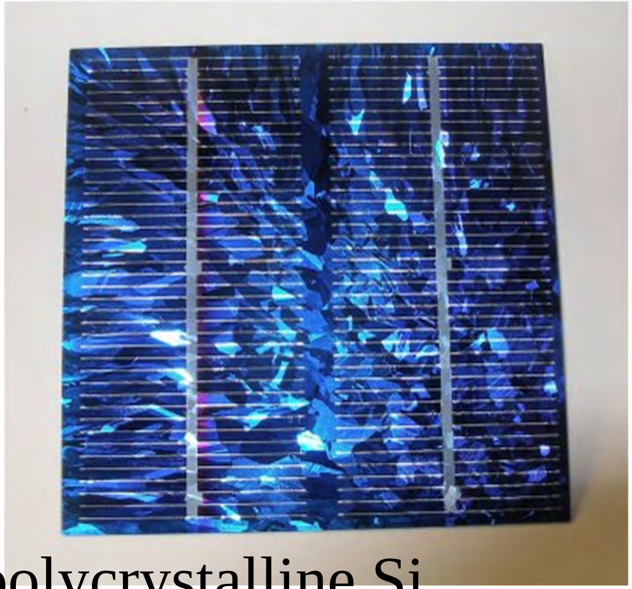
single crystal Si





Xunlight

2nd gen.: thin film amorphous Si and CdTe

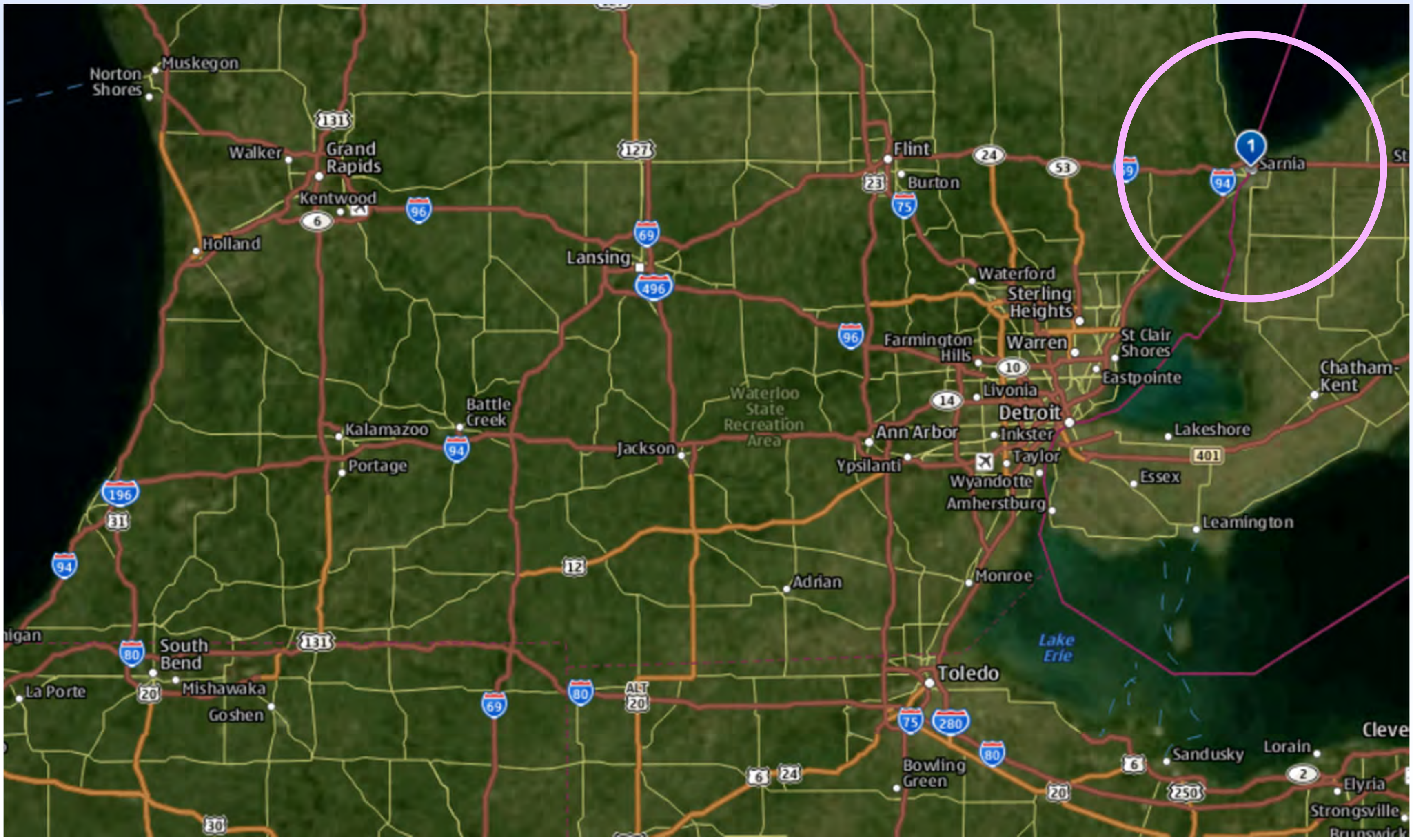


polycrystalline Si

First Solar

The biggest PV power plant (North America)

The Sarnia Solar Project is the largest PV installation in North America (97 MW).



Toledo and UT in the PV news (again)

Toledo reinvents itself as a solar-power innovator

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Enlarge By J.D. Pooley for USA TODAY

Rosa Zartman, 23, a 2009 University of Toledo graduate, works in the school's solar lab.

By Judy Keen, USA TODAY

TOLEDO — This city is trying to swap its Rust Belt image for a new identity as a hub of solar-energy research and production.

The mission is being led by an unusual partnership of business, academia and government that could be a model for other aging industrial cities. "We are ready to do anything; we are ready to try anything," says University of Toledo President Lloyd Jacobs.

Like many manufacturing cities, Toledo has struggled with the loss of jobs and tax revenue, but it has taken pieces of its past as the glass capital to create a new future in solar energy.

The payoff so far: At least 6,000 people work in the area's solar industry. First Solar (FSLR), which makes solar panels, was founded here and employs more than 1,000 at its 900,000-square-foot plant here. There are more than a dozen solar-related start-up companies in the area. The University of Toledo is home to top solar researchers and has a business incubator that provides business services to solar entrepreneurs. It has graduated four solar companies and is working with six more. Owens Community College, which had 13 students in its first solar class in 2004, has trained 255 solar installers.

"In the solar world, Toledo is a hot spot," says Xunming Deng, a physics professor on leave from the University of Toledo. He's developing Xunlight, the company he founded here in 2002 to produce thin, flexible solar panels. It has about 100 employees.

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