Energy and Power for 7.06 Billion People

PHYS 4400, Principles and Varieties of Solar Energy

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The University of Toledo

January 8, 2013

But First, discussions of:

- science
- units
- significant figures
- graphs
- Igor Pro
- quizzes
- office hours

Key Elements of the Scientific Method

Scientific method: ask and answer scientific questions through experiment and observation.

The steps of the scientific method are to:

1. Define the question
2. Gather information and resources (observe)
3. Form hypothesis
4. Perform experiment and collect data
5. Analyze data
6. Interpret data and draw conclusions that serve as a starting point for new hypothesis
7. Publish results
8. Retest (frequently done by other scientists)

The iterative cycle inherent in this step-by-step methodology goes from point 3 to 6 back to 3 again.

It is important for your experiment to be a fair test. A "fair test" occurs when you change only one factor (variable) and keep all other conditions the same.

Thoughts on the Scientific Method

Ibn al-Haytham (Alhazen, 965–1039), pointed out the emphasis on seeking truth:

Truth is sought for its own sake. And those who are engaged upon the quest for anything for its own sake are not interested in other things. Finding the truth is difficult, and the road to it is rough.

According to William Whewell (1794–1866), "invention, sagacity, genius" are required at every step in scientific method. It is not enough to base scientific method on experience alone; multiple steps are needed in scientific method, ranging from our experience to our imagination, back and forth.

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

Scientific Method: Beliefs and Biases

The Epsom Derby (1821) by Géricault, Jean Louis Théodore. Oil on canvas.

Eadweard Muybridge's (1830 – 1904) studies of a horse galloping

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

On units

Use Standard International units wherever possible, and if in doubt, convert your answers back to SI units.

At times, we will use non-SI units – for example, we often talk about photon energy in terms of eV, and you should/will become familiar with how to convert between J and eV.

When converting from one set of units to another, always show your work (see the example near the top of HW #1).

Units analysis allows you to check your work. If you're trying to calculate the rate at which photons strike a surface (photons/sec) and your units end up showing photons/meter, you'll know something's wrong and that you need to go back and correct your work.

Significant figures

"Sig figs"

What do we mean?

Sig figs include all digits except (a) trailing zeros such as 1,000,000 (feel free to use scientific notation: 1.0×10^6, which shows two sig figs), and (b) extra digits that are not merited, arising either from a calculation with numerous digits in the answer, or more digits than are justified by actual or hypothetical instrumentation.

What do we want to avoid?

Avoid including numbers of digits that are clearly beyond our interest for the answers we seek. What is the energy of a 351 nm photon? Three sig figs should do as a start:

$(1240 \text{ eV nm}^{-1}) / 351 \text{ nm} = 3.53 \text{ eV}$ (not 3.53276 eV)

Creating a good graph

We will create graphs of data at times, and when we do, let's make them useful and visually attractive. Think about what your graph is trying to show, and consider how to best present the data.

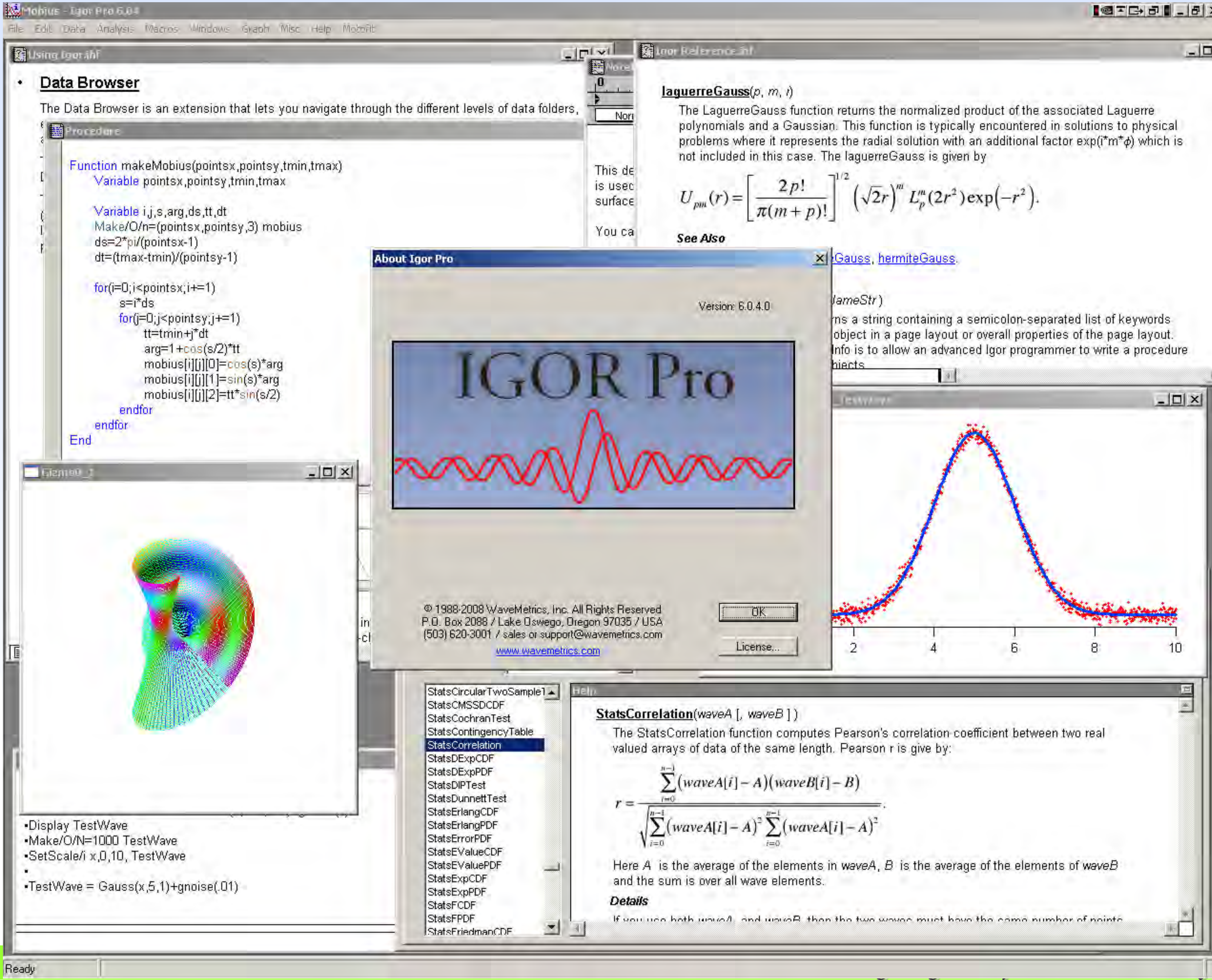
Always include: axes, axis numerical values and axis labels (with units!).

Use symbols/lines so that even in black and white one can discern the different traces. If you have multiple data sets graphed, include a legend.

Annotate your graph as necessary to tell your story; sometimes the reader/viewer can actually tell almost everything from the graph, and the caption is non-critical.

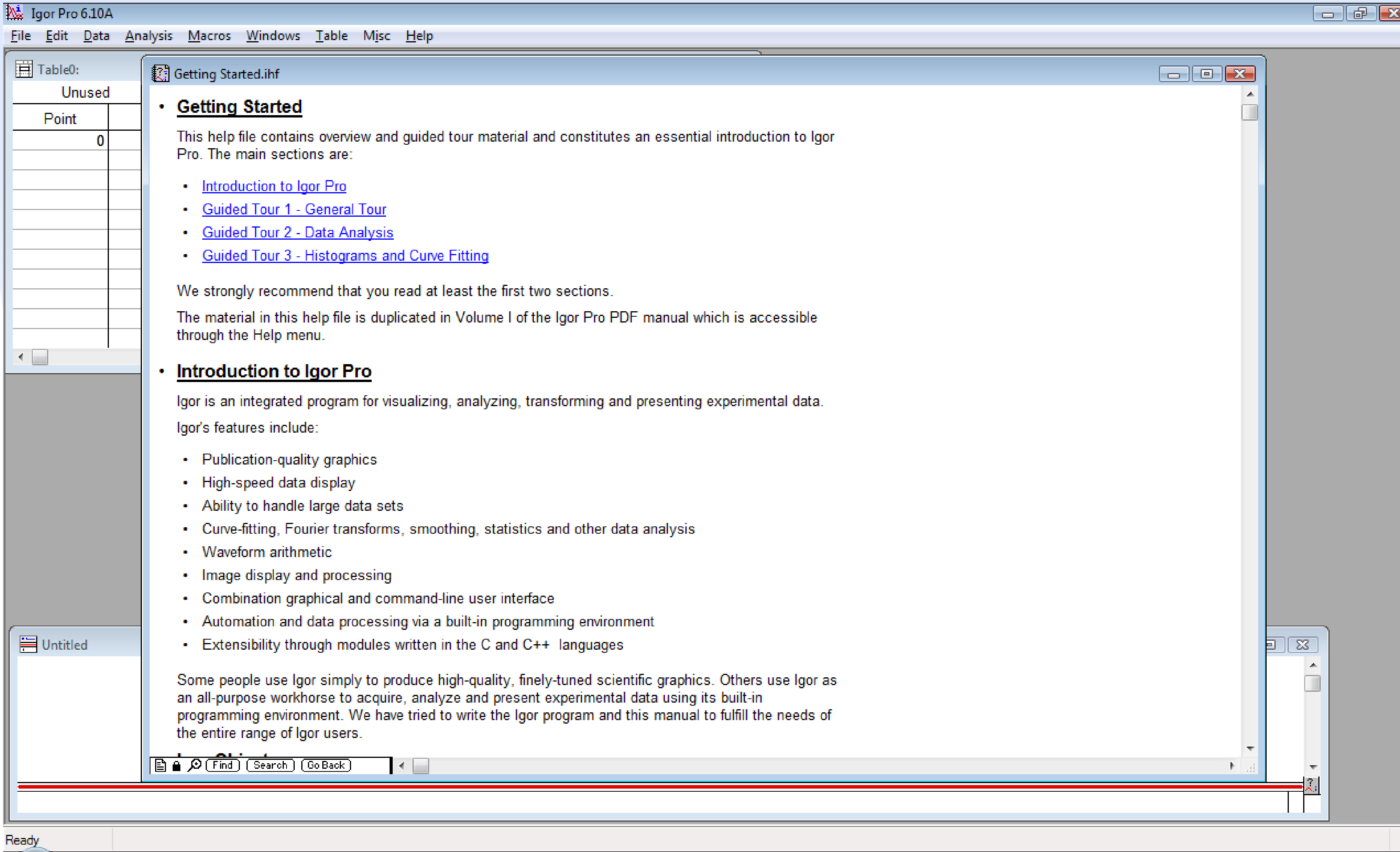
Nonetheless, always include a caption such as "Figure 1. My cat's power output as a function of the time of day, averaged over 3 days."

Igor Pro 6.1



Mobius - Igor Pro 6.04
File Edit Data Analysis Macros Windows Graph Misc Help Mobius
Using Igor.ihf
Data Browser
The Data Browser is an extension that lets you navigate through the different levels of data folders,
Procedure
Function makeMobius(pointsx,pointsy,tmin,tmax)
Variable pointsx,pointsy,tmin,tmax
Variable i,j,s,arg,ds,tt,dt
Make/O/n=(pointsx,pointsy,3) mobius
ds=2*pi/(pointsx-1)
dt=(tmax-tmin)/(pointsy-1)
for(i=0;i<pointsx;i+=1)
s=i*ds
for(j=0;j<pointsy;j+=1)
tt=tmin+j*dt
arg=1+cos(s/2)*tt
mobius[i][j][0]=cos(s)*arg
mobius[i][j][1]=sin(s)*arg
mobius[i][j][2]=tt*sin(s/2)
endfor
endfor
End
Igor Reference.ihf
laguerreGauss(p, m, r)
The LaguerreGauss function returns the normalized product of the associated Laguerre polynomials and a Gaussian. This function is typically encountered in solutions to physical problems where it represents the radial solution with an additional factor exp(i*m*φ) which is not included in this case. The laguerreGauss is given by
$U_{pm}(r) = \left[\frac{2p!}{\pi(m+p)!}\right]^{1/2}\left(\sqrt{2}r\right)^m L_p^m(2r^2)\exp(-r^2).$
See Also
Gauss, hermiteGauss.
About Igor Pro
Version: 6.0.4.0
IGOR Pro
© 1988-2008 WaveMetrics, Inc. All Rights Reserved
P.O. Box 2088 / Lake Oswego, Oregon 97035 / USA
(503) 620-3001 / sales or support@wavemetrics.com
www.wavemetrics.com
OK
License...
•Display TestWave
•Make/O/N=1000 TestWave
•SetScale/i x,0,10, TestWave
•TestWave = Gauss(x,5,1)+gnoise(.01)
2
4
6
8
10
StatsCircularTwoSample1
StatsCMSSDCDF
StatsCochranTest
StatsContingencyTable
StatsCorrelation
StatsDExpCDF
StatsDExpPDF
StatsDIPTest
StatsDunnettTest
StatsErlangCDF
StatsErlangPDF
StatsErrorPDF
StatsEValueCDF
StatsEValuePDF
StatsExpCDF
StatsExpPDF
StatsFCDF
StatsFPDF
Help
StatsCorrelation(waveA [, waveB])
The StatsCorrelation function computes Pearson's correlation coefficient between two real valued arrays of data of the same length. Pearson r is give by:
$r = \frac{\sum_{i=0}^{n-1}(waveA[i]-A)(waveB[i]-B)}{\sqrt{\sum_{i=0}^{n-1}(waveA[i]-A)^2\sum_{i=0}^{n-1}(waveA[i]-A)^2}}.$
Here A is the average of the elements in waveA, B is the average of the elements of waveB and the sum is over all wave elements.
Details
Ready

Igor Pro 6.1 (www.wavemetrics.com)



Igor Pro information (please note)

http://www.wavemetrics.com/support/demos.htm

Download the IgorPro Demo (available for either Mac or Windows), and use this information for the S/N and the Activation Key.

Serial Number: 50023

Activation Key: x

Quizzes and Office Hours

Quizzes will be slightly longer than previously indicted in the syllabus – probably 20-25 minutes. The primary goal is not to increase their difficulty but rather to make sure that you're not as rushed as you might be, and to be certain we can test your knowledge fairly.

Our goal here is for you to learn a great deal about solar energy, and if some of the material we're studying doesn't stick, we'll try again on the most important aspects.

My philosophy on office hours is that I am quite available each week and almost each day – you can contact me by email, by phone (530-3874), or in person – and I will respond as quickly as I can. So I normally do not schedule office hours, but I can if you request this.

I encourage students who are facing barriers to keep me informed and feel free to arrange to meet with me. Students are expected to work hard and solve problems on their own, but as the instructor, I am here to help keep you on that path when you need ideas on how to proceed.

Humanity's Top Ten Problems for next 50 years

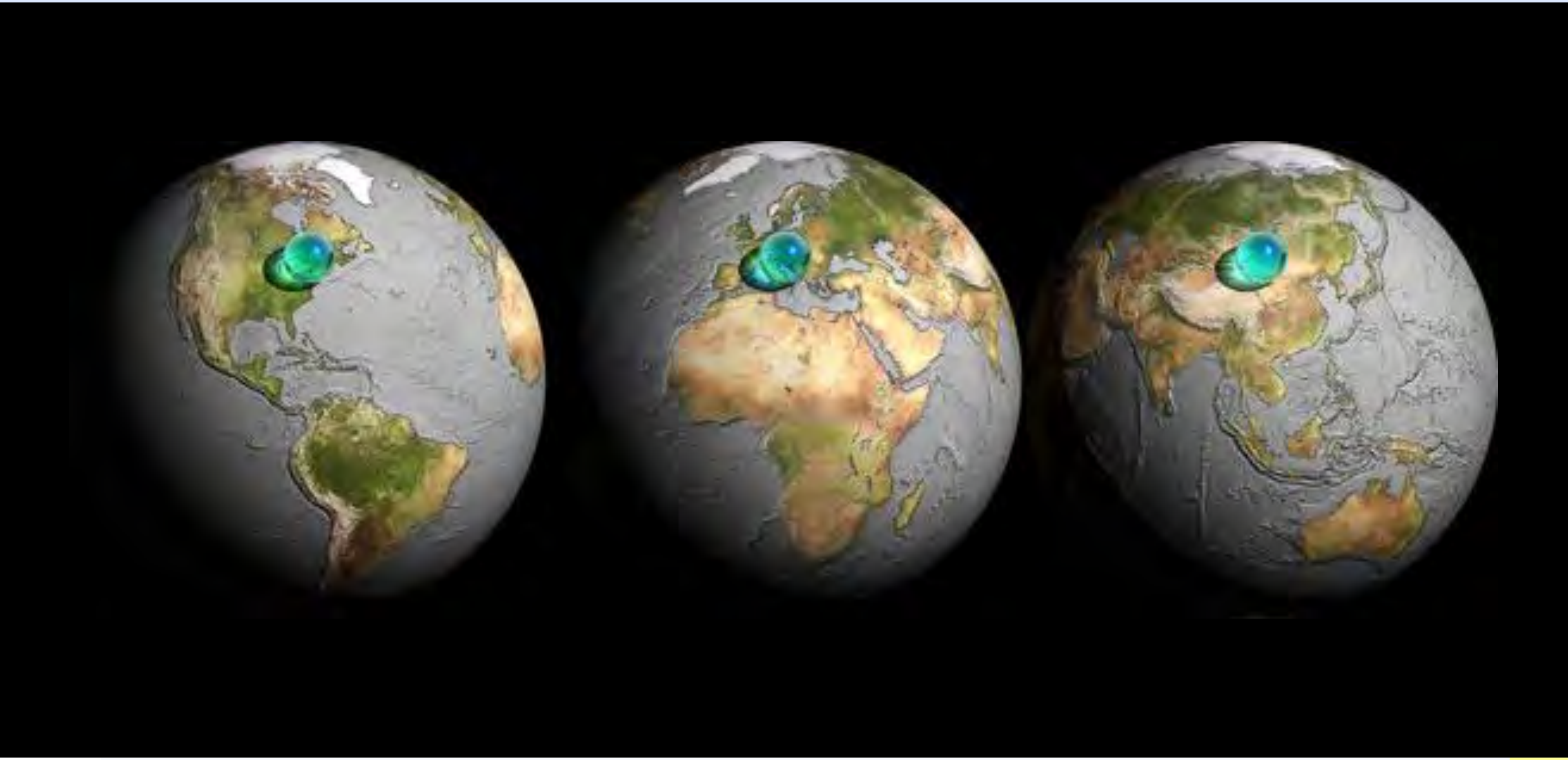
1. ***ENERGY***
2. *WATER*
3. *FOOD*
4. *ENVIRONMENT*
5. *POVERTY*
6. *TERRORISM & WAR*
7. *DISEASE*
8. *EDUCATION*
9. *DEMOCRACY*
10. *POPULATION*

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

~~**2006**~~	~~**~ 6.5**~~	~~**Billion People**~~
2013	**~ 7.1**	**Billion People**
2050	**~ 10**	**Billion People**

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

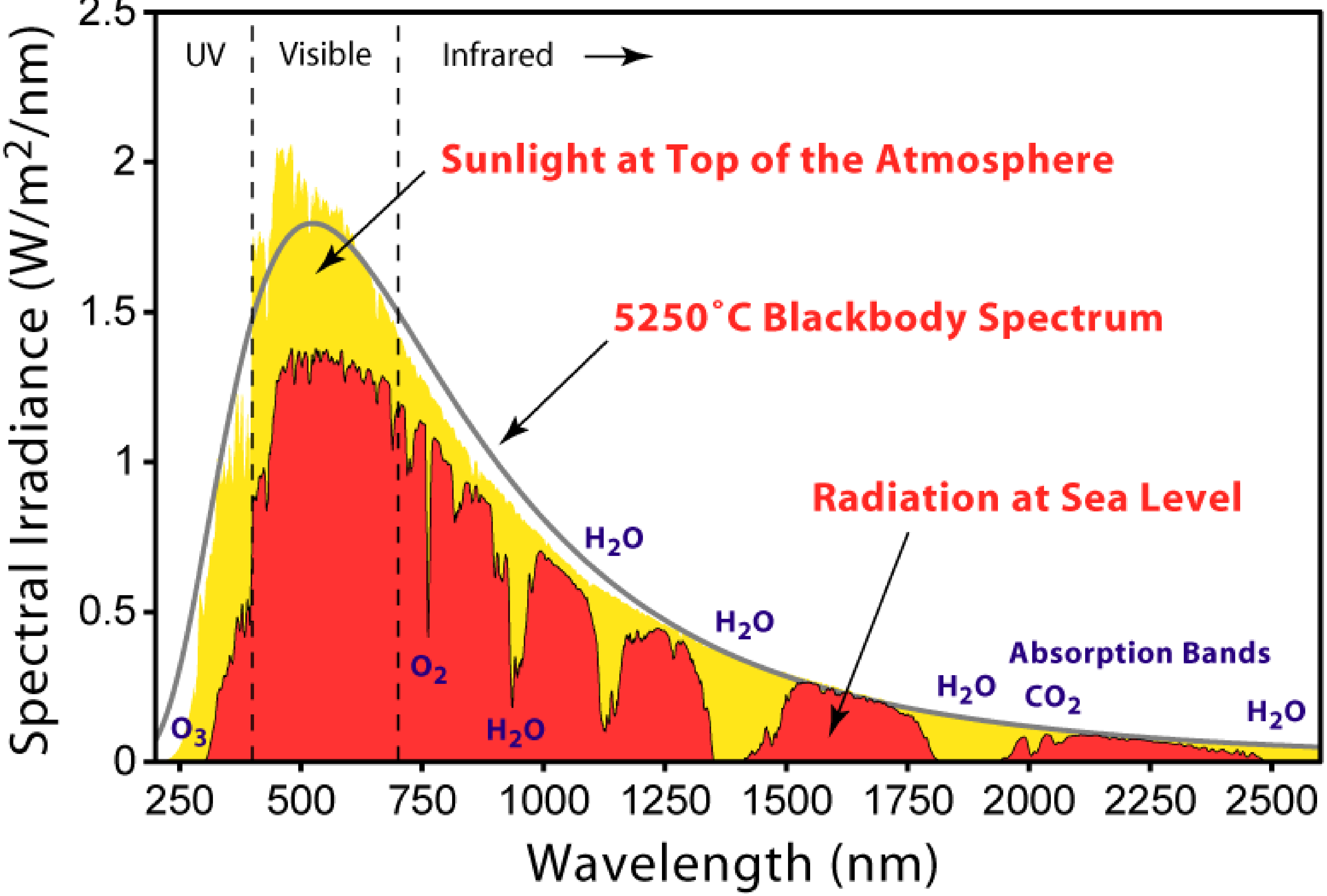
Earth's key natural resources: water and air



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

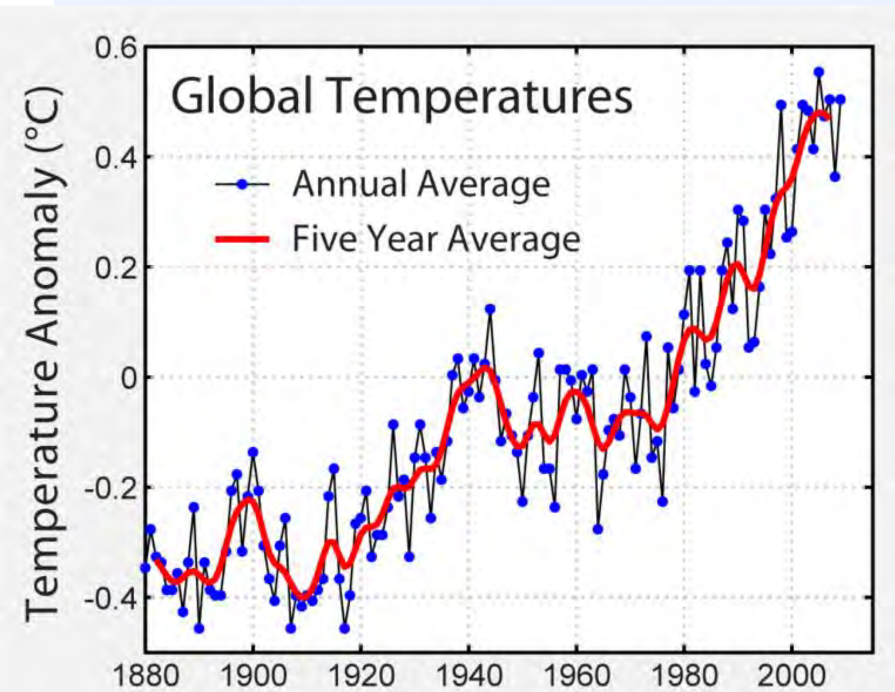
Photo & caption info: ADAM NIEMAN / SCIENCE PHOTO LIBRARY

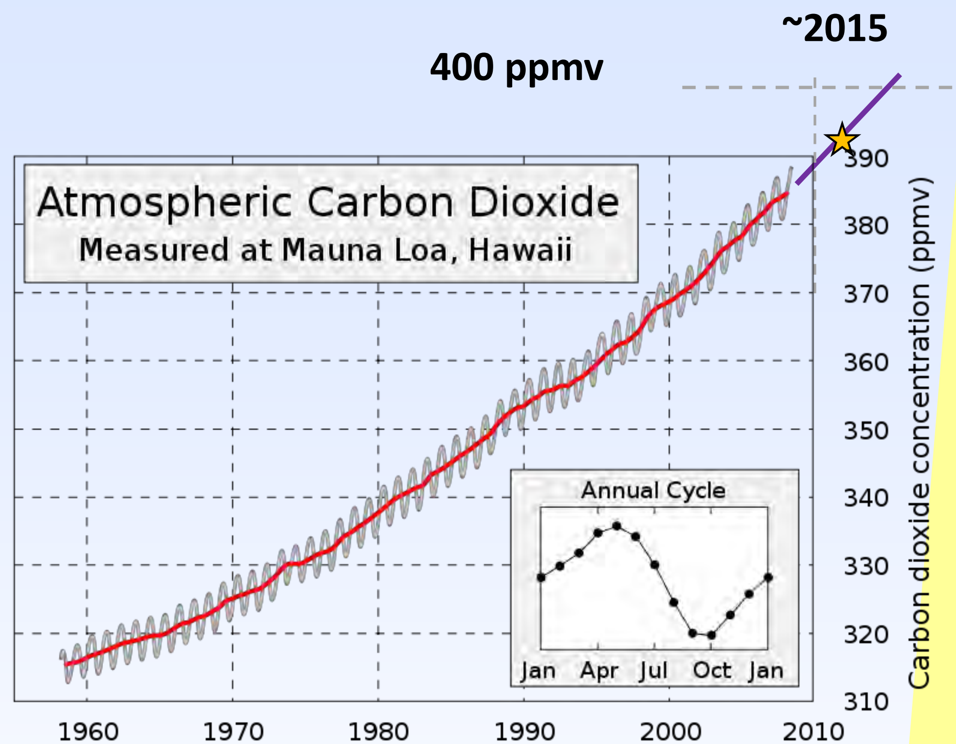
Solar Radiation Spectrum



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.



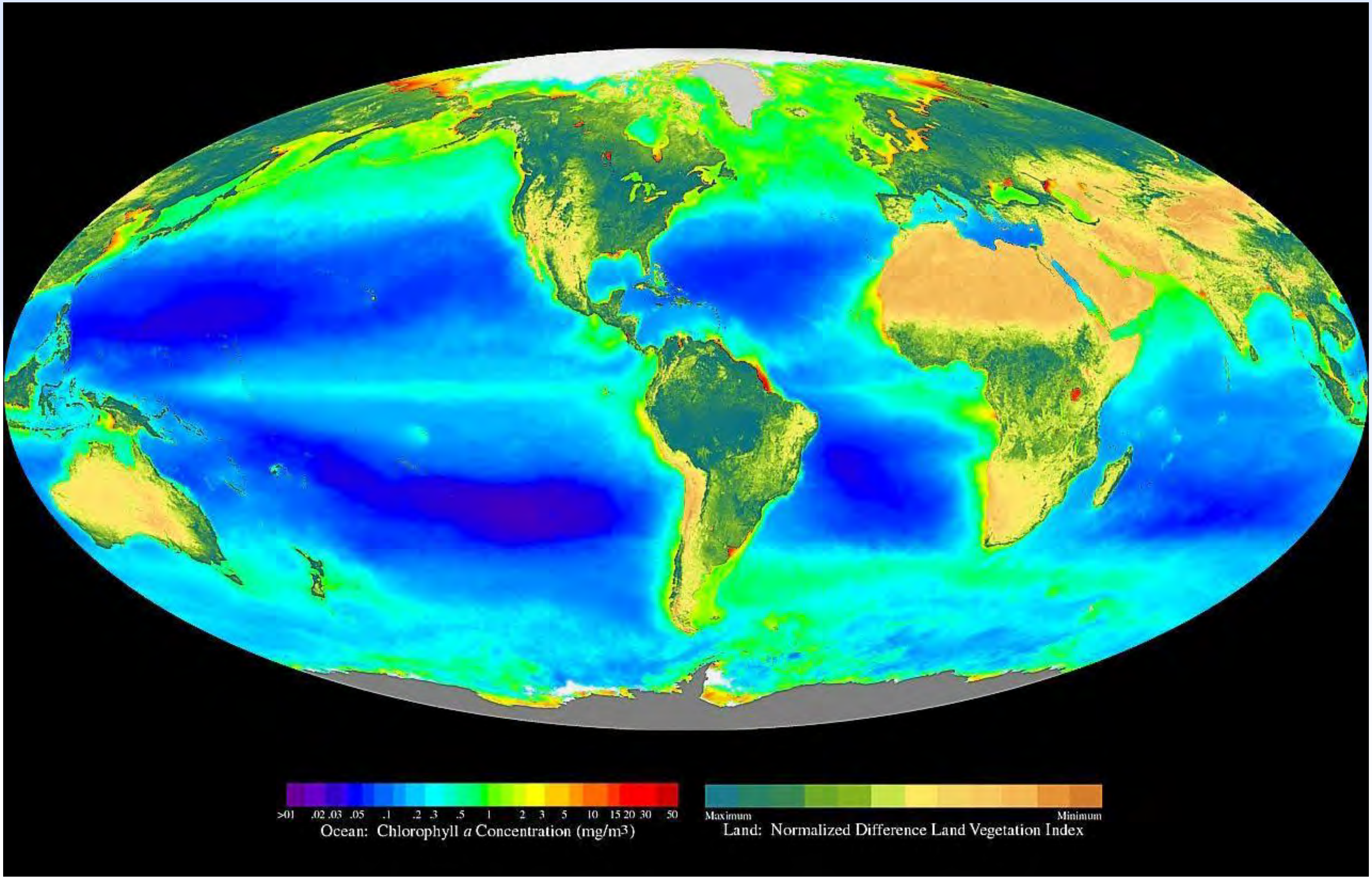


Keeling curve, data from Mauna Loa, Hawaii. (Charles David Keeling)

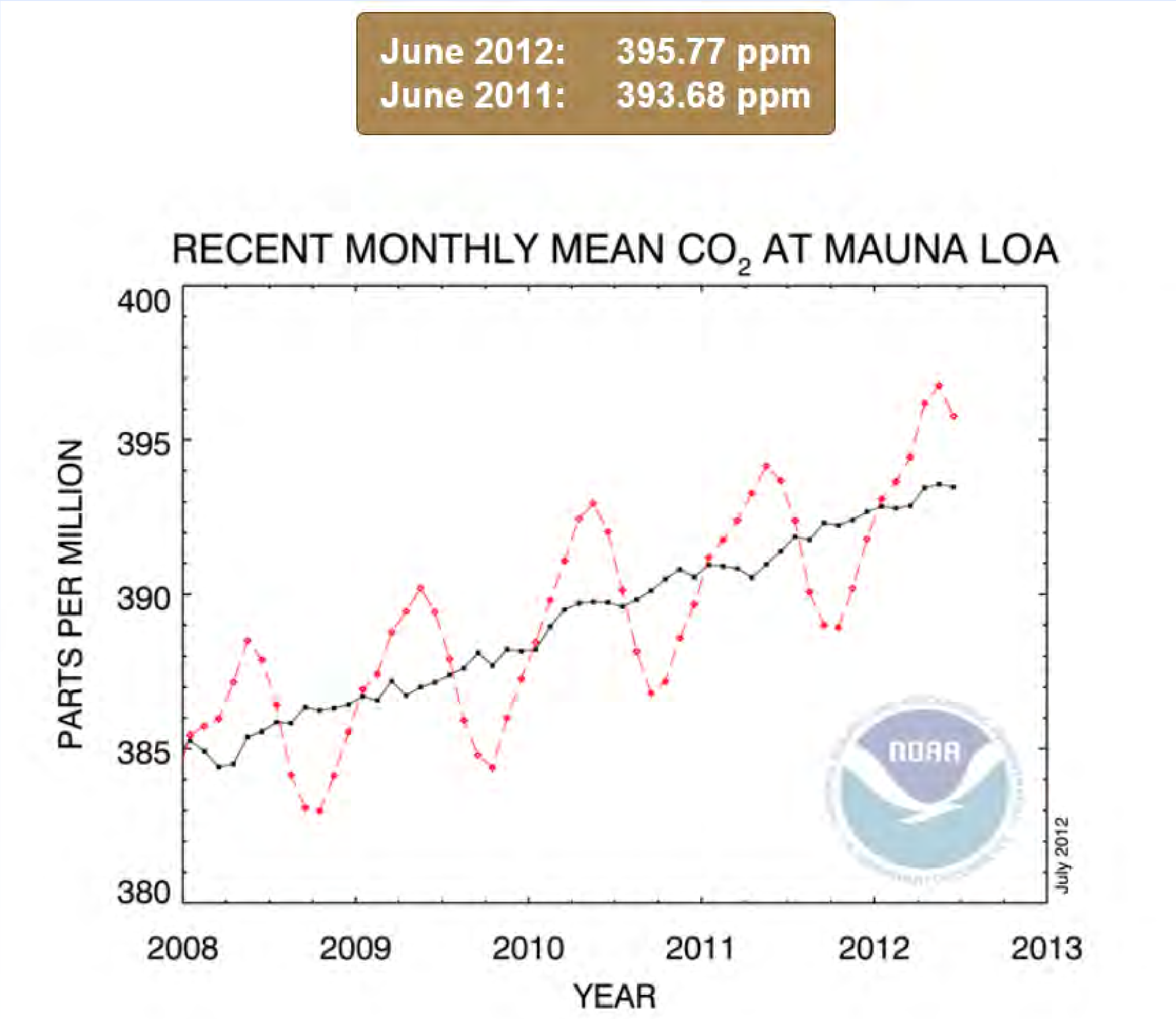
- All 2012 measurements show CO_2 > 390 ppmv

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

Global distribution of photosynthesis, including both oceanic phytoplankton and terrestrial vegetation

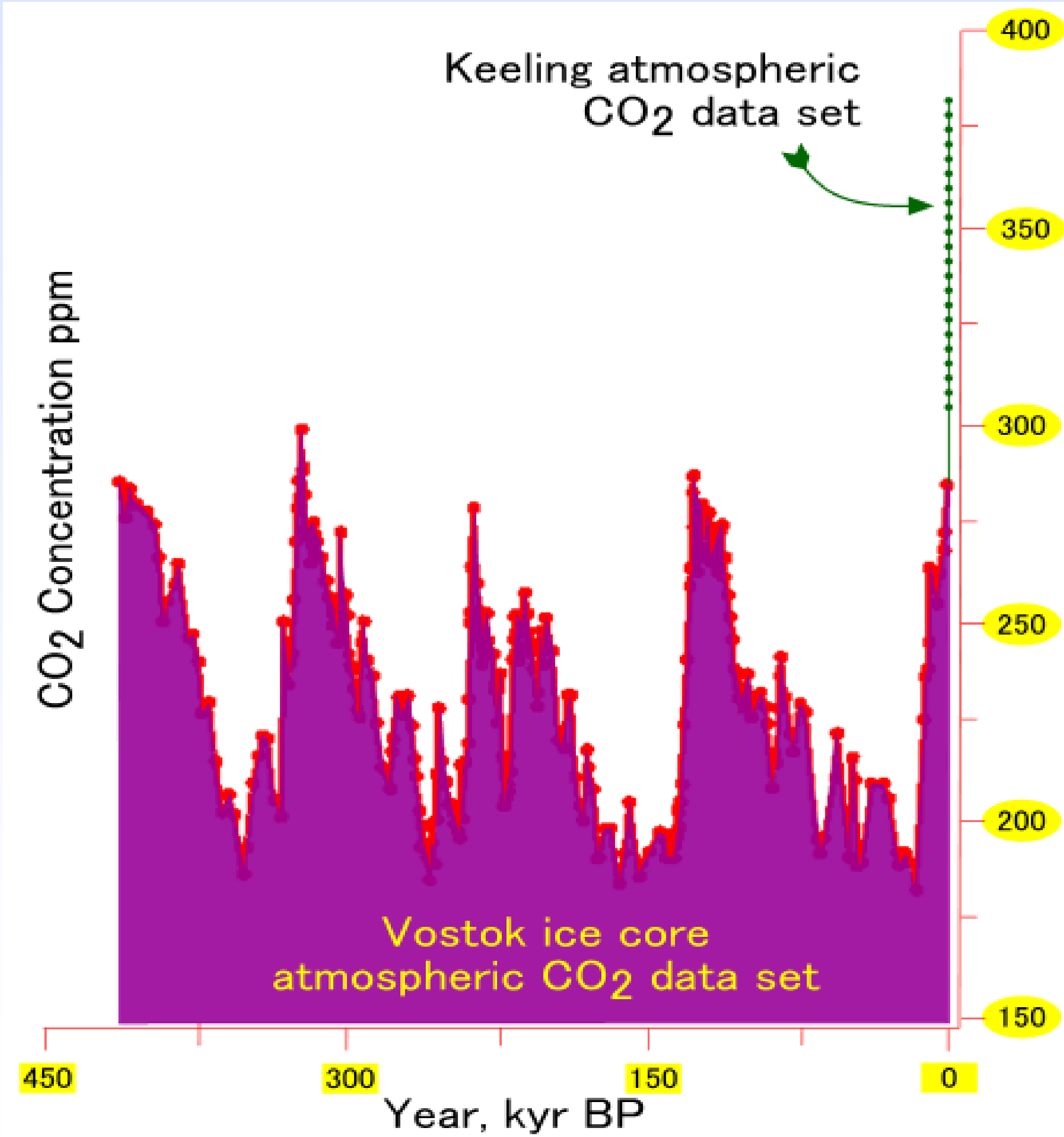


On watch: global temperatures, atmospheric CO_2



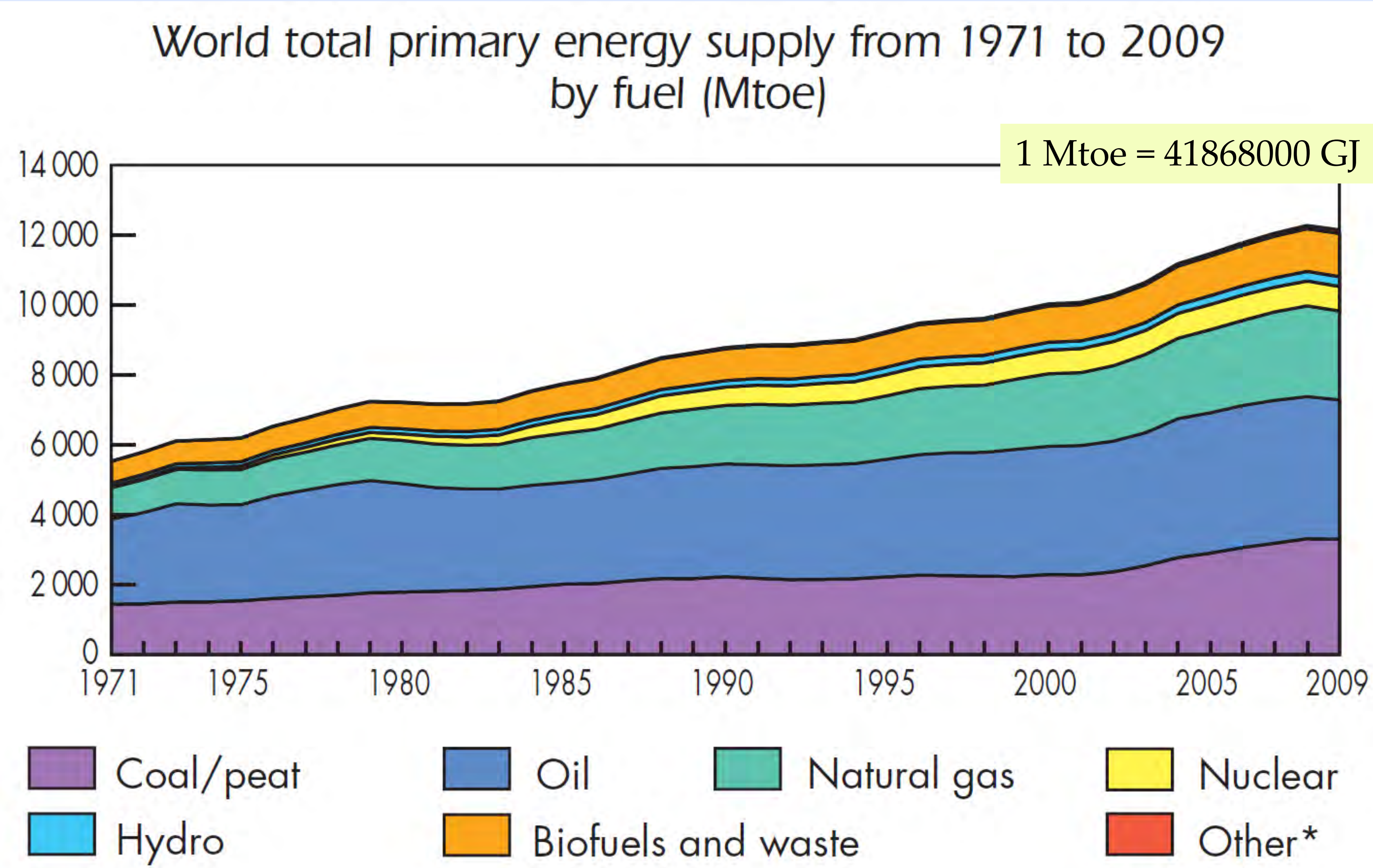
http://www.esrl.noaa.gov/gmd/ccgg/trends/

420,000+ years of atmospheric CO_2 levels



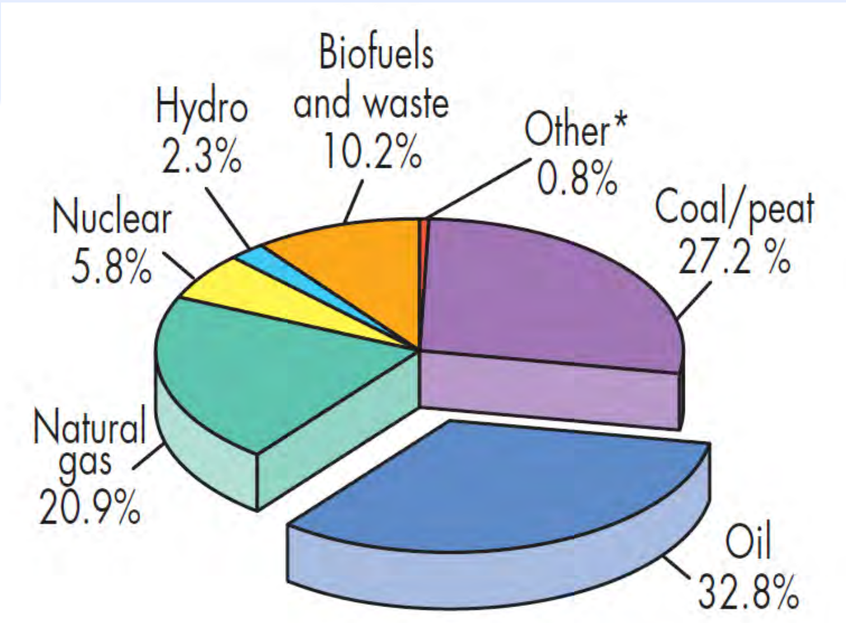
from N. Lewis, Cal Tech

Energy for People (forms of energy)



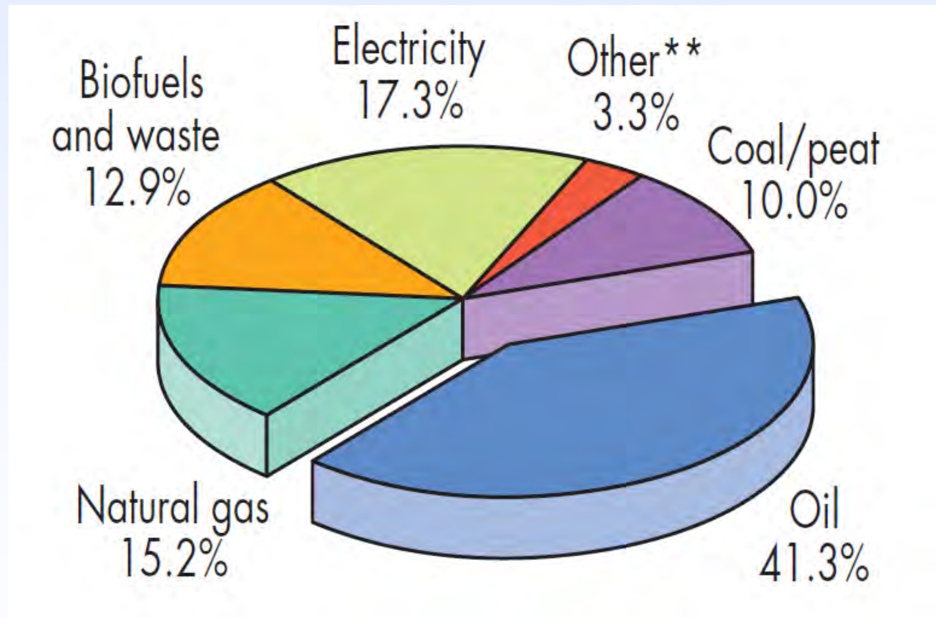
Energy for People: *2009*

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



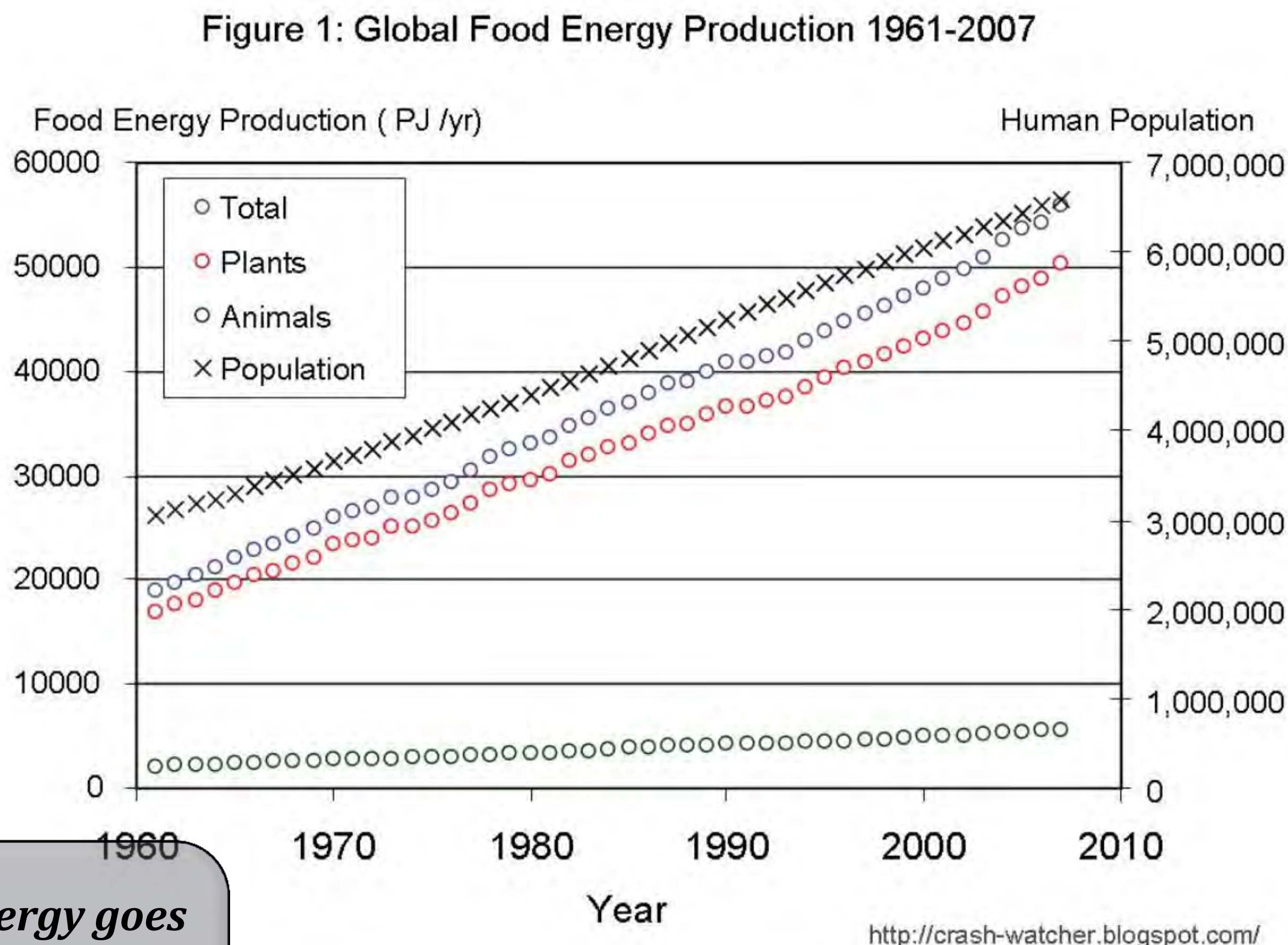
Fossil fuels sum to ~81% of our primary energy.

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



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…

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?

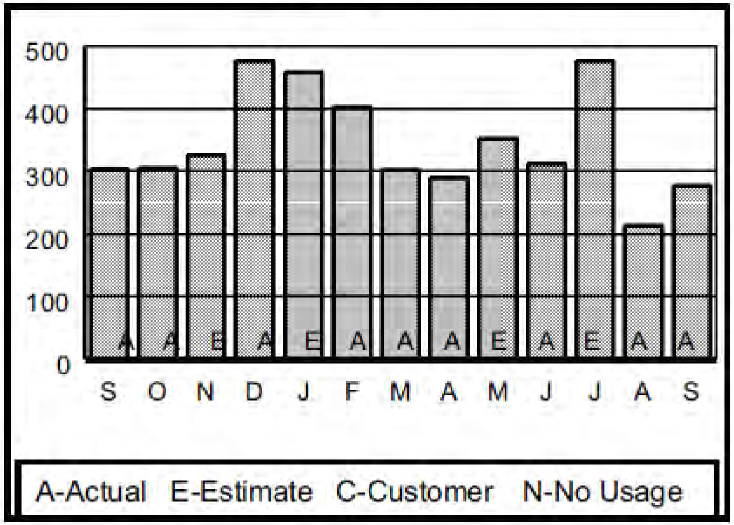
* Average cat generates ~5 W of heat during sleep, and ~24 W walking briskly

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



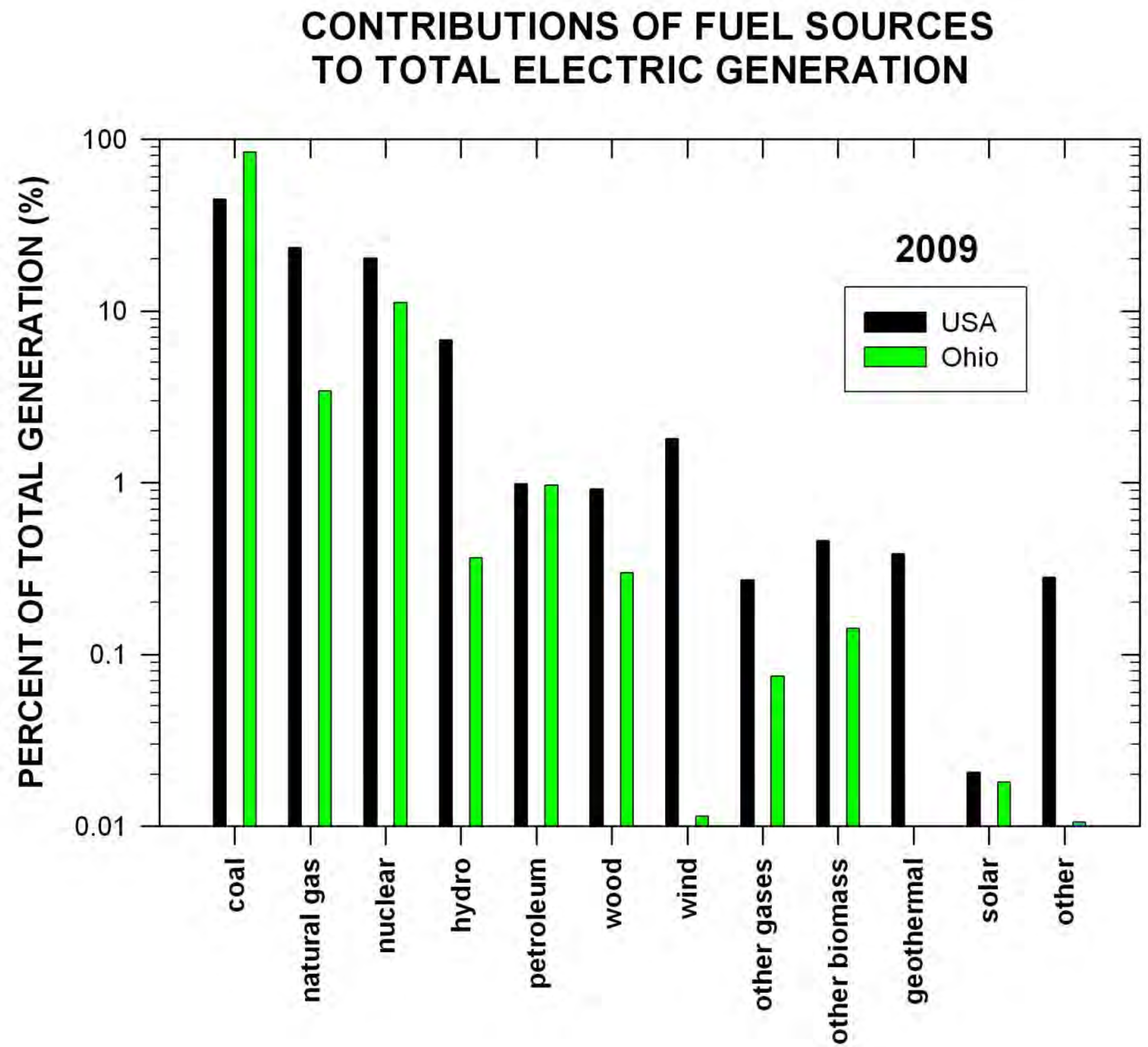
Historical Usage Information

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.

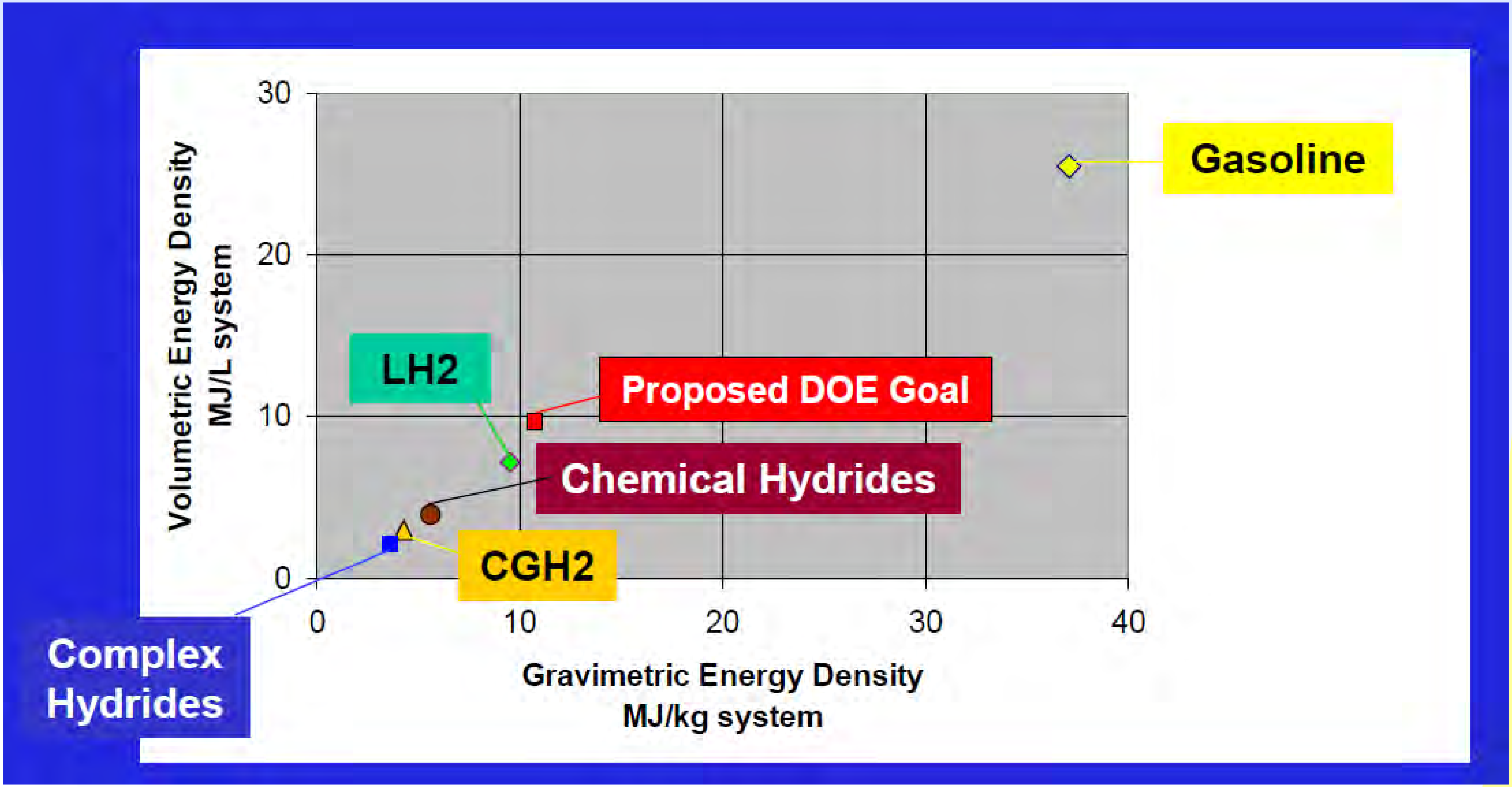
How Ohio's Electric Power Generation Stacks Up



Data Source: Energy Information Administration
U.S. Department.of Energy

Graphs by Brooks Martner, Lafayette, CO

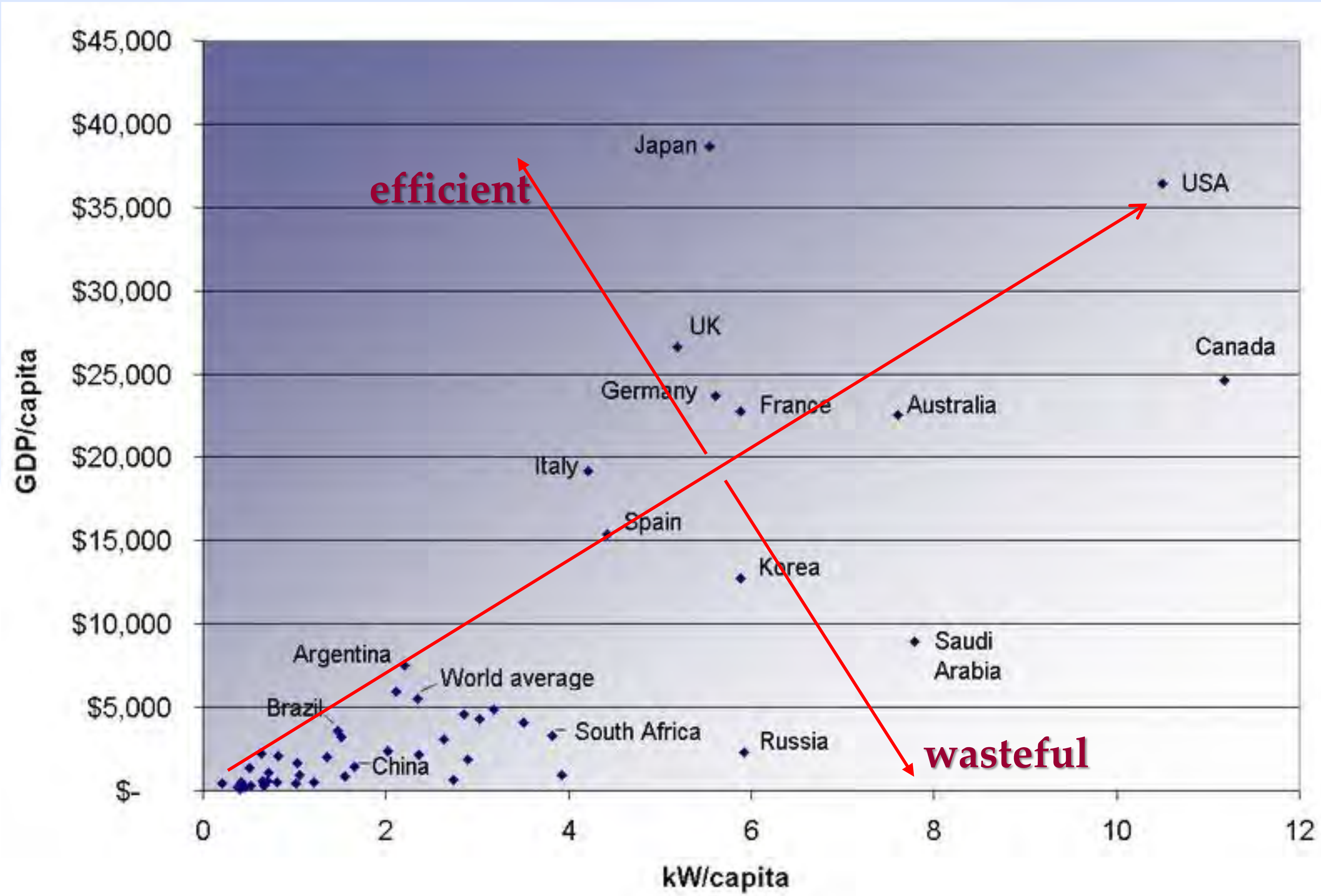
Transportation fuel energy density



“Gasoline was great.”

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

Energy Consumption and GDP



From: Wikimedia Commons

Forms of Energy (physics problems)

- Gravitational potential energy: $Pe_g = mgh$
  http://hyperphysics.phy-astr.gsu.edu/hbase/gpot.html
  Note: mass in kg, g in m/s^2, and h in m yields units of kg m^2 s^{-2}, which is equivalent to the joule
  Ignoring air resistance (friction), an object dropped from a height h will reach a velocity such that the PE has been converted fully to KE (see below) by the point just before striking the ground.

- Kinetic energy: KE = $\frac{1}{2} mv^2$, where for m in kg and v in m/s, we again arrive at kg m^2 s^{-2}

- Light energy: the energy of a photon is given by $E_{ph} = hc/\lambda = h\nu$, where h is Planck's constant = 6.63×10^{-34} J s, so that e.g. a photon of wavelength λ = 500 nm has a frequency $\nu = c/\lambda = (3 \times 10^8$ m/s)/500 nm = $(3 \times 10^8$ m/s) / $(500 \times 10^{-9}$ m) = 6×10^{14} Hz = 600 THz; and the energy of the photon is $E_{ph} = (6.63 \times 10^{-34}$ J s)$(3 \times 10^8$ m/s) / $(500 \times 10^{-9}$ m) $= 3.98 \times 10^{-19}$ J.

- Thermal energy: What is the (thermal) energy of a sheet of Al foil (weight = 2 g) in an oven at 350 F?

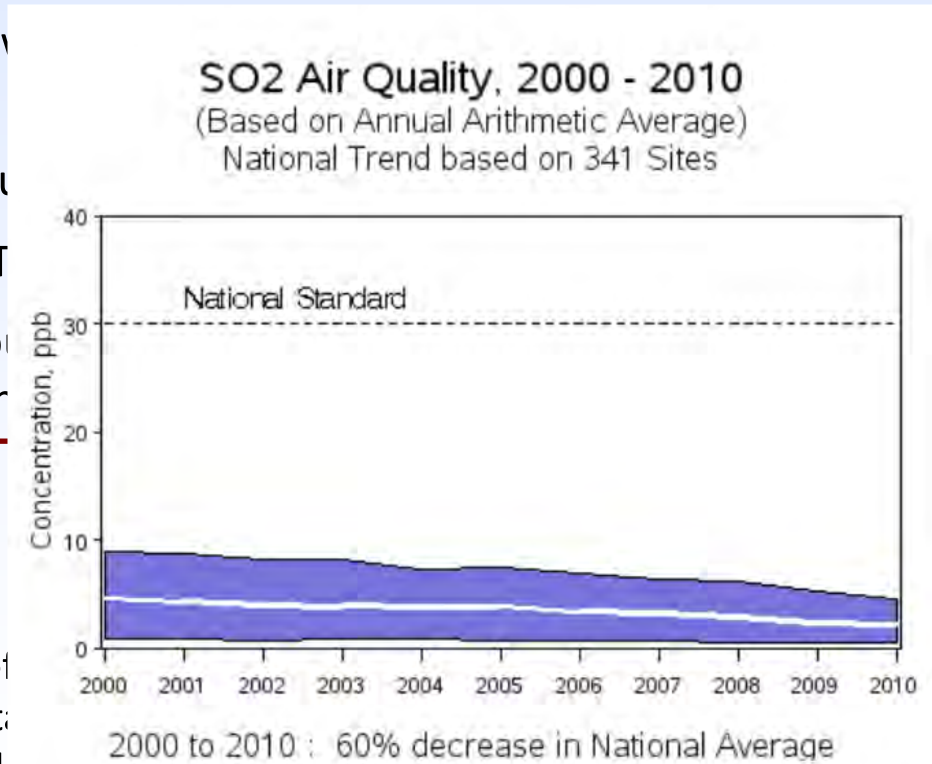
Need for clean energy

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****
- Popı … ries → increased
  C- ir



Health

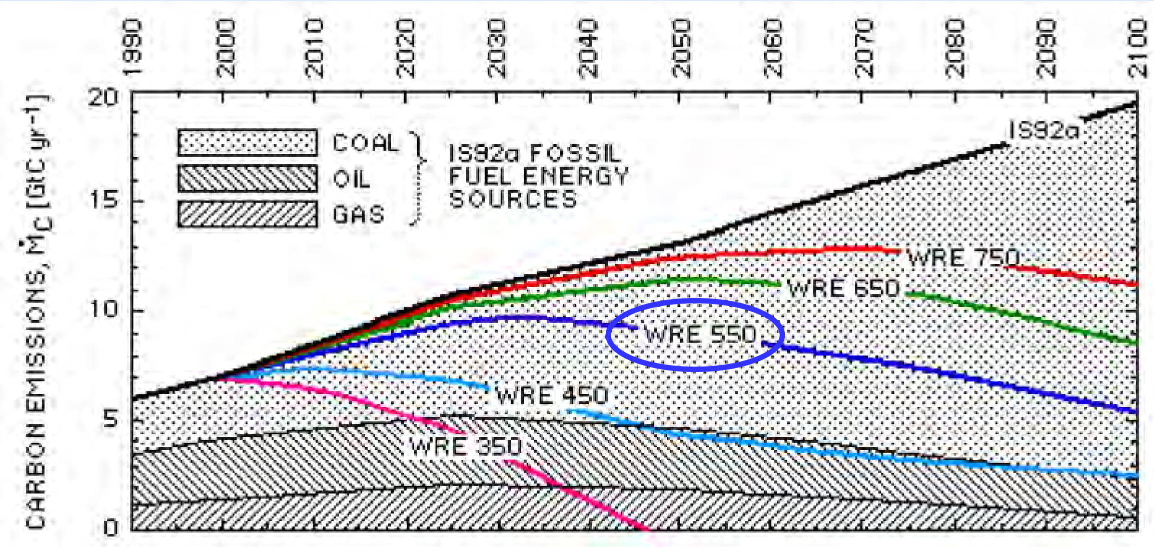
Coal-fired power … smog (ozone), soot →

- significant … ecosystems, respiratory
- majority of … unhealthy lungs (incl.
- ~4% of tot
- largest pol… velopmental toxin, affecting unborn children

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

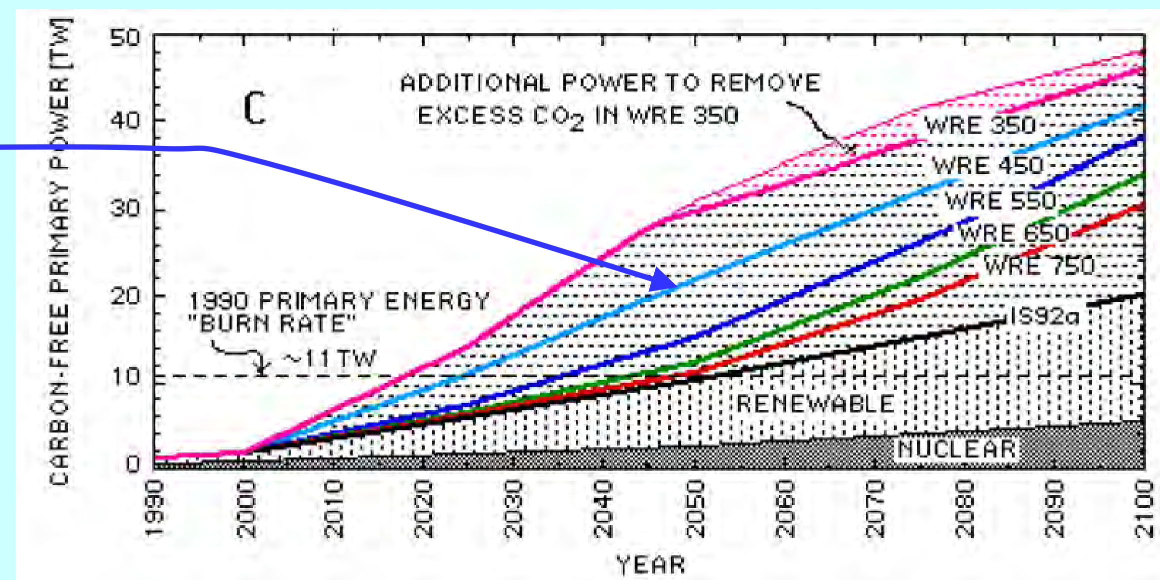
[Sources – U.S. DOE and U.S. EPA]

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

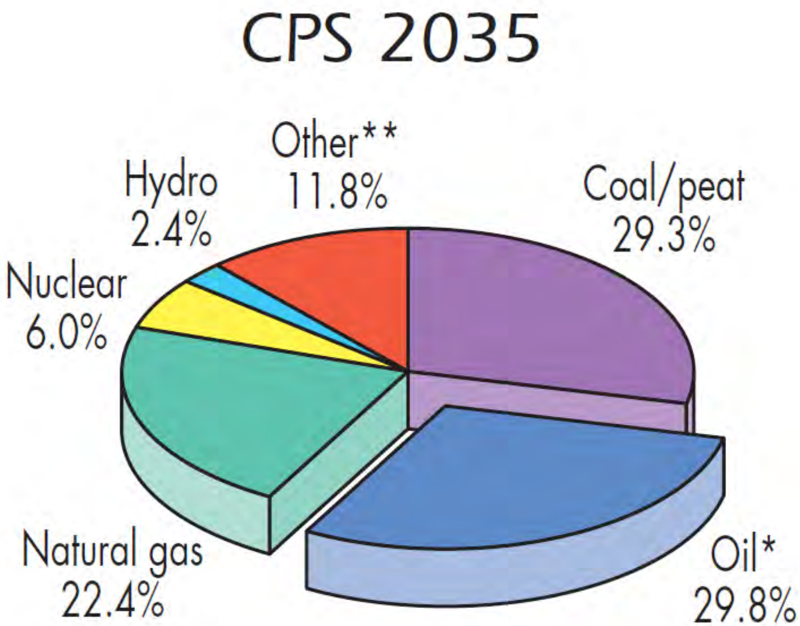


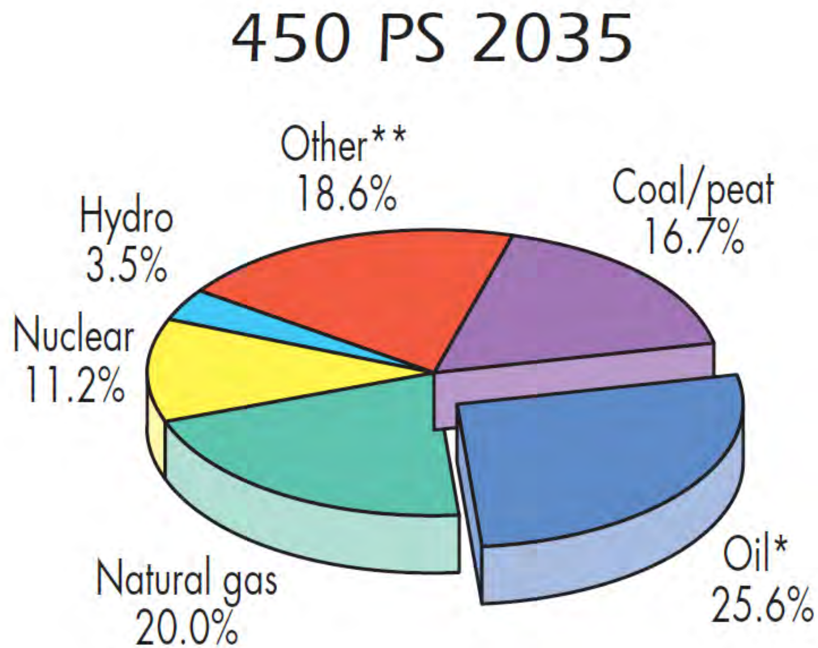
By 2100, carbon-free power requirement jumps to ~40 TW.

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

Total primary energy in 2035

Current Policy Scenario vs.
450 Policy Scenario





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

2008 global energy consumption = 474 EJ ($\sim 5\times 10^{20}$ J) with ~85% derived from the combustion of fossil fuels. The average power consumption rate was 15 terawatts (1.5×10^{13} W).

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

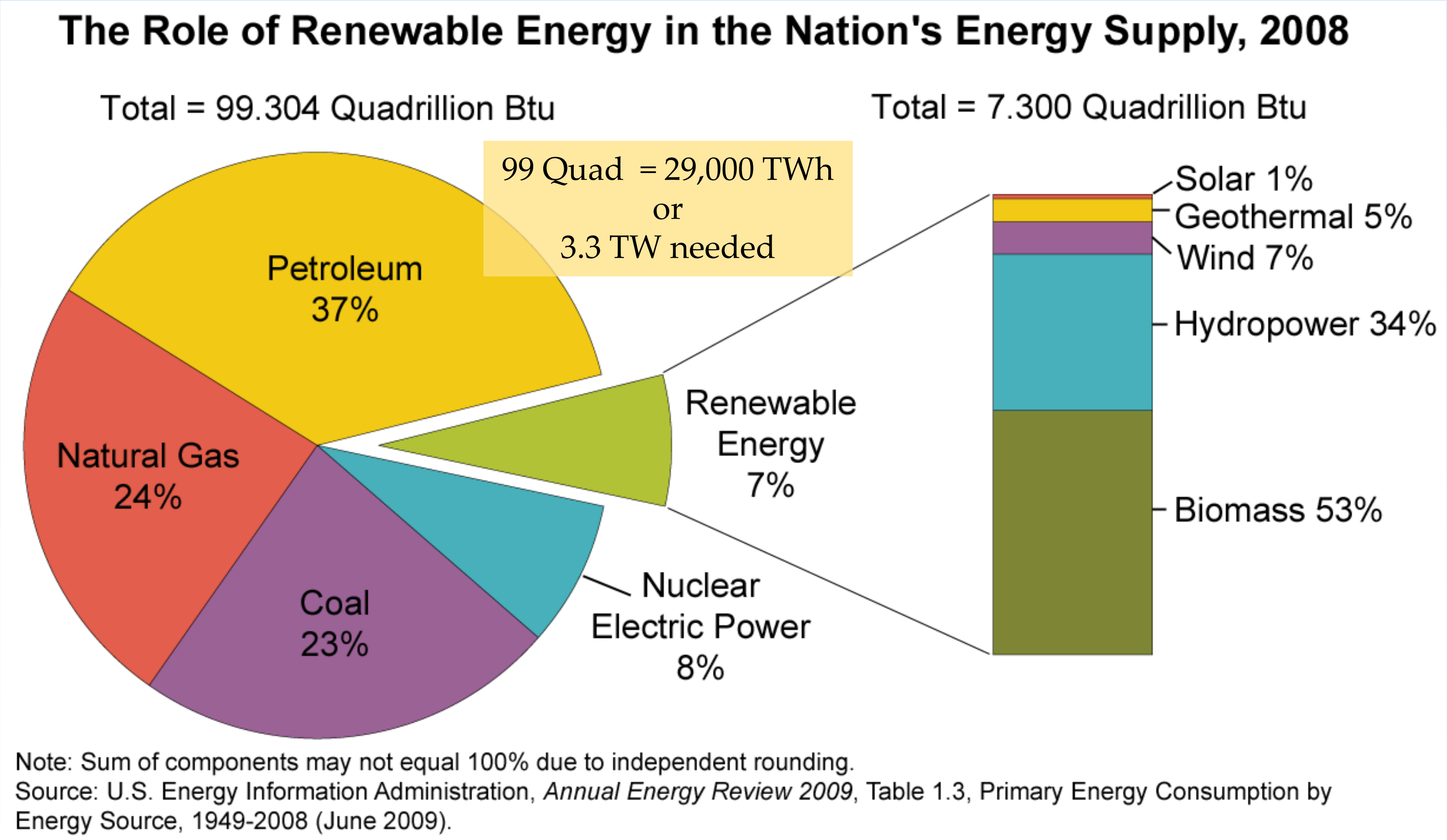
Tough Reality

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 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

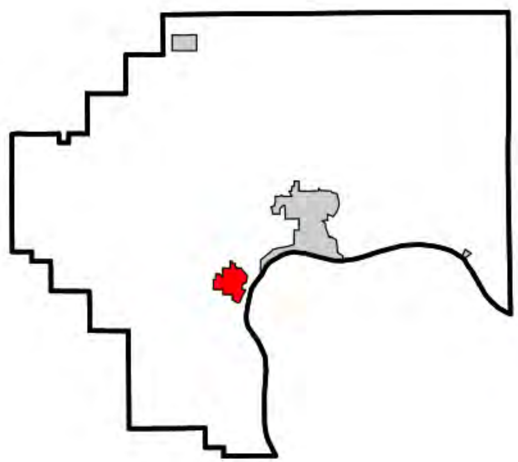
• Hydroelectric (technically feasible) 2.1 TW economically feasible, 0.9 TW in 2010	3.8 TW
• Geothermal (installed capacity)	10.9 GW
• Tides/Waves	1 TW
• Wind	70 TW
• Solar (120,000 TW solar energy incident on Earth)	600 TW

* 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

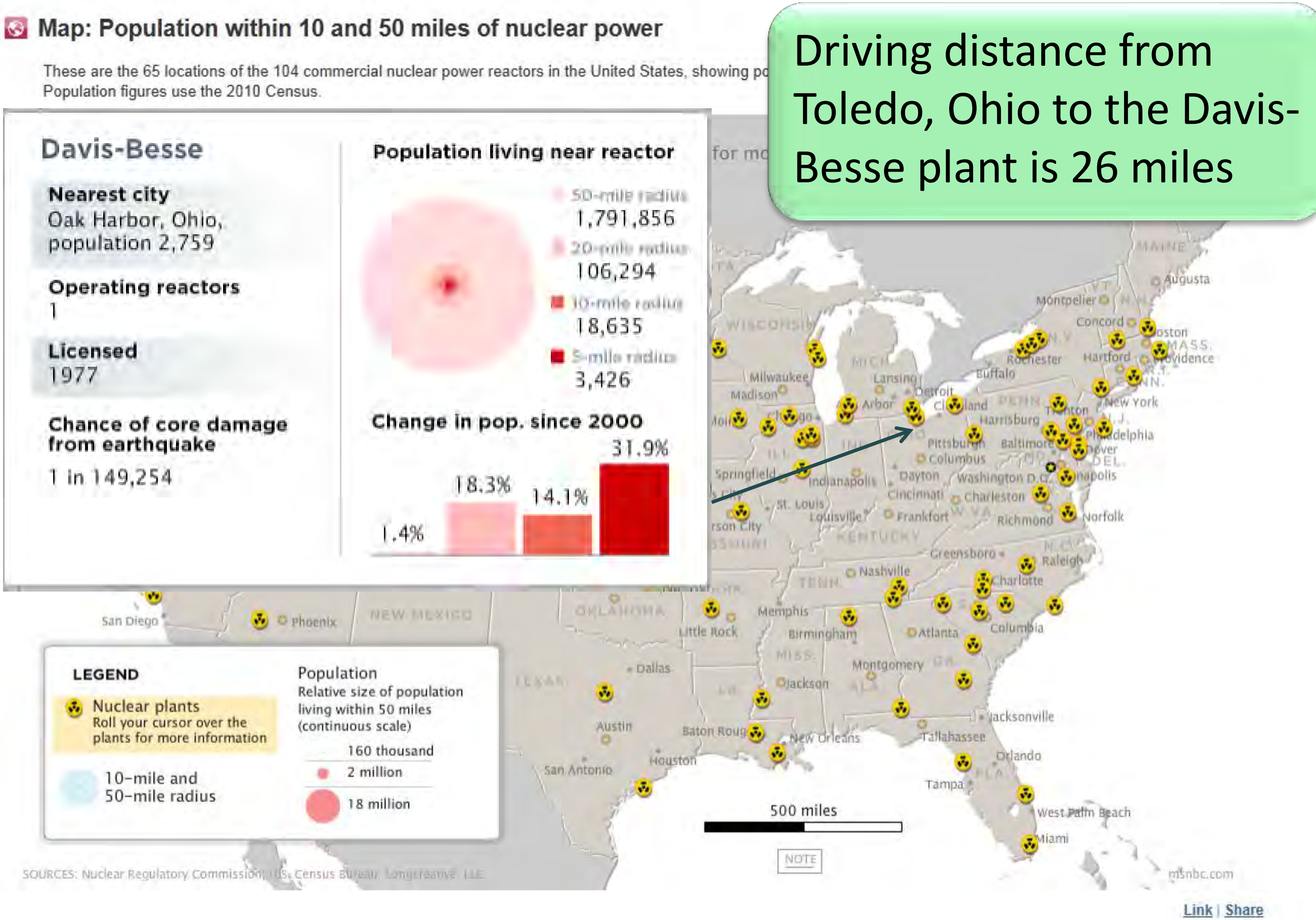
What about … Nuclear Power?

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



Nuclear never far away in the eastern half of US

Driving distance from Toledo, Ohio to the Davis-Besse plant is 26 miles

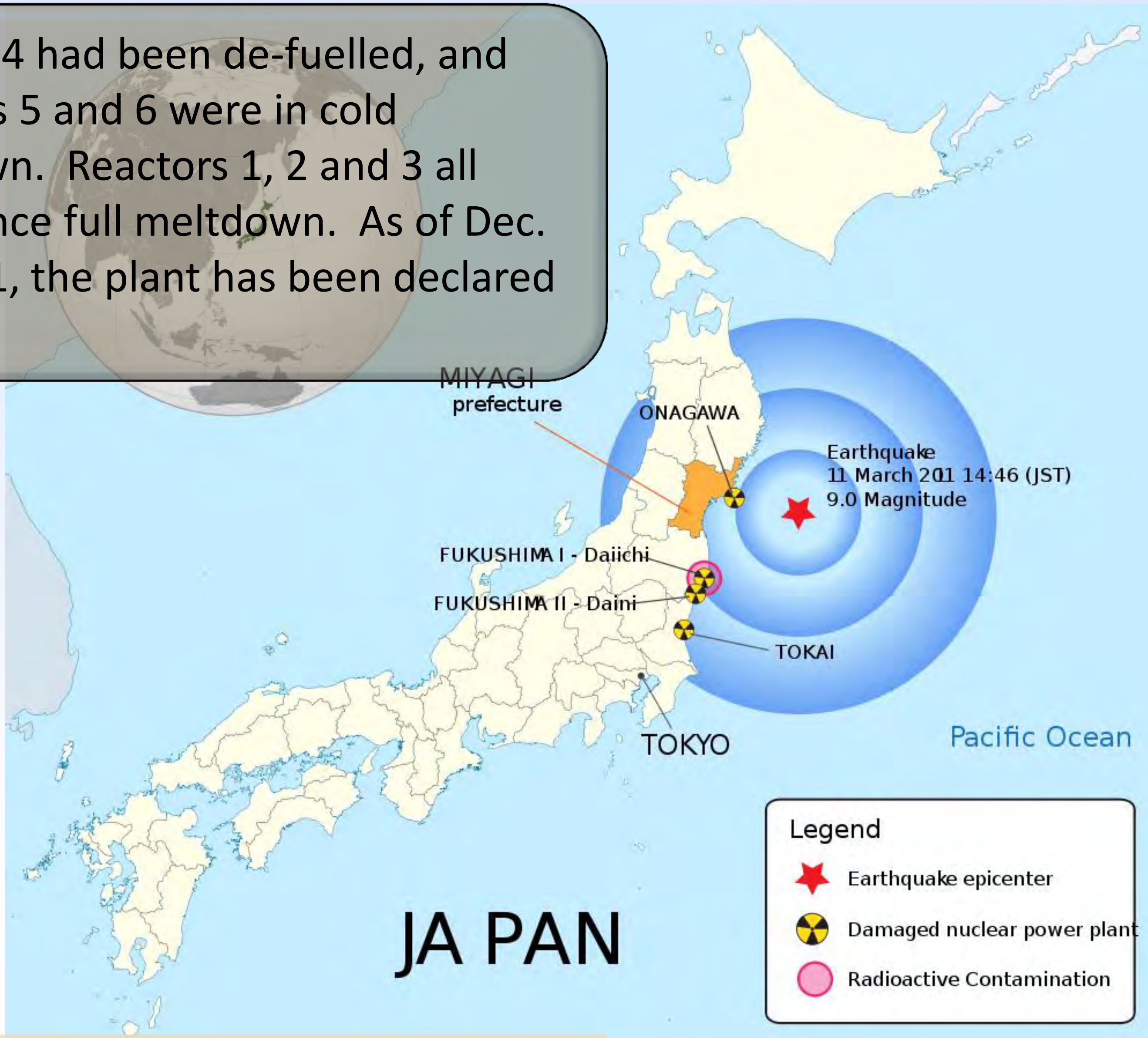


Nuclear Power

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

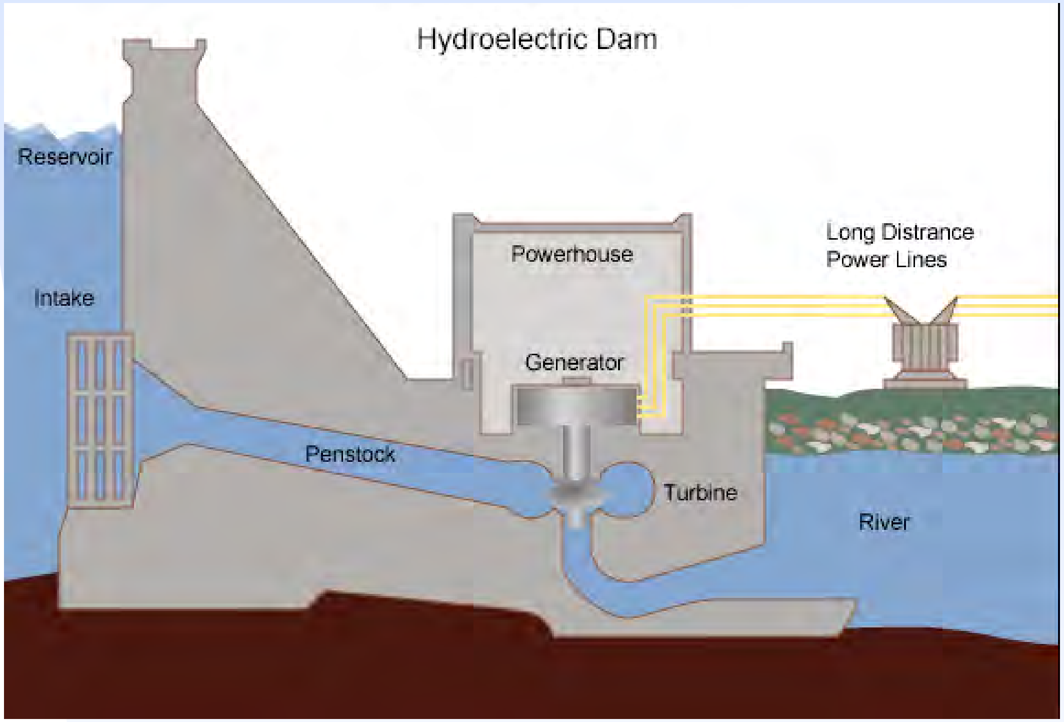
2011 Japan earthquake: Fukushima Daiichi nuclear disaster

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

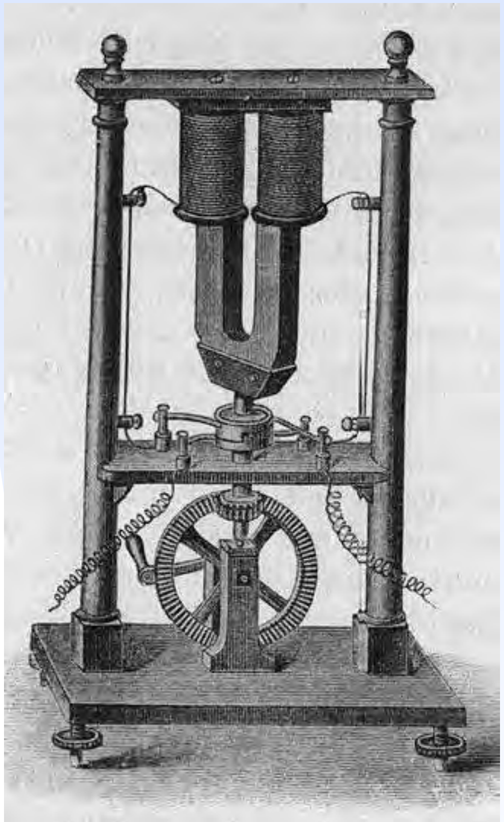
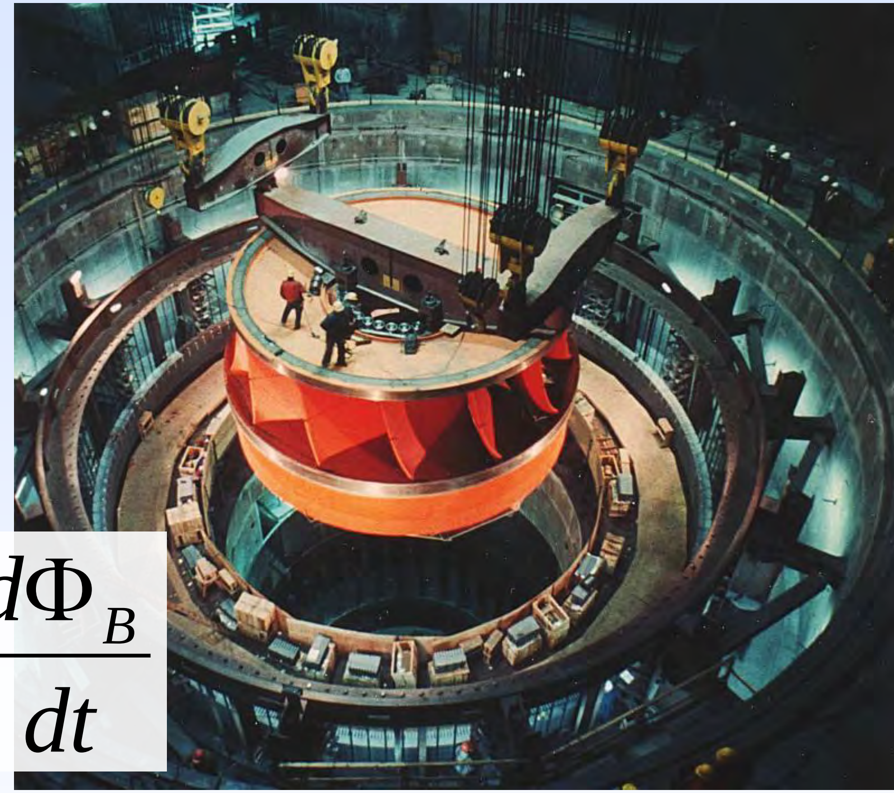


Fig. 33.



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

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

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

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

electric motor $\longleftrightarrow$ *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	-	-	

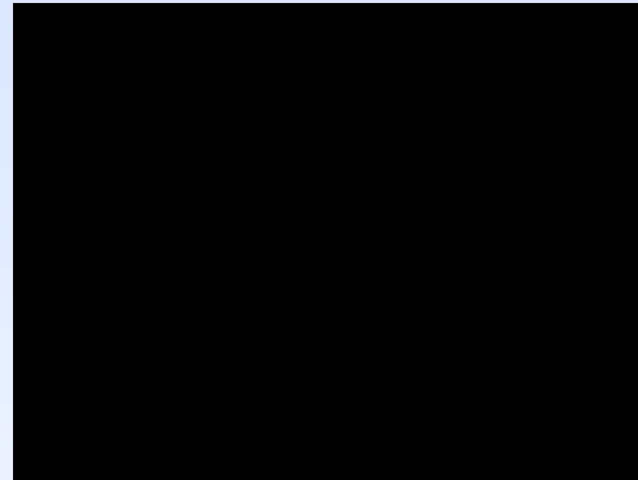
Potential capacity of 3.8 TW; ultimately driven by the Sun.

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

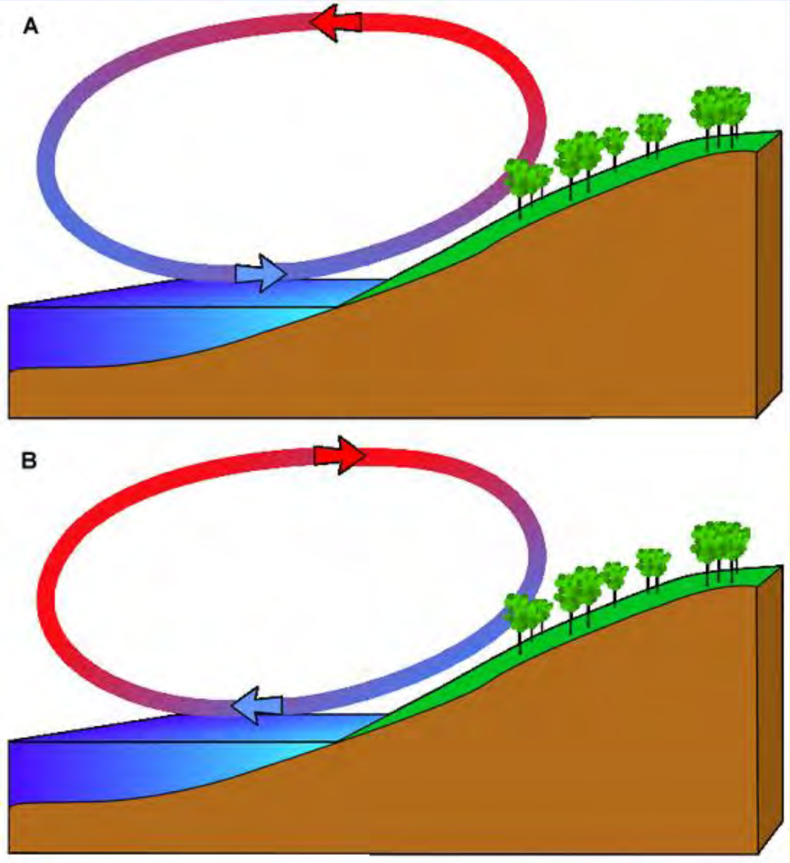
Origins of Wind

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

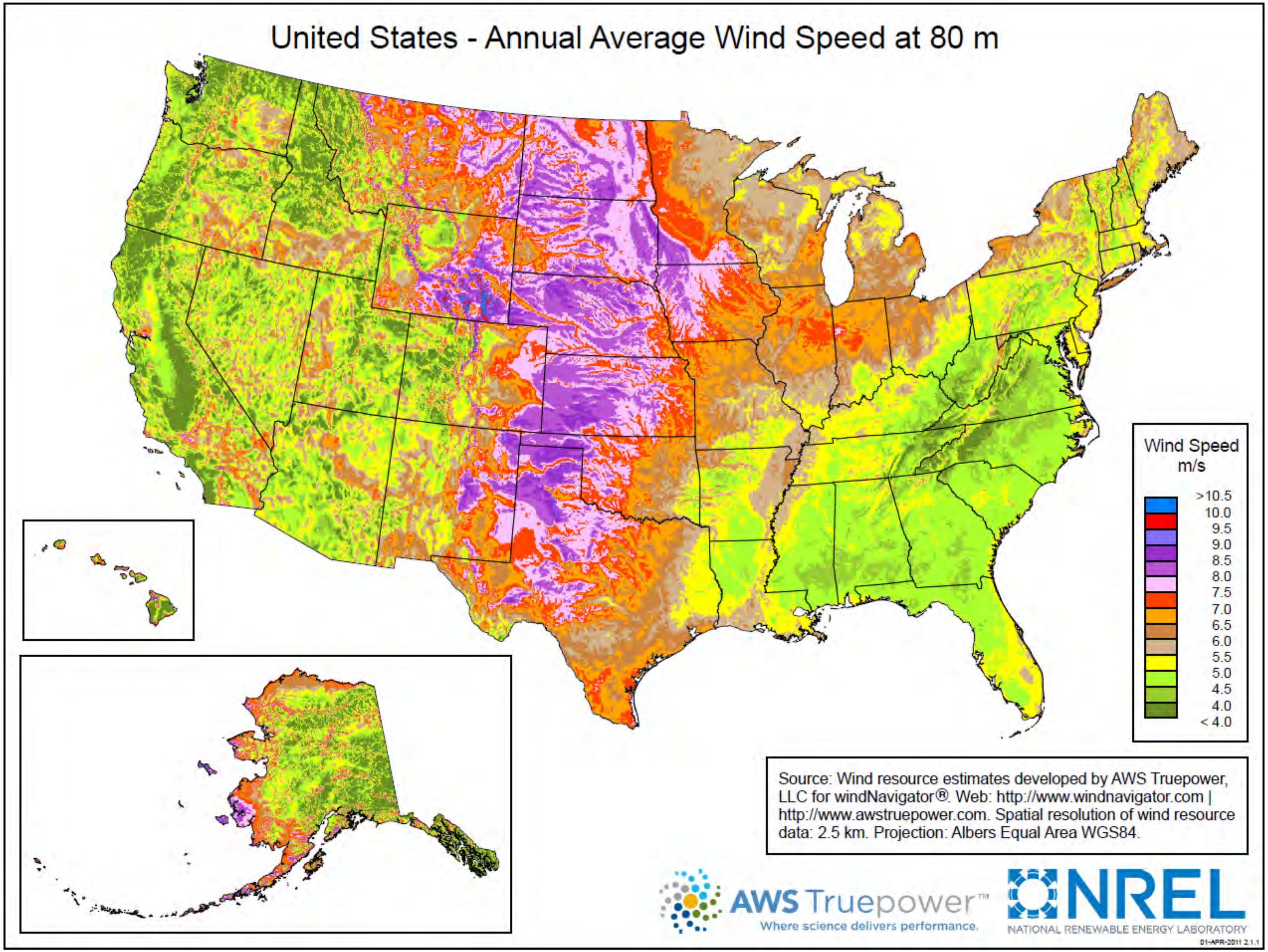
… growth in the forecasts can be attributed to the increasingly common use of very large turbines that rise to almost 100 meters.
Wind speeds are greater at higher elevations. Previous wind studies were based on the deployment of 50- to 80-meter turbines.

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

$$P = \frac{1}{2} A \cdot v \cdot \rho \cdot v^2 = \frac{1}{2} A \cdot \rho \cdot v^3$$

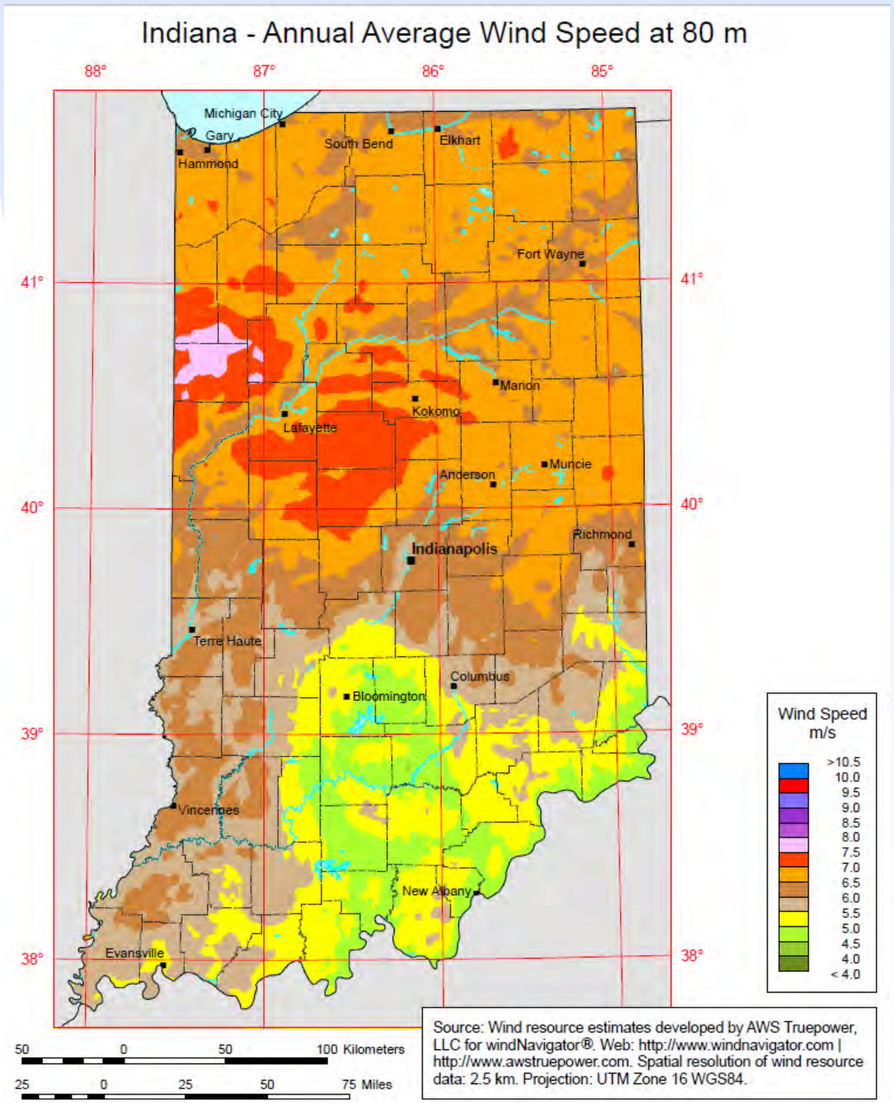
Global potential for wind-generated electricity
Xi Lu, Michael B. McElroya,, and Juha Kiviluomac
www.pnas.orgcgidoi10.1073pnas.0904101106

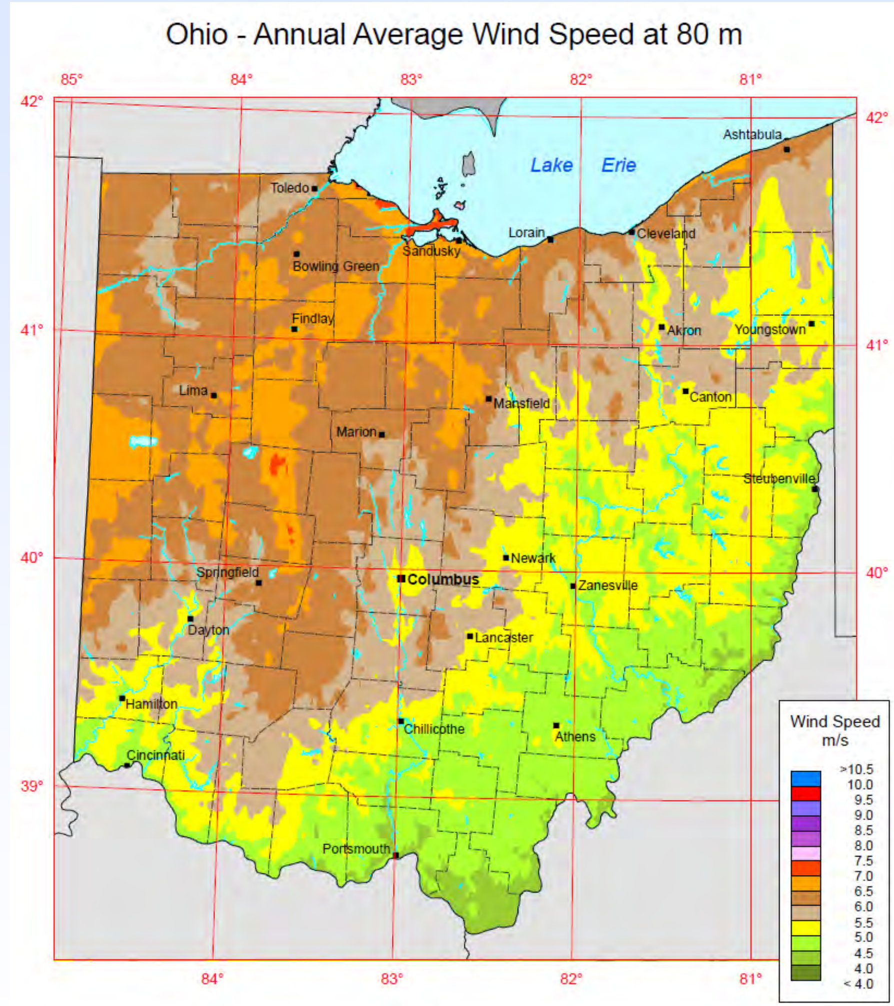
Wind Power



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

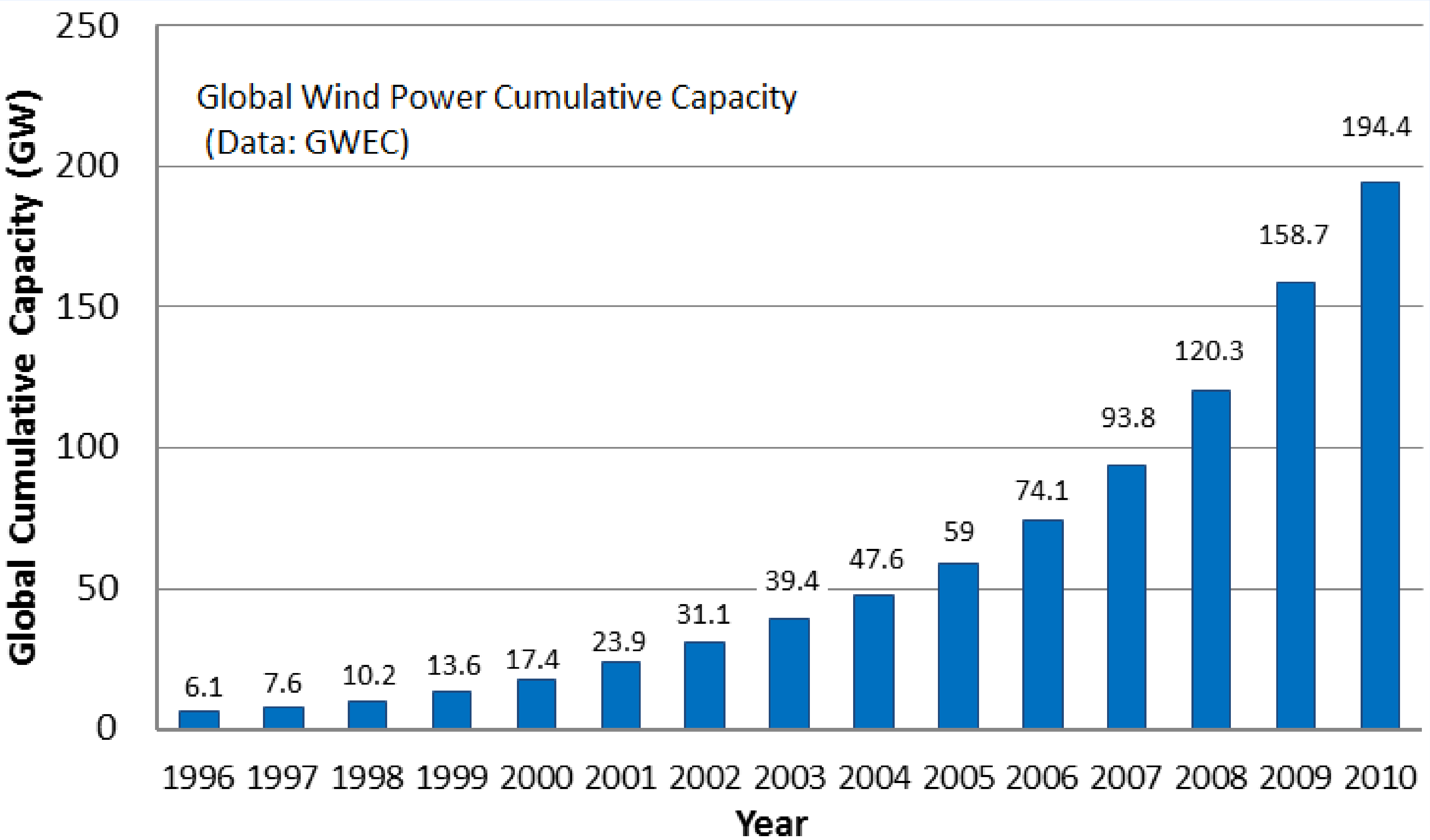
Indiana and Ohio Wind Power

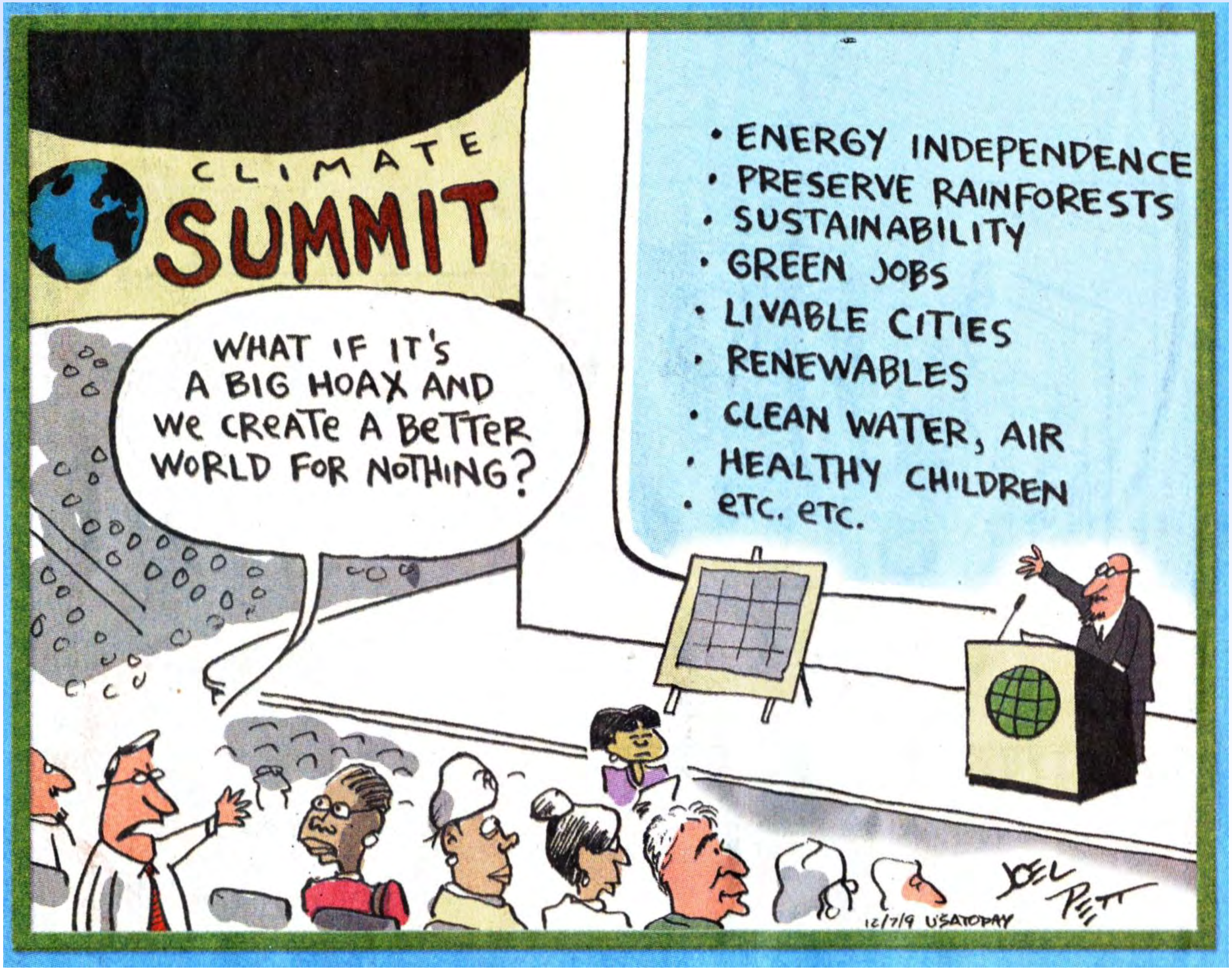




Global Wind Power

22% year-over-year growth in 2010




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.
12/7/9 USATODAY
JOEL PETT

The Sun (worth revering)

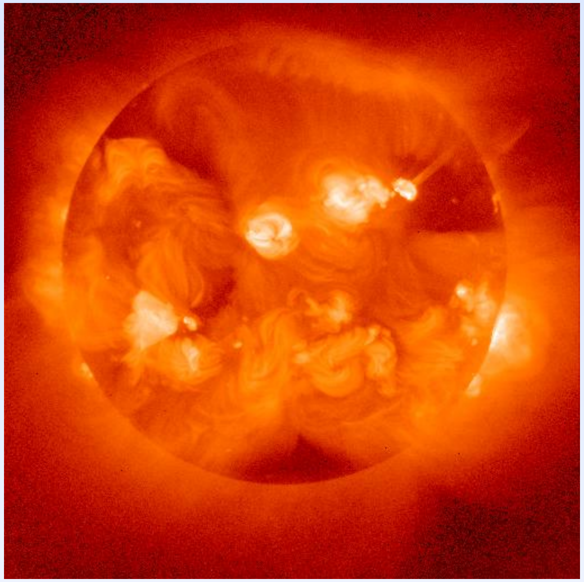
"Why Does the Sun Shine?"
by *They Might Be Giants*

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: $1.2x10^5$ TW solar energy potential (1.76 $x10^5$ 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

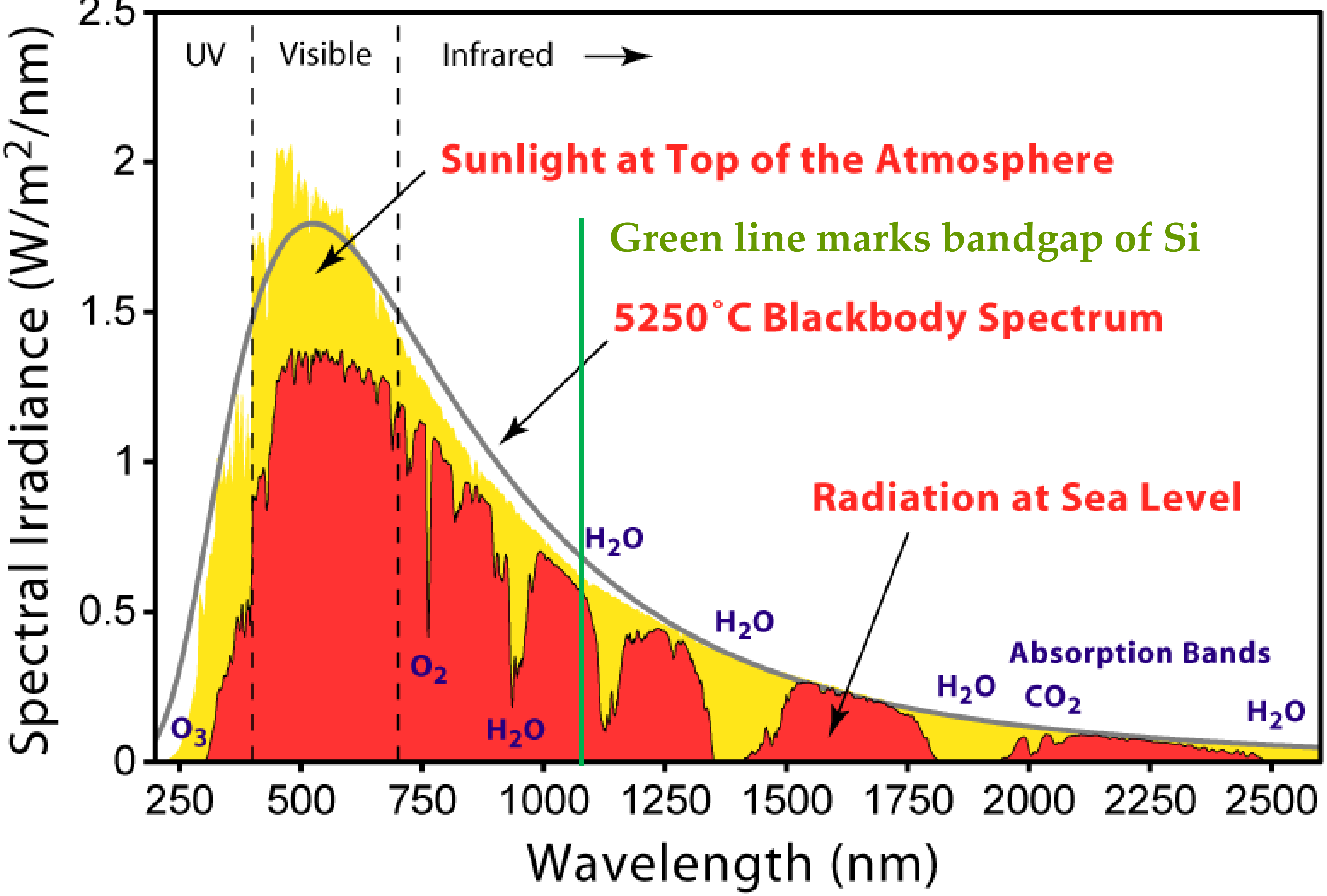


Image created by Robert A. Rohde / Global Warming Art

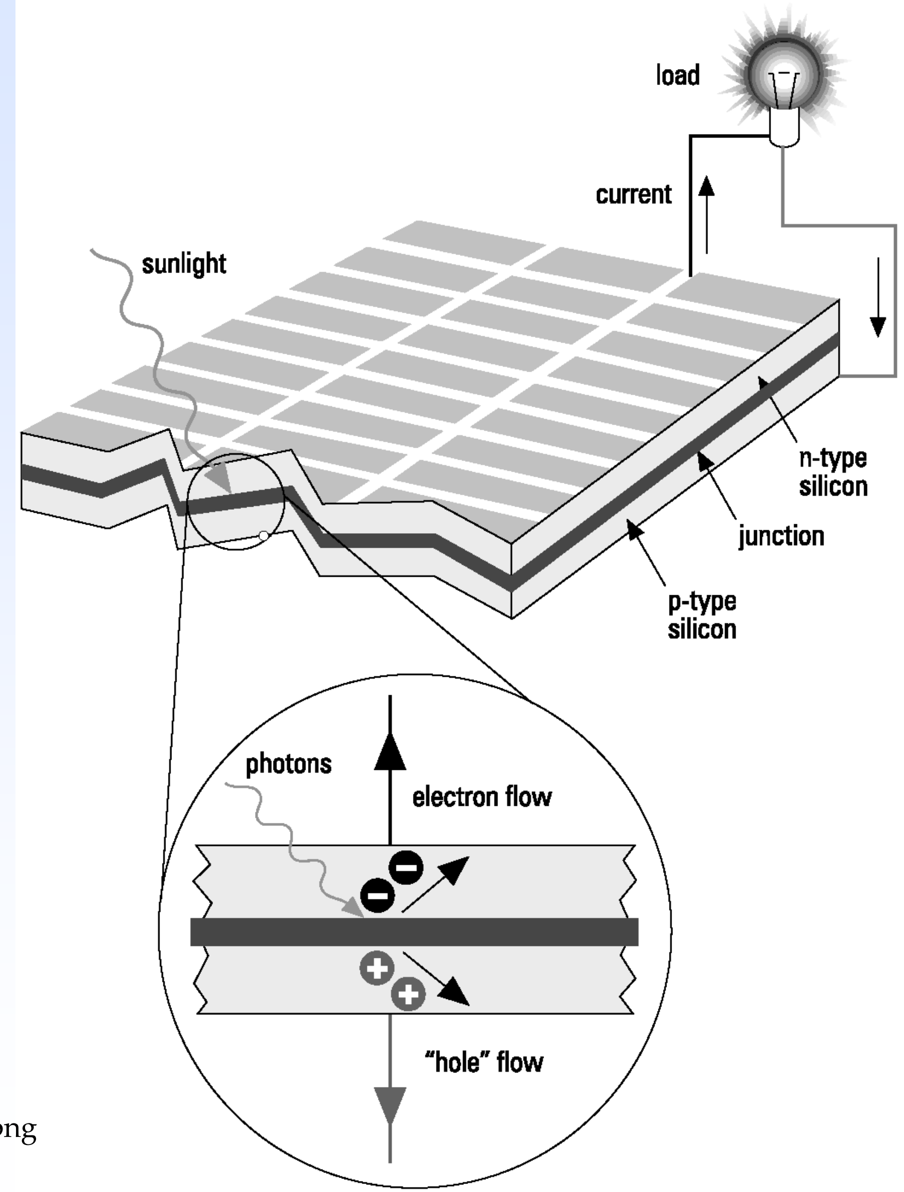
The Solar Resource in the US

PV covering area of square ~133 miles x 133 miles
more than satisfies all US energy needs.

Basic silicon photovoltaic (solar) cell operation

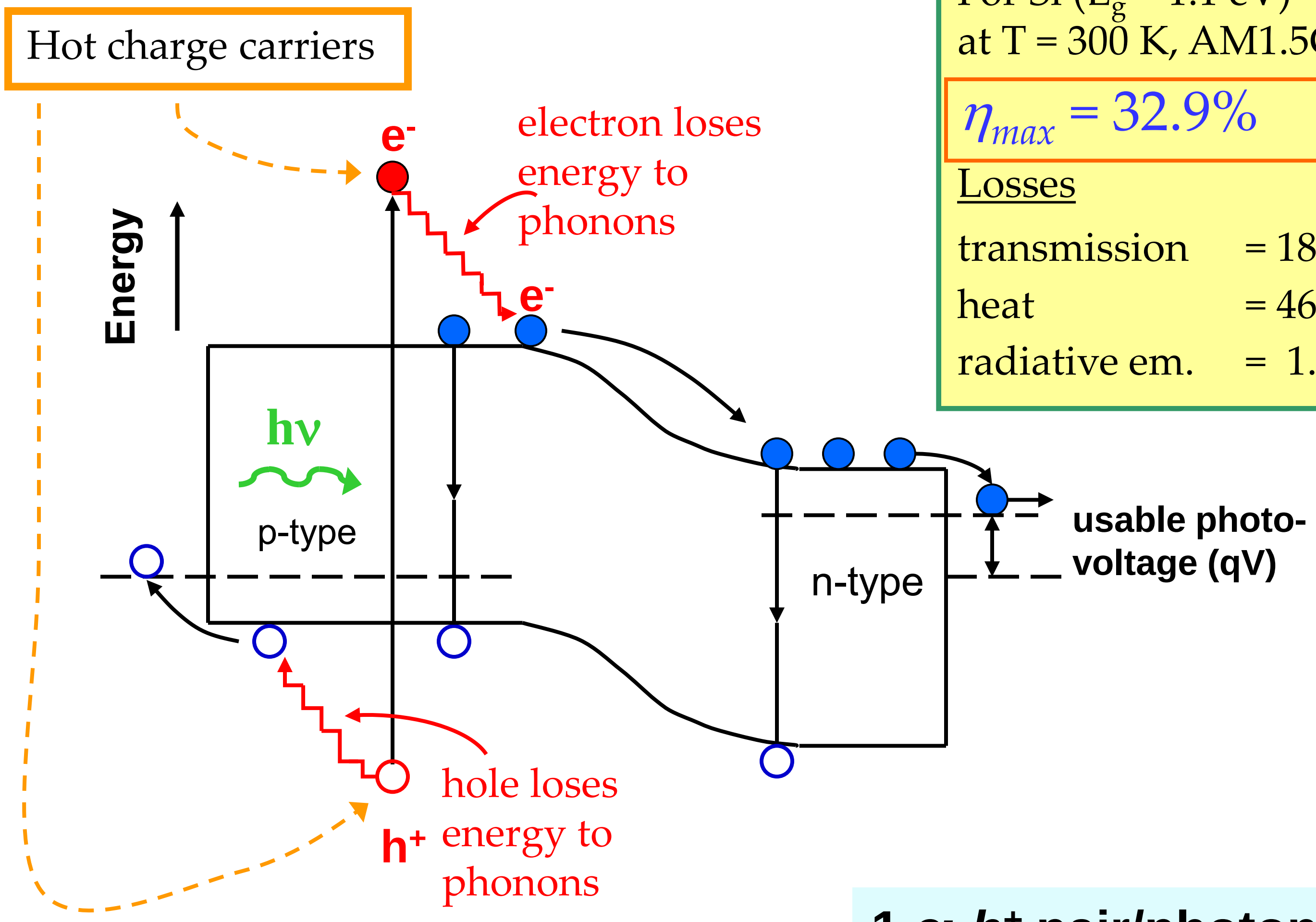
Key functions of a solar cell

- 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

η_{max} = 32.9%

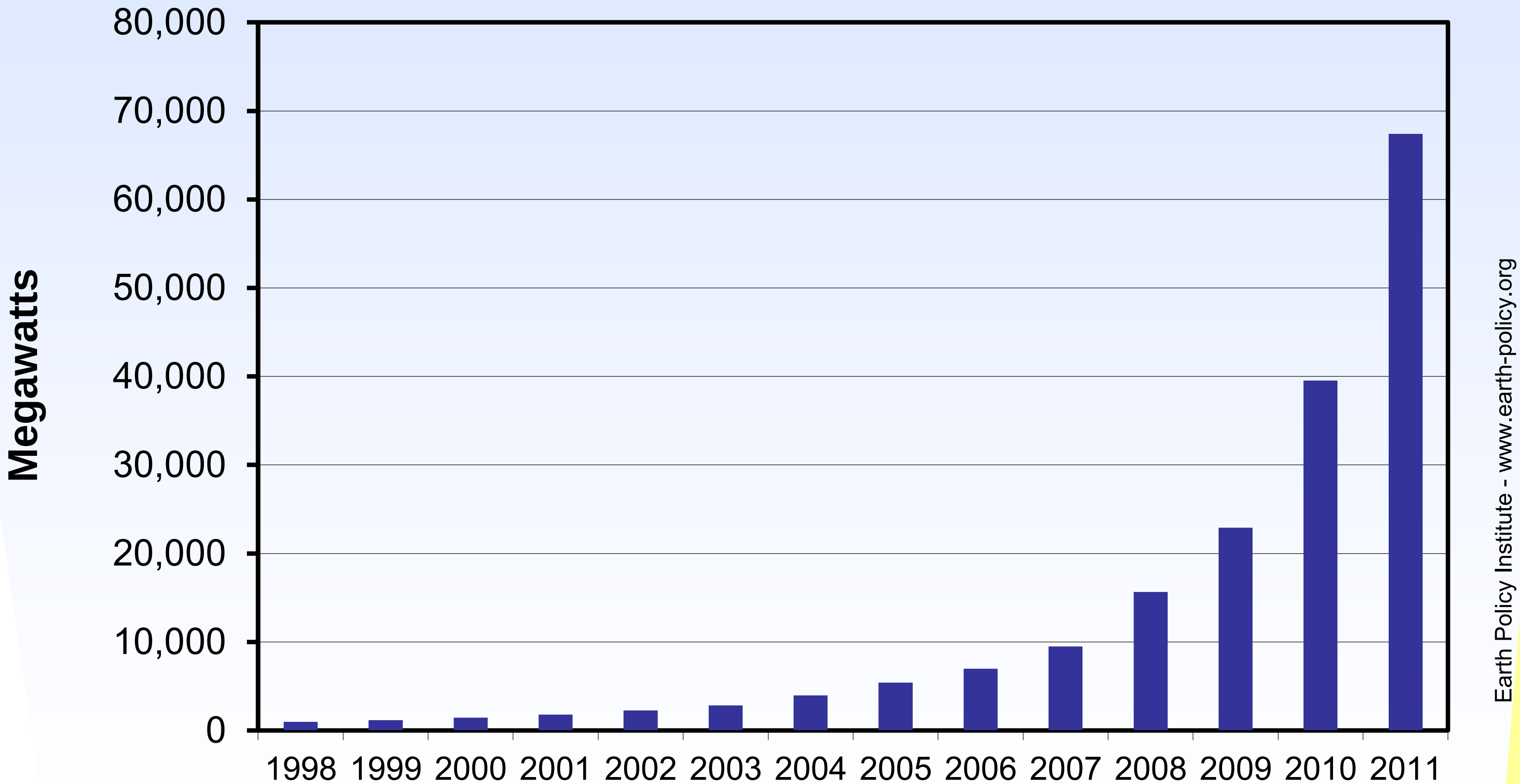
Losses

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

1 e^--h^+ pair/photon

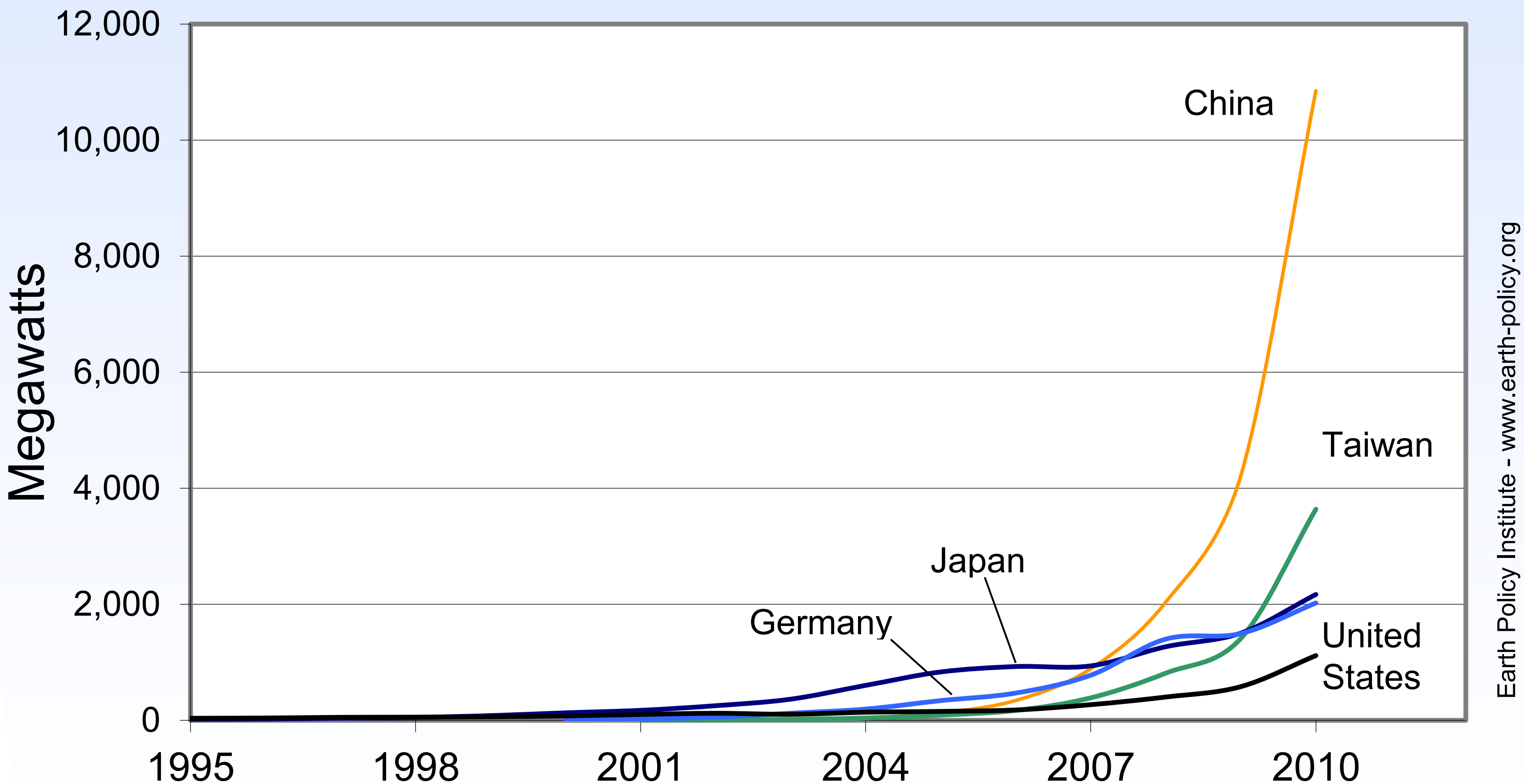
World Cumulative Solar Photovoltaics Installations, 1998-2011

70% year-over-year growth in 2010



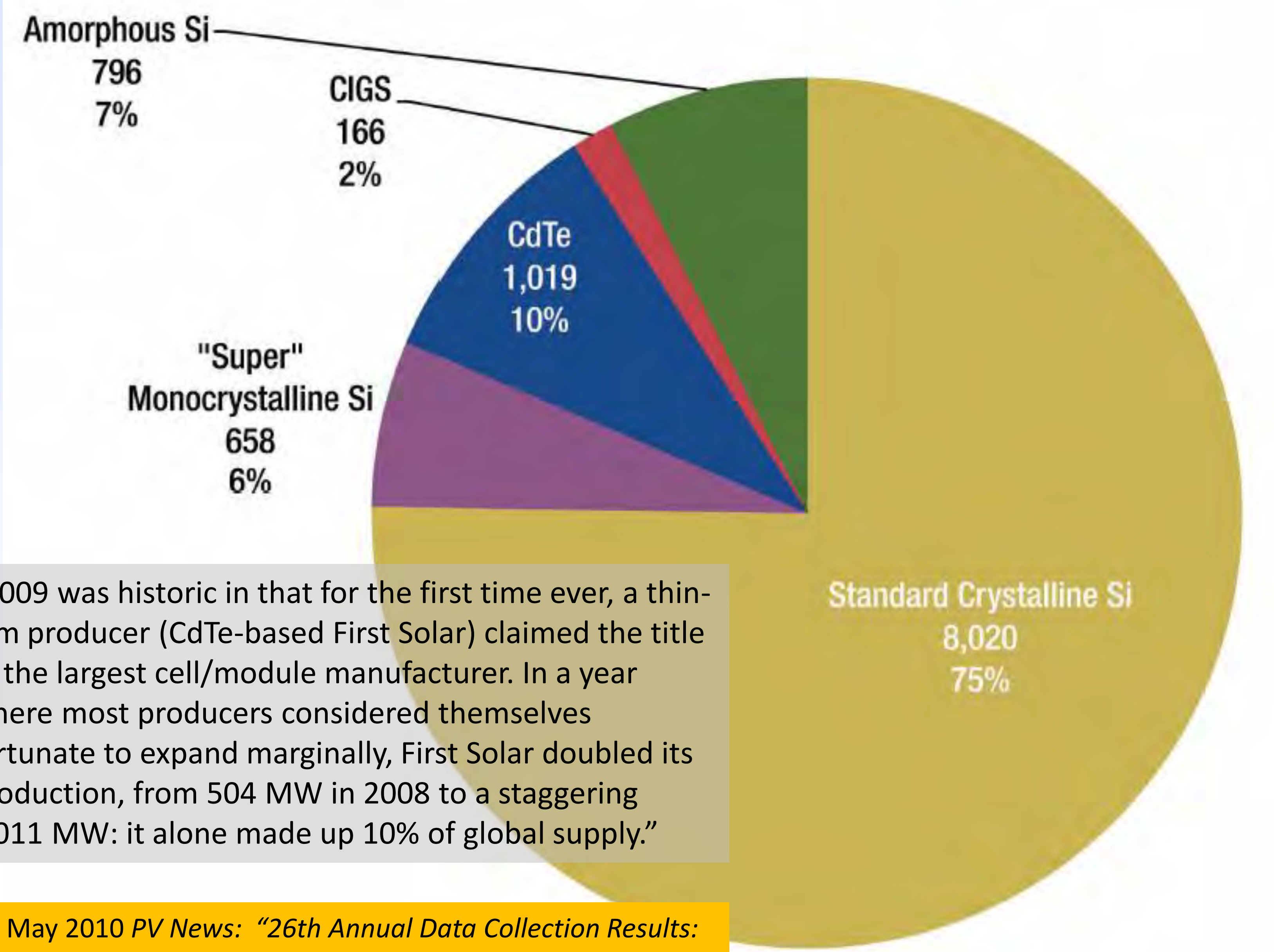
Source: EPI from EPIA

Annual Solar Photovoltaics Production in Selected Countries, 1995-2010



Source: EPI from Worldwatch; Prometheus Institute; Greentech Media

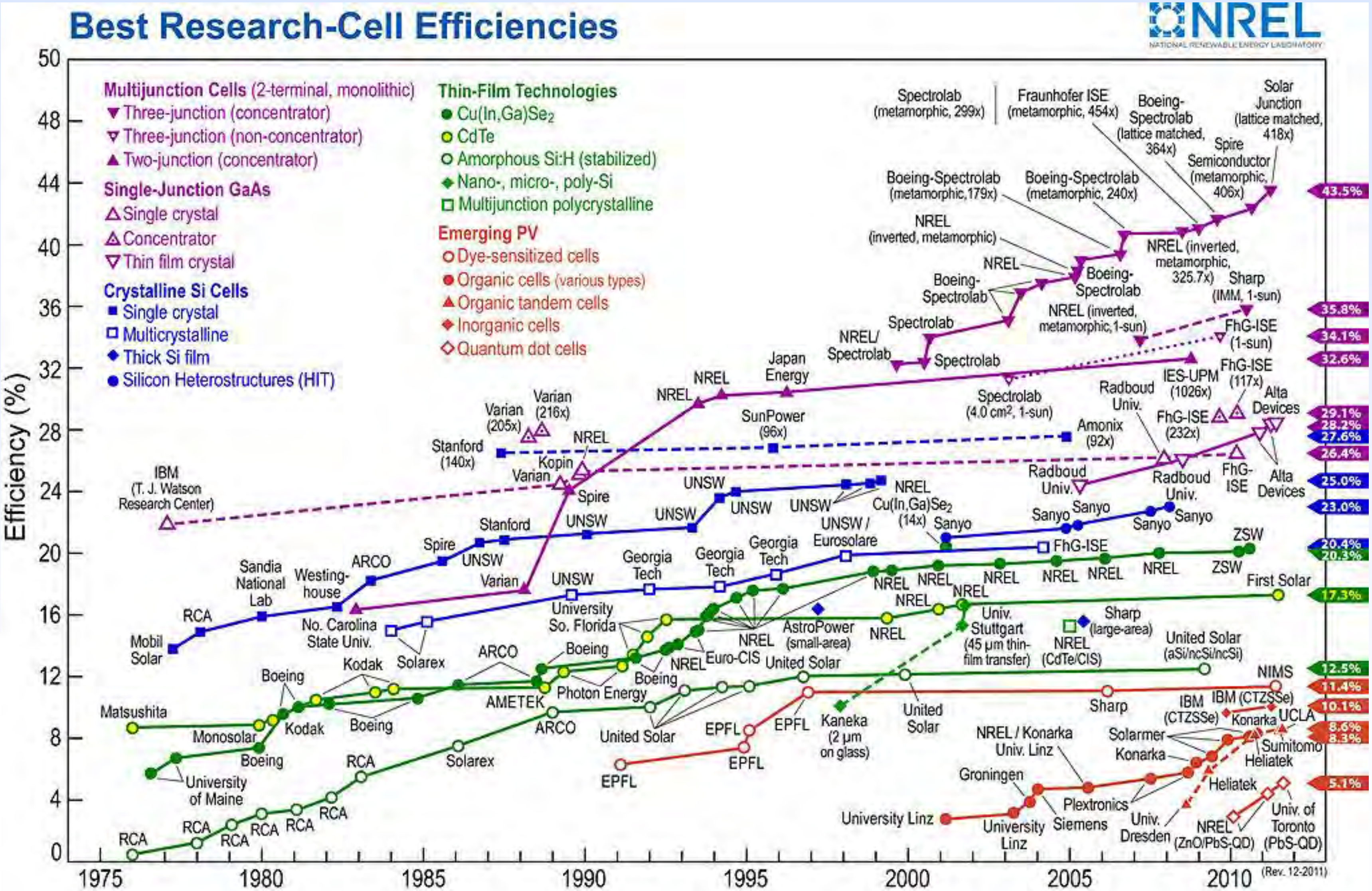
Commercial Photovoltaics as of 2010



"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



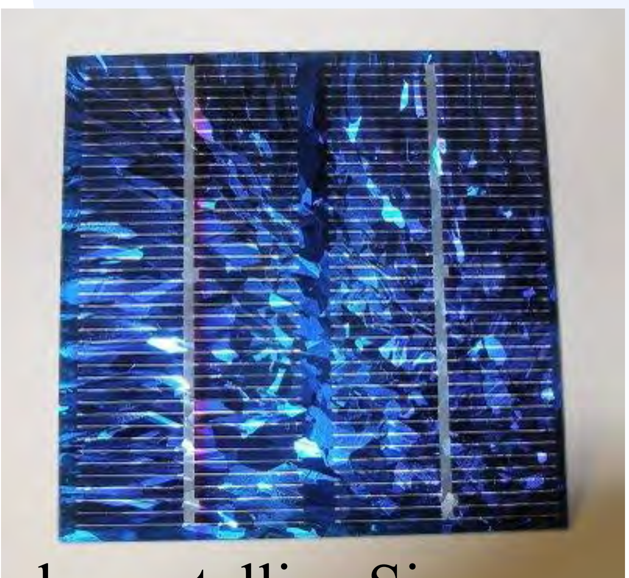
Many different solar cell technologies are being developed, for various applications (rooftops, solar power plants, satellites, backpacks or clothing, etc.).

1st gen.

single crystal Si

Xunlight

2nd gen.: thin film amorphous Si and CdTe



polycrystalline Si

First Solar

One large North American PV power plant

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