Principles and Varieties of Solar Energy (PHYS 4400)
and
Fundamentals of Solar Cells (PHYS 6980)

Prof. Randy J. Ellingson, Physics and Astronomy
Prof. Mike J. Heben, Physics and Astronomy, and Chemistry

The University of Toledo

Wright Center for Photovoltaics Innovation and Commercialization (PVIC – www.pvic.org) and

School for Solar and Advanced Renewable Energy (SSARE)

Course Website: http://astro1.panet.utoledo.edu/~relling2/teach/6980.4400/spring2011_phys_6980.4400.html

Energy for Planet Earth: The Role of "Carbon-Free" Energy Sources

Prof. Randy J. Ellingson, Physics and Astronomy
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PHYS 4400, PHYS 6980
January 11, 2011

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*

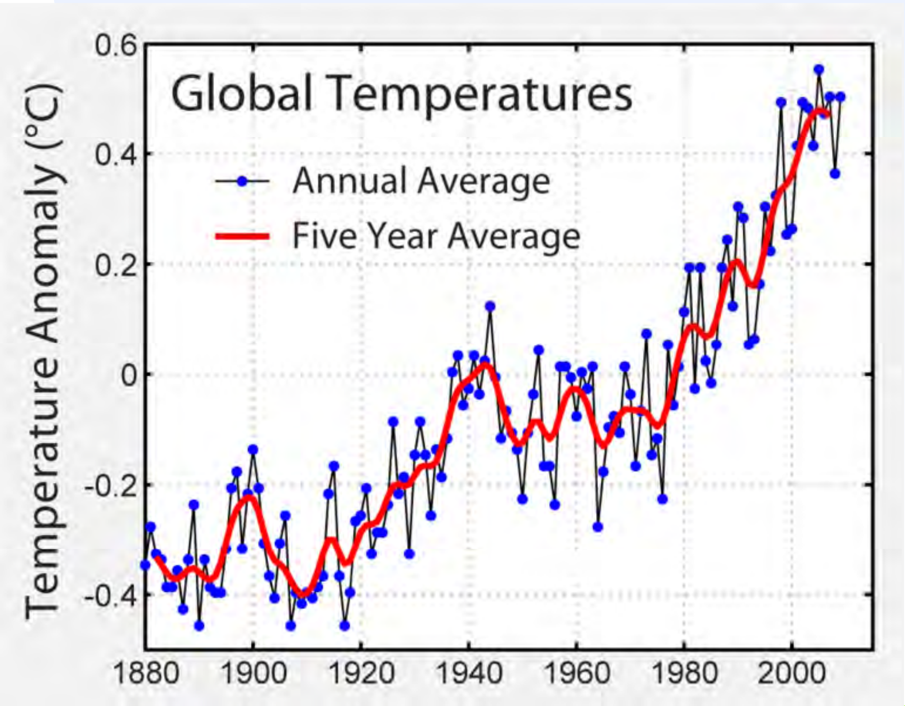
2006	**~ 6.5**	**Billion People**
2050	**~ 10**	**Billion People**

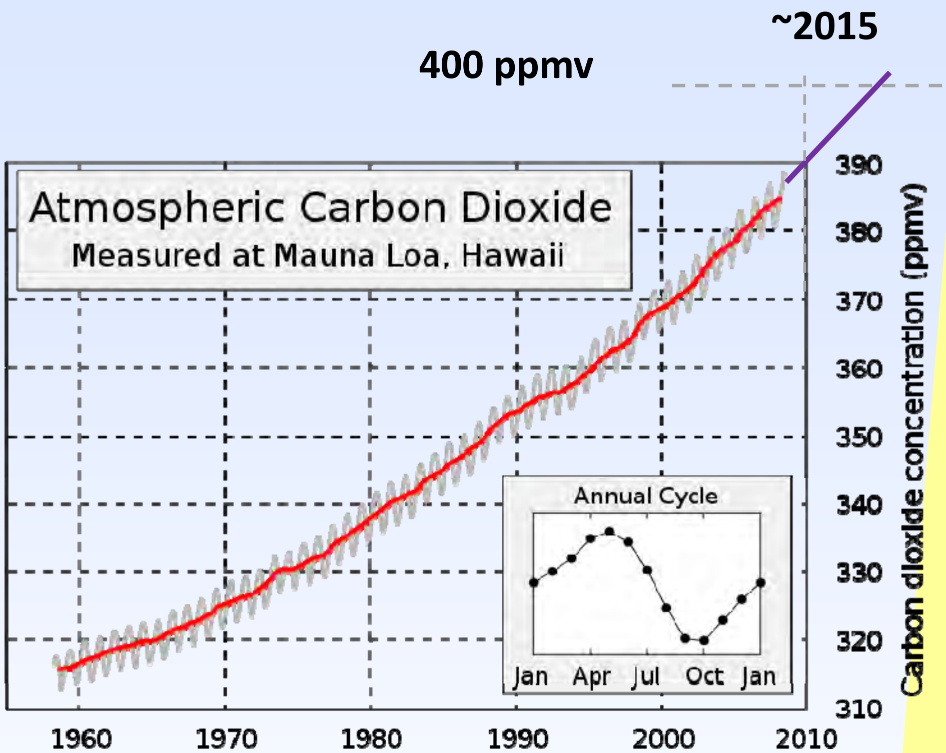
Slide from R. Smalley, Rice University

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

On watch: global temperatures, atmospheric CO_2

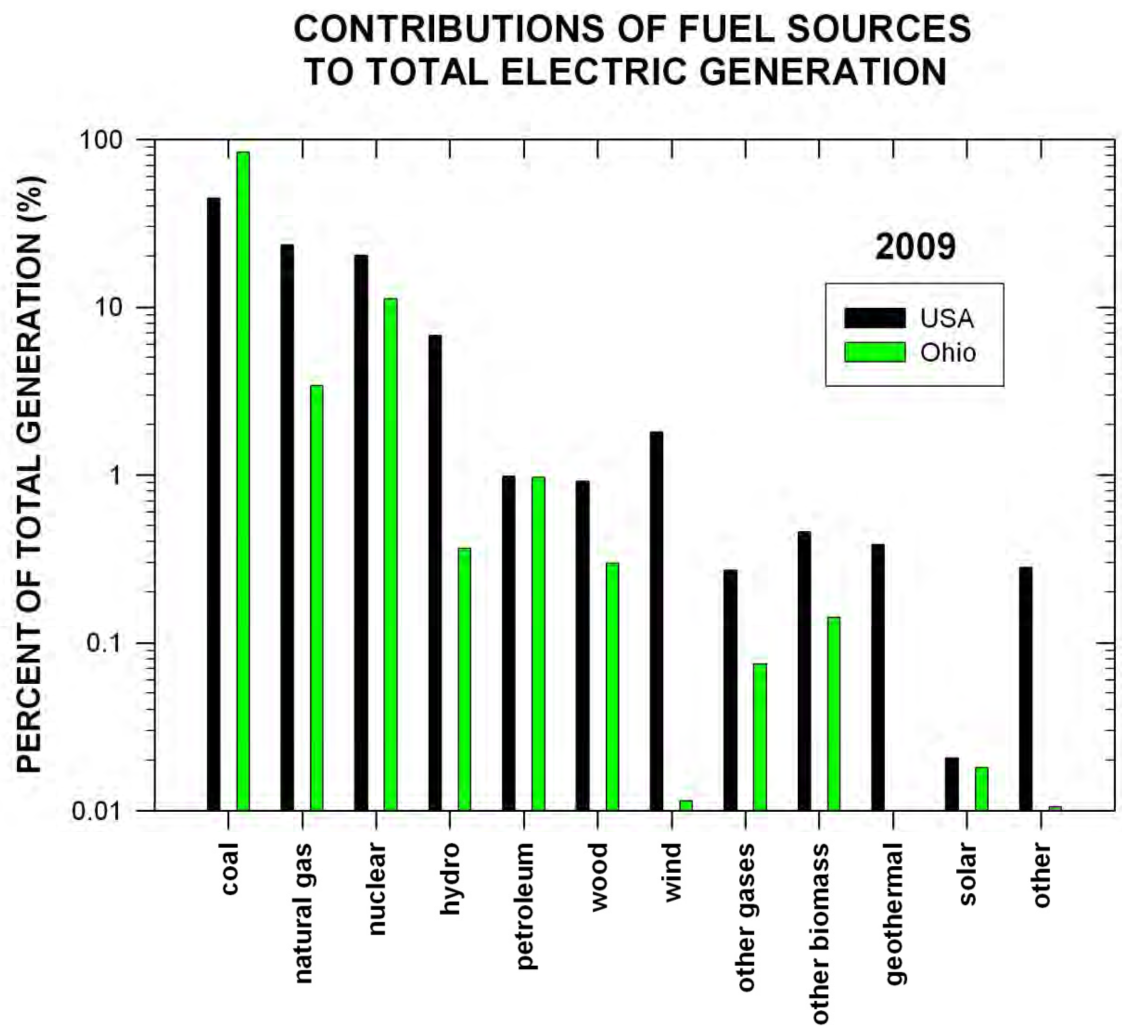
Global average temperatures from NASA's Goddard Institute for Space Studies (Columbia University in NYC). Data set follows methodology developed by James Hansen [Hansen, J., et al. (2006) "*Global temperature change*", Proc. Natl. Acad. Sci. 103: 14288-14293].





Keeling curve, data from Mauna Loa, Hawaii.

How Ohio's Electric Power Generation Stacks Up



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

Graphs prepared by B. Martner, Lafayette, CO

Need for clean energy

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

Growth

- Growth in global energy consumption predicted to average ~1.6-1.7% per year.
- Includes for 1%/yr. efficiency improvement
- 28 TW global power consumption by 2050
- Population growth primarily in less-developed countries → increased C-intensity.

Health

Coal-fired power plants:

- 59% of total U.S. sulfur dioxide pollution
- 18% of total nitrous oxides every year
- largest polluter of toxic mercury pollution

Acid rain, smog (ozone), soot → unhealthy ecosystems, respiratory problems, unhealthy lungs (incl. asthma)

A developmental toxin, affecting unborn children

All U.S. power plants: release over 40% of U.S. CO_2
[Sources – U.S. DOE and U.S. EPA]

A Power and Energy Primer

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

1 kW·hr = 3.6×10^6 J

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

Energy is the amount of 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.

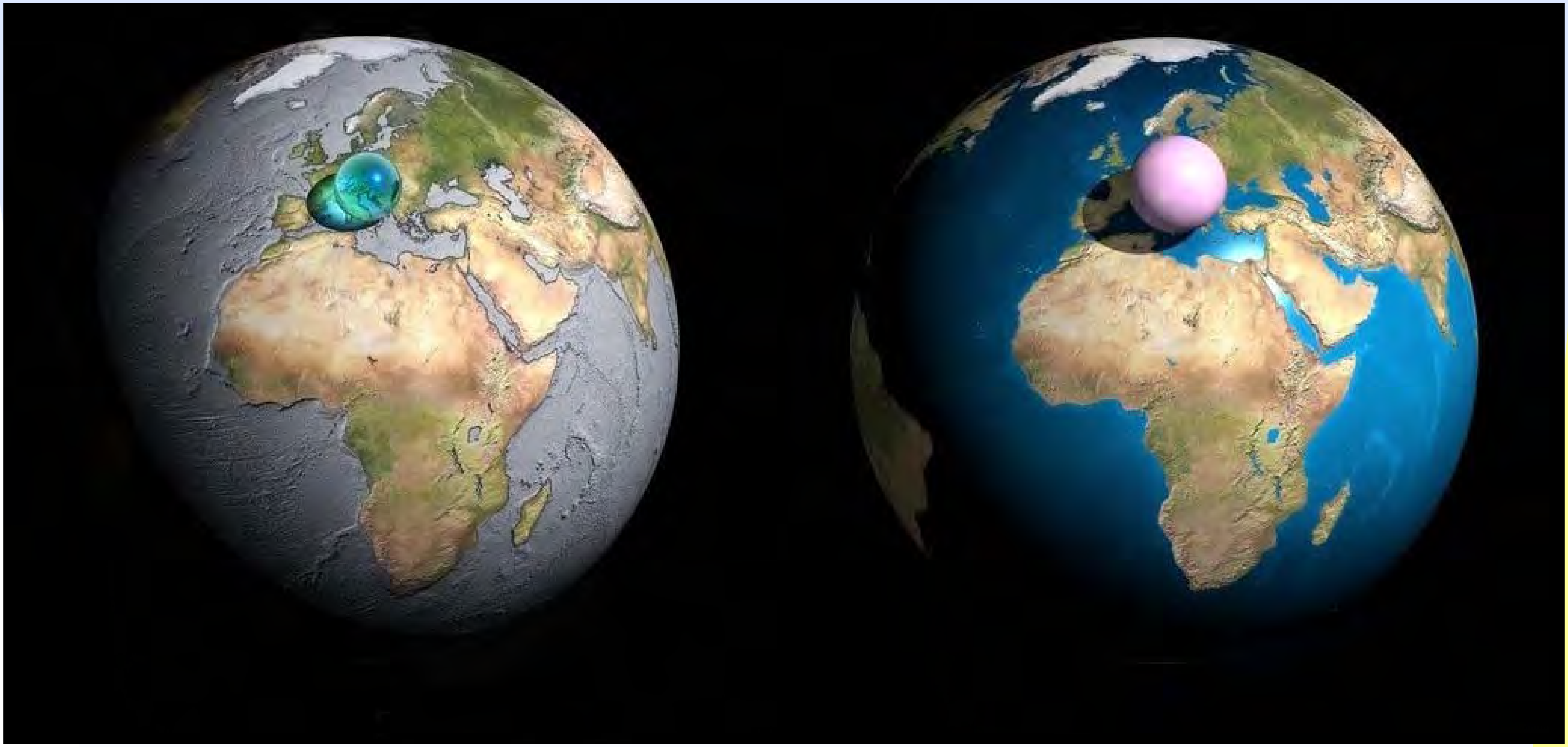
Leave a toaster on for an hour continuously →

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 during sleep, and ~24 W walking briskly

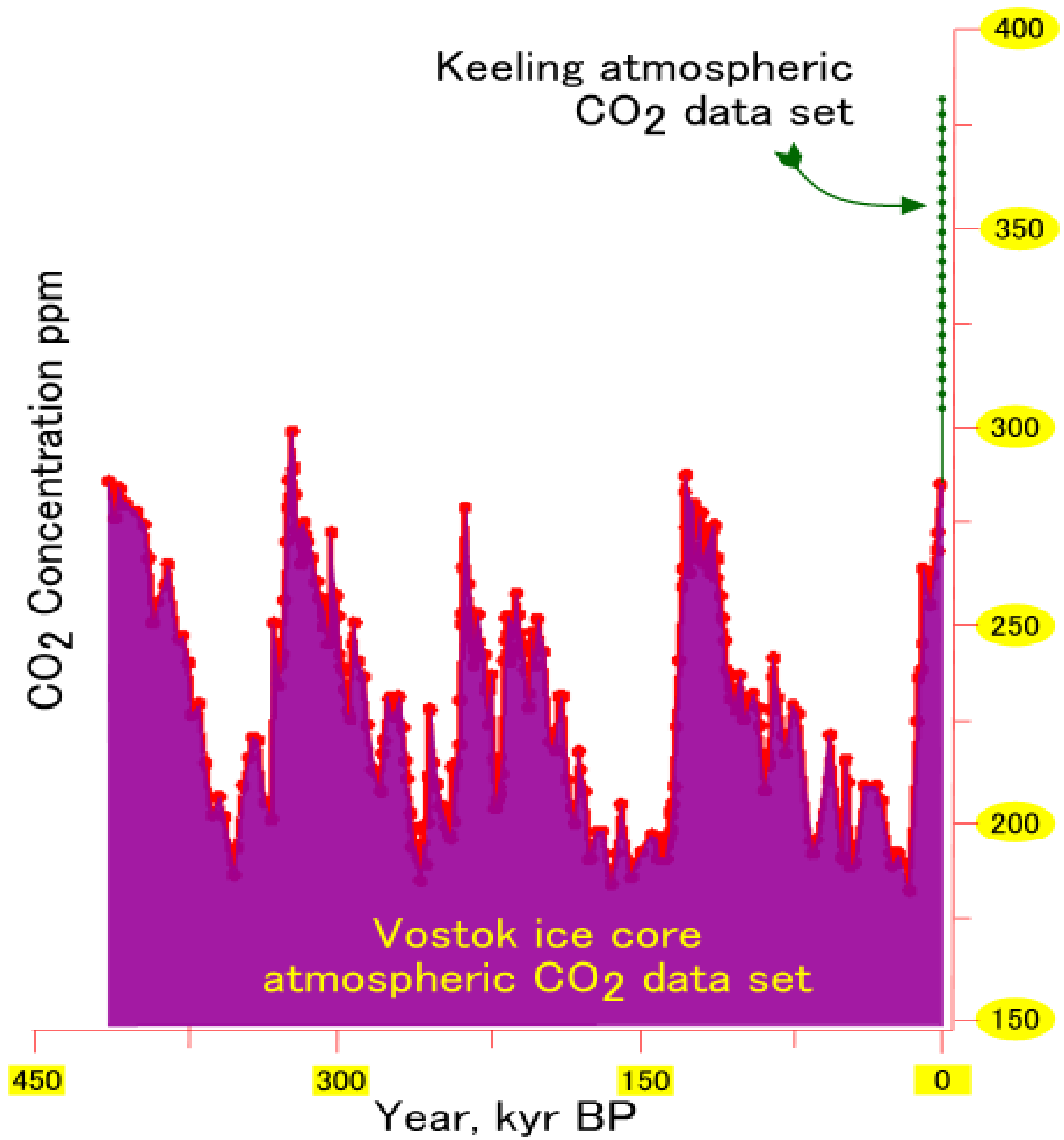
Earth’s key natural resources: water and air



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

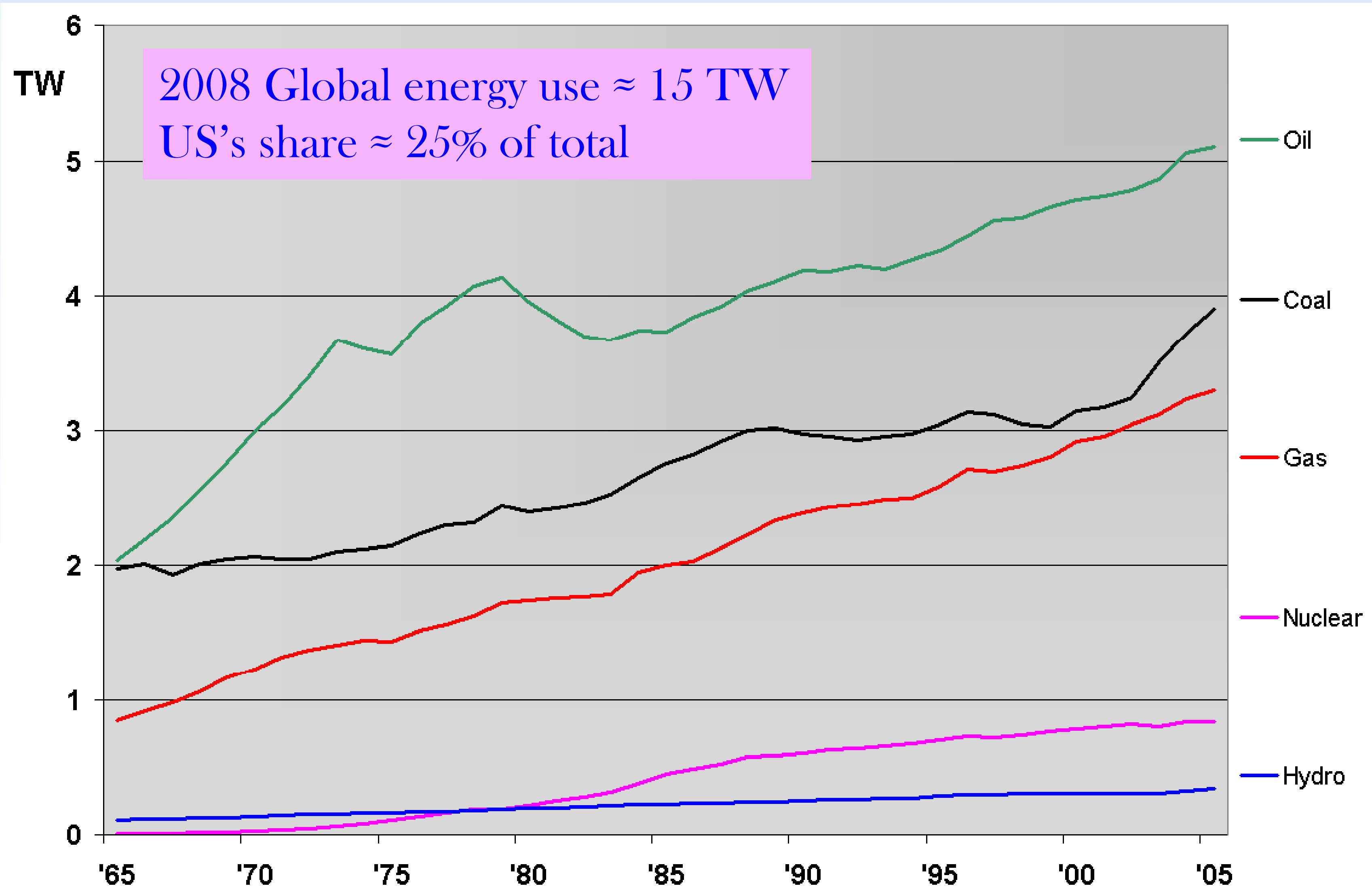
Photo & caption info: ADAM NIEMAN / SCIENCE PHOTO LIBRARY

420,000+ years of atmospheric CO_2 levels



from N. Lewis, Cal Tech

Earth's energy consumption

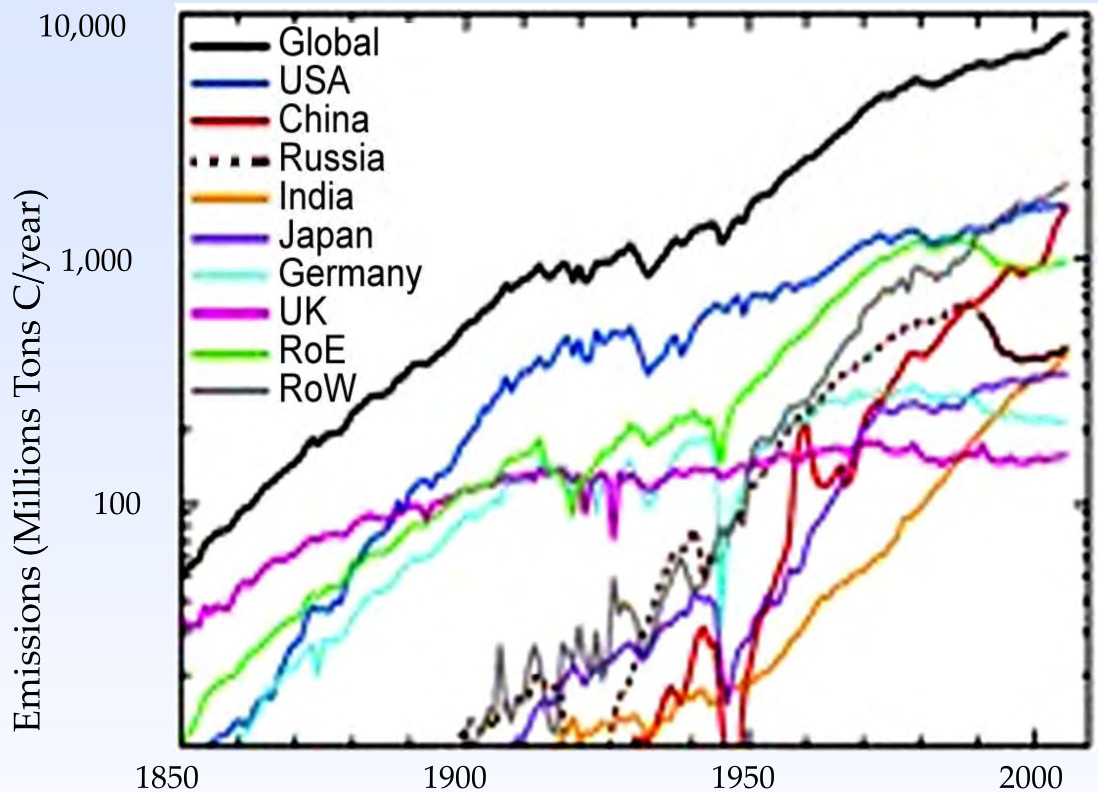


http://en.wikipedia.org/wiki/World_energy_resources_and_consumption

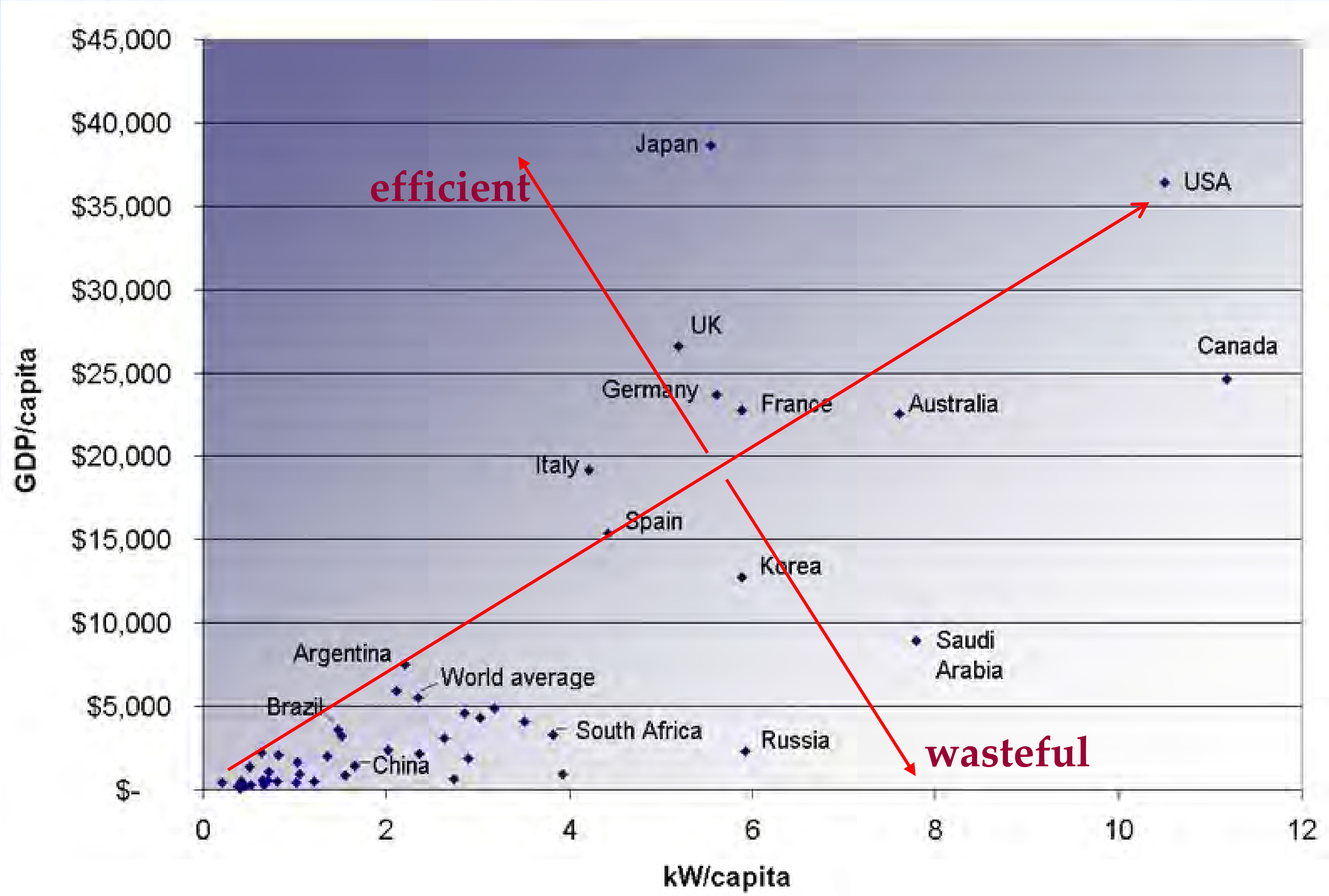
Fossil fuel emissions

>China has emitted 8.2% of cumulative emissions, as compared to 27.5% emitted by the US (3 times that of any other country).
>China became the emissions leader in 2006.
>China's population is more than 4 times that of the US, so per capita emissions were roughly 1/4 of the US's.
>Per capita emissions from China could double or triple in coming decades

From China Sustainable Energy Program: http://www.efchina.org

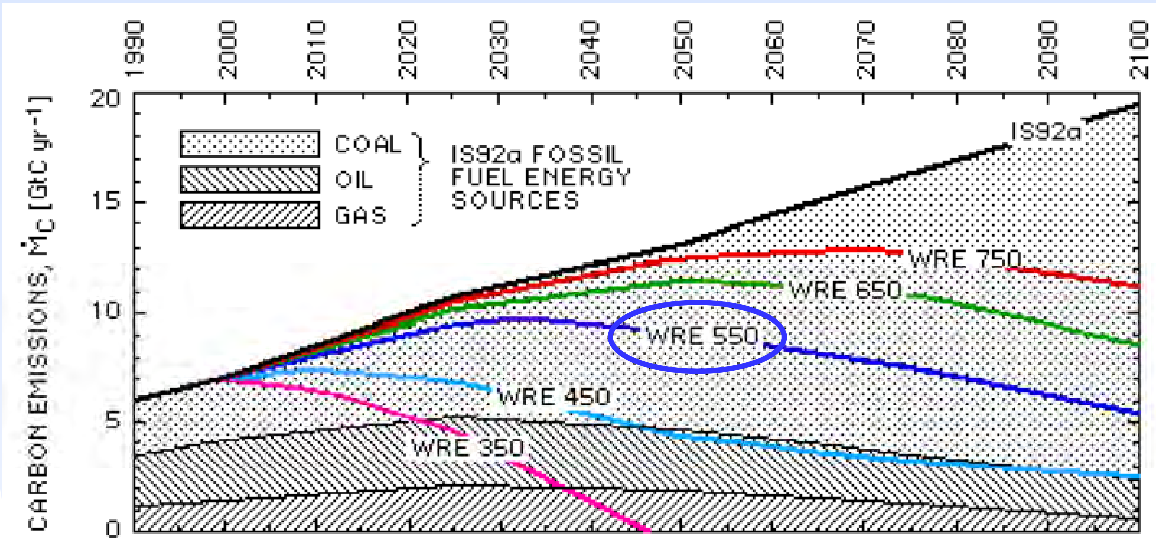


Energy Consumption and GDP



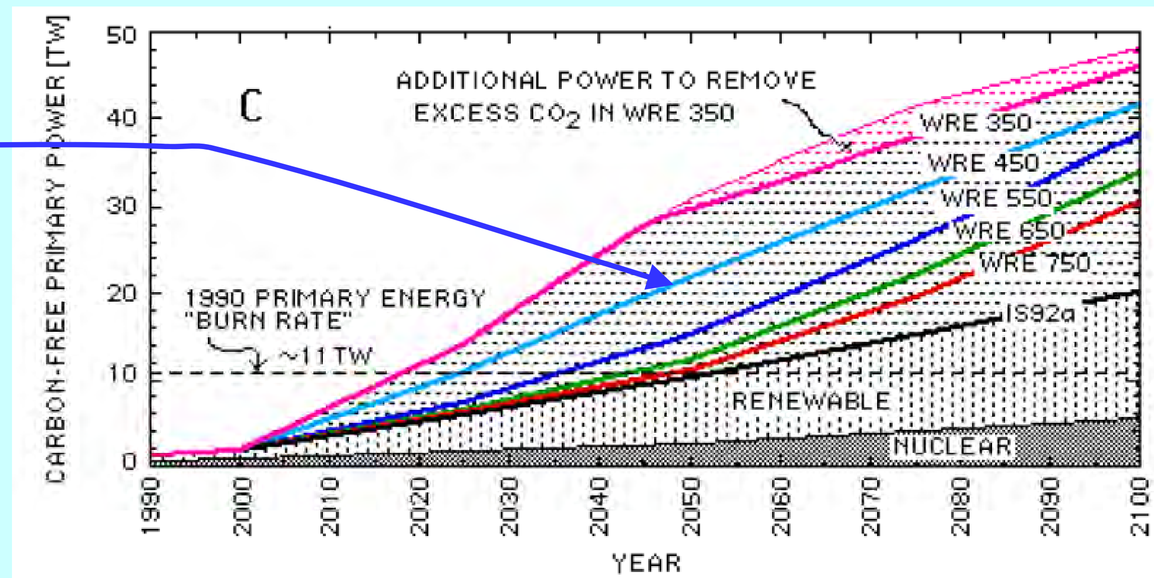
From: Wikimedia Commons

Earth's energy problem



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

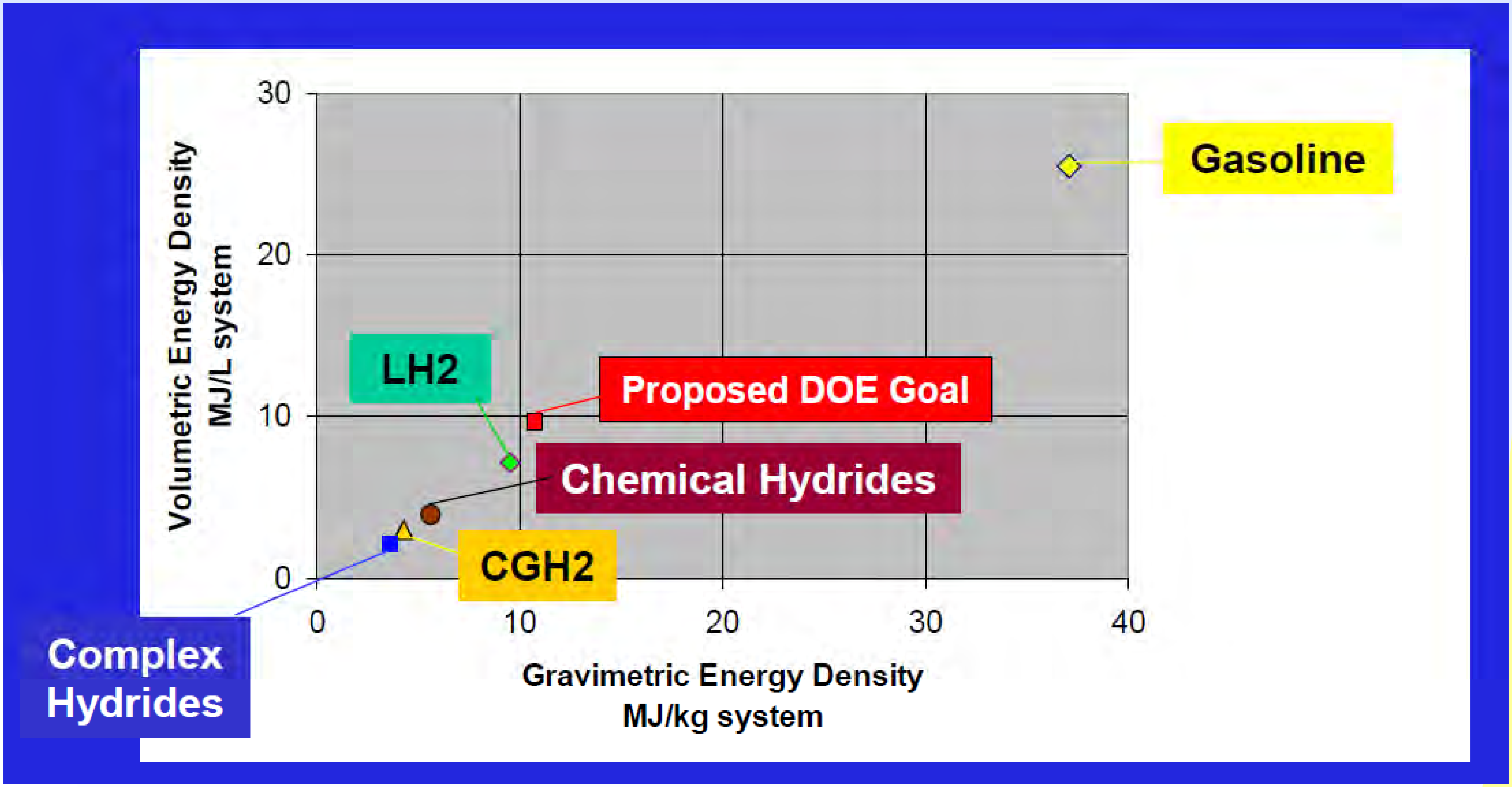
Carbon-free power required by 2050 to stabilize atmospheric CO_2 at 450 ppm ~15 TW



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

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

Transportation fuel energy density

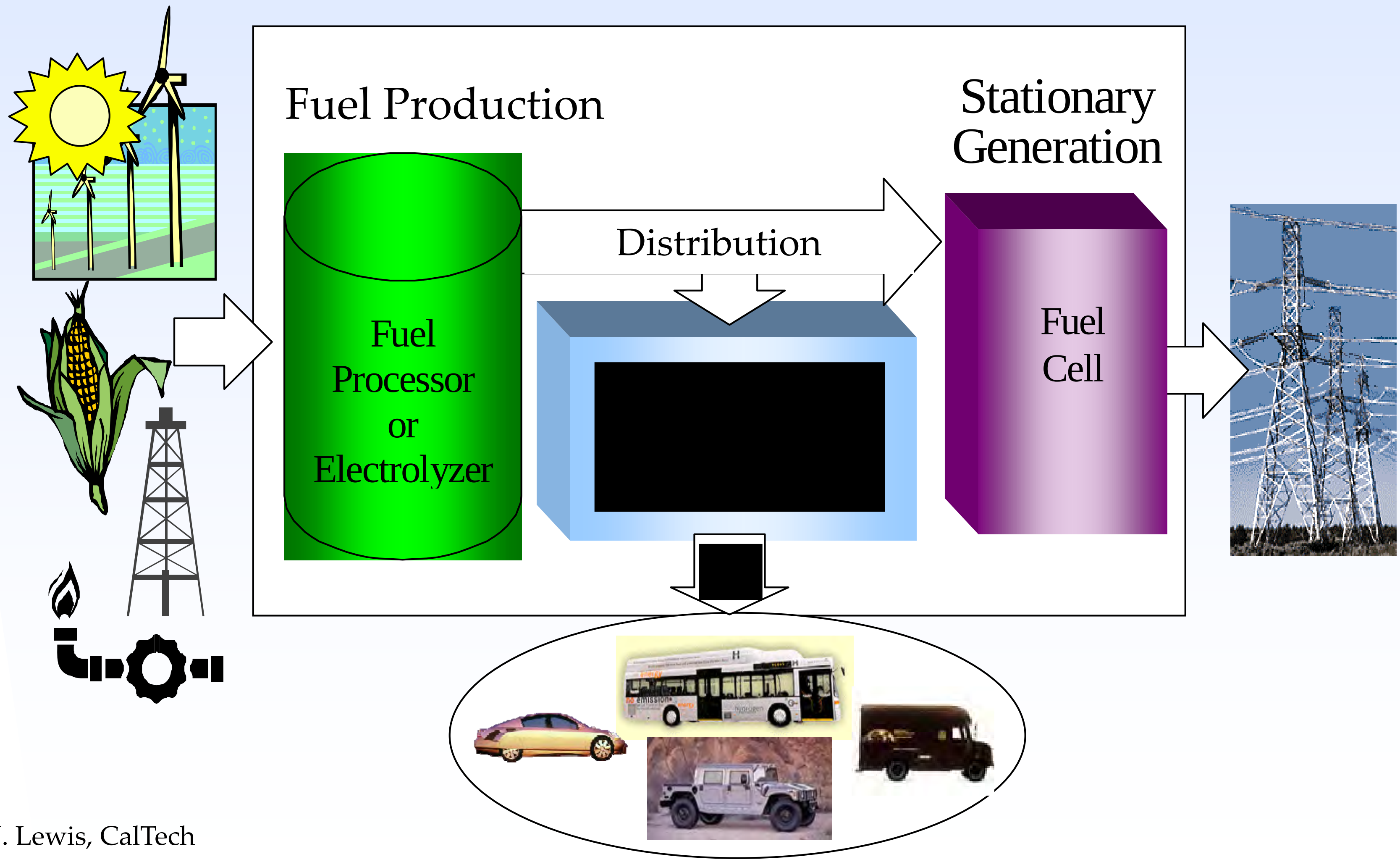


"Gasoline was great."

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

The Need to Produce Fuel

"Power Park Concept"



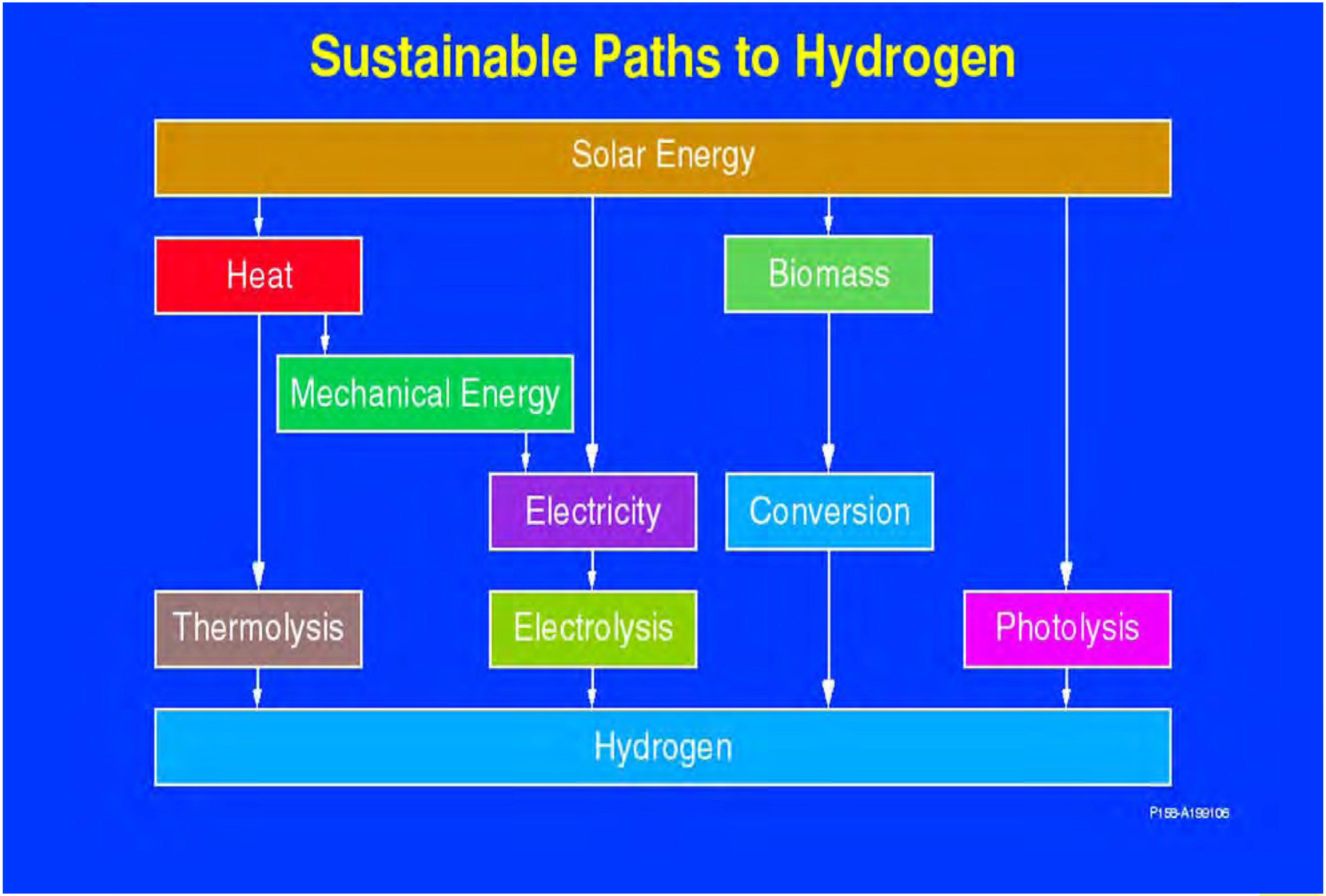
From N. Lewis, CalTech

Oil: The Haves and the Have-nots

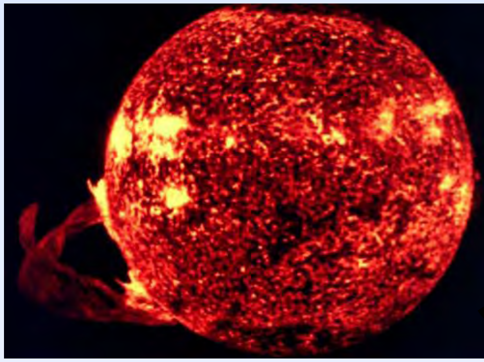
Nations that HAVE oil (% of Global Reserves)		Nations that NEED oil (% of Global Consumption)	
Saudi Arabia	26%	U.S.	26%
Iraq	11%	Japan	7%
Kuwait	10%	China	6%
Iran	9%	Germany	4%
UAE	8%	Russia	3%
Venezuela	6%	S. Korea	3%
Russia	5%	France	3%
Mexico	3%	Italy	3%
Libya	3%	Mexico	3%
China	3%	Brazil	3%
Nigeria	2%	Canada	3%
U.S.	2%	India	3%

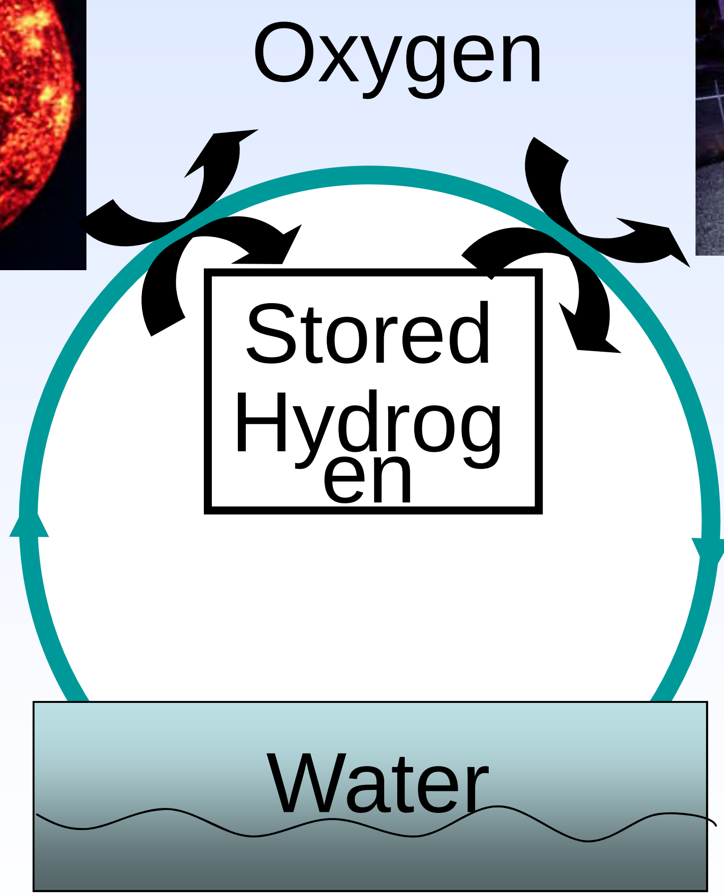
Source: EIA International Energy Annual 1999

•*From Sam Baldwin's contribution to "Basic Research Need to Assure a Secure Energy Future", A Report from DOE's Basic Energy Sciences Advisory Committee*


Sustainable Paths to Hydrogen
Solar Energy
Heat
Biomass
Mechanical Energy
Electricity
Conversion
Thermolysis
Electrolysis
Photolysis
Hydrogen
P158-A199106

H_2 Energy Cycle with Fuel Cells





Inputs:

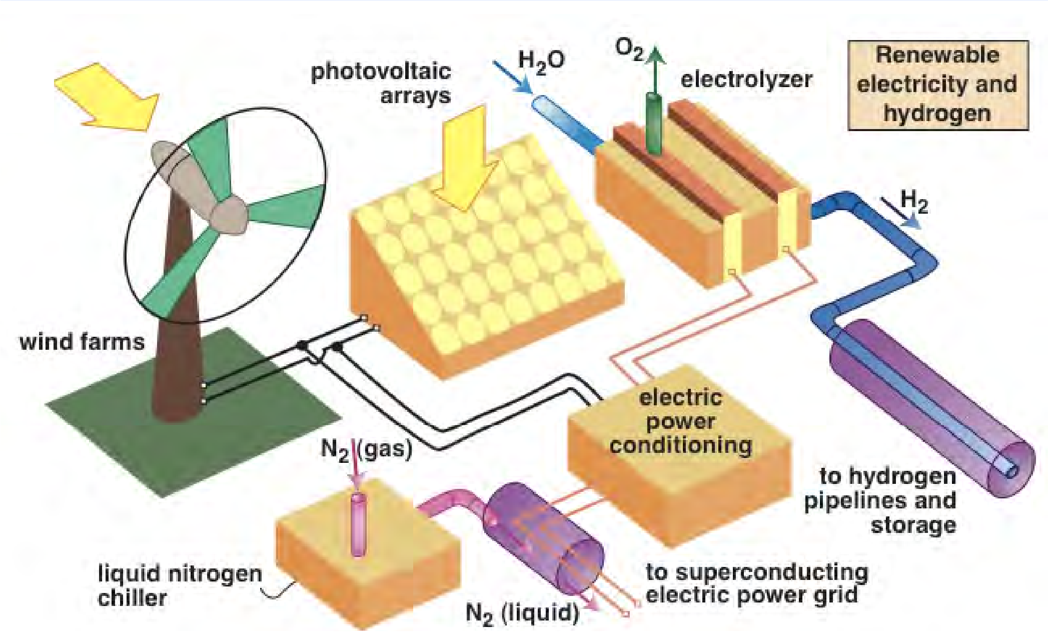
- Solar Energy
- Water
- Nuclear Energy
- Fossil Fuel

Outputs:

- Electricity
- Heat
- Water
- Nuclear Waste
- CO_2 w Fossil

Adapted from John Turner, NREL

Integrated Large- and Small-Scale Systems
(distributed energy systems)



Hoffert, *et al.*, *Science*, 298 (2002)

World energy resources and consumption

From Wikipedia, the free encyclopedia

(Redirected from World Energy)

In 2008, total worldwide energy consumption was 474 exajoules (5×10^{20} J) with 80 to 90 percent derived from the combustion of fossil fuels.[1] This is equivalent to an average power consumption rate of 15 terawatts (1.504×10^{13} W) or a yearly energy consumption of 133 Petawatt•hr (132.8×10^{15} Wh). [snip]

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.

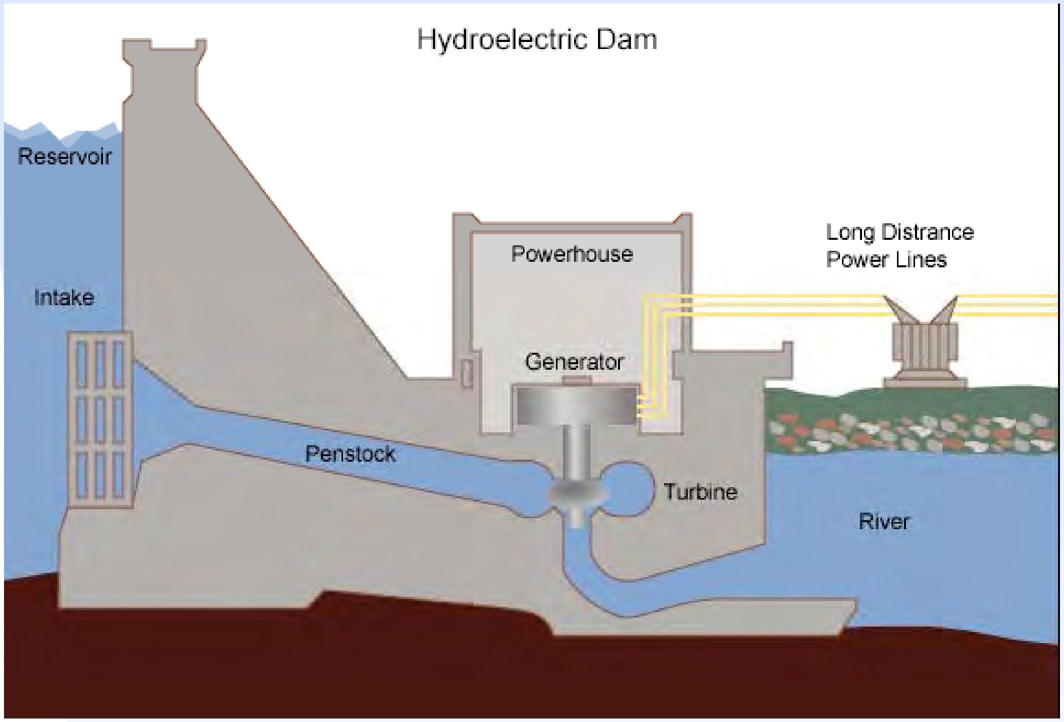
Sources of renewable*, carbon-free energy

Potential Sources for Significant Carbon-Free Energy	
• Hydroelectric (1.5 TW technically feasible – 0.777 TW generated in 2006)	1.5 TW
• Geothermal (installed capacity in 2007)	10 GW
• Tides/Waves	1 TW
• Wind	65 TW
• Solar (120,000 TW solar energy striking Earth globally)	600 TW*

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

* Renewable only as long as our Sun shines

Hydroelectric Power

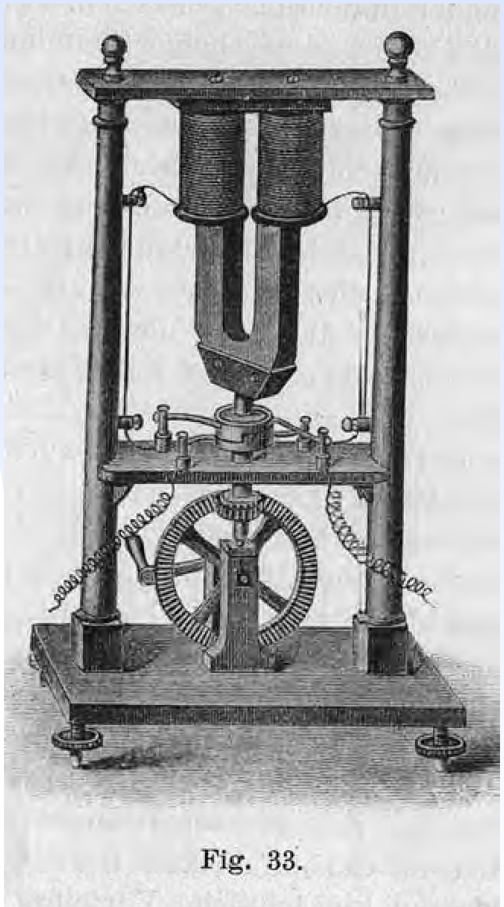


Power produced depends on factors such as the density of water ($\rho = 1000$ kg/m^3), the "hydraulic height" (h), the flow rate in cubic meters per second (r), the gravitational constant (g), and the efficiency factor (k):

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

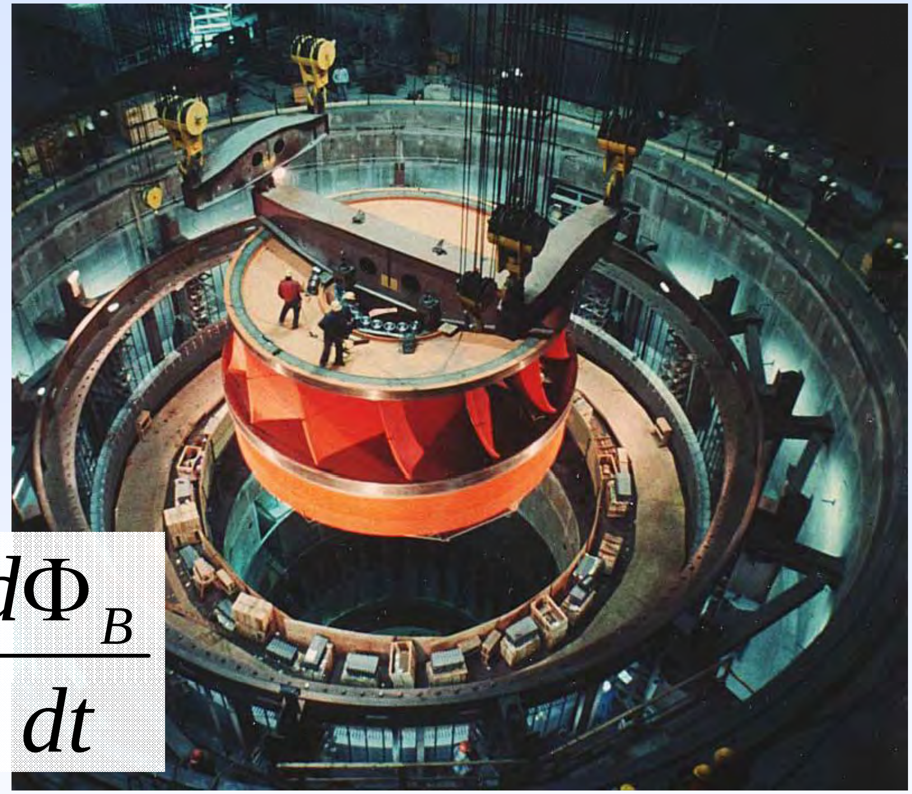
- eliminates cost of fuel;
- long-lived power production compared to fuel-fired plants;
- operates without CO_2 emissions;
- no nuclear waste
- sizeable hazard (dam failures among largest human-created disasters);
- siltation ultimately limits "economic" life;
- environmental impacts: spawning, downstream 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 1.5 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

How much: 10 GW of electricity generated in 2007; 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

Reminder: We need 15 – 40 TW total CfP

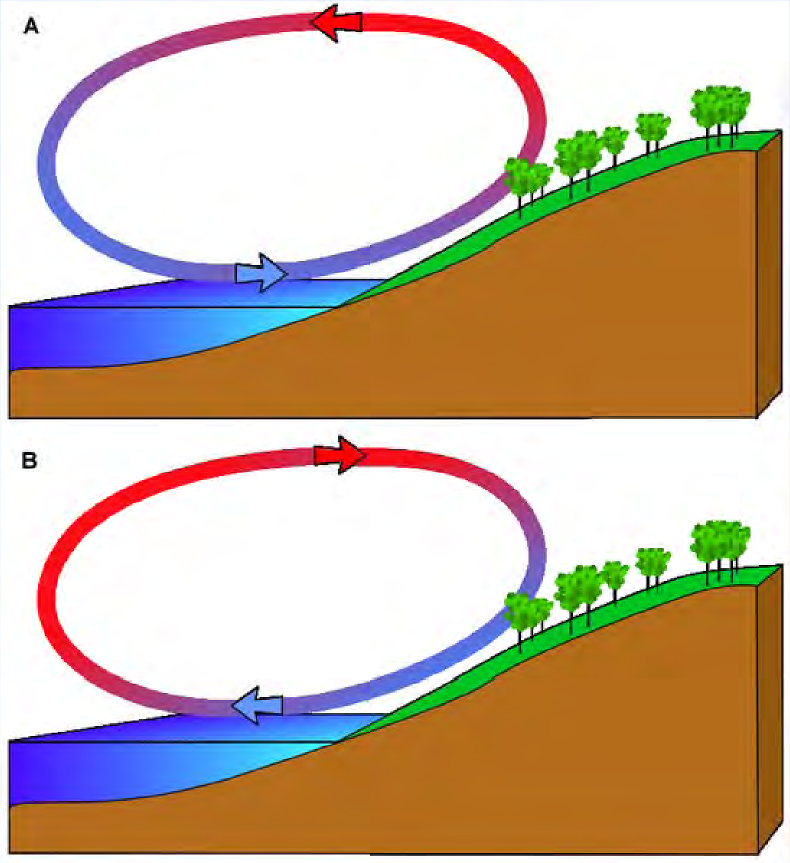
Origins of Wind

Wind results from pressure differentials in the atmosphere; local effects include variations in heating and cooling (e.g., land vs. a body of water).

Air subsequently moves to alleviate these pressure differences; since air has mass, it's movement (wind) carries with it 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

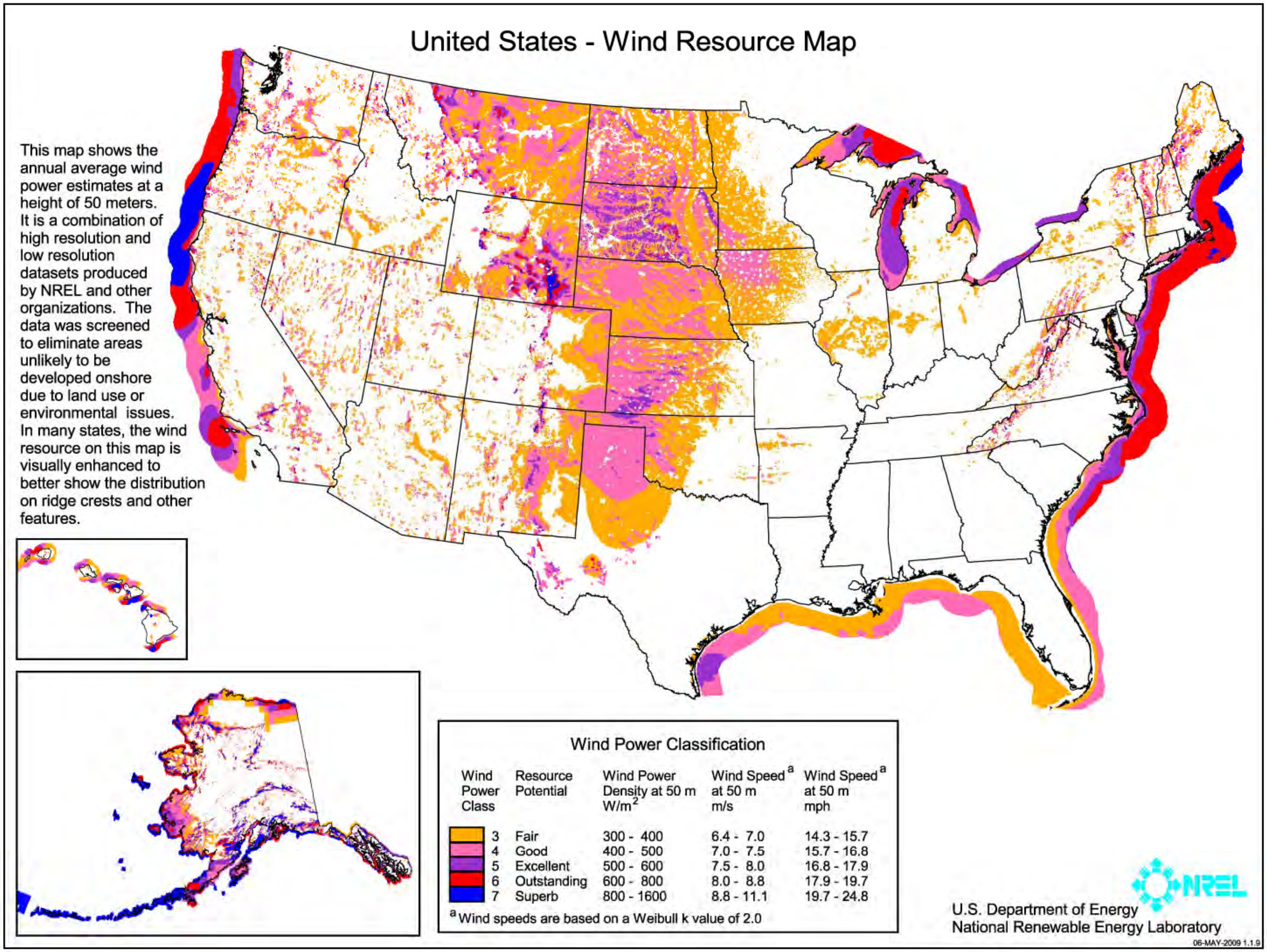
… growth in the forecasts can be attributed to the increasingly common use of very large turbines that rise to almost 100 meters.
Wind speeds are greater at higher elevations. Previous wind studies were based on the deployment of 50- to 80-meter turbines.

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

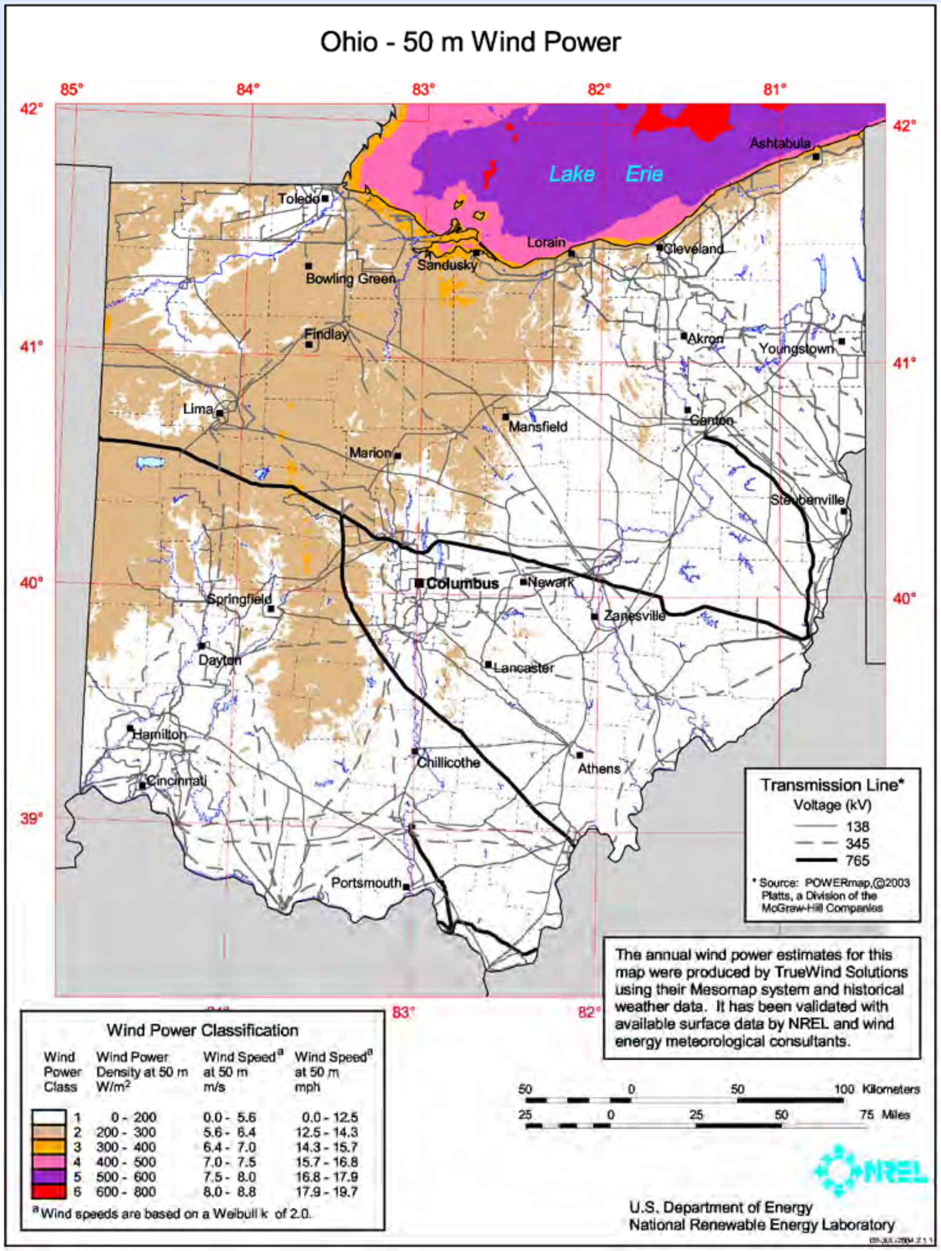
Global potential for wind-generated electricity
Xi Lu, Michael B. McElroya,, and Juha Kiviluomac
www.pnas.orgcgidoi10.1073pnas.0904101106

Reminder: We need 15 – 40 TW total CfP

Wind Power

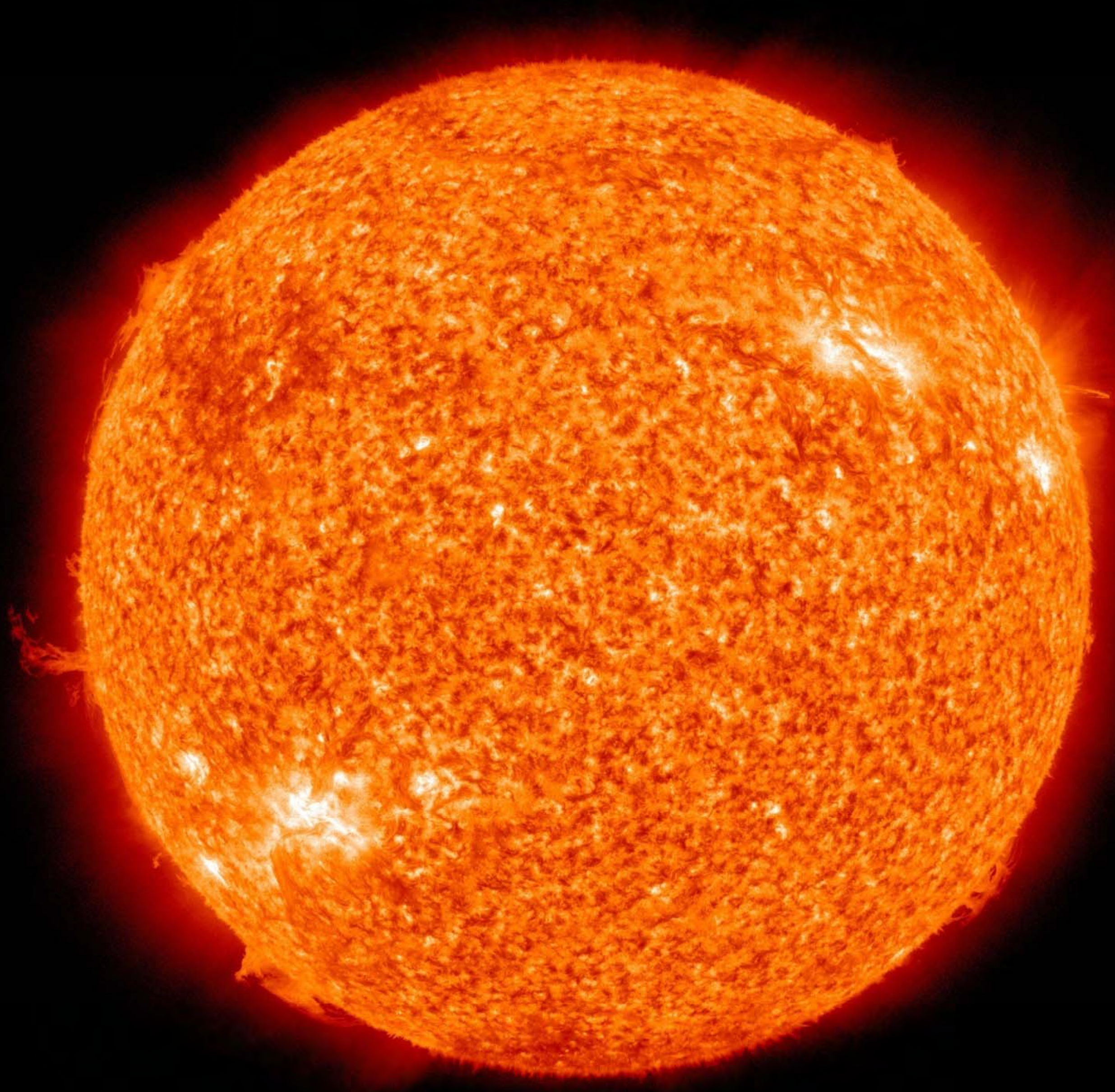

United States - Wind Resource Map
This map shows the annual average wind power estimates at a height of 50 meters. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.
Wind Power Classification
Wind Power Class
Resource Potential
Wind Power Density at 50 m W/m²
Wind Speed a at 50 m m/s
Wind Speed a at 50 m mph
3 Fair 300 - 400 6.4 - 7.0 14.3 - 15.7
4 Good 400 - 500 7.0 - 7.5 15.7 - 16.8
5 Excellent 500 - 600 7.5 - 8.0 16.8 - 17.9
6 Outstanding 600 - 800 8.0 - 8.8 17.9 - 19.7
7 Superb 800 - 1600 8.8 - 11.1 19.7 - 24.8
a Wind speeds are based on a Weibull k value of 2.0
NREL
U.S. Department of Energy
National Renewable Energy Laboratory
06-MAY-2009 1.1.9

Ohio Wind Power



Wind farms are under consideration and/or planned along the shores of, or out on the open water of, Lake Erie.

The Sun



“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

The Sun

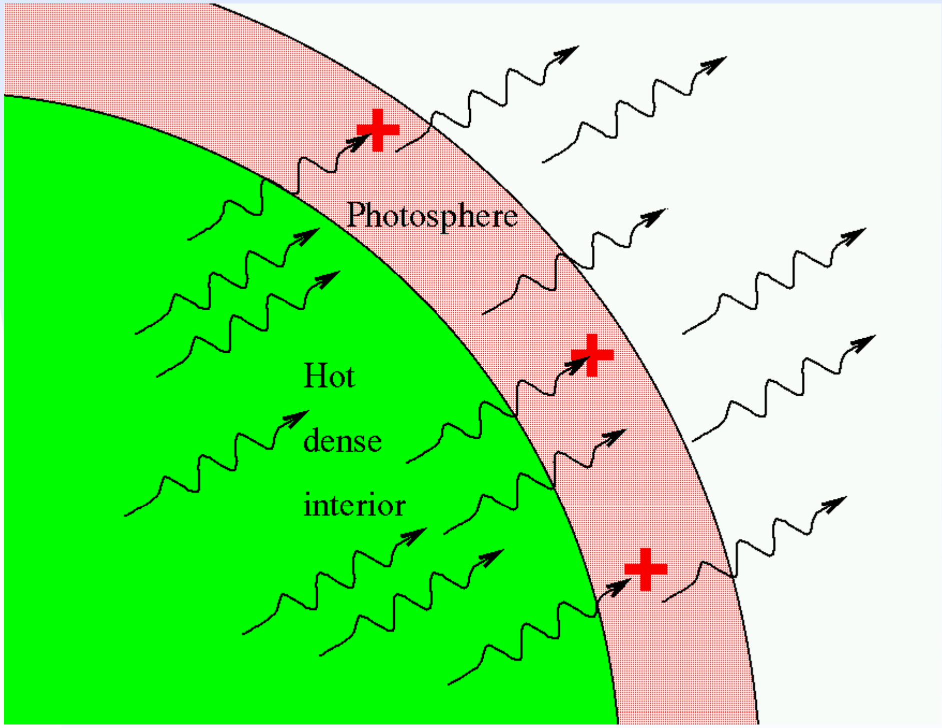
Mean diameter	1.392×10^{6} km
Equatorial radius	6.955×10^{5} km
Equatorial circumference	4.379×10^{6} km

109 times the Earth's diameter, radius, circumference

Sidereal* rotation period (at equator) 25.05 days

* Sidereal means: "Of or relating to the stars"
(http://en.wiktionary.org/wiki/sidereal)

The Sun's "Photosphere"



http://spiff.rit.edu/classes/phys301/lectures/spec_lines/spec_lines.html

The **photosphere** of an astronomical object is the region from which externally received light originates. It extends into a star's surface until the gas becomes opaque, equivalent to an optical depth of approximately 2/3. In other words, a **photosphere** is the deepest region of a luminous object, usually a star, that is transparent to photons of certain wavelengths.

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

The Sun's Hydrogen

$$E_n = -\frac{13.6}{n^2}\,\mathrm{eV}$$

approximation

$$E_n = -\frac{13.6057}{n^2}\,\mathrm{eV}$$

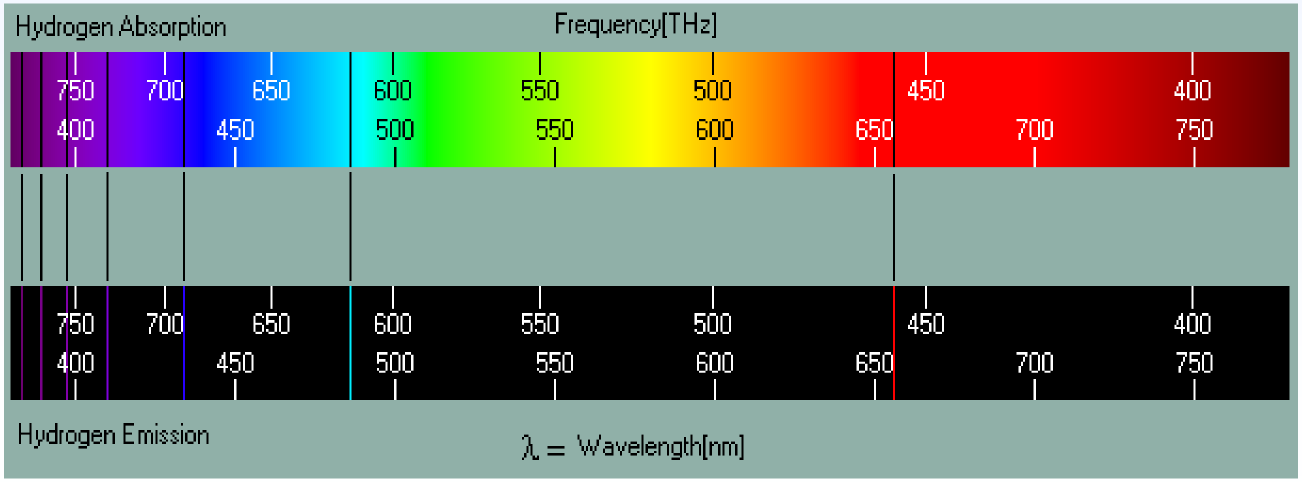
more sig figs

$$E_n = -\frac{13.5983}{n^2}\,\mathrm{eV}$$

with reduced mass

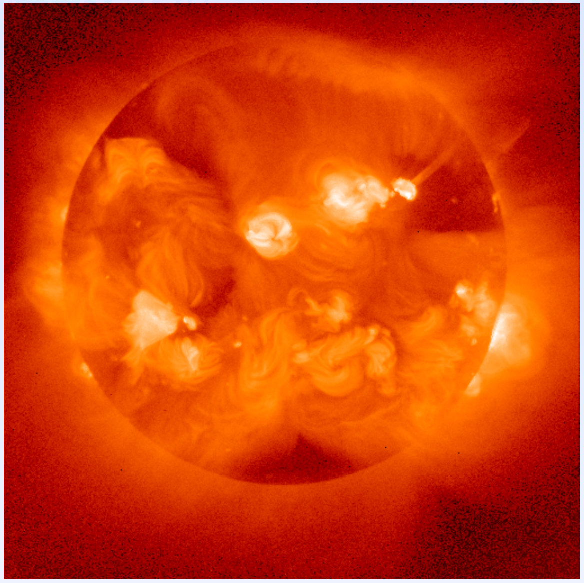
Balmer Series: H-atom transitions for which final state is n = 2!

$$E_{photon} = E_n - E_2 = -13.5983\,\mathrm{eV}\cdot\left(\frac{1}{n^2} - \frac{1}{2^2}\right)$$



http://www.horrorseek.com/home/halloween/wolfstone/Lighting/colvis_ColorVision.html

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: > On-shore electricity generation potential of ≈ 600 TW (10% conversion efficiency).
- *Photosynthesis*: 90 TW

Solar Radiation Spectrum

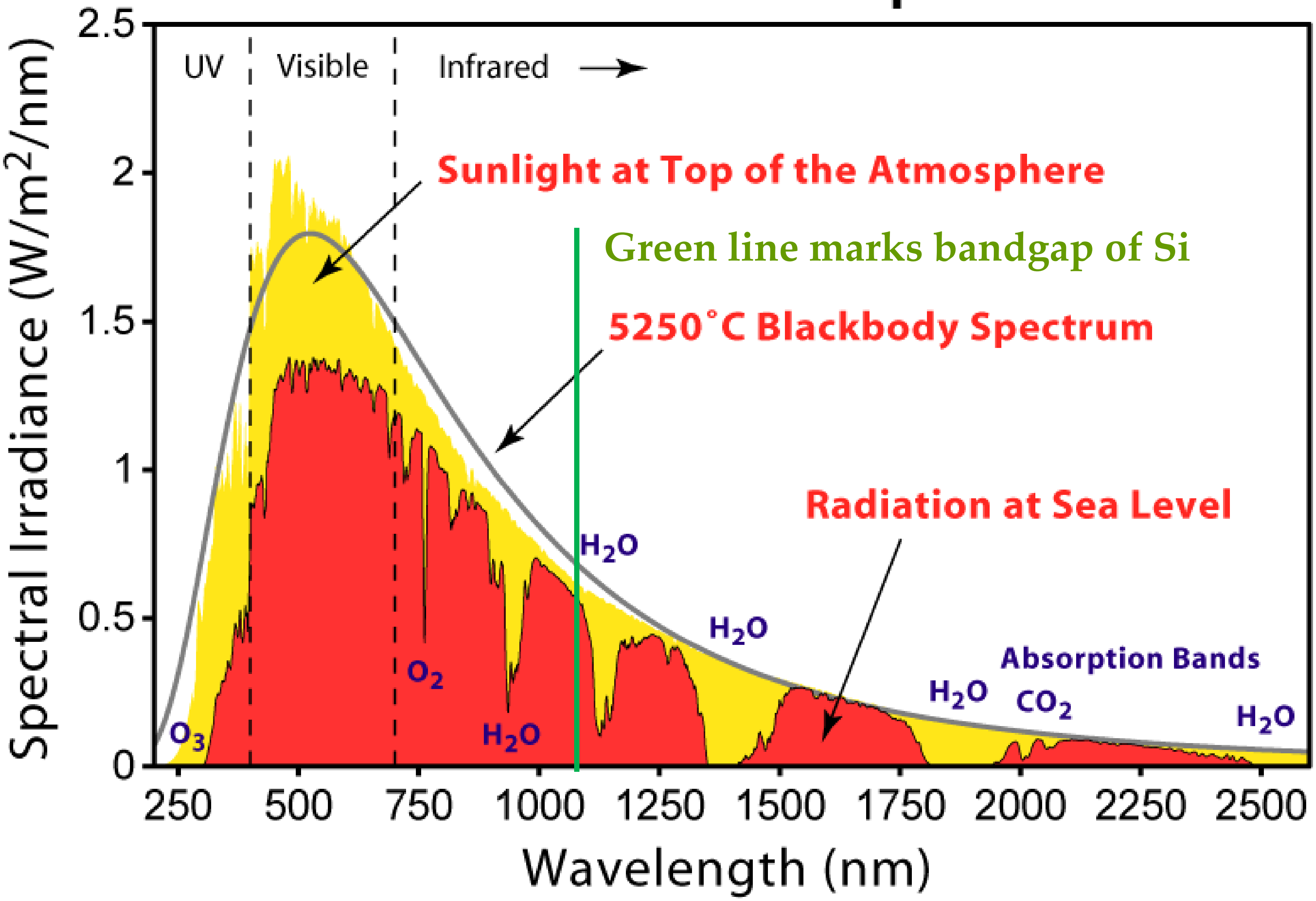
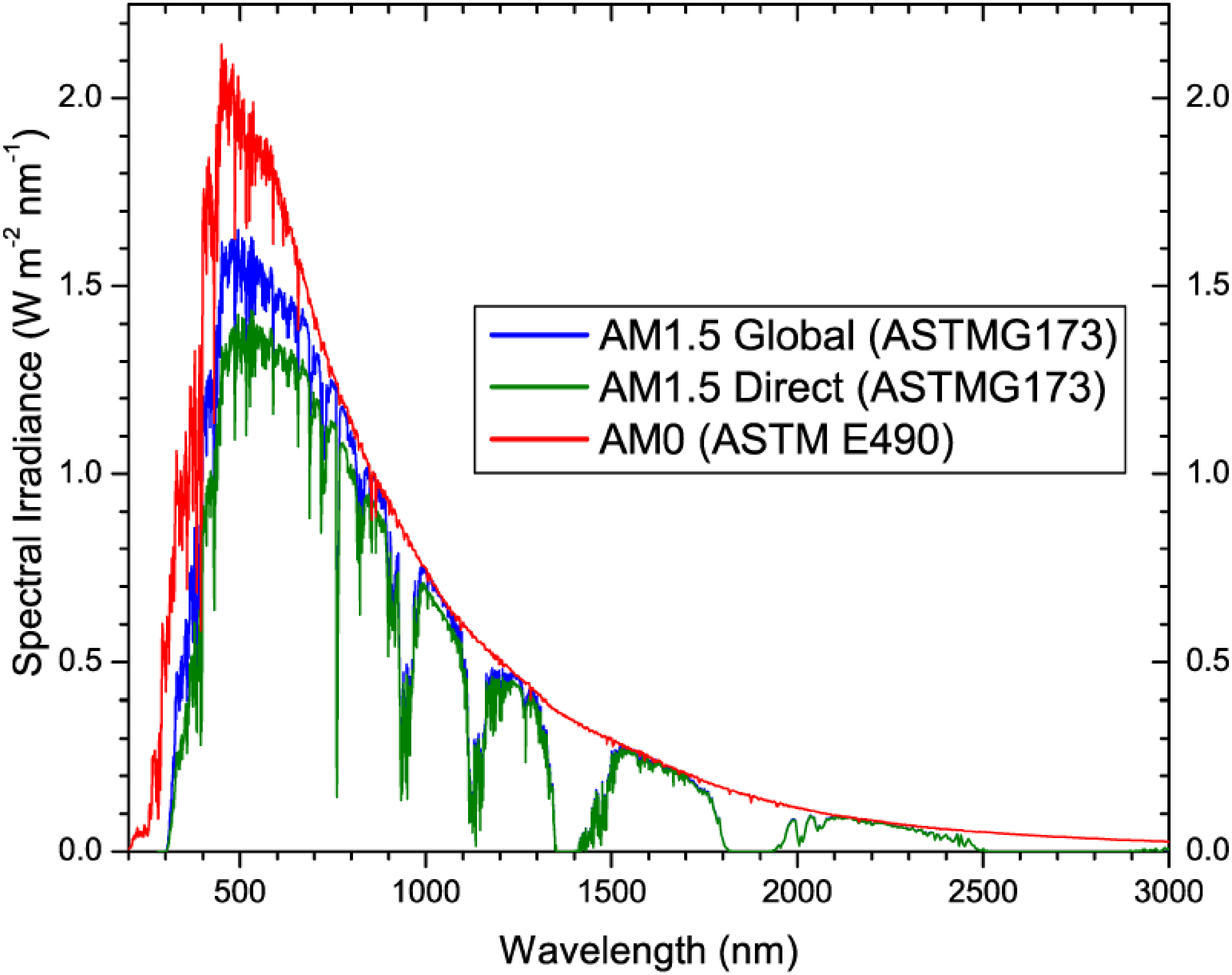


Image created by Robert A. Rohde / Global Warming Art

Solar spectra at Earth



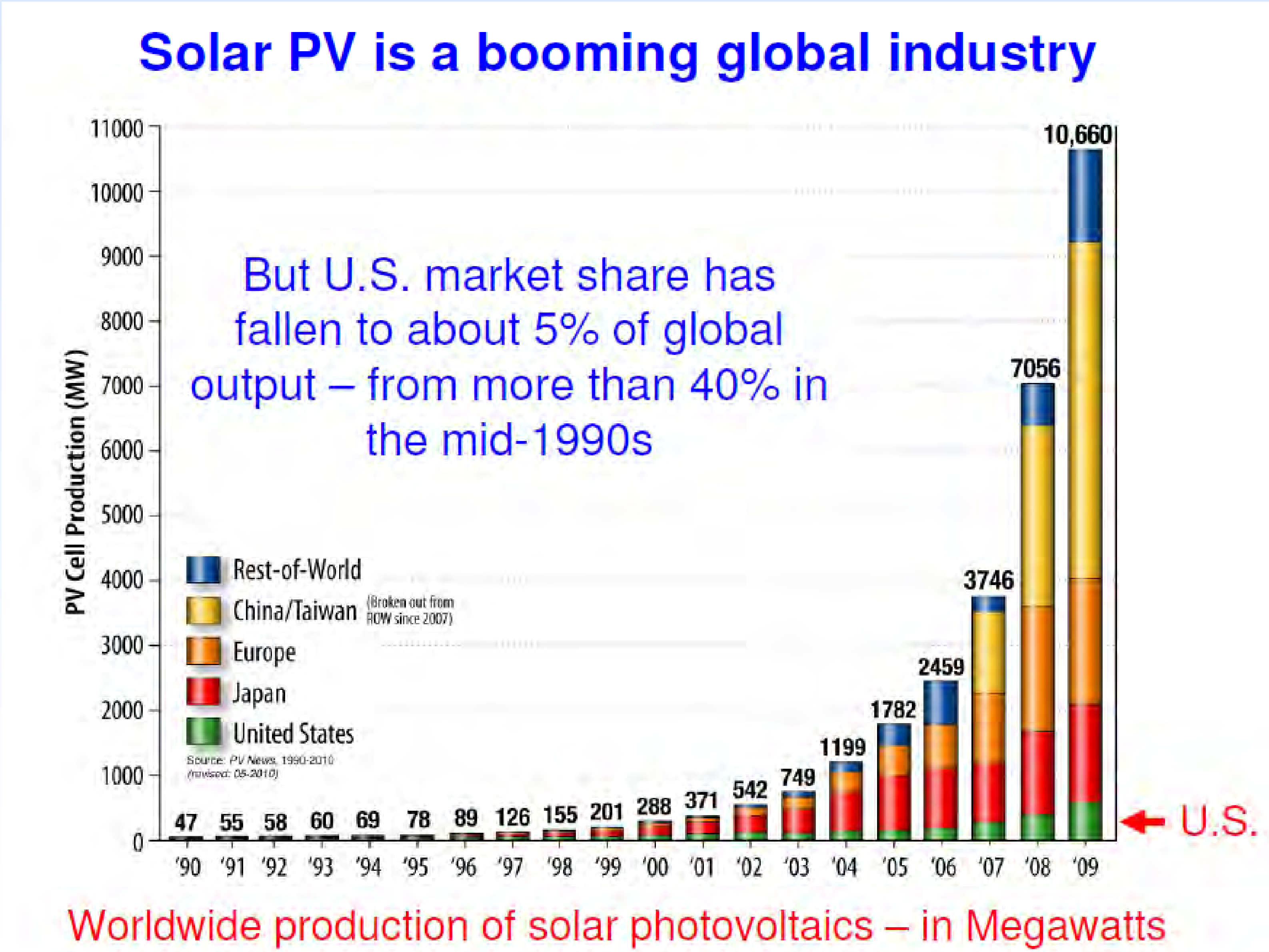
http://pvcdrom.pveducation.org/APPEND/Am1_5.htm

The Solar Resource in the US

3 TW

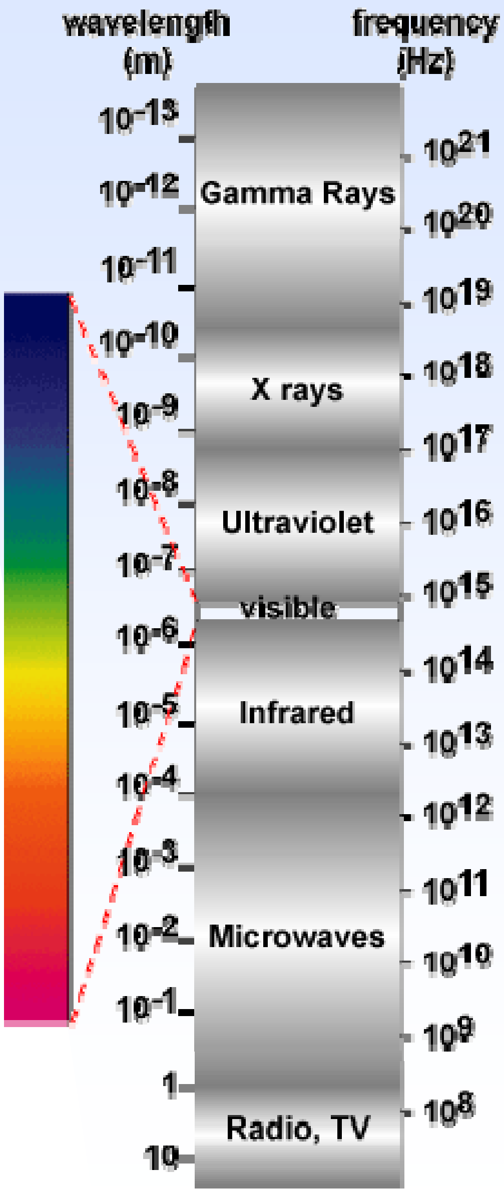
PV covering area of square ~110 miles x 110 miles could satisfy all of US energy needs.

PV electricity at $1/Watt



http://www1.eere.energy.gov/solar/pdfs/dpw_chu.pdf

Properties of light



Energy of a photon: $E = \frac{hc}{\lambda}$

Convenient relation: $E = \frac{1.24}{\lambda(\mu m)}$

1 eV = 1.602 x 10^{-19} J

Definition of photon flux: $\Phi = \frac{\#\ of\ photons}{sec\, m^2}$

Spectral irradiance:

$$F = \left(\frac{W}{m^2 \mu m}\right) = q\Phi \frac{1.24}{\lambda^2(\mu m)} = q\Phi \frac{E^2(eV)}{1.24}$$

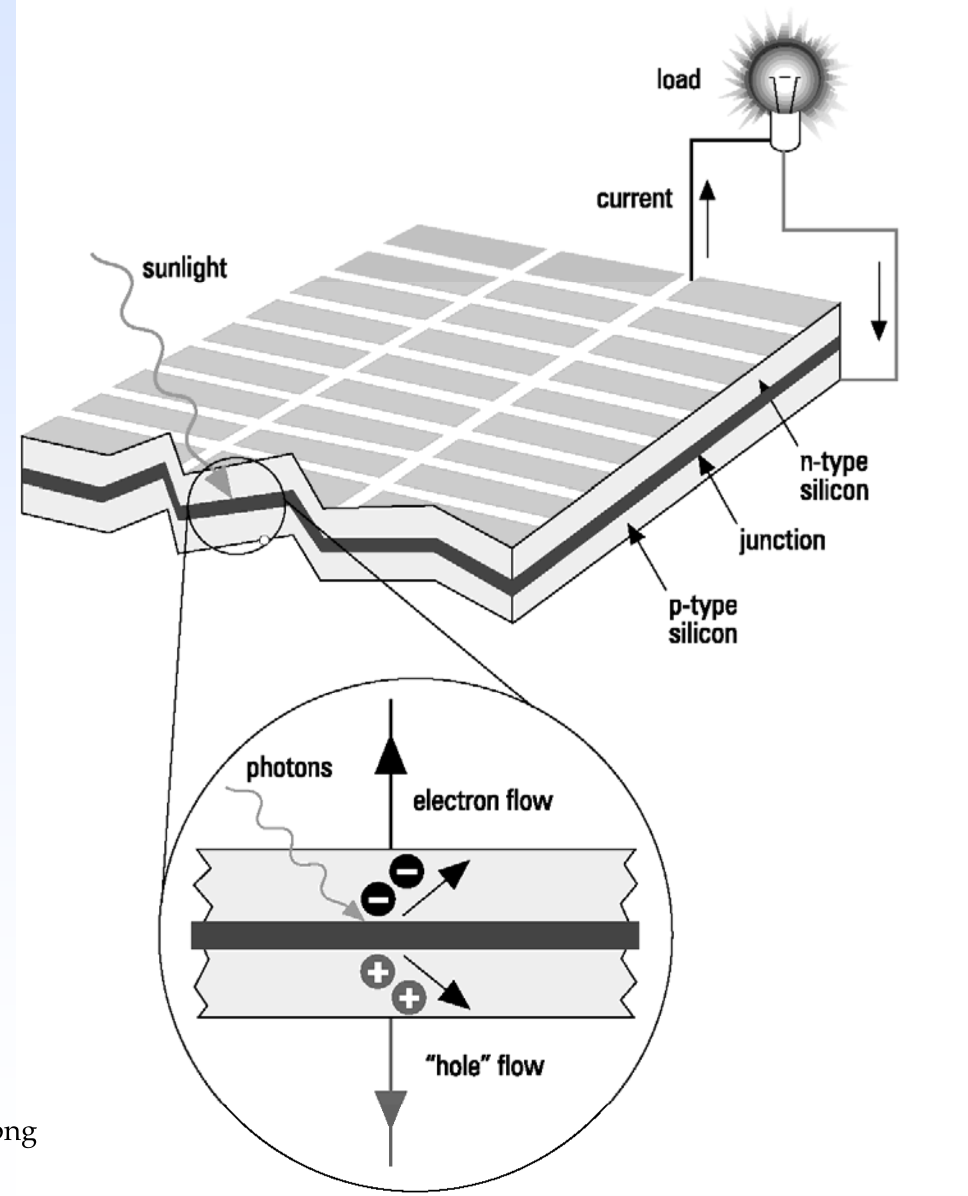
F is the spectral irradiance in $Wm^{-2}\mu m^{-1}$; Φ is the photon flux in # photons $m^{-2}sec^{-1}$; E and λ are the energy and wavelength of the photon in eV and μm respectively; and q, h and c are constants.

An excellent resource:
http://www.pveducation.org

Basic silicon photovoltaic (solar) cell operation

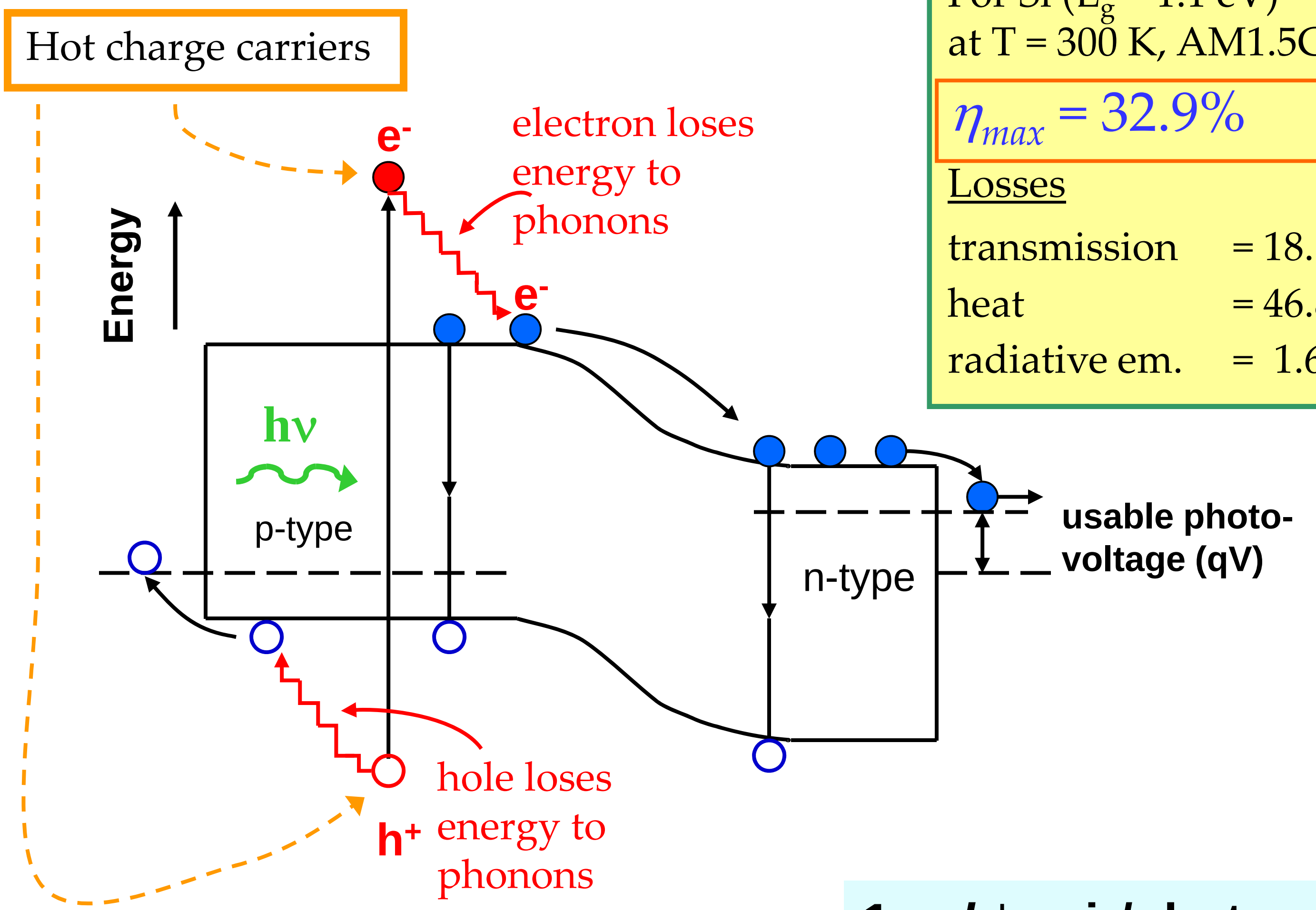
<u>Key functions of a solar cell</u>

- 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

η_{max} = 32.9%

<u>Losses</u>

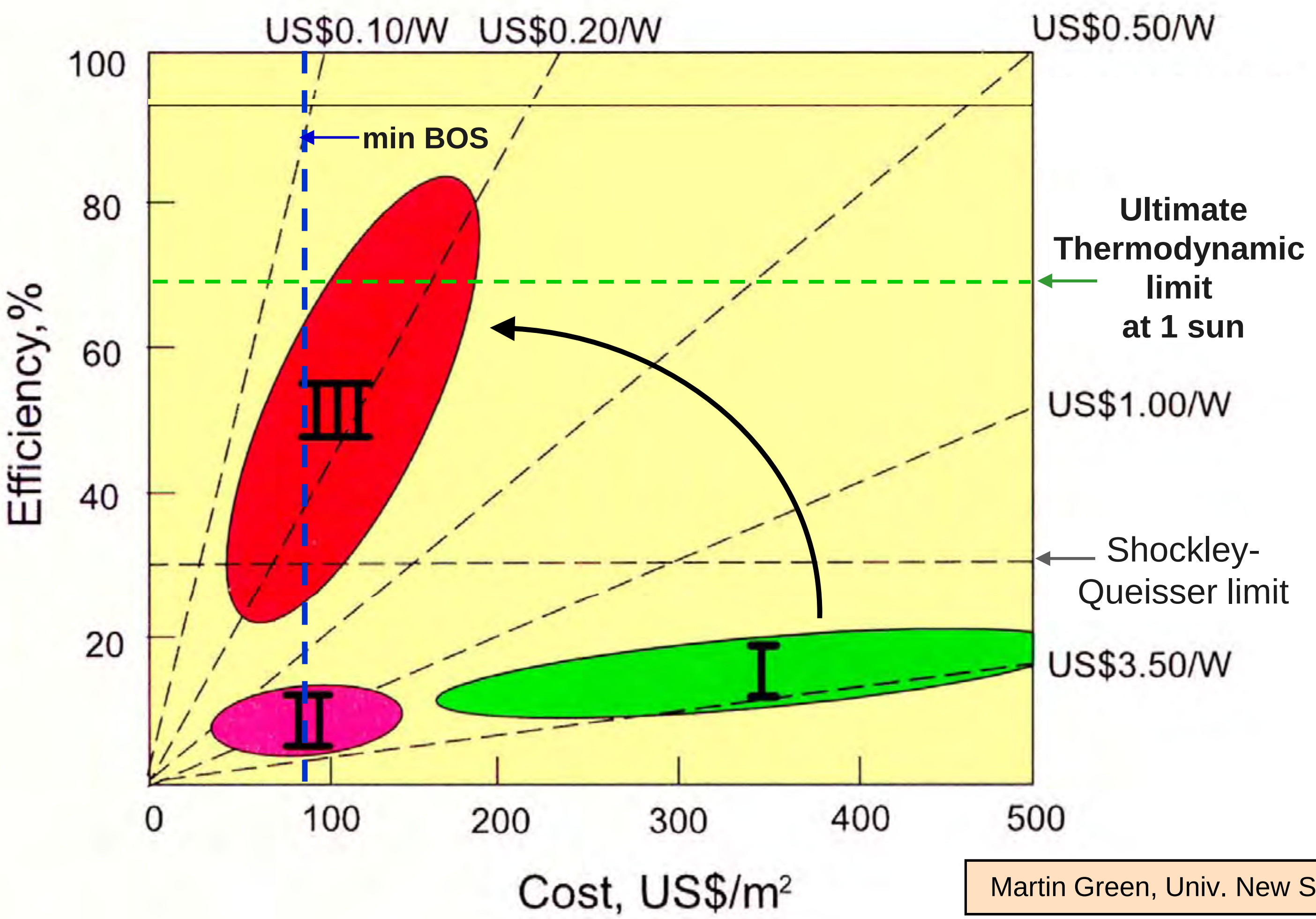
transmission	= 18.7%
heat	= 46.8%
radiative em.	= 1.6%

1 e^--h^+ pair/photon

"Generations" of photovoltaic cells

- *1st generation:* ***crystalline silicon***
- *2nd generation:* ***thin films***
  e.g. amorphous Si, CdTe, $CuInGaSe_2$ (CIGS)
- *3rd generation:* ***nanostructures, organic materials, and advanced concepts.***

Economics of solar conversion cost and efficiency

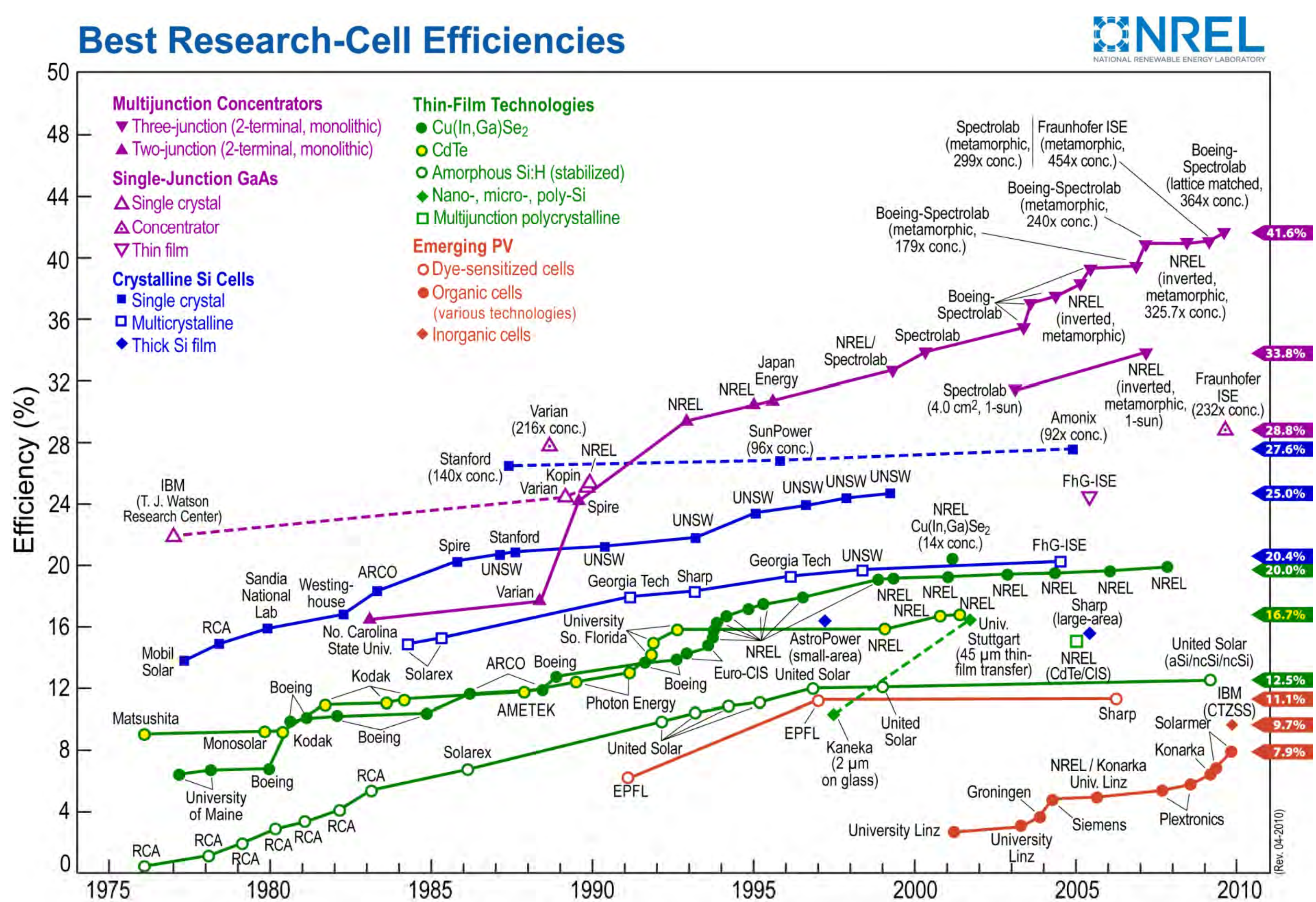


Martin Green, Univ. New S. Wales, Australia

To provide the level of CO_2-free energy required for electricity and fuel:
Power cost needs to be 2-3 cents/kWh (module cost of \$0.20 – \$0.30/W)

BOS = Balance of System, incl. inverter, installation, etc.

Trends in solar cell efficiencies



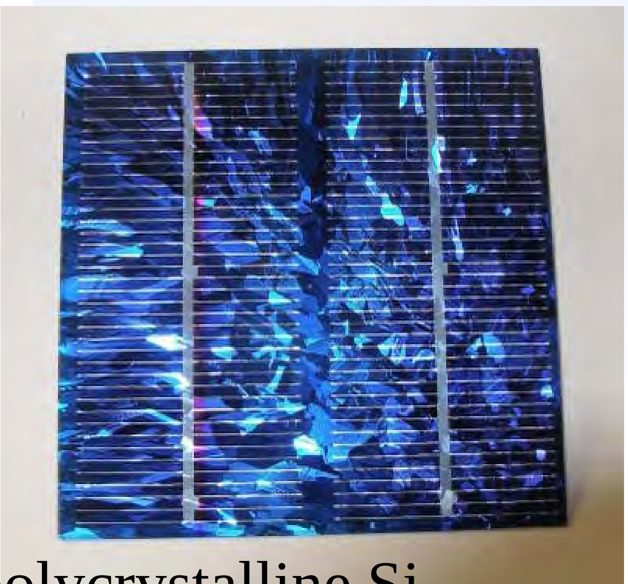
Many different solar cell technologies are being developed, for various applications (rooftops, solar power plants, satellites, backpacks or clothing, etc.).

1st gen.

single crystal Si

Xunlight

2nd gen.: thin film amorphous Si and CdTe



polycrystalline Si

First Solar

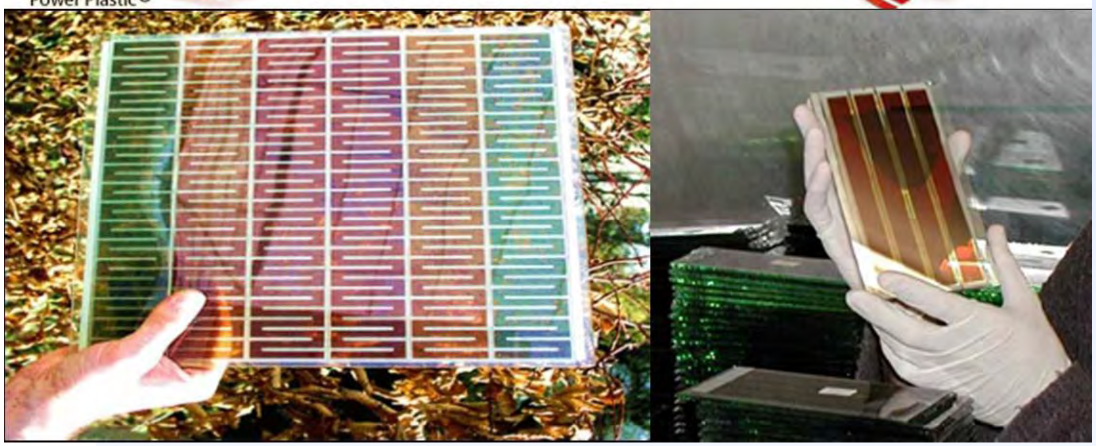
The biggest PV power plant (so far)

The Olmedilla Photovoltaic (PV) Park uses 162,000 flat solar photovoltaic panels to deliver **60 MW** of electricity on a sunny day. The entire plant was completed in 15 months at a **cost of about $530 million** at current exchange rates. Olmedilla was built with **conventional solar panels**, which are made with **silicon** and tend to be heavy and expensive. So-called "thin-film" solar panels, although less efficient per square meter, tend to be much cheaper to produce, and they are the technology being tapped to realize the world's largest proposed PV plant, the Rancho Cielo Solar Farm in Belen, N. Mex., which is **expected to cost $840 million**, cover an area of 700 acres (285 hectares), and produce **600 MW** of power.

http://www.scientificamerican.com/article.cfm?id=10-largest-renewable-energy-projects

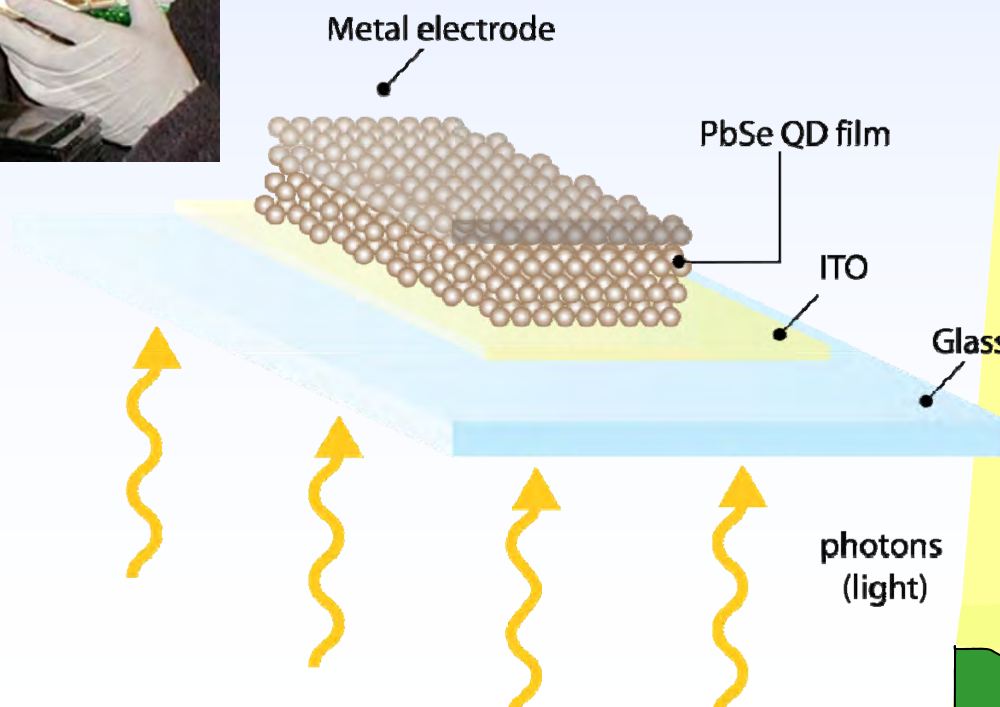
3rd Generation Solar Cells

Polymer solar cell



Dye-sensitized solar cell

Nanocrystal solar cell



Toledo and UT in the PV news (again)

Toledo reinvents itself as a solar-power innovator

Updated 13h 5m ago | Comments 27 | Recommend 3

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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

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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.

Photovoltaic Goal of $1 per Watt

Science and Technology has given us solutions in the past.

With the right government policies, it will come to our aid in the future.

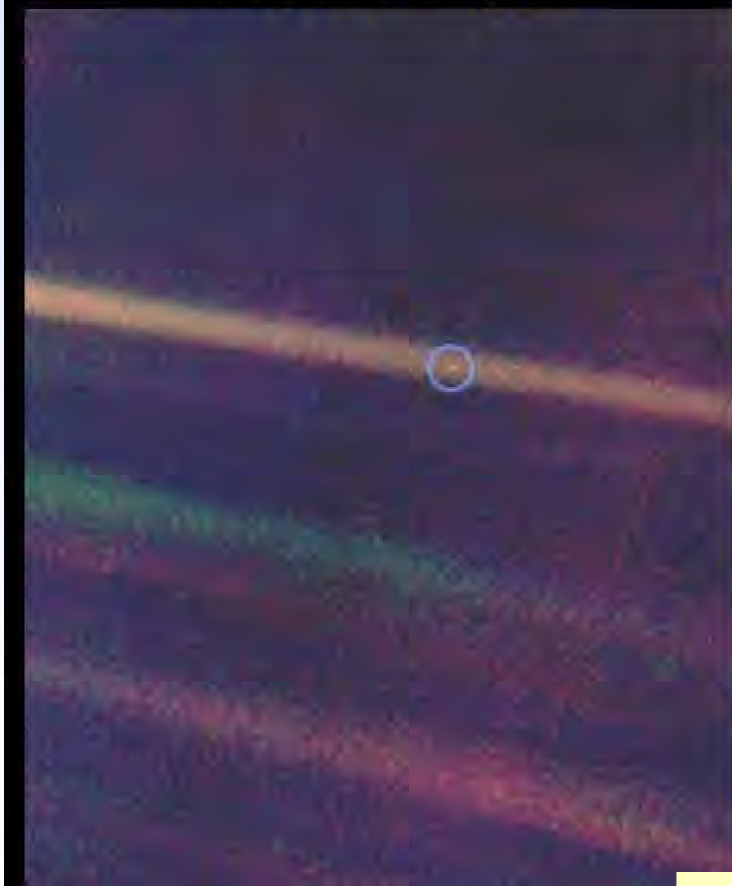
-- Energy Secretary, Steve Chu

$ per Watt Workshop held Aug. 11-12, 2010 [http://www1.eere.energy.gov/solar/dollar_per_watt.html].

http://www1.eere.energy.gov/solar/pdfs/dpw_chu.pdf

Photovoltaic Goal of $1 per Watt

In 1990, Carl Sagan convinced NASA engineers to turn Voyager for one last, homeward look before leaving the solar system



"Look again at that dot. That's here. That's home. That's us. On it, everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives …. Every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, … every saint and sinner in the history of our species lived there--on a mote of dust suspended in a sunbeam."

"….The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate … Like it or not, for the moment the Earth is where we make our stand."

-- Energy Secretary, Steve Chu

$ per Watt Workshop held Aug. 11-12, 2010 [http://www1.eere.energy.gov/solar/dollar_per_watt.html].

http://www1.eere.energy.gov/solar/pdfs/dpw_chu.pdf