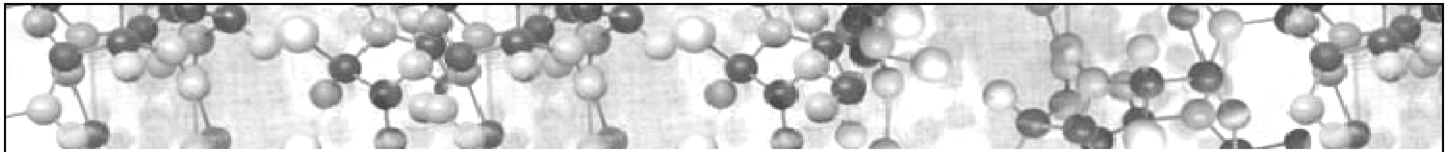


Prospects for a Carbon-Neutral Society

Renewable Energy Technologies and the Factors that Limit their Implementation

Shane Ardo

Department of Chemistry

Johns Hopkins University

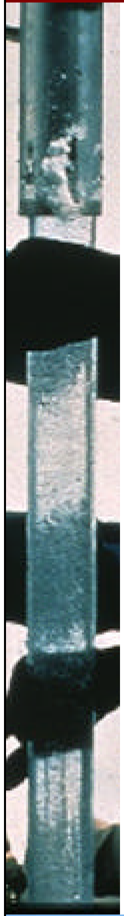
Saturday, March 28, 2009

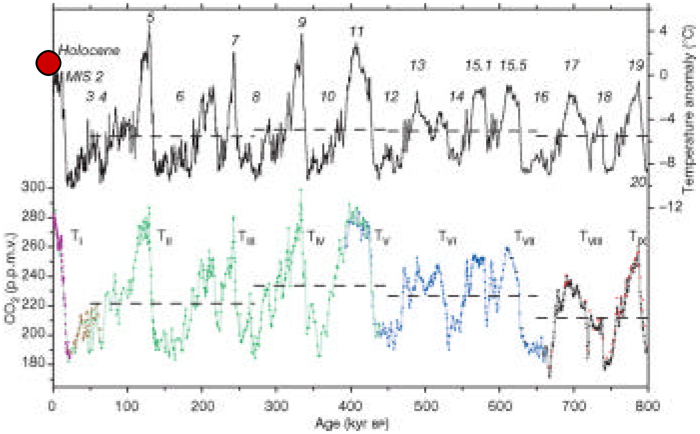
The College of William and Mary

JOHNS HOPKINS UNIVERSITY

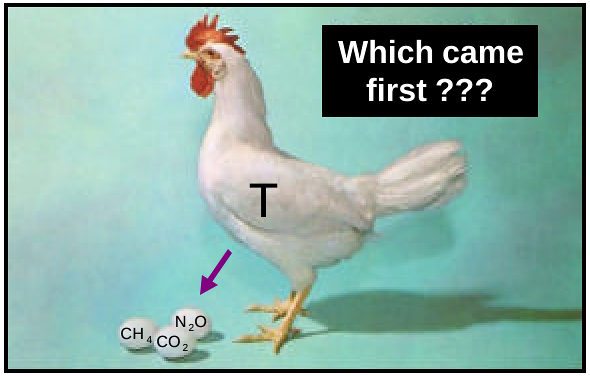
Department of Chemistry

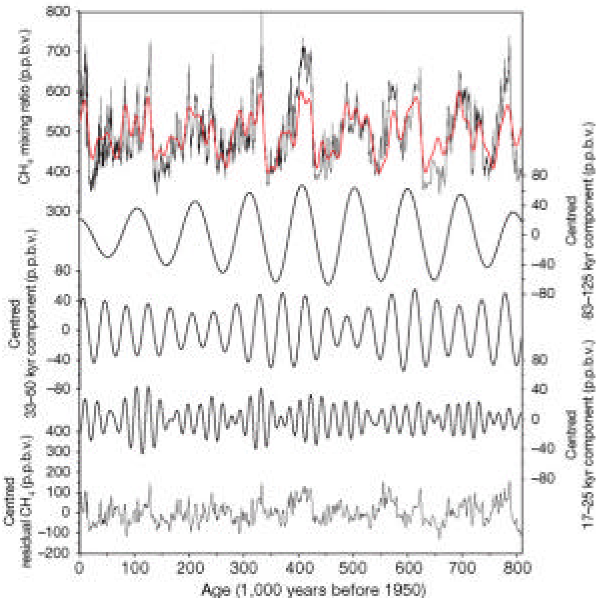
Correlation Between Temperature & GHGs





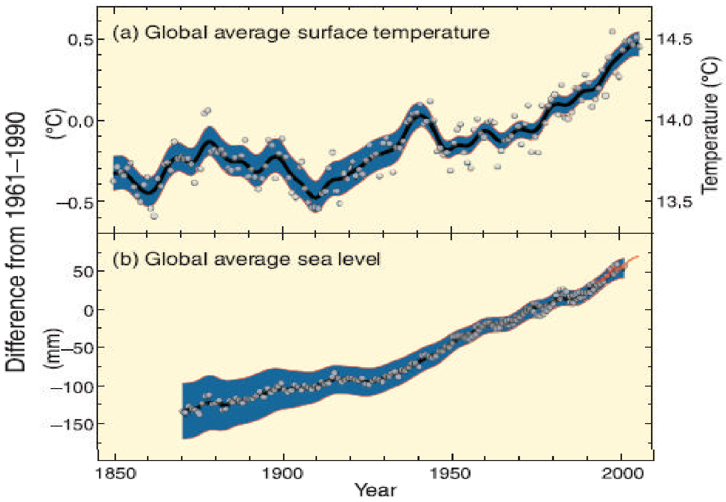
Source: Nature (2008) 453, 379

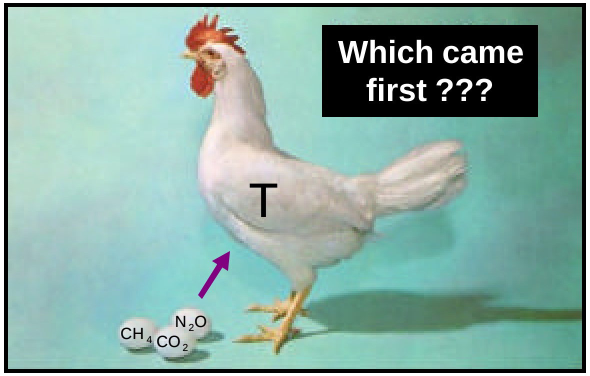


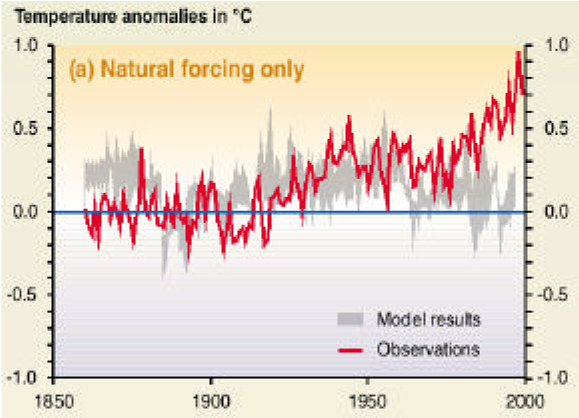


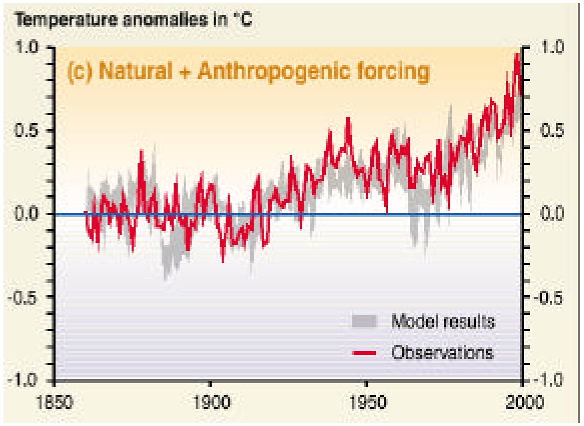
Sources: Nature (2008) 453, 383 & J Geophys Res (2004) 109, D12104

Recent Trends and Model Fitting



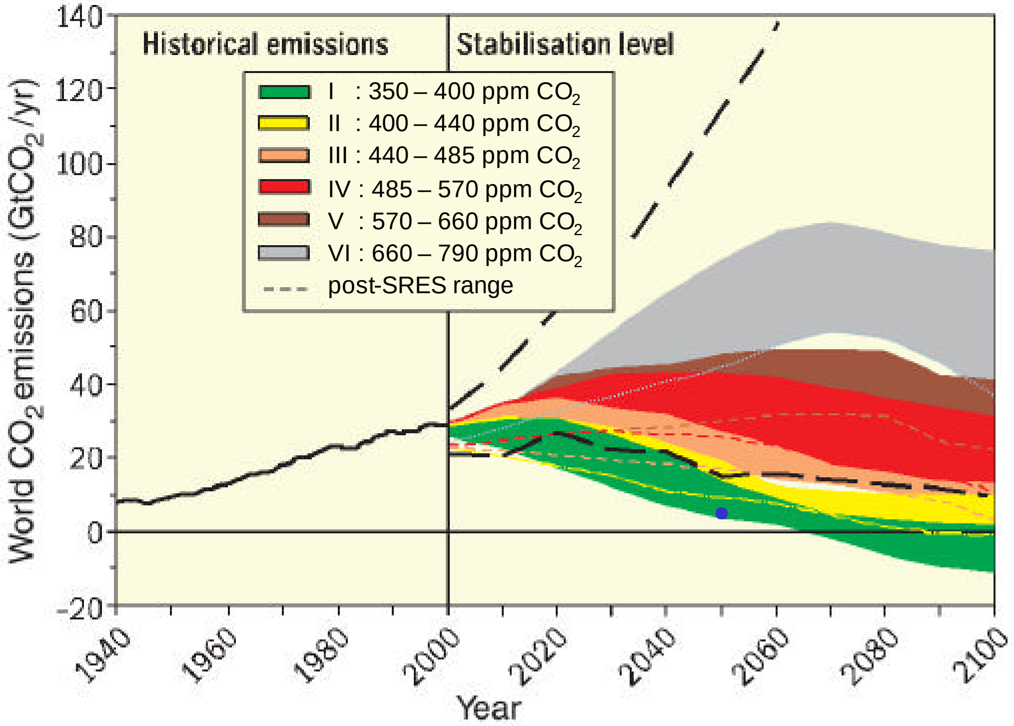






Source: Intergovernmental Panel on Climate Change, 4th Assessment Report: Climate Change (2007)

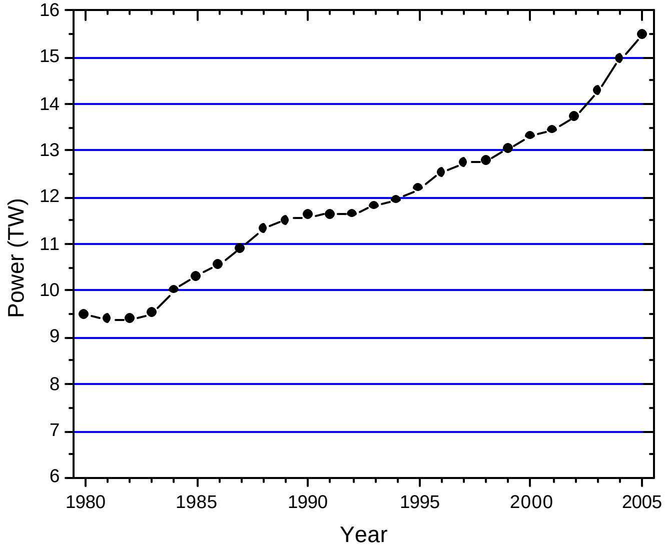
Extrapolations and Predictions



"Making predictions is very difficult, especially about the future."
– Niels Bohr

Sources: Intergovernmental Panel on Climate Change, 4th Assessment Report: Climate Change (2007) & Special Report: Emissions Scenarios (2000)

How Much Power do we **NEED** ???

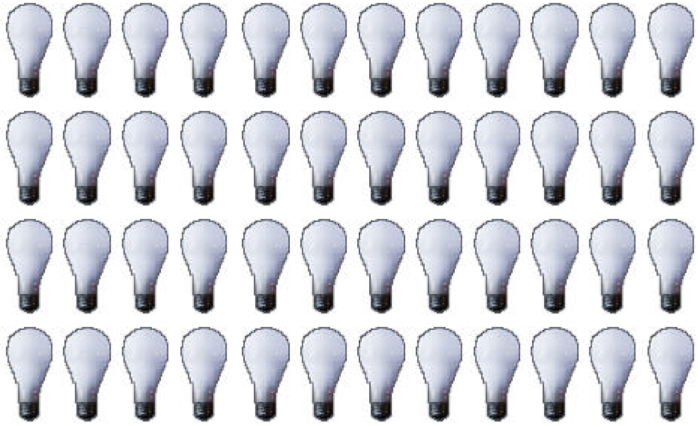


Source: Energy Information Administration: http://www.eia.doe.gov/emeu/international/contents.html

(A) 2000 Calories / day
= 2 x 10^6 cal / day
= 8.37 10^6 J / day
= 96.9 J / s = ~ 100 W

(B) 15.5 x 10^{12} W; 6.4 x 10^9 people
Divide to get ~2400 W / person
Given a 100 W light bulb
= ~24 light bulbs / person

How Much Power do we **USE** ???



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(B) 15.5 x 10^{12} W; 6.4 x 10^9 people
Divide to get ~2400 W / person
Given a 100 W light bulb
= ~24 light bulbs / person

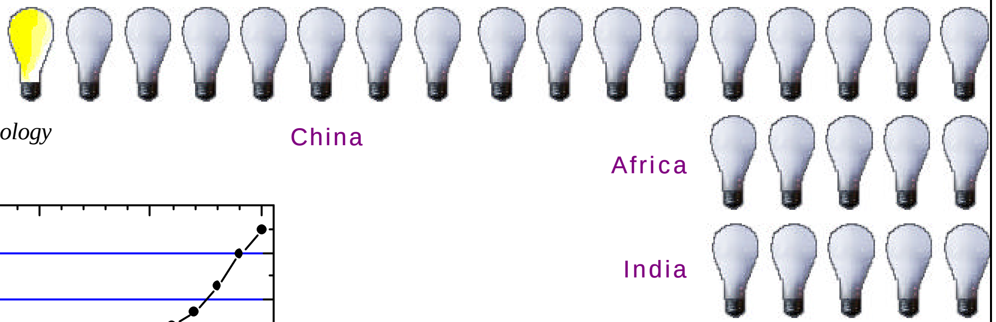
(C) 3.4 x 10^{12} W; 0.3 x 10^9 people
~114 light bulbs / person

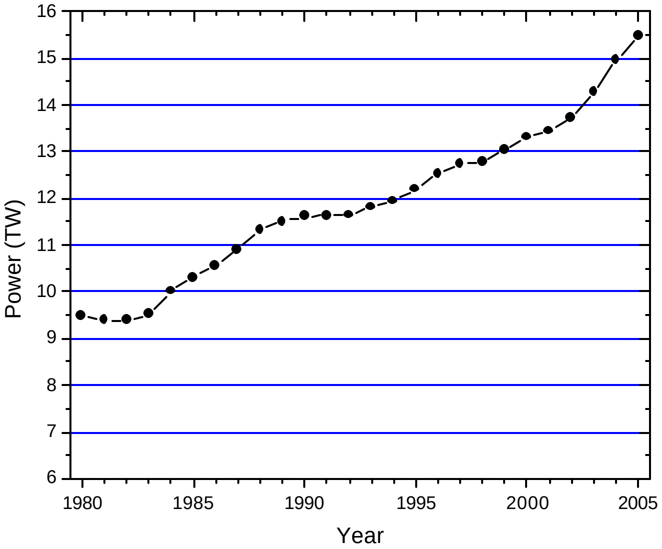
How Much Power will we NEED ???

$$Power = N \times \frac{GDP}{N} \times \frac{Power}{GDP}$$

$$Power = people \times (goods + services) \times technology$$

Source: Nature (1998) 395, 881





Source: Energy Information Administration: http://www.eia.doe.gov/emeu/international/contents.html

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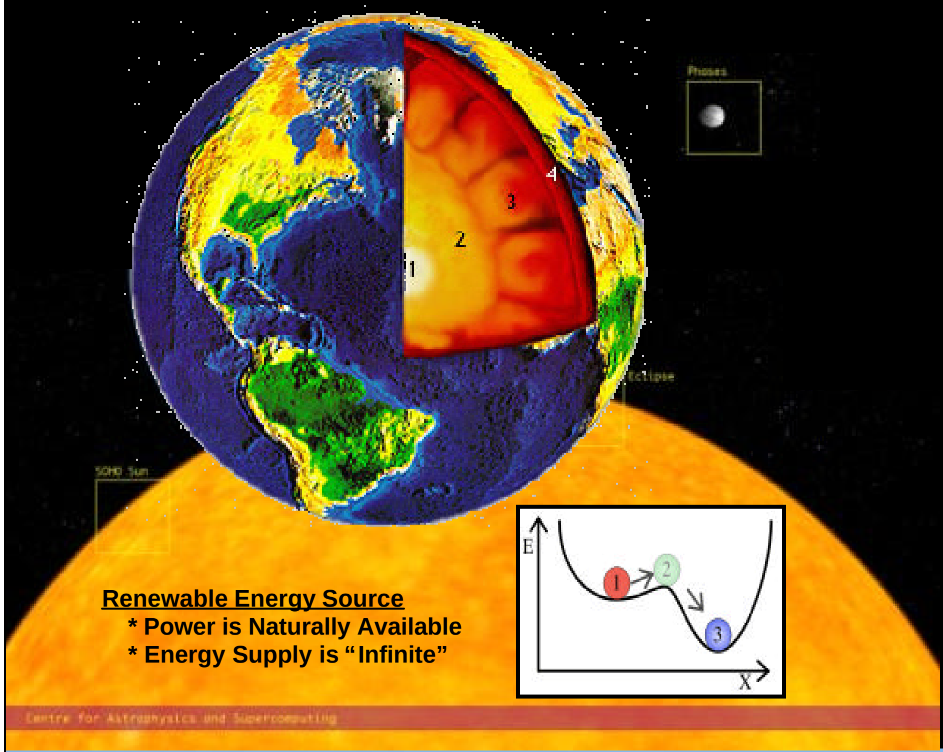
~114 light bulbs / person

* Extrapolating projections to 2050 results in 29.4 TW, or almost **double** 2005 values
* Extrapolating projections to 2100 results in 44.5 TW, or almost **triple** 2005 values

Remnants of the Big Bang

- *Energy*
- ***Electrochemical Potential → Photovoltaics***
- ***Biochemical Potential → Fuel / Storage / Heat***
- ***Thermal Kinetic → Heat / Steam Turbine / Heat Engine***
- ***Kinetic → Turbine***



<u>**Renewable Energy Source**</u>

*** Power is Naturally Available**

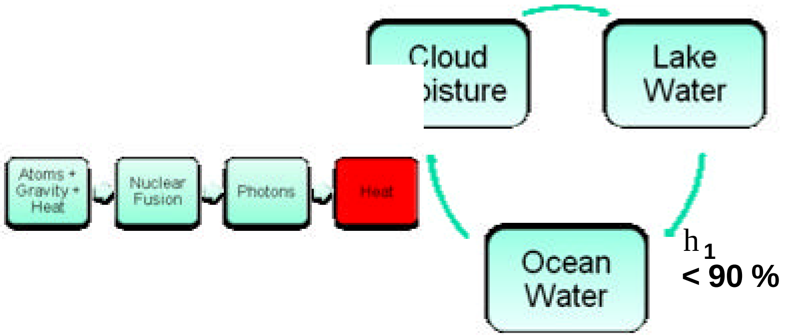
*** Energy Supply is "Infinite"**

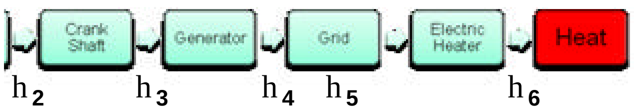
Big Bang

- Moon Motion + Ocean (Kinetic + Gravitational Potential)
  - ***Tides***
- Nuclei + Heat/Pressure (Nuclear Potential --> Light/Heat)
  - ***Nuclear Power Plants (Fission Reactions)***
  - Earth's Crust/Mantle/Core (Isotopic Decay)
    - ***Geothermal***
  - Sun (Fusion Reactions --> Photons)
    - IR Light
      - ***Solar Thermal***
      - Air Temperature Gradient
        - ***Wind***
          - ***Waves / Surface Currents***
      - Water Temperature Gradient
        - ***Ocean Thermal***
        - ***Hydro***
        - ***Deep Ocean Currents***
    - UV/Visible Light
      - ***Photovoltaics***
      - Photosynthesis / Life
        - ***Biomass***
          - ***Fossil Fuels***
          - ***Biofuels***

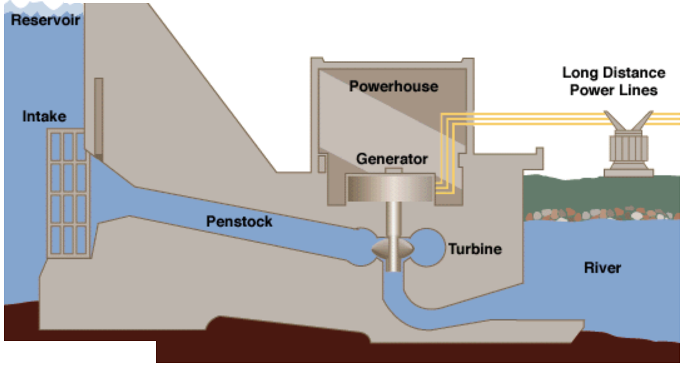
Secondary vs. Primary Power

- *Electrochemical Potential → Photovoltaics*
- *Biochemical Potential → Fossil Fuels / Biofuels*
- *Thermal Kinetic → Solar- / Geo- / Ocean-thermal / Nuclear*
- *Kinetic → Wind / Hydro / Tides / Waves / Currents*





$$h_{Total} = h_1 \cdot h_2 \cdot h_3 \cdot h_4 \cdot h_5 \cdot h_6$$



Rationale → Sources → Conversion → Storage/Transportation → End Use

Economics

- *Electrochemical Potential → Photovoltaics*
- *Biochemical Potential → Fossil Fuels / Biofuels*
- *Thermal Kinetic → Solar- / Ocean- / Geo-thermal / Nuclear*
- *Kinetic → Wind / Waves / Currents / Hydro / Tides*

Energy Source	Energy Outcome	Energy Cost, 2006, ¢ kWhr^{-1}
Fossil Fuels	**Oil**	**~ 6.1**[i]
	Coal	**~ 1.1**[i]
	Natural Gas	**~ 3.8**[i]
Nuclear	**Electricity**	**1.2 – 6**[ii,iii]
Wind, (On/Off)	Electricity	5 – 8 / 8 – 12
Hydro (Sm/Lg)	Electricity	4 – 7 / 3 – 4
Ocean/Marine	**Thermal**	**15 – 40**
	Tides/Waves/ Currents	5 – 30[ii]
Geothermal	**Heat**	**0.5 – 2**
	Electricity	4 – 7
Solar-Biomass	**Heat**	**1 – 6**
	Electricity	5 – 12
	Ethanol	2.8 – 5.6
	Biodiesel	5.1 – 10.3
Solar	**Low T Heat**	**1 – 8**
	Thermal	**12 – 18**
	Photovoltaics	**40 – 80**

All from REN21, Renewables – Global Status Report (2007) except:

[i] EIA, online (2006); data averaged

[ii] REN21, Changing Climates, 2006, pg. 11, Table 3.1

[iii] IEA, WEO (2006) pg. 493, Table for 2004; pp. 368-369 (and pg. 383, Table 13.14)

$$\frac{¢}{kW \cdot hr} = \frac{Cost}{P \times h \times t}$$

Economics

- *Electrochemical Potential → Photovoltaics*
- *Biochemical Potential → Fossil Fuels / Biofuels*
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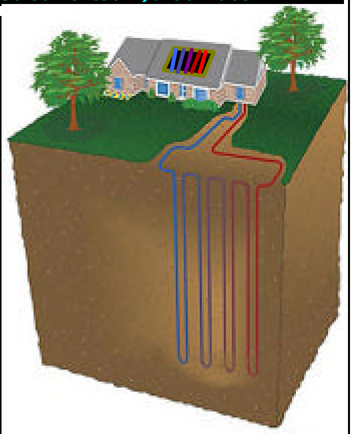
- *Kinetic → Wind / Waves / Currents / Hydro / Tides*

Energy Source	Energy Outcome	Energy Cost, 2006, ¢ kWhr^{-1}	2050 Projected Cost[a], ¢ kWhr^{-1}
Fossil Fuels	Oil	~ 6.1[i]	
	Coal	~ 1.1[i]	
	Natural Gas	~ 3.8[i]	
Nuclear	Electricity	1.2 – 6[ii,iii]	
Wind, (On/Off)	Electricity	5 – 8 / 8 – 12	3 – 10
Hydro (Sm/Lg)	Electricity	4 – 7 / 3 – 4	2 – 10
Ocean/Marine	**Thermal**	**15 – 40**	**7 – 20**
	Tides/Waves/ Currents	5 – 30[ii]	4 – 15
Geothermal	**Heat**	**0.5 – 2**	**0.5 – 5**
	Electricity	4 – 7	1 – 8
Solar-Biomass	**Heat**	**1 – 6**	**1 – 5**
	Electricity	5 – 12	4 – 10
	Ethanol	2.8 – 5.6	2 – 4
	Biodiesel	5.1 – 10.3	4 – 5
Solar	**Low T Heat**	**1 – 8**	**2 – 10**
	Thermal	**12 – 18**	**4 – 20**
	Photovoltaics	40 – 80	5 – 25



$$h = 1 - \frac{T_C + 273.15}{T_H + 273.15}$$

Thermodynamics

- *Electrochemical Potential → Photovoltaics*
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- *Thermal Kinetic → Solar- / Ocean- / Geo-thermal / Nuclear*
- *Kinetic → Wind / Waves / Currents / Hydro / Tides*

Energy Source	Energy Outcome	Power Used, 2006, TW
Wind (On/Off)	Electricity	0.074
Hydro (Sm/Lg)	Electricity	0.073 / **0.770**
Ocean/Marine	Thermal → Electric	–
	Tides/Waves/ Currents	0.0003
Geothermal *(surface / total)*	Heat	0.033
	Electricity	0.0095
Solar-Biomass	Heat	0.235
	Electricity	0.045
	Ethanol (C/S)	0.0012
	Biodiesel (SB/RS)	0.0003
	Algae Fuel (K/A)	–
Solar *(at Earth / at Sun)*	Low T Heat	0.105
	Thermal → Electric	0.0004
	Photovoltaics	0.0078
TOTAL		**1.35**
	Photosynthesis[iii]	**70**
Global[i]		**15.5**

All from REN21, Renewables – Global Status Report (2007) except:

[i] EIA, online, 2005

[ii] Twidell/Weir, Renewable Energy Resources (2006), Chapter 11, pg. 363, Table 11.4

[iii] *ibid*, pg. 351

[a] UNDP, WEA (2004)

[b] UNDP, WEA (2000)

[c] Aβmann/Laumanns/Uh, Renewable Energy (2006), Chapter 2, pp 15-47

[d] REN21, Global Potential of Renewable Energy Sources (2008), pg. 39, Table 13

[e] NASA Sun Fact Sheet, http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

- Expensive, for the time being
- As cheap as can be but only direct heating

Thermodynamics

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Energy Source	Energy Outcome	Power Used, 2006, TW	2050 Projected Power[a,b,c,d], TW	Theoretical Power[a,b,c,e], TW
Wind (On/Off)	Electricity	0.074	12.0 / 0.70	**183.8**
Hydro (Sm/Lg)	Electricity	0.073 / 0.770	1.58	**4.66**
Ocean/Marine	Thermal → Electric	–	10.43	**228.2**
	Tides/Waves/ Currents	0.0003		**4.56**
Geothermal *(surface / total)*	Heat	0.033	157.0	**8.94 / 4,436,332**
	Electricity	0.0095	1.43	
Solar-Biomass	Heat	0.235	10.90	**91.9**
	Electricity	0.045		
	Ethanol (C/S)	0.0012	< 6.58 / 12.8[ii]	
	Biodiesel (SB/RS)	0.0003	< 1.71 / 2.56[ii]	
	Algae Fuel (K/A)	–	> 94.0 / 85.4[ii]	
Solar *(at Earth / at Sun)*	Low T Heat	0.105	3.90	**174,000 / 384,600,000,000,000**
	Thermal → Electric	0.0004	31.4	
	Photovoltaics	0.0078	53.6	
TOTAL		**1.35**		
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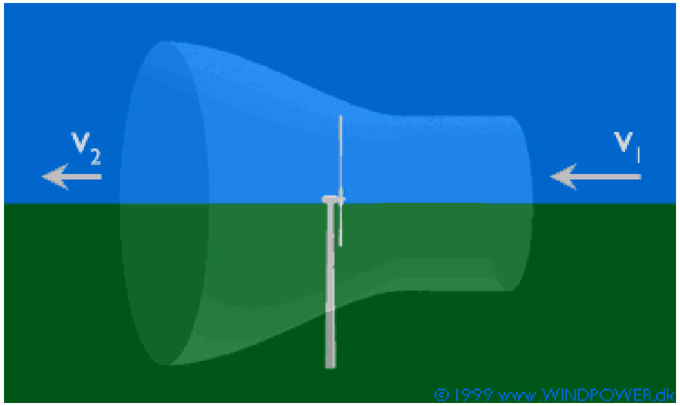
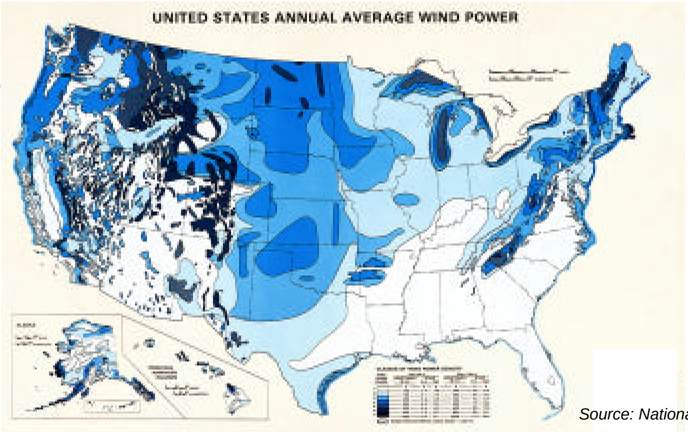
Wind (& Waves / Currents)



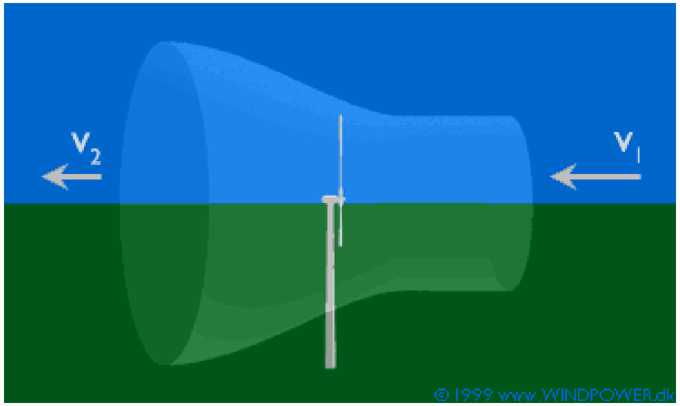


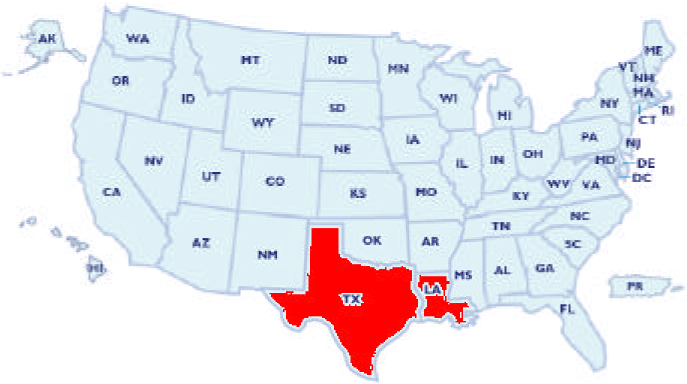
h_{Max} = 59.3 %

- The Betz Limit (1919)
- Occurs when wind speed at turbine is $^2/_3 v_1$, $v_2 = {^1/_3}\, v_1$ and axial force is 88.9 %
- $P = \eta\, (\frac{1}{2} \rho A v_1^3)_{avg}$
  - Density of water is ~1000x greater
  - Velocity of water is ~10x slower
- Larger + Higher ($^1/_7$ law) = Better
  - 5 diameters between turbines
  - 9 diameters between rows
- 87.8 % of 50 States as **> Class 2** = 5.8 % of world land

Source: National Renewable Energy Laboratory (NREL), Renewable Resource Data Center (RReDC)

Wind (Indirect) vs. Solar (Direct)





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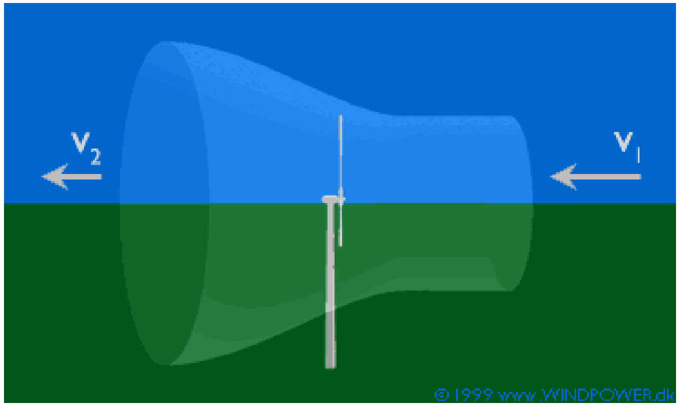

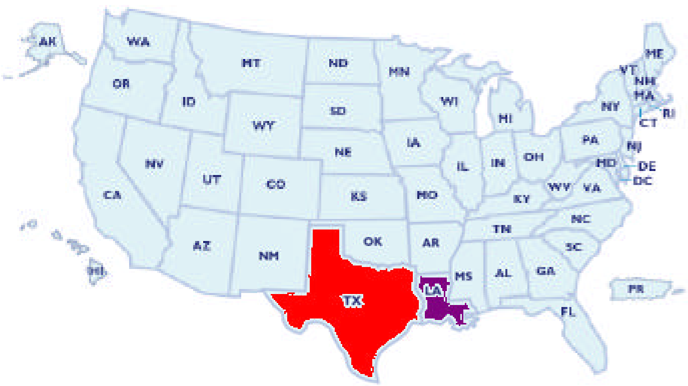

Sources: PNAS (2004) 101, 16115 & J Geophys Res (2004) 109, D19101

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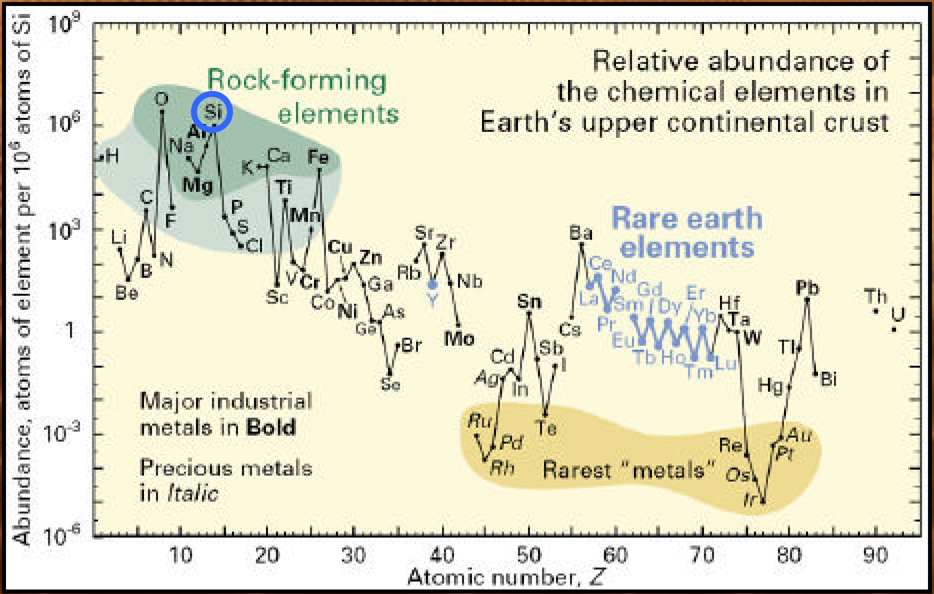
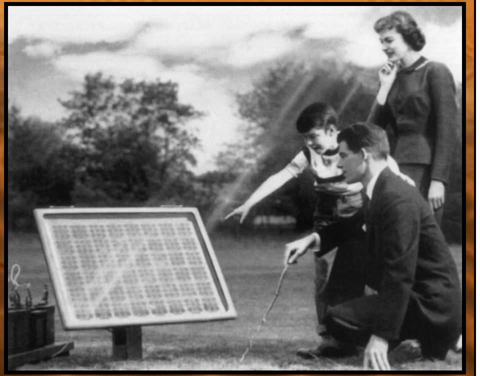
- 87.8 % of 50 States as **> Class 2** = 5.8 % of world land
- **SOLAR**: 93.3 % of TX + LA
- **WIND'**: 93.4 % of LA
- Issue: Taking 15.5 TW of wind

Photovoltaics: 0.5 % of World Land



Source: United States Geological Survey, Rare Earth Elements – Critical Resources for High Technology Fact Sheet (2002)

$$40-80\ {}^{¢}\!/_{kW\cdot hr} = \frac{Cost}{P \times h \times t}$$

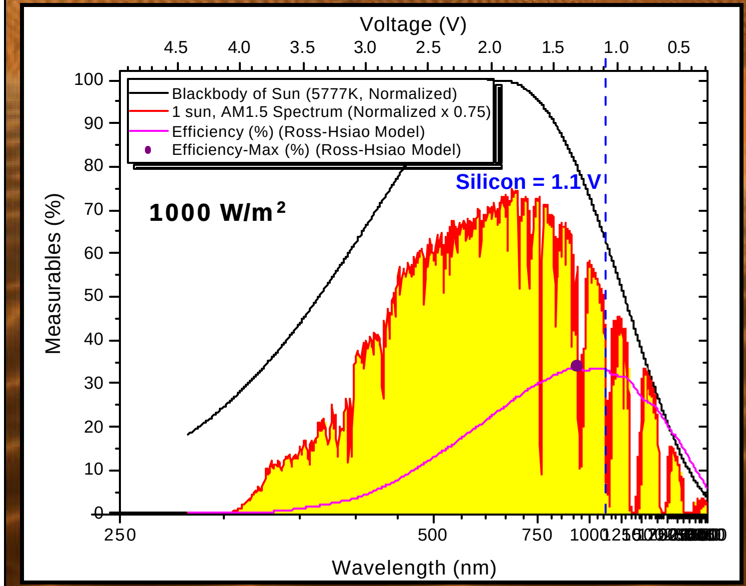


Bell System Solar Battery, Bell Telephone Laboratories (1954)

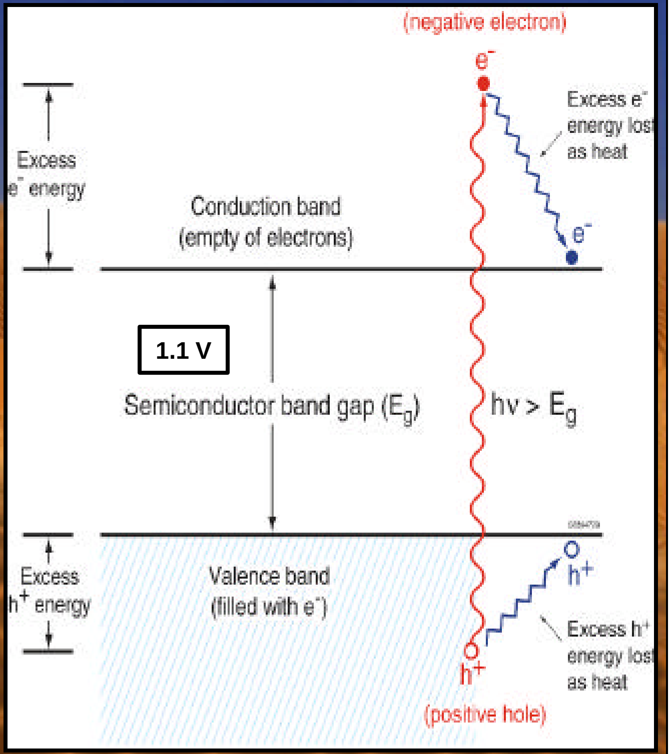
Photovoltaics: 0.5 % of World Land

Energy Source	Temperature, °C	Theoretical Efficiency, %
Sun	5505	95
Solar Thermal	> 3000	**> 91**
Solar PV	–	**31**

Source: J Appl Phys (1961) 32, 510

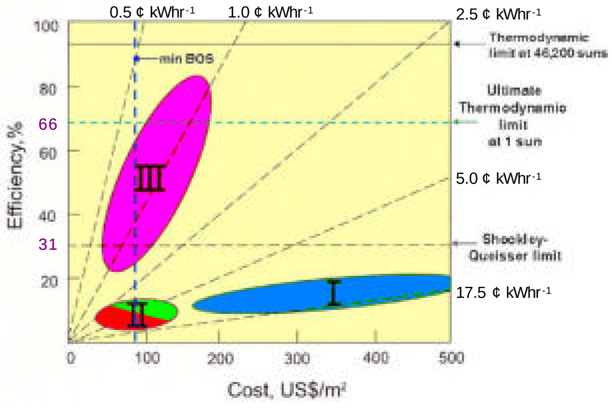


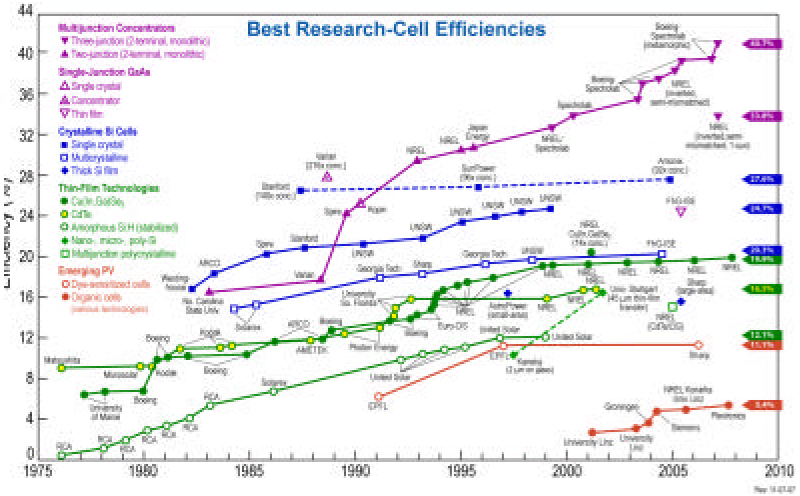
Source: National Renewable Energy Laboratory (NREL), Renewable Resource Data Center (RReDC)



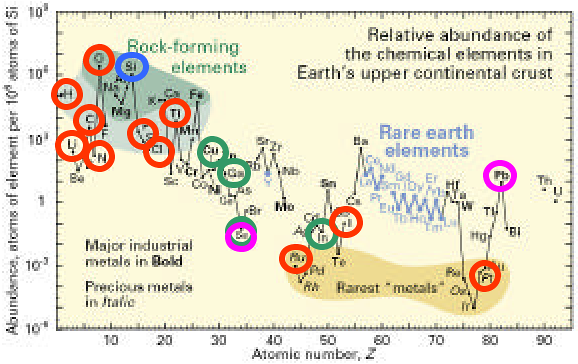
$$h = 1 - \frac{287.65}{T_H + 273.15}$$

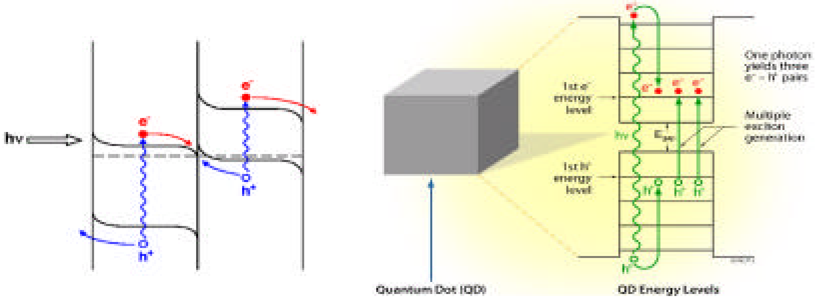
Towards Class III Solar Cells





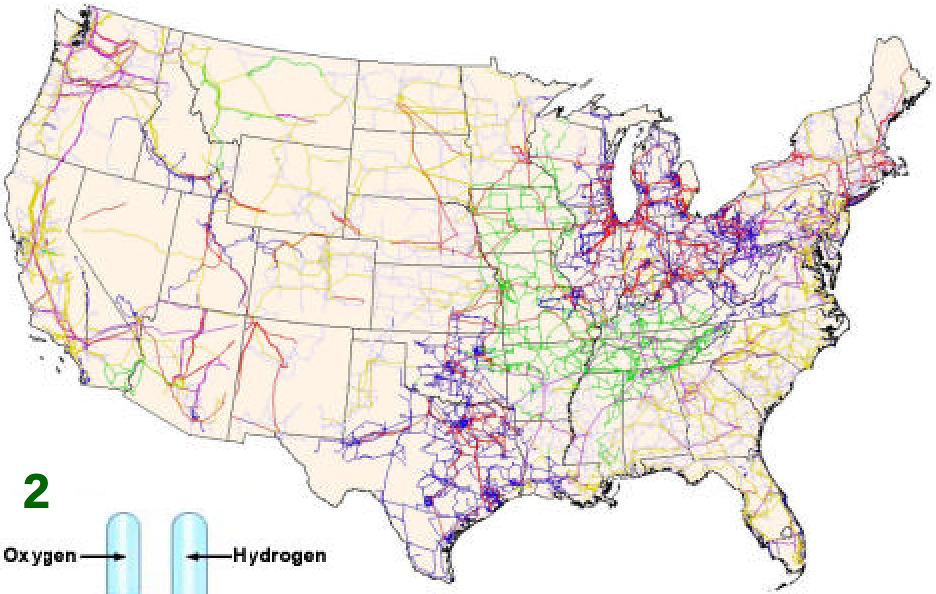
Source: Department of Energy, Basic Research Needs for Solar Energy Utilization (2005)





Sources: **CM:** *Nature Phys (2005) 1, 189 & Phys Rev B (2008) 78, 125325*
SF: *J Am Chem Soc (2006) 128, 16546*

Intermittent Sources Can't Power the Planet



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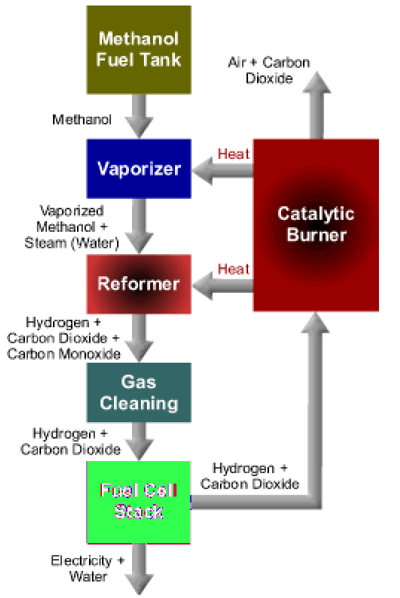

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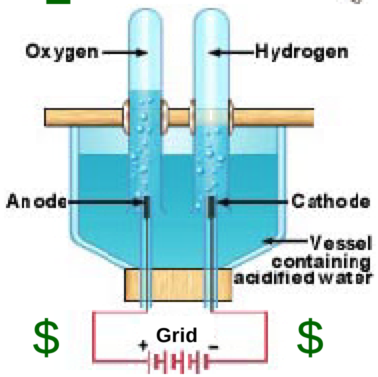
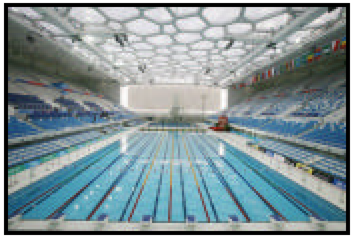
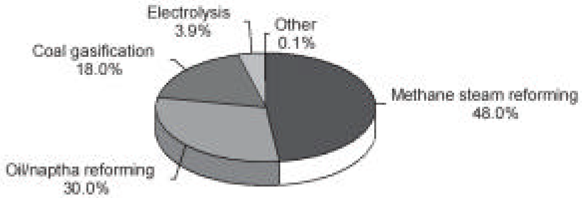
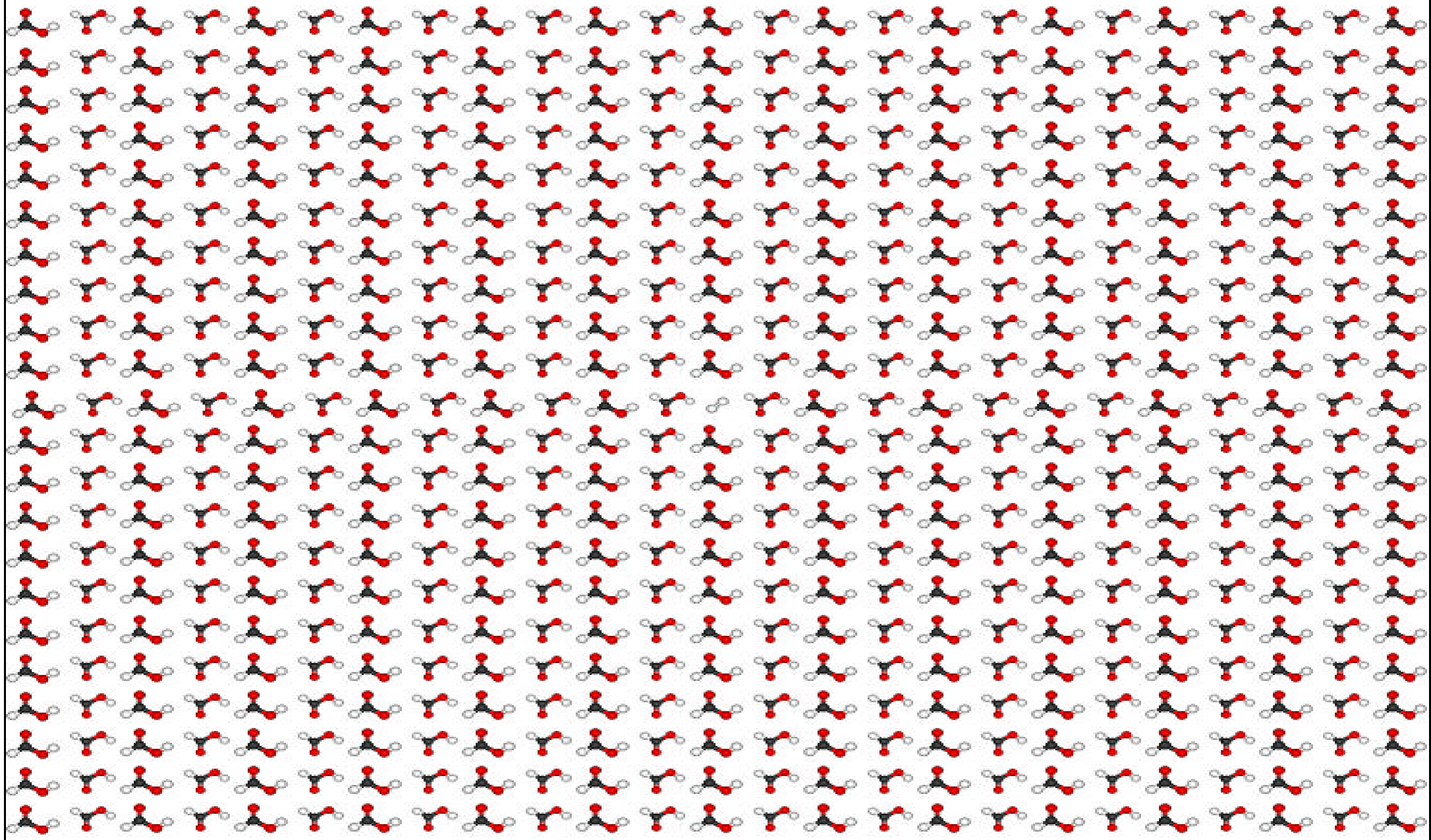






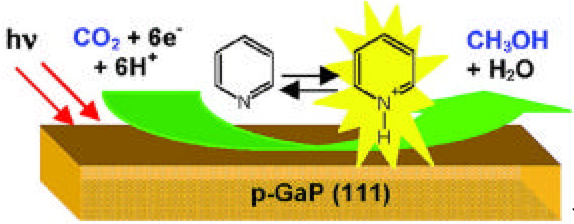
Source: Int J Hydrogen Energy (2005) 30, 809

Is there a "Better" Fuel ???

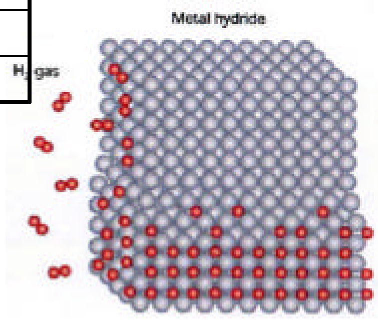


CO_2 Fixation and Net Carbon Loss

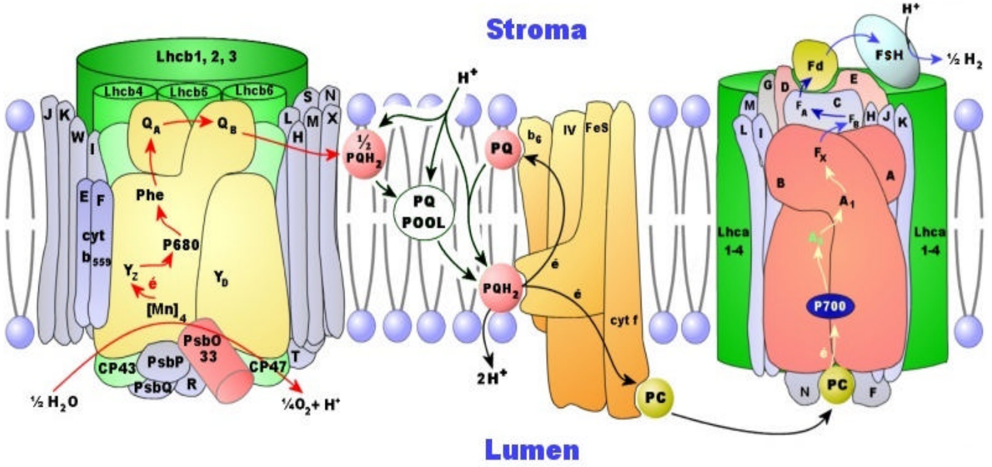
Reactants	Products	Energy Density ($kJ\ L^{-1}$)	Energy Density ($kJ\ kg^{-1}$)
$2\ H_2O$	$2\ H_2 + 2\ O_2$	10.6	117,647
Liquid H_2 (20.3 K), 5 kg tank (***NET***)		**5000 (*3075*)**	**6200 (*3813*)**
Metal-Hydride		**3500 – 17,600**	**1500 – 21,200**
Metal-Organic Framework		**< 5900**	**< 9500**
$2\ CO_2 + 4\ H_2O$	$2\ CH_3OH + 3\ O_2$	**17,154**	**21,665**
Diesel oil		**39,000**	**45,000**
Coal		**45,000**	**29,000**
Batteries (lithium thionyl chloride)		**180 – 1440 (5112)**	**150 – 720**
Capacitors		**0.001 – 36**	**0.005 – 10**
Pumped Hydro		**1**	**1**
Compressed Air (20 atm)		**2000**	**200 – 2000**
Flywheel		**150 – 400**	**50**

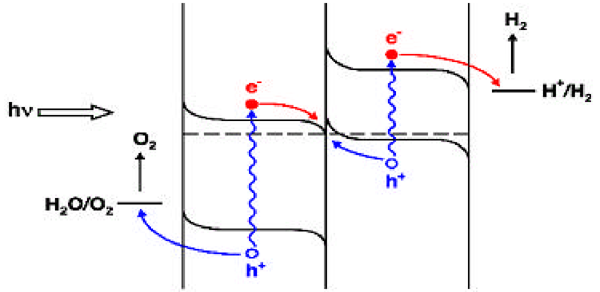


Source: *J Am Chem Soc* (2008) 130, 6342

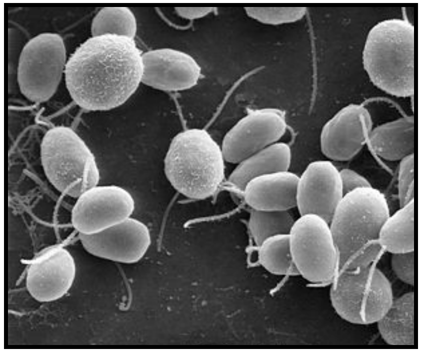


Biomimetic-Based Approaches





Chlamydomonas reinhardtii algae



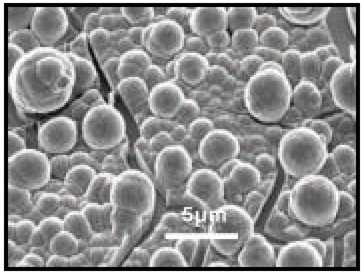
Source: Planta (2007) 226, 1075

Nature, can we beat it?   Sure we can…

Bird vs. Airplane; Brain vs. Computer; Eye vs. Camera

- Vincenzo Balzani

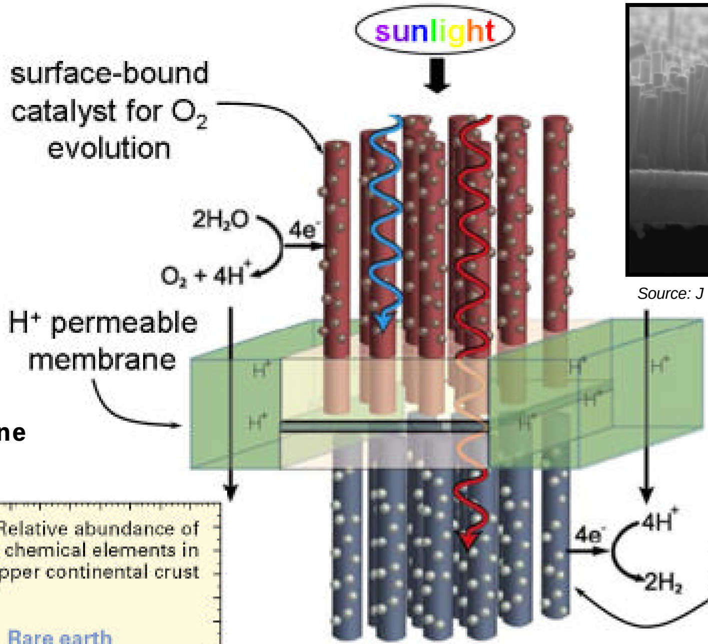
Black ‘Grass-Microalgae’

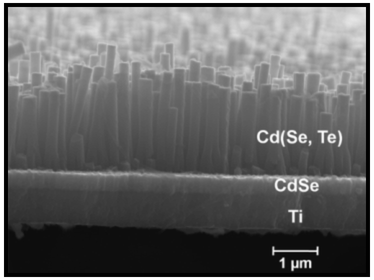


Co-O-P

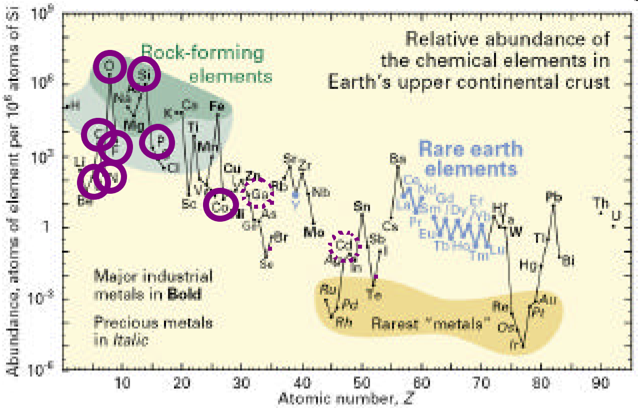
Source: Science (2008) 321, 1072

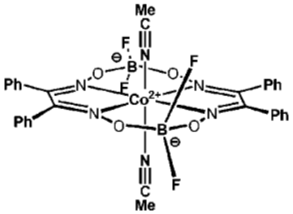
Breakthrough-of-the-Year Runner-Up in Science Magazine



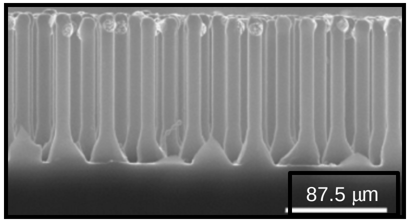


Source: J Phys Chem C (2008) 112, 955 & 6186





Source: J Am Chem Soc (2007) 129, 8988



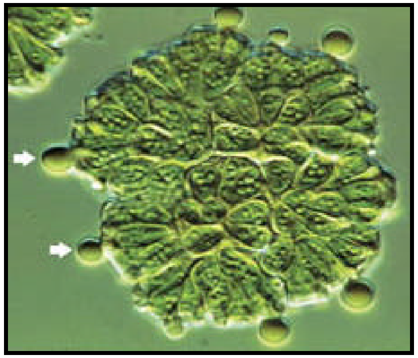
Source: J Am Chem Soc (2007) 129, 12346

($1^{st}/2^{nd}/3^{rd}$) Utilizing Nature to (4^{th}) 'Playing God'

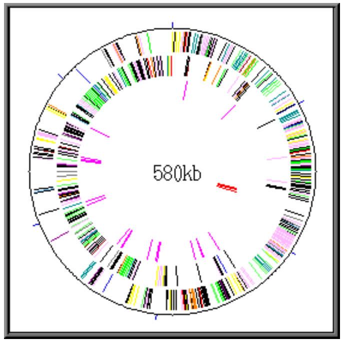
Source: Time Magazine, April 7, 2008

Sources: Science (2007) 317, 632 & Science (2008) 319, 1215

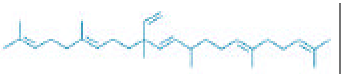
***Botryococcus braunii* algae**



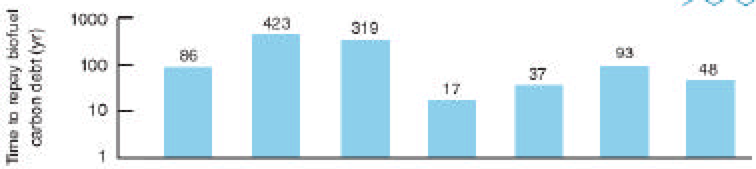
Source: Chemical and Engineering News (2008) 86, 45



***Mycoplasma genitalium* genome**

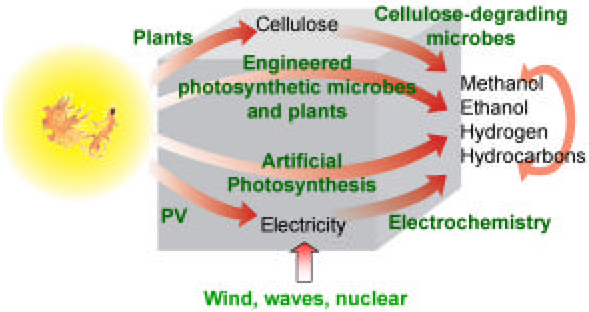


C_{30} botryococcene



Biofuel	Palm biodiesel	Palm biodiesel	Soybean biodiesel	Sugarcane ethanol	Soybean biodiesel	Corn ethanol	Corn ethanol
Former ecosystem	Tropical rainforest	Peatland rainforest	Tropical rainforest	Cerrado wooded	Cerrado grassland	Central grassland	Abandoned cropland
Location	Indonesia/ Malaysia	Indonesia/ Malaysia	Brazil	Brazil	Brazil	US	US

Sources: Science (2008) 319, 1235 & Science (2008) 319, 1238



Source: Steven Chu, Secretary of Energy, AAAS Keynote Presentation (2007)

A Carbon-Neutral Society ???

- Anthropogenic GHGs Cause **Recent** Global Warming **(≥ 90 %)**
- Every American = **114 Light Bulbs** !!!
- There is no Magic 'Silver Bullet'
  - A Mixture of Technologies, Distributed and Centralized, Seems Most Sustainable but **Wind is "Ready"** and **MHs / MOFs / Batteries** will do
  - Use of Direct Heating and Lighting from **Primary Power** is Inexpensive
  - Nuclear Fusion Reactions can Power Our Planet **(0.5 % to S-Q to Carnot)**
  - Water-Splitting Energy Storage from Intermittent Power Sources will require at least an **Olympic-sized Swimming Pool Every 2 Seconds** !!!
- The Bottom Line is, *unfortunately*, Cost and is ultimately based on:
  - Supply and Demand
  - Economics
  - Politics
  - R & D

"Keep in mind that all scenarios are thought experiments. No likelihood of the realization of any scenario can be assigned due to the important fact that policies will affect the conditions of the marketplace [especially subsidies to 'buy down' experience curves and taxes to discourage others], and ongoing R & D will provide new opportunities."

Johansson, et al., Editor of the UNDP, WEA (**2004**)

Source: Chapter 2: The Potentials of Renewable Energy. In Renewable Energy: A Global Review of Technologies, Policies and Markets, Aßmann, Laumanns, Uh (Eds.) Earthscan: London (2006)

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- Graduate Research Symposium Selection Committee
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  - Drs. Meyer (Chem/MS), Erlebacher, Searson (MS), Herman, Meneveau, Hemker (ME), Hansen (BChem)
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- The Many Influential Scientists and Politicians
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  - Drs. Gray, Nocera, Lewis, *et al.* (PP–CCI Solar)
  - Drs. Styring, Hammarström, Hagfeldt, *et al.* (SCAP)
  - Drs. Venter, Smith, Hutchinson, *et al.* (JCVI & SG)
  - Drs. Melis, Ghirardi, Seibert, *et al.* (DOE Algae)
  - Drs. Grätzel, Augustynski, O'Regan, *et al.* (TC/DSSC)
  - Chu, Browner, Holdren, *et al.* (DOE/OECCP/OSTP)

Gore & Pachauri

- Many Organizations
  DOE(BES/EERE), DOI(USGS), EIA, FAO, Greenpeace, GWEC, IEA, IPCC, NEA, NREL, NSF, PCAST, REN21, UK-DfT(UFA), UN, UNDP(MDGs/WEA), WB, WEC
- **Audience for Listening !!!**