Basic Research Needs for Solar Energy Utilization

Report of the Basic Energy Sciences Workshop on Solar Energy Utilization

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April 18-21, 2005

BES Workshop on Basic Research Needs for Solar Energy Utilization

April 21-24, 2005

Workshop Chair: Nathan Lewis, Caltech
Co-chair: George Crabtree, Argonne

Panel Chairs

Arthur Nozik, NREL: Solar Electric
Mike Wasielewski, NU: Solar Fuel
Paul Alivisatos, UC-Berkeley: Solar Thermal

Topics

Photovoltaics
Photoelectrochemistry
Bio-inspired Photochemistry
Natural Photosynthetic Systems
Photocatalytic Reactions
Bio Fuels
Heat Conversion & Utilization
Elementary Processes
Materials Synthesis
New Tools

Plenary Speakers

Pat Dehmer, DOE/BES
Nathan Lewis, Caltech
Jeff Mazer, DOE/EERE
Marty Hoffert, NYU
Tom Feist, GE

Charge

To identify basic research needs and opportunities in solar electric, fuels, thermal and related areas, with a focus on new, emerging and scientifically challenging areas that have the potential for significant impact in science and technologies.

200 participants

universities, national labs, industry
US, Europe, Asia
EERE, SC, BES

Basic Research Needs for Solar Energy

- ***The Sun is a singular solution to our future energy needs***
  - capacity dwarfs fossil, nuclear, wind . . .
  - sunlight delivers more energy in one hour than the earth uses in one year
  - free of greenhouse gases and pollutants
  - secure from geo-political constraints

- ***Enormous gap between our tiny use of solar energy and its immense potential***
  - Incremental advances in today's technology will not bridge the gap
  - Conceptual breakthroughs are needed that come only from high risk-high payoff basic research

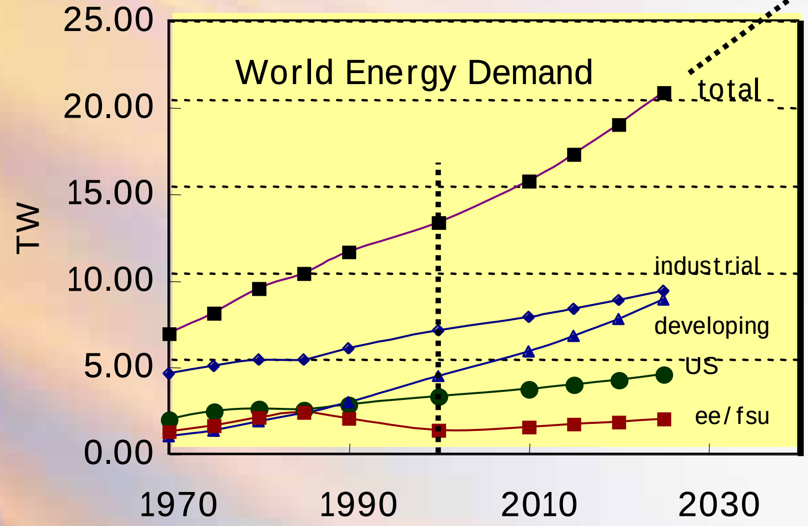
- ***Interdisciplinary research is required***

  physics, chemistry, biology, materials, nanoscience

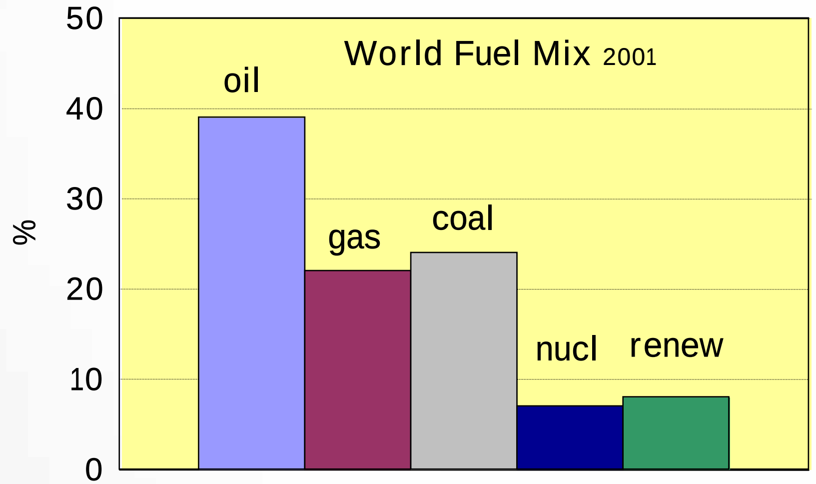
- ***Basic and applied science should couple seamlessly***

World Energy Demand

2100: 40-50 TW
2050: 25-30 TW



energy gap
~ 14 TW by 2050
~ 33 TW by 2100



85% fossil

EIA Intl Energy Outlook 2004
http://www.eia.doe.gov/oiaf/ieo/index.html

Hoffert et al Nature 395, 883,1998

The Energy Gap

- ~ 14 TW of additional power by 2050
- ~ 33 TW of additional power by 2100

2004 capacity: 13 TW

fossil energy

after oil production peaks, switch to gas and coal

capture/store 22 Gtonnes of CO_2/yr (current emissions)

- 12,500 km^3 at atmospheric pressure = volume of Lake Superior
- 600 times CO_2 injected in oil wells/yr to spur production
- 100 times the natural gas drawn in and out of geologic storage/yr to smooth demand
- 20,000 times CO_2 stored/yr in Norway's Sleipner offshore reservior
- no leaks: 1% leak rate nullifies storage in 100 yrs

nuclear energy

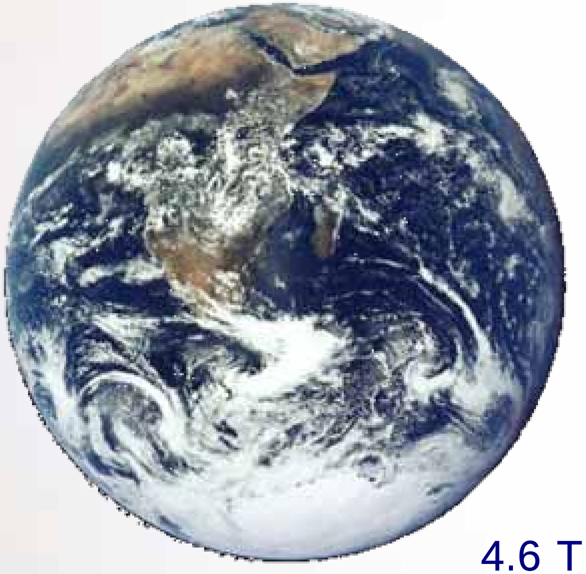
14,000 1 GW_e fission reactors - 1 new reactor/day for 38 years

Renewable Energy

Solar
1.2×10^5 TW at Earth surface
>> 600 TW practical

energy gap
~ 14 TW by 2050
~ 33 TW by 2100

Wind
2-4 TW extractable



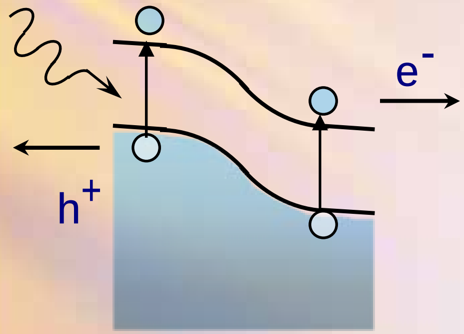
Biomass
5-7 TW gross
all cultivatable
land not used
for food

Tide/Ocean Currents
2 TW gross

Hydroelectric
4.6 TW gross
1.6 TW technically feasible
0.9 TW economically feasible
0.6 TW installed capacity

Geothermal
12 TW gross over land
small fraction recoverable

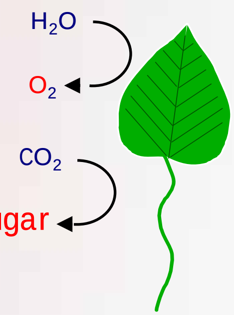
Solar Energy Utilization



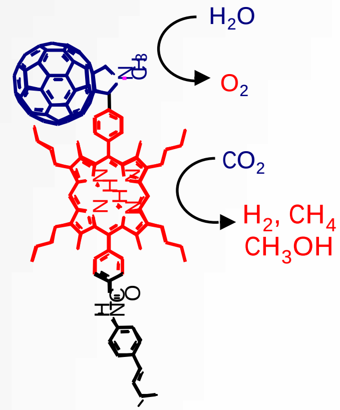
Solar Electric

.001 TW PV
$0.30/kWh w/o storage

1.5 TW electricity
$0.03-$0.06/kWh (fossil)



natural
photosynthesis

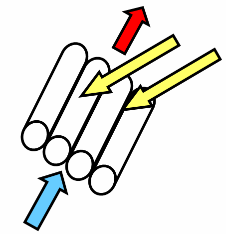


artificial
photosynthesis

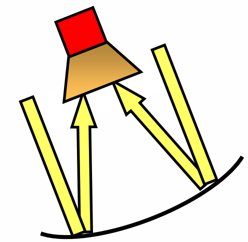
Solar Fuel

1.4 TW solar fuel (biomass)

11 TW fossil fuel
(present use)



50 - 200 °C
space, water
heating



500 - 3000 °C
heat engines
electricity generation
process heat

Solar Thermal

0.002 TW

2 TW
space and water
heating

~ 14 TW additional energy by 2050

Solar Energy Challenges

Solar electric

Solar fuels

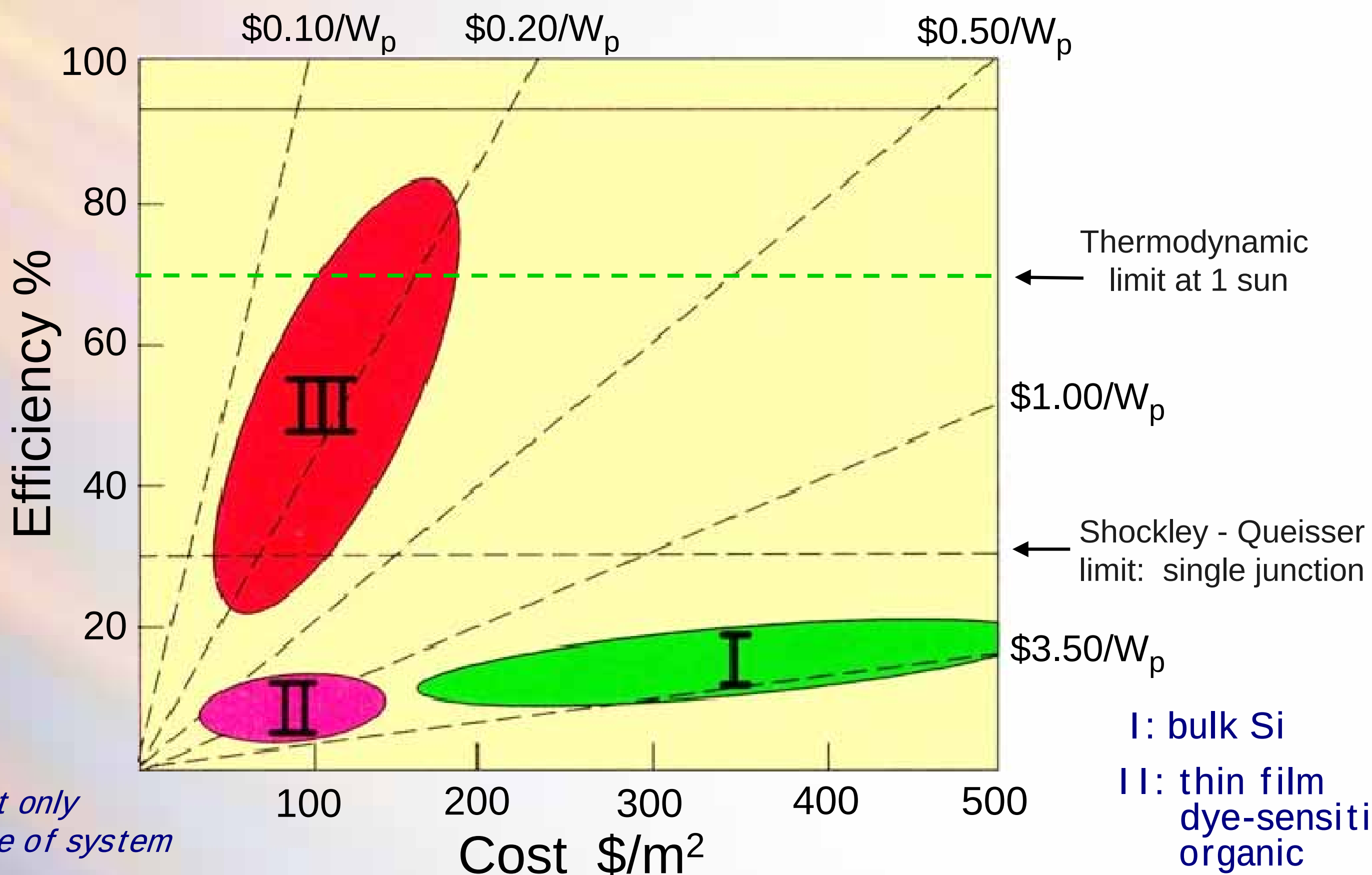
Solar thermal

Cross-cutting research

Solar Electric

- Despite 30-40% growth rate in installation, photovoltaics generate
  - *less* than 0.1% of our electricity
  - *less* than 0.01% of total energy
- Decrease *cost*/watt by a factor 10 - 20 to be competitive with fossil electricity (without storage)
- Find effective method for *storage* of photovoltaic-generated electricity

Cost of Solar Electric Power



module cost only
double for balance of system

I: bulk Si

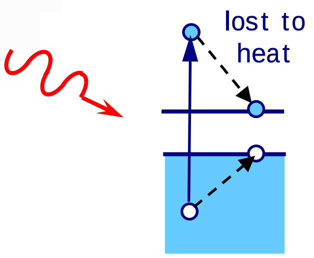
II: thin film
dye-sensitized
organic

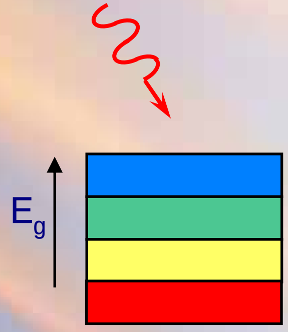
III: next generation

competitive electric power: \$0.40/W_p = \$0.02/kWh
competitive primary power: \$0.20/W_p = \$0.01/kWh
assuming no cost for storage

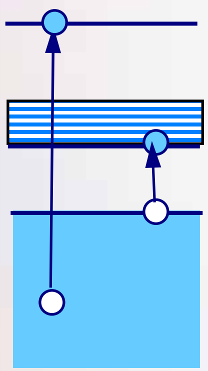
Revolutionary Photovoltaics: 50% Efficient Solar Cells

present technology: 32% limit for
- single junction
- one exciton per photon
- relaxation to band edge

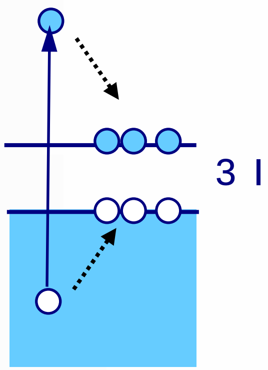




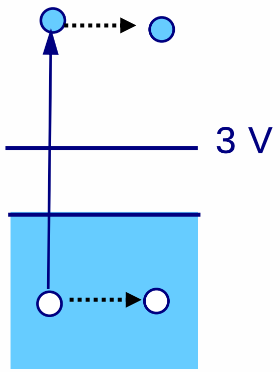
multiple junctions



multiple gaps



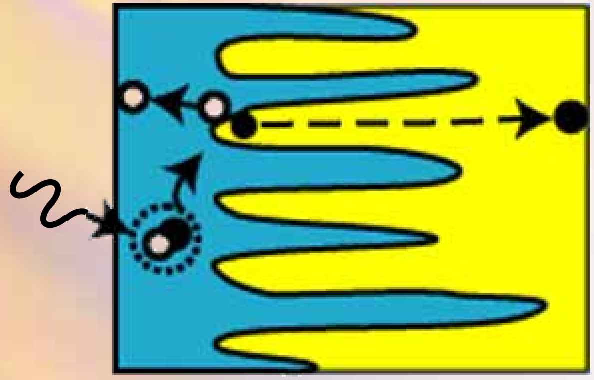
multiple excitons per photon



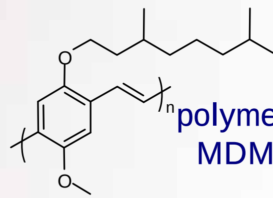
hot carriers

rich variety of new physical phenomena
understand and implement

Organic Photovoltaics: Plastic Photocells

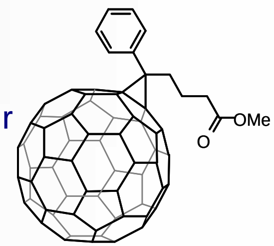


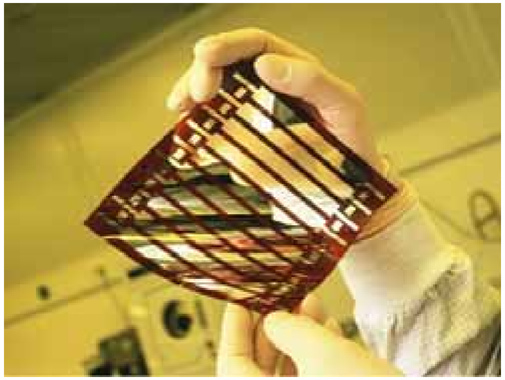
donor-acceptor junction



polymer donor
MDMO-PPV

fullerene acceptor
PCBM

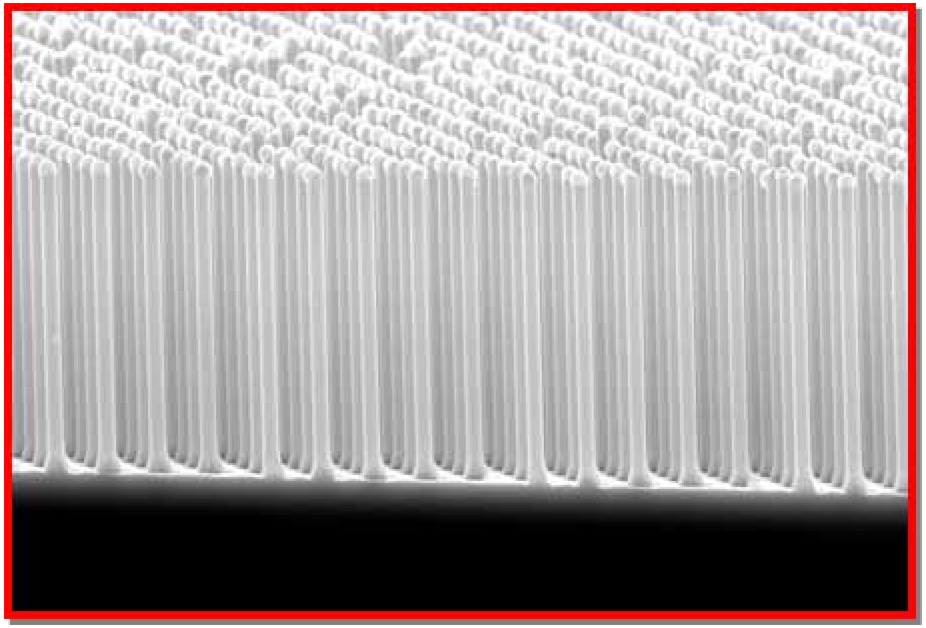


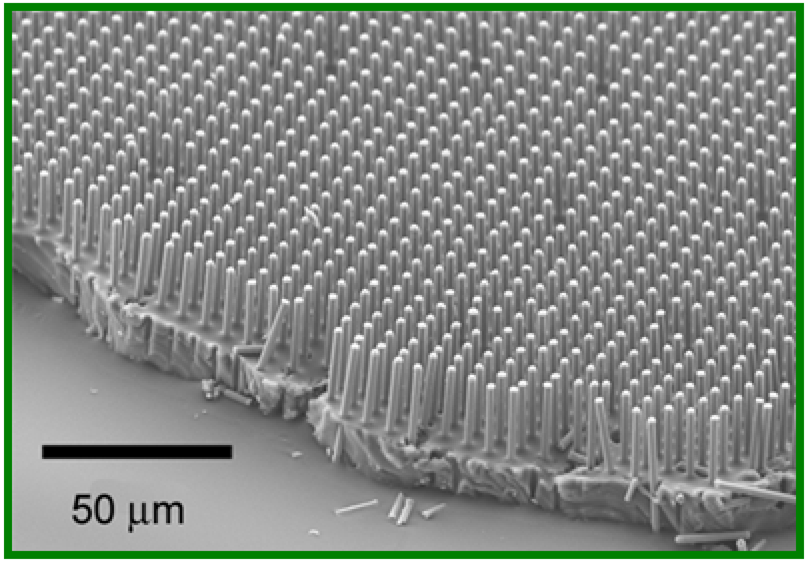


opportunities
inexpensive materials, conformal coating, self-assembling fabrication, wide choice of molecular structures, “cheap solar paint”

challenges
low efficiency (2-5%), high defect density, low mobility, full absorption spectrum, nanostructured architecture

Large Area Si Rod Arrays





- Large area arrays (> 1 cm^2) transferred in one piece.

Solar Energy Challenges

Solar electric

Solar fuels

Solar thermal

Cross-cutting research

Solar Fuels: Solving the Storage Problem

- Biomass inefficient: too much land area.
  Increase efficiency 5 - 10 times
- Designer plants and bacteria for designer fuels:
  H_2, CH_4, methanol and ethanol
- Develop artificial photosynthesis

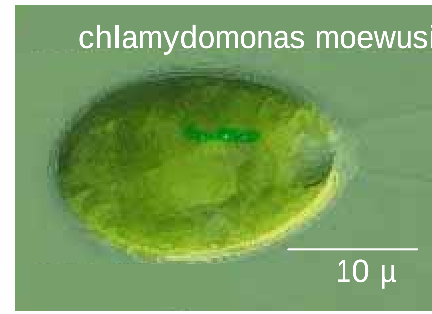
Leveraging Photosynthesis for Efficient Energy Production

- photosynthesis converts ~ 100 TW of sunlight to sugars: nature's fuel
- low efficiency (< 1%) requires too much land area

switchgrass

Modify the biochemistry of plants and bacteria

- improve efficiency by a factor of 5–10
- produce a convenient fuel methanol, ethanol, H_2, CH_4

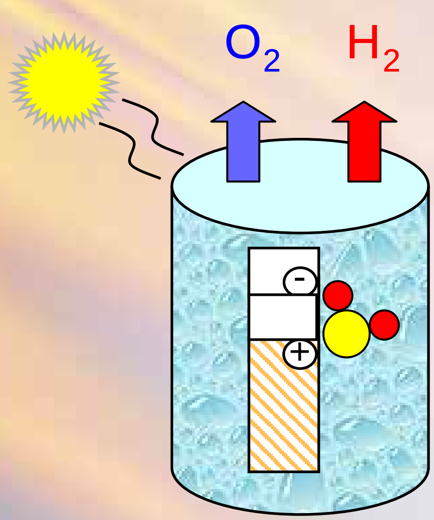


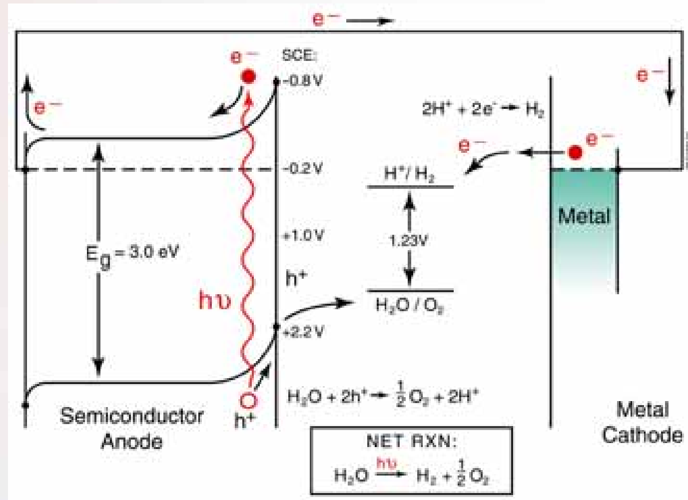
hydrogenase
$2H^+ + 2e^- \Leftrightarrow H_2$

Scientific Challenges

- understand and modify genetically controlled biochemistry that limits growth
- elucidate plant cell wall structure and its efficient conversion to ethanol or other fuels
- capture high efficiency early steps of photosynthesis to produce fuels like ethanol and H_2
- modify bacteria to more efficiently produce fuels
- improved catalysts for biofuels production

Efficient Solar Water Splitting





demonstrated efficiencies 10-18% in laboratory

Scientific Challenges

- cheap materials that are robust in water
- catalysts for the redox reactions at each electrode
- nanoscale architecture for electron excitation $\Rightarrow$ transfer $\Rightarrow$ reaction

Nanorod-based Membrane Offers Several Advantages

Tandem junction system

Increased light absorption

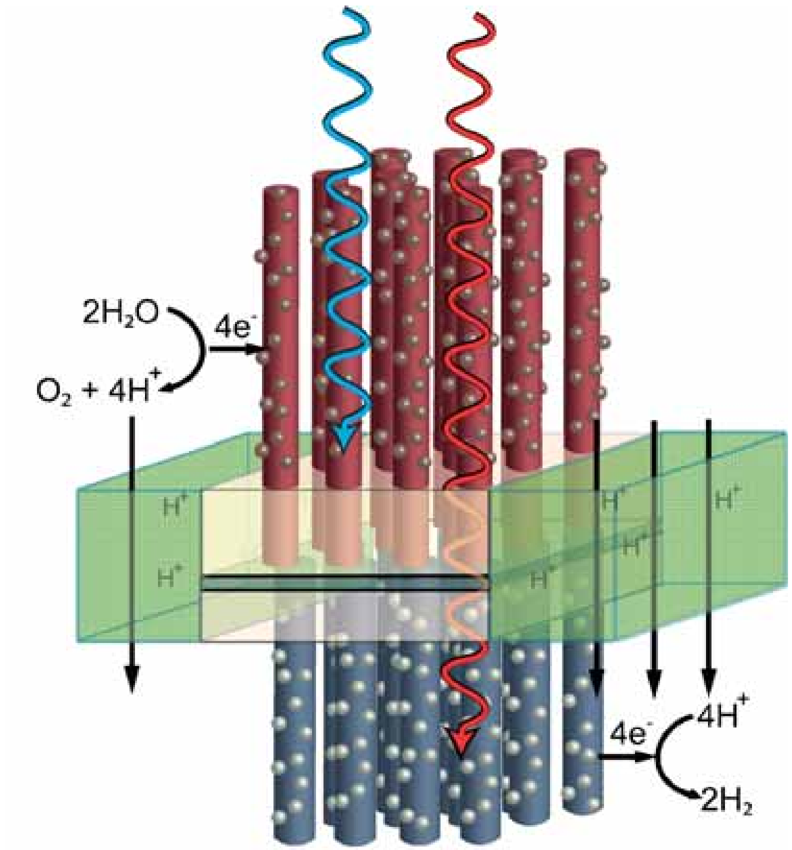
Nanorod geometry orthogonalizes directions of light absorption and carrier collection

Long nanorods can absorb all incident light

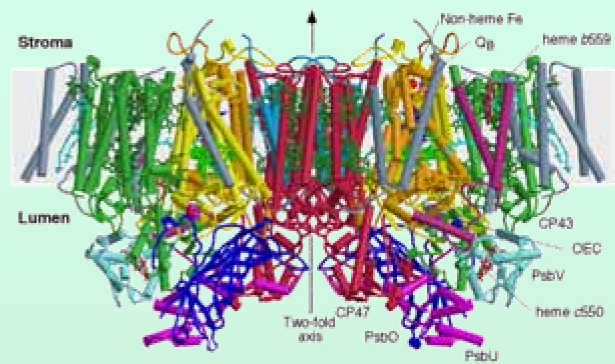
Carriers need only travel radially to the nanorod sidewalls to be separated and collected

Greater flexibility in materials selection

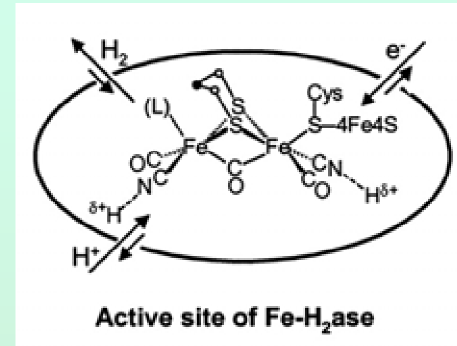
Potential candidates: WO_3 and Si



Solar-Powered Catalysts for Fuel Formation



photosystem II



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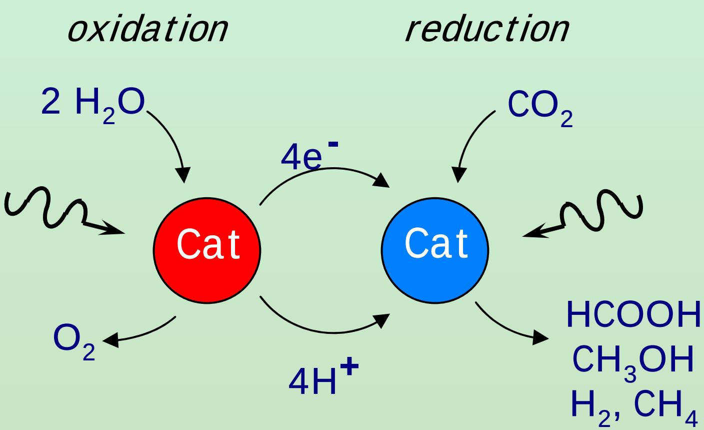
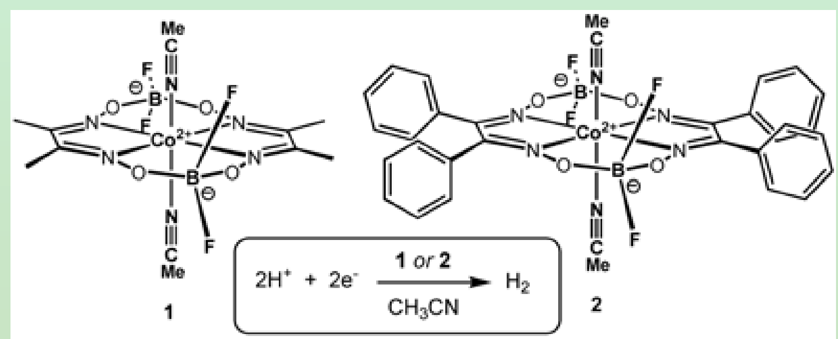




Solar Energy Challenges

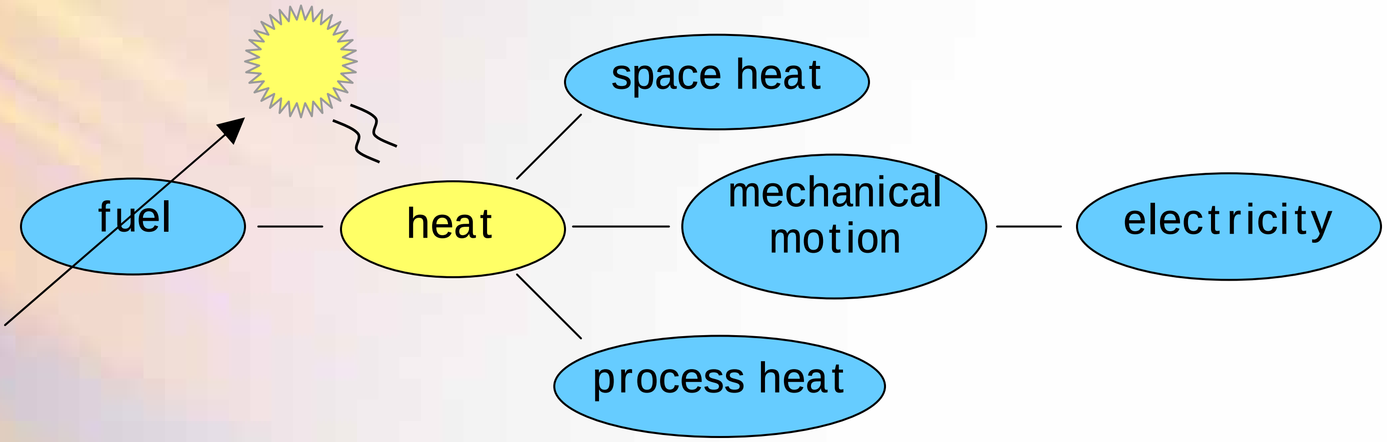
Solar electric

Solar fuels

Solar thermal

Cross-cutting research

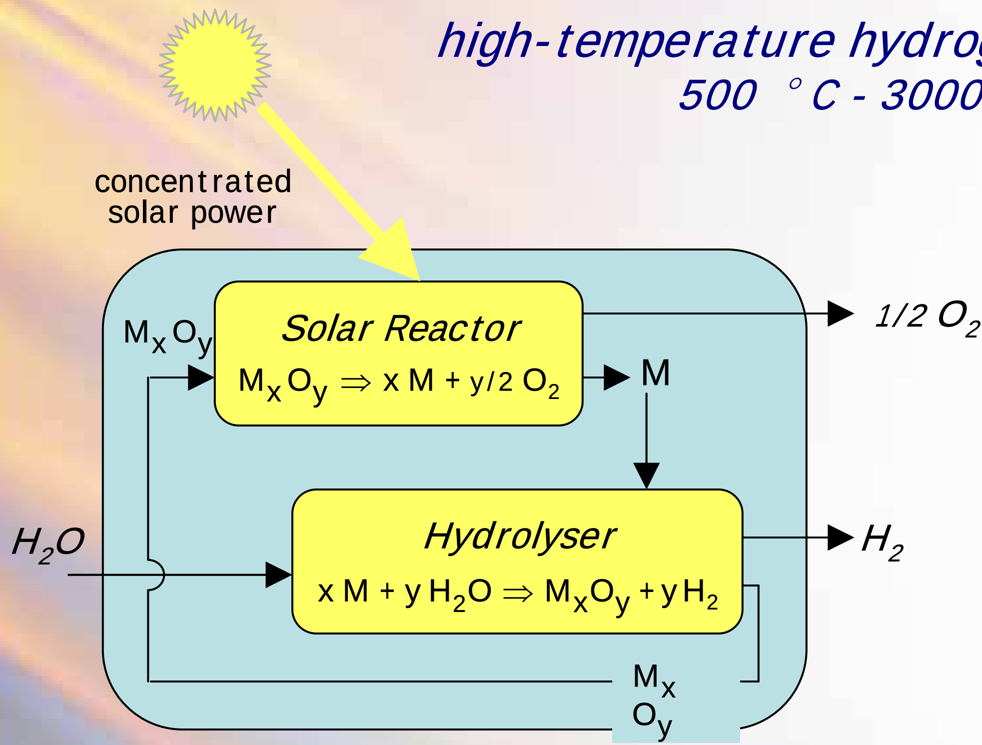
Solar Thermal

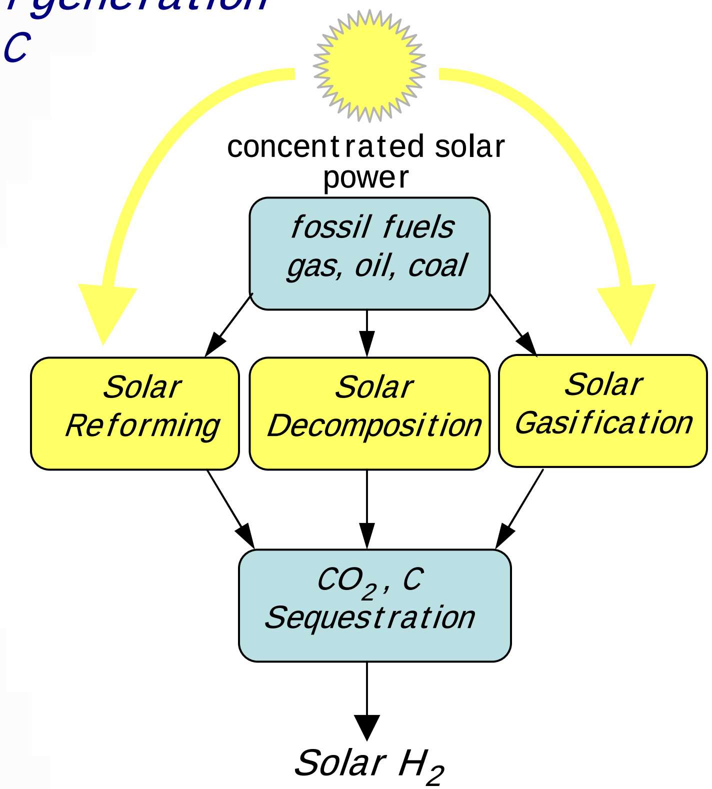


- heat is the first link in our existing energy networks
- solar heat replaces combustion heat from fossil fuels
- solar steam turbines currently produce the lowest cost solar electricity
- challenges:
  new uses for solar heat
  store solar heat for later distribution

Solar Thermochemical Fuel Production

high-temperature hydrogen generation
500 °C - 3000 °C





Scientific Challenges

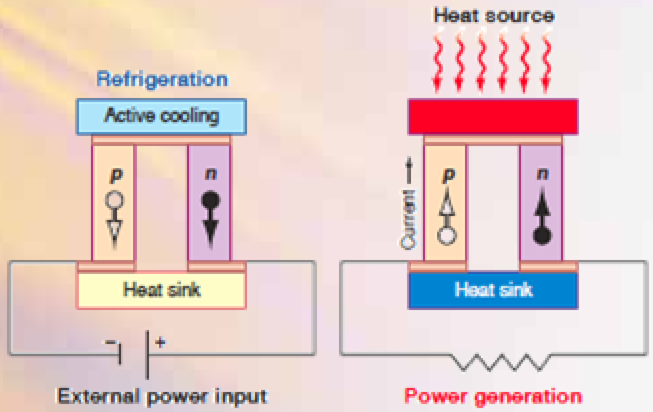
high temperature reaction kinetics of

- metal oxide decomposition
- fossil fuel chemistry

robust chemical reactor designs and materials

A. Streinfeld, Solar Energy, 78,603 (2005)

Thermoelectric Conversion

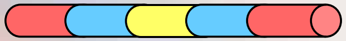


thermal gradient ⇔ electricity

figure of merit: ZT ~ (σ / κ) T

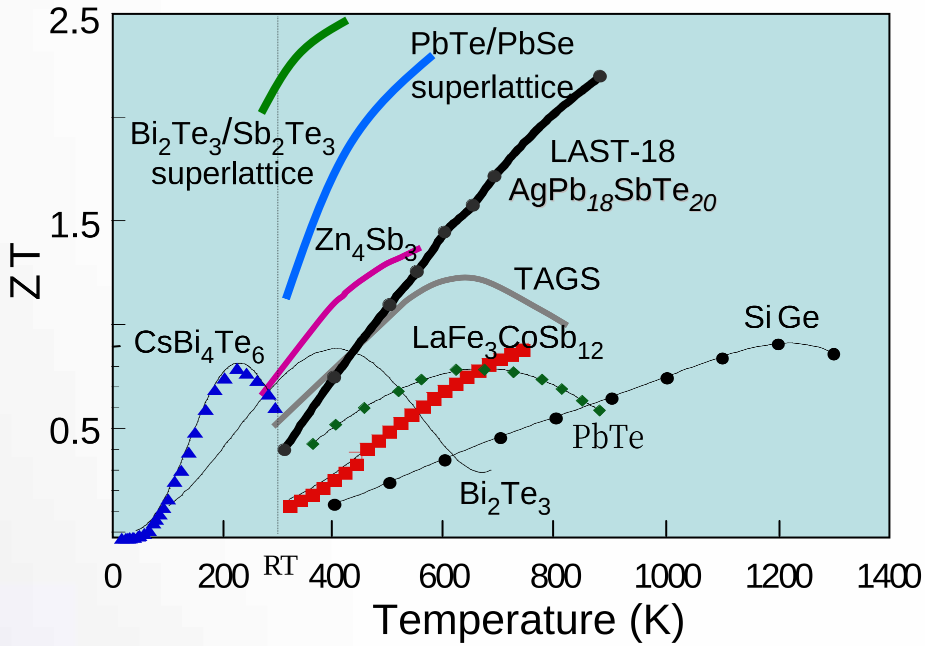
ZT ~ 3: efficiency ~ heat engines
no moving parts

Scientific Challenges
increase electrical conductivity
decrease thermal conductivity



nanowire superlattice

nanoscale architectures
interfaces block heat transport
confinement tunes density of states
doping adjusts Fermi level



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Solar Energy Challenges

Solar electric

Solar fuels

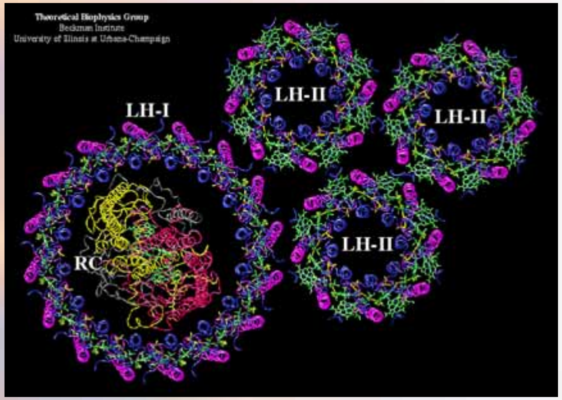
Solar thermal

Cross-cutting research

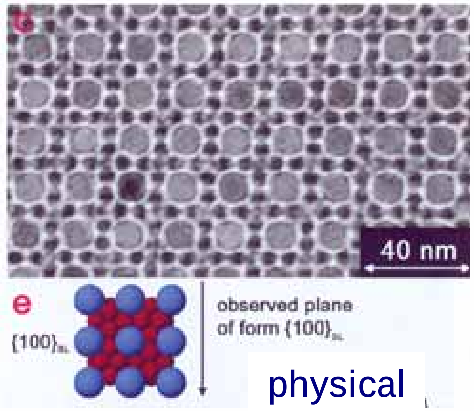
Molecular Self-Assembly at All Length Scales

The major cost of solar energy conversion is materials fabrication

Self-assembly is a route to cheap, efficient, functional production



biological



physical

Scientific Challenges

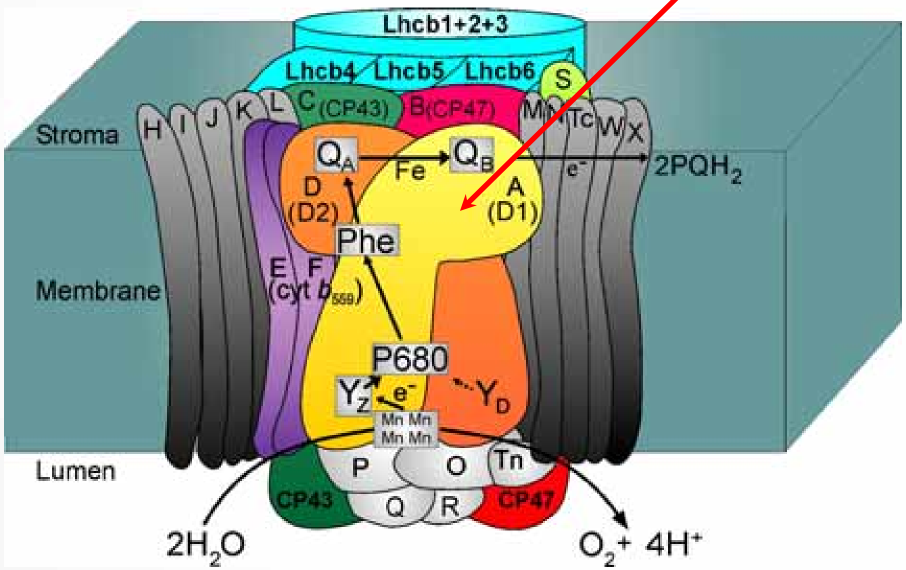
- innovative architectures for coupling light-harvesting, redox, and catalytic components
- understanding electronic and molecular interactions responsible for self-assembly
- understanding the reactivity of hybrid molecular materials on many length scales

Defect Tolerance and Self-repair

- Understand defect formation in photovoltaic materials and self-repair mechanisms in photosynthesis

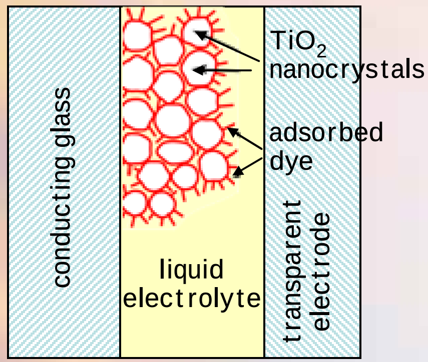
- Achieve defect tolerance and active self-repair in solar energy conversion devices, enabling 20–30 year operation

the water splitting protein in Photosystem II is replaced every hour!

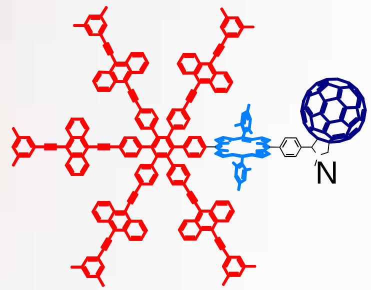


Nanoscience

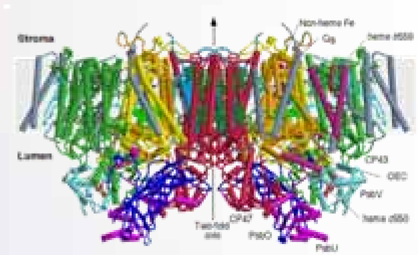
manipulation of photons, electrons, and molecules



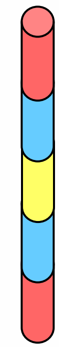
quantum dot solar cells



artificial photosynthesis



natural photosynthesis



nanostructured thermoelectrics

nanoscale architectures
top down lithography
bottom up self-assembly
multi-scale integration

characterization
scanning probes
electrons, neutrons, x-rays
smaller length and time scales

theory and modeling
multi-node computer clusters
density functional theory
10 000 atom assemblies

Solar energy is interdisciplinary nanoscience

Perspective

The Energy Challenge

~ 14 TW by 2050

~ 33 TW by 2100

13 TW in 2004

Solar Potential

125,000 TW at earth's surface

at least 600 TW practical

Breakthrough basic research needed

Solar energy is a young science

- spurred by 1970s energy crises
- fossil energy science spurred by industrial revolution - 1750s

solar energy horizon is distant and unexplored

Preview

Grand energy challenge

- double demand by 2050, triple demand by 2100

Sunlight is a singular energy resource

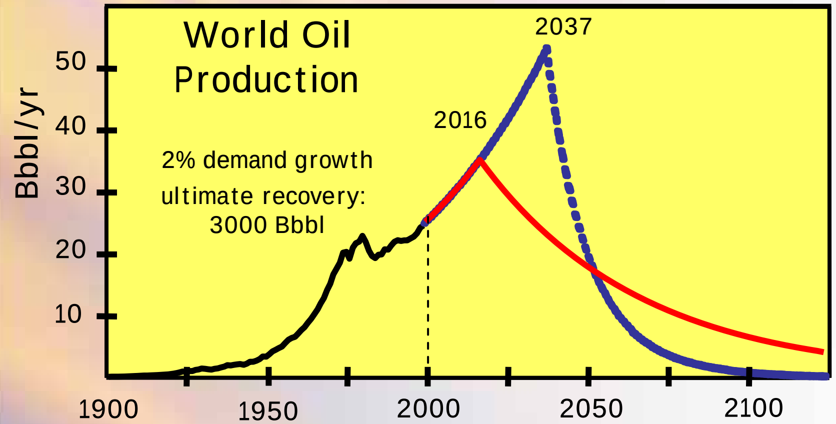
- capacity, environmental impact, geo-political security

Breakthrough research directions for mature solar energy

- solar electric
- solar fuels
- solar thermal

Fossil: Supply and Security

When Will Production Peak?



EIA: http://tonto.eia.doe.gov/FTPROOT/presentations/long_term_supply/index.htm

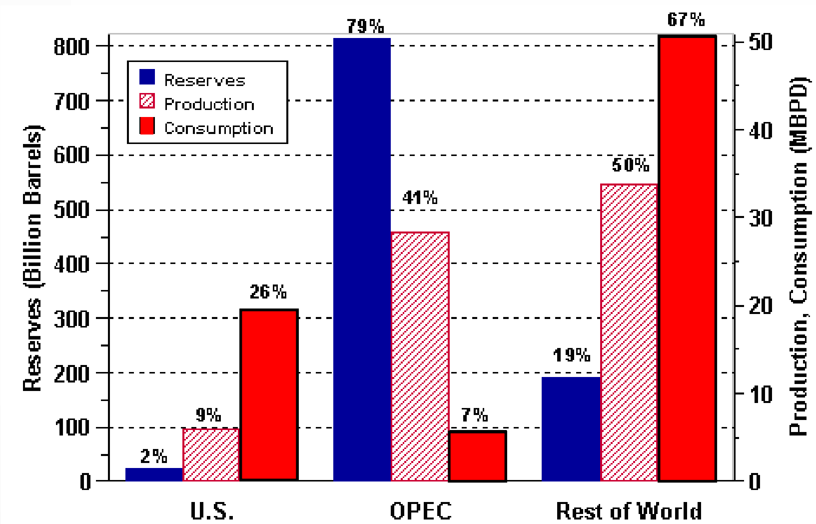
gas: beyond oil
coal: > 200 yrs

production peak
demand exceeds supply
price increases
geo-political restrictions

World Oil Reserves/Consumption
2001

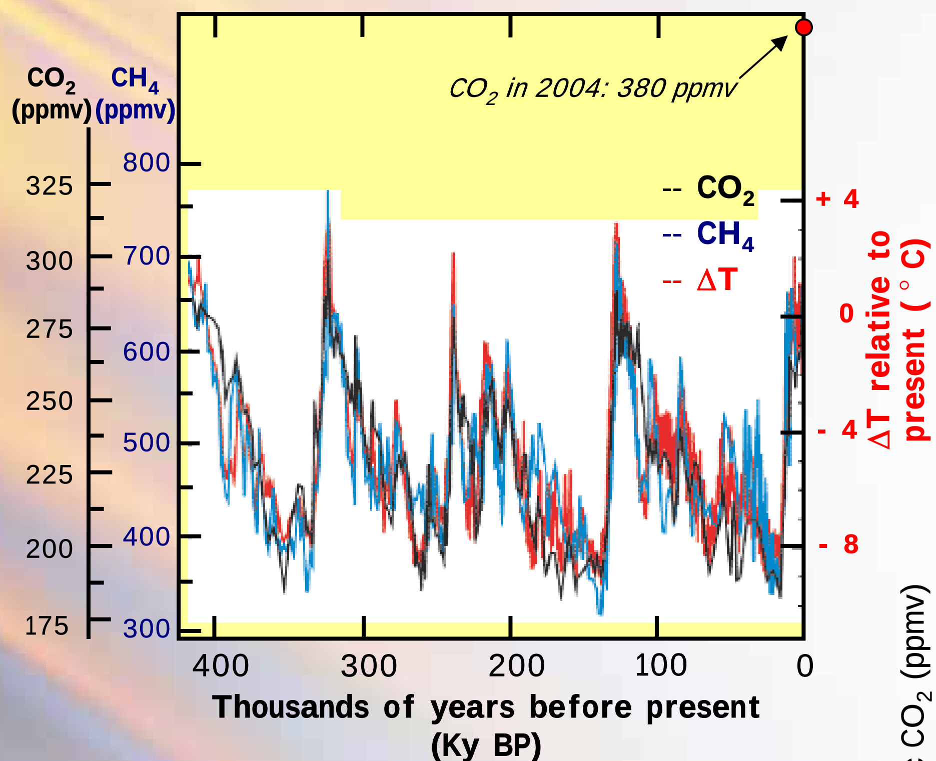
unequal supply ⇒ insecure access

http://www.eere.energy.gov/vehiclesandfuels/facts/2004/fcvt_fotw336.shtml



OPEC: Venezuela, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, United Arab Emirates, Algeria, Libya, Nigeria, and Indonesia

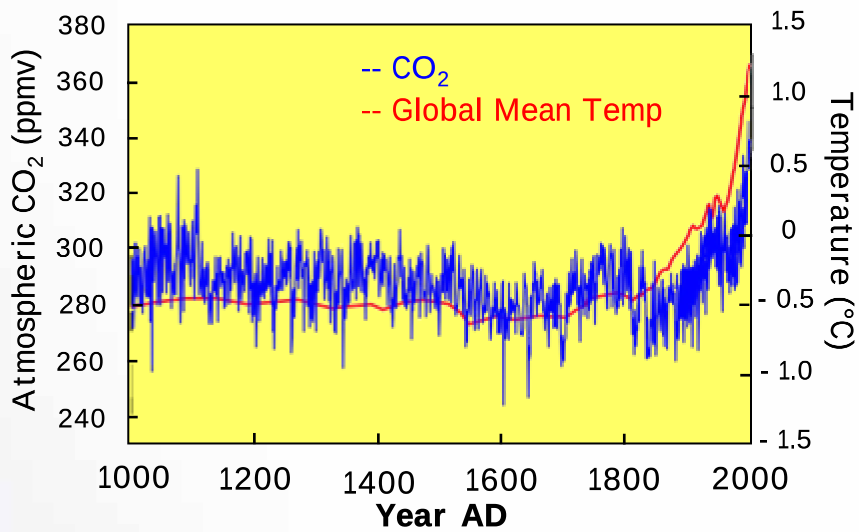
Fossil: Climate Change



Climate Change 2001: The Scientific Basis, Fig 2.22

Relaxation time

transport of CO_2 or heat to deep ocean: 400 - >3000 years

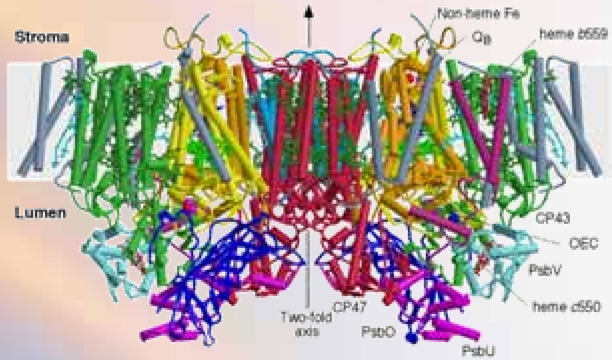


Intergovernmental Panel on Climate Change, 2001
http://www.ipcc.ch

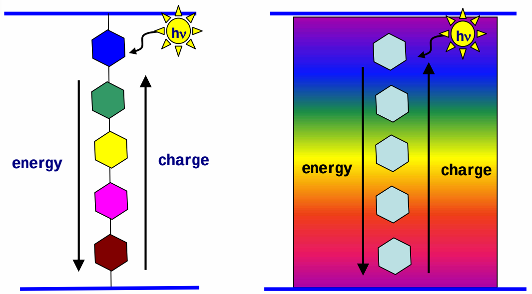
*N. Oreskes, Science **306**, 1686, 2004*
*D. A. Stainforth et al, Nature **433**, 403, 2005*

Smart Matrices for Solar Fuel Production

- Biology: protein structures dynamically control energy and charge flow
- Smart matrices: adapt biological paradigm to artificial systems



photosystem II



smart matrices carry energy and charge

Scientific Challenges

- engineer tailored active environments with bio-inspired components
- novel experiments to characterize the coupling among matrix, charge, and energy
- multi-scale theory of charge and energy transfer by molecular assemblies
- design electronic and structural pathways for efficient formation of solar fuels