

Basic Research Needs for Solar Energy Utilization

*Report of the Basic Energy Sciences Workshop on Solar Energy
Utilization*

Nathan S. Lewis

*Division of Chemistry and Chemical
Engineering*

*California Institute of Technology
Pasadena, CA 91125*

with

George Crabtree, Argonne

Arthur Nozik, NREL

Mike Wasielewski, NU

Paul Alivisatos, UC-Berkeley

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

200 participants

universities, national labs, industry

US, Europe, Asia

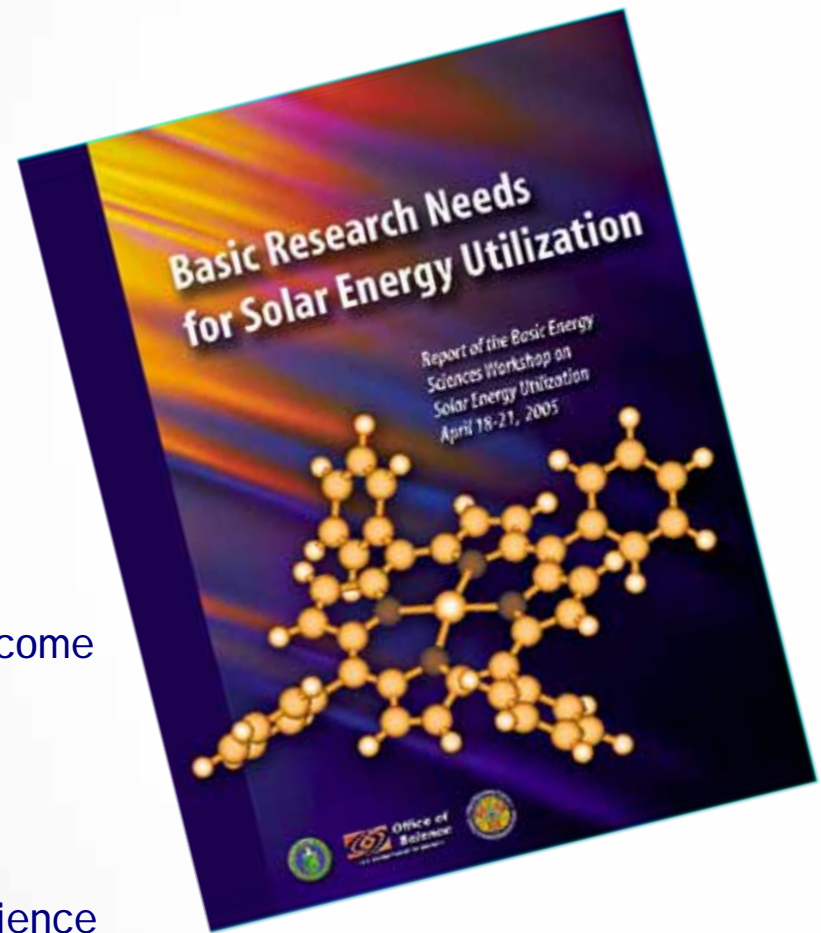
EERE, SC, BES

Charge

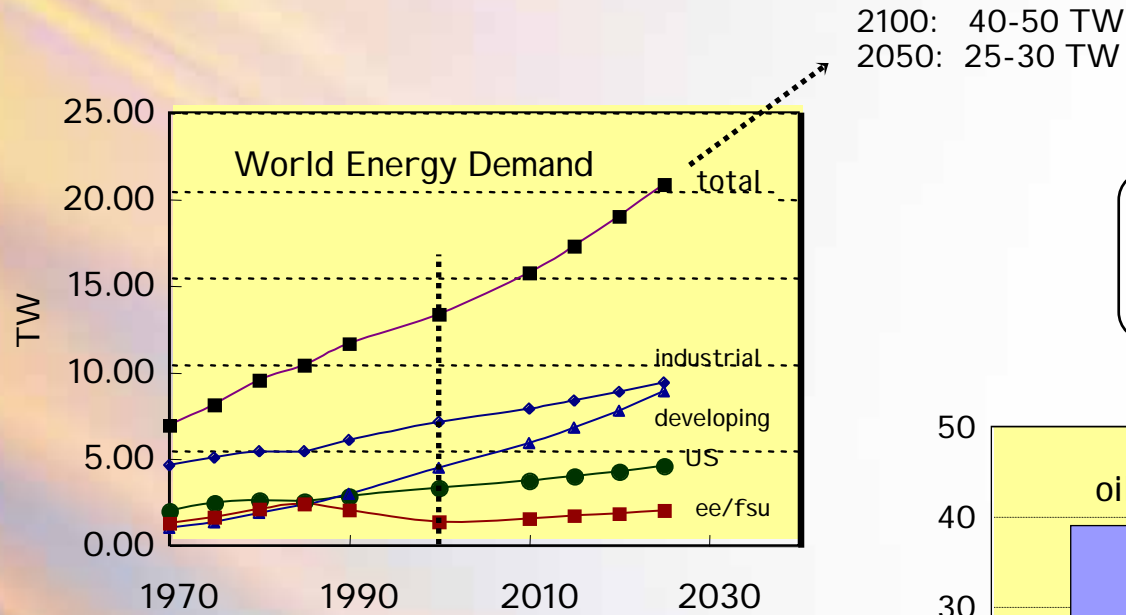
To identify basic research needs and opportunities in solar electric, fuels, thermal and related areas, with a focus on new, emerging and scientifically challenging areas that have the potential for significant impact in science and technologies.

Basic Research Needs for Solar Energy

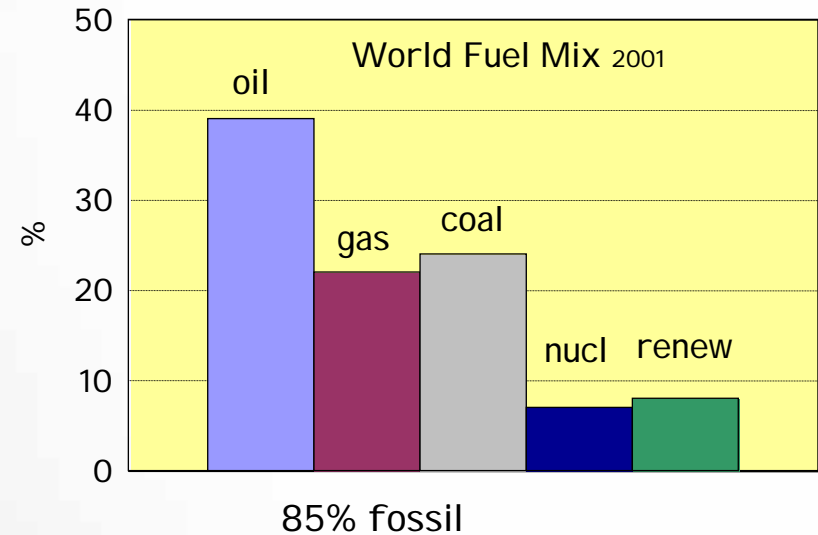
- ***The Sun is a singular solution to our future energy needs***
 - capacity dwarfs fossil, nuclear, wind . . .
 - sunlight delivers more energy in one hour than the earth uses in one year
 - free of greenhouse gases and pollutants
 - secure from geo-political constraints
- ***Enormous gap between our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



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



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 CO₂/yr (current emissions)

- 12,500 km³ at atmospheric pressure = volume of Lake Superior
- 600 times CO₂ 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 CO₂ stored/yr in Norway's Sleipner offshore reservoir
- 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



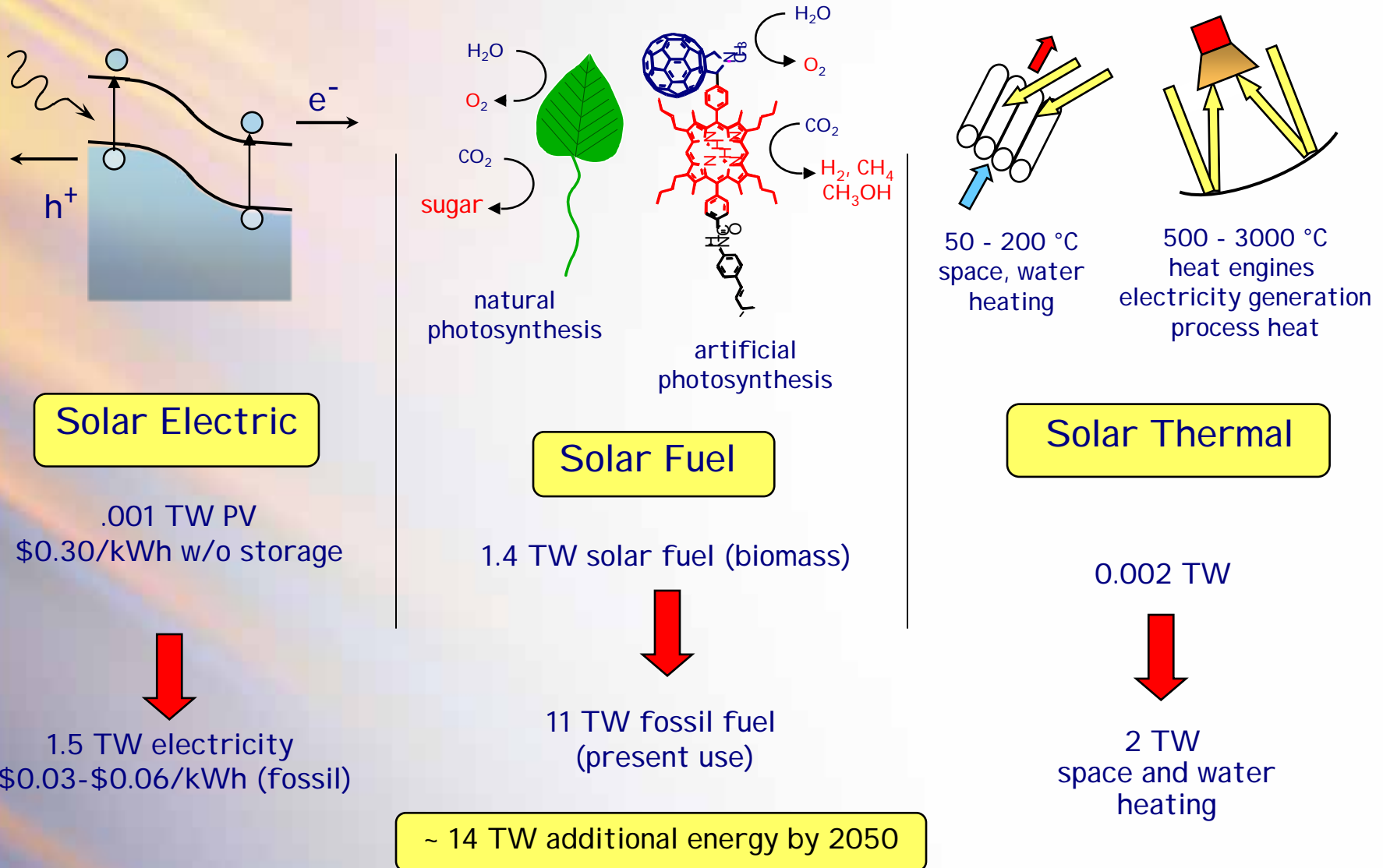
Hydroelectric

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

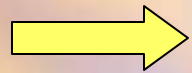
Geothermal

12 TW gross over land
small fraction recoverable

Solar Energy Utilization



Solar Energy Challenges



Solar electric

Solar fuels

Solar thermal

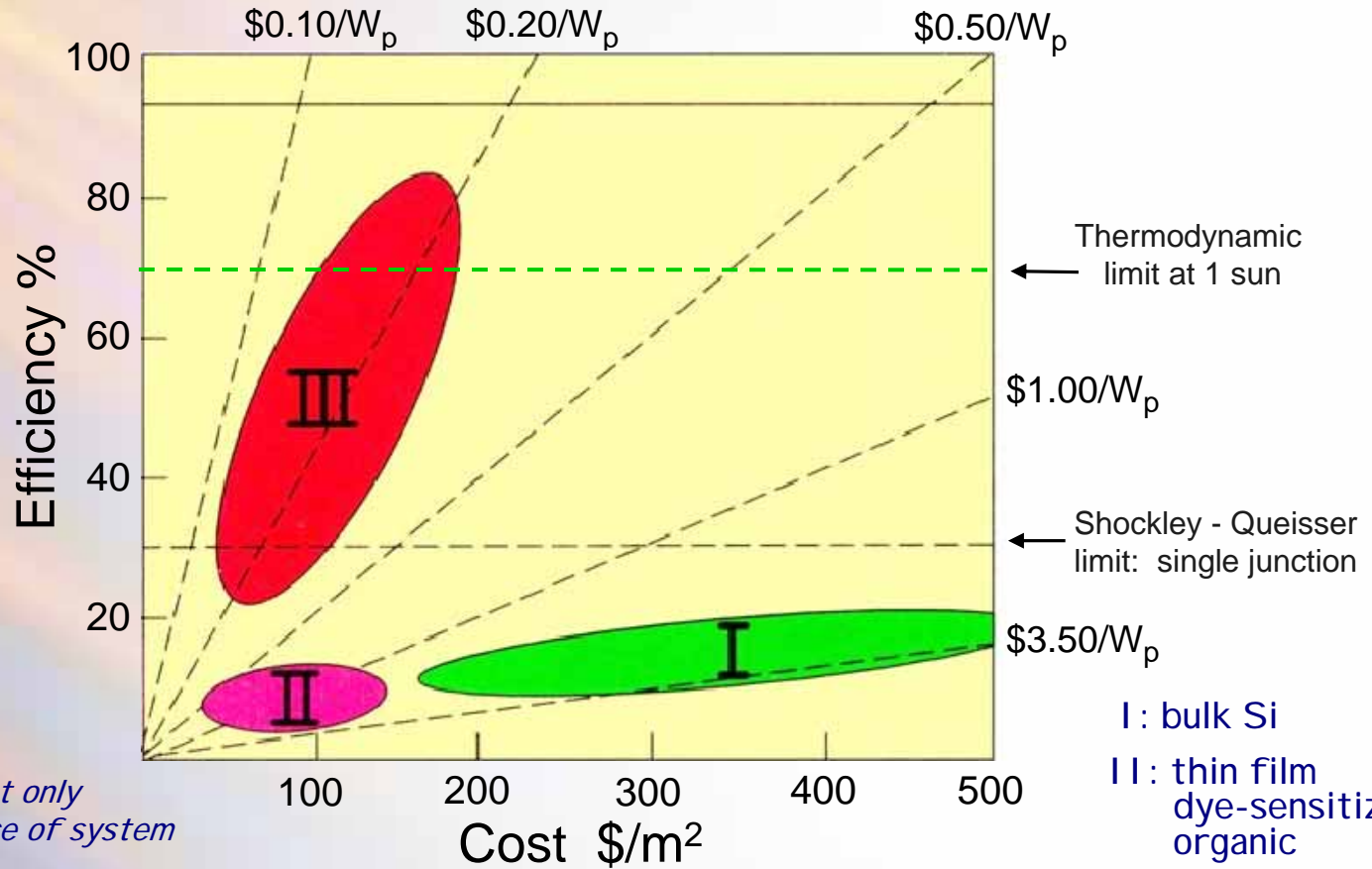
Cross-cutting research



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*

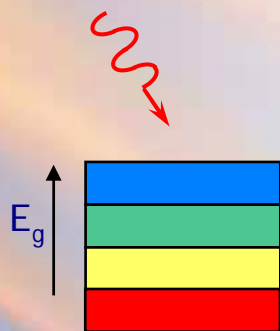
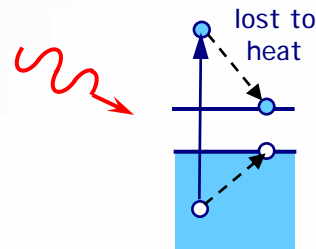
competitive electric power: $\$0.40/W_p = \$0.02/kWh$
 competitive primary power: $\$0.20/W_p = \$0.01/kWh$
assuming no cost for storage

- I : bulk Si
- II : thin film dye-sensitized organic
- III : next generation

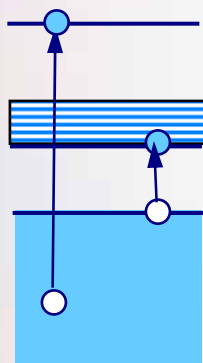
Revolutionary Photovoltaics: 50% Efficient Solar Cells

present technology: 32% limit for

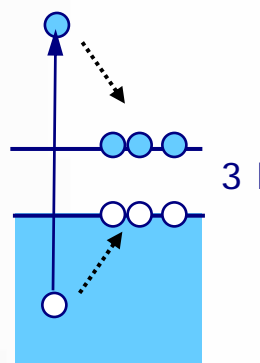
- single junction
- one exciton per photon
- relaxation to band edge



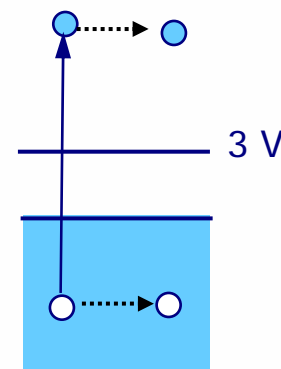
multiple junctions



multiple gaps



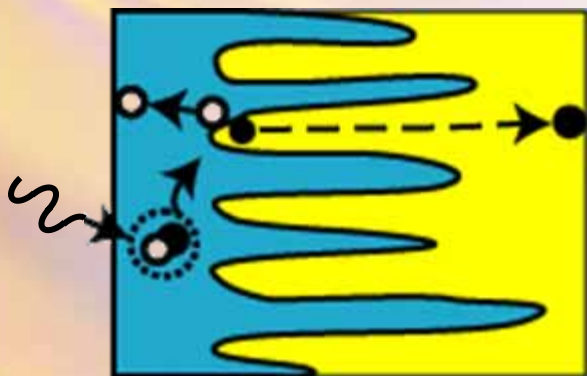
multiple excitons
per photon



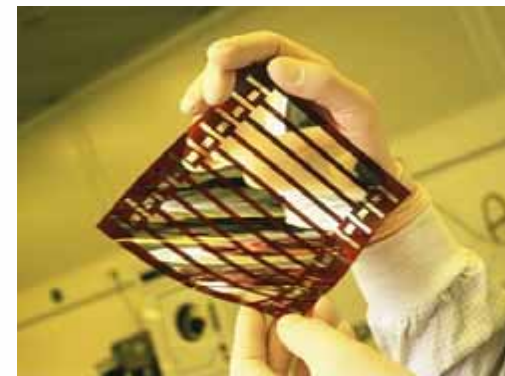
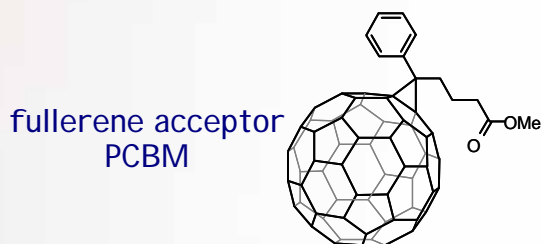
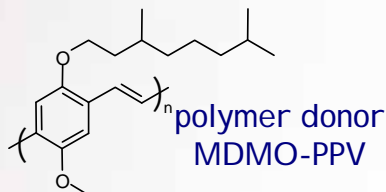
hot carriers

rich variety of new physical phenomena
understand and implement

Organic Photovoltaics: Plastic Photocells



donor-acceptor junction



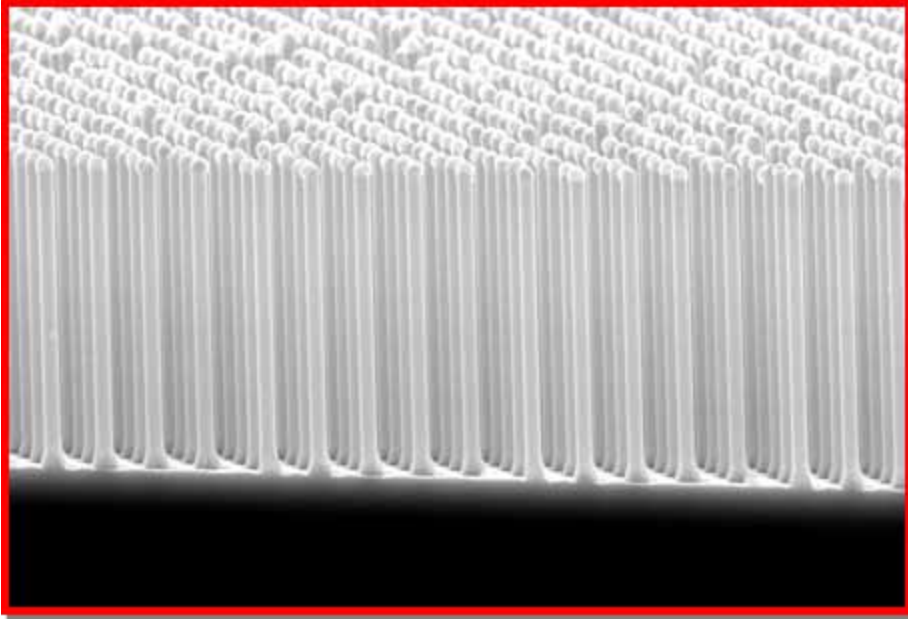
opportunities

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

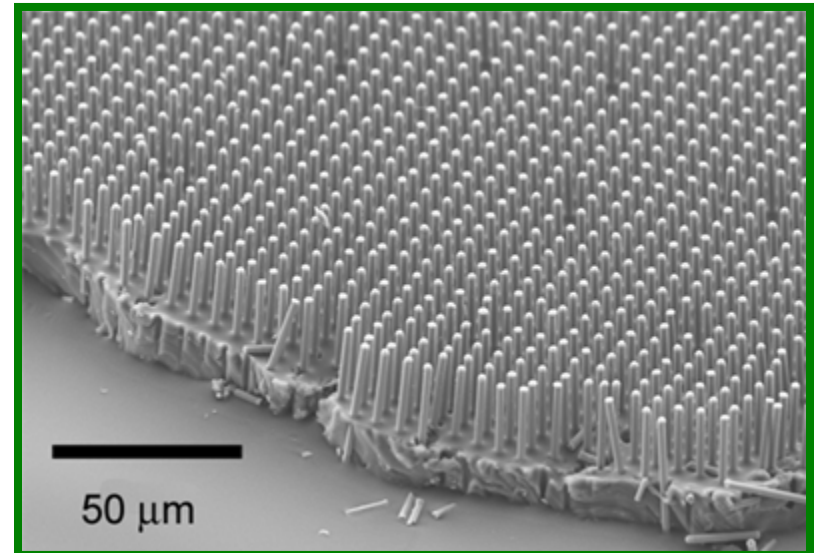
challenges

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

Large Area Si Rod Arrays



- Large area arrays ($> 1 \text{ cm}^2$) 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:
H₂, CH₄, 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, H₂, CH₄

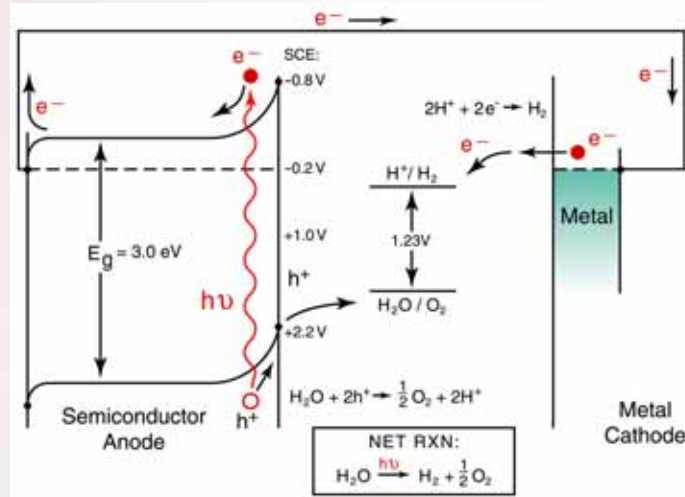
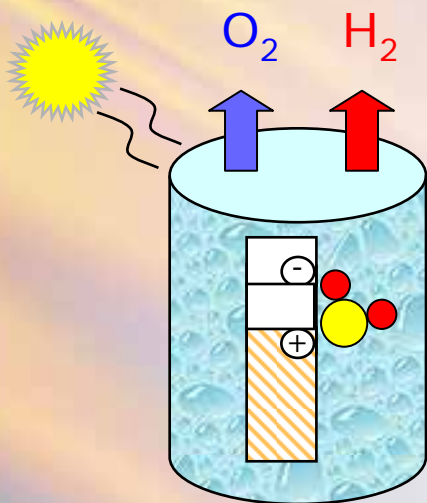


hydrogenase
 $2\text{H}^+ + 2\text{e}^- \rightleftharpoons \text{H}_2$

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 H₂
- 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

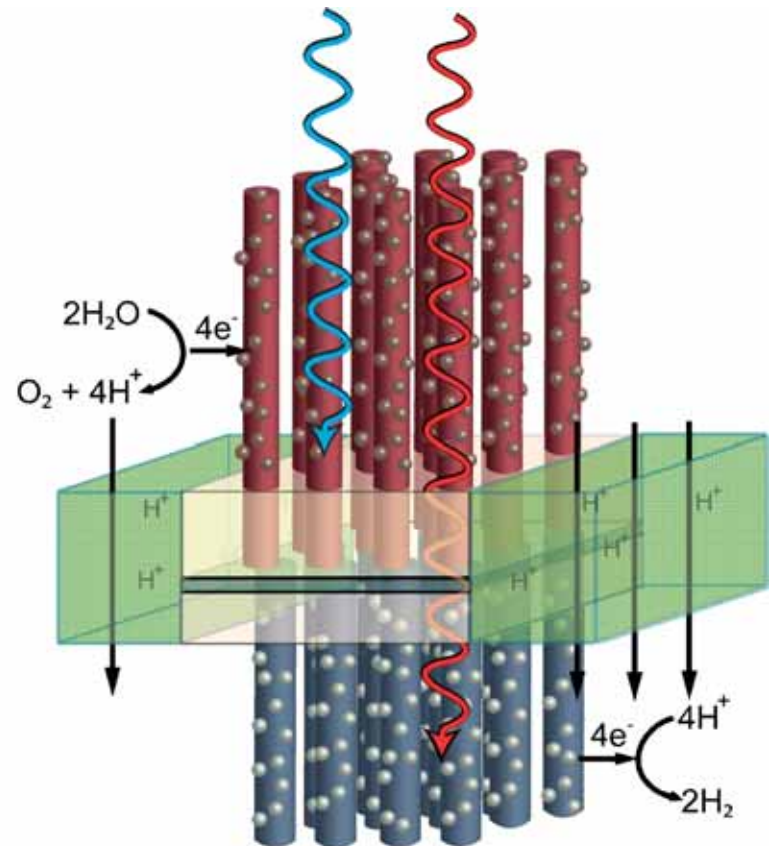
Increased light absorption

Nanorod geometry orthogonalizes directions of light absorption and carrier collection

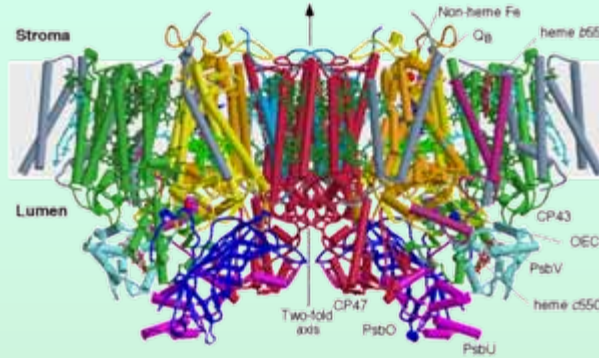
Long nanorods can absorb all incident light

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

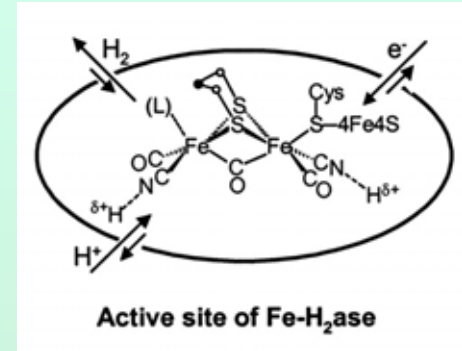
Greater flexibility in materials selection
Potential candidates: WO_3 and Si



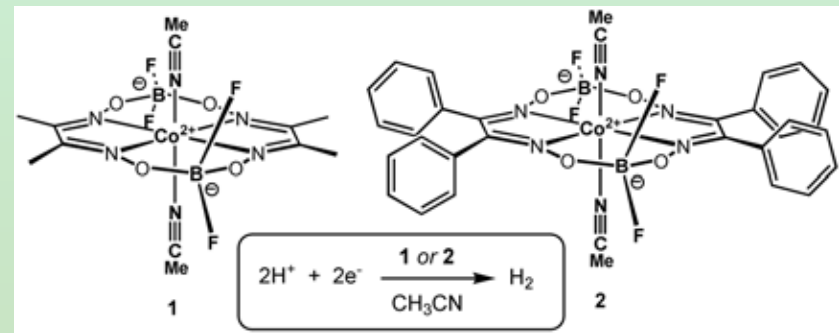
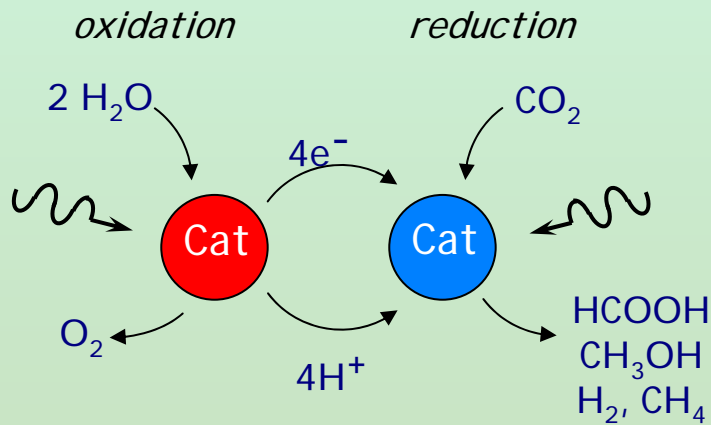
Solar-Powered Catalysts for Fuel Formation



photosystem II



hydrogenase
 $2\text{H}^+ + 2\text{e}^- \rightleftharpoons \text{H}_2$



Solar Energy Challenges

Solar electric

Solar fuels

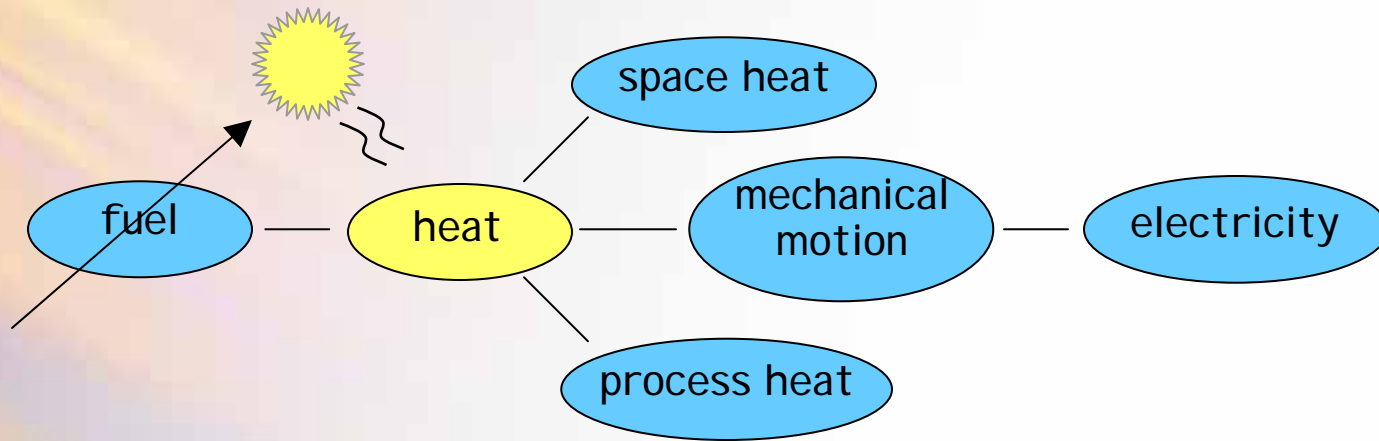


Solar thermal

Cross-cutting research



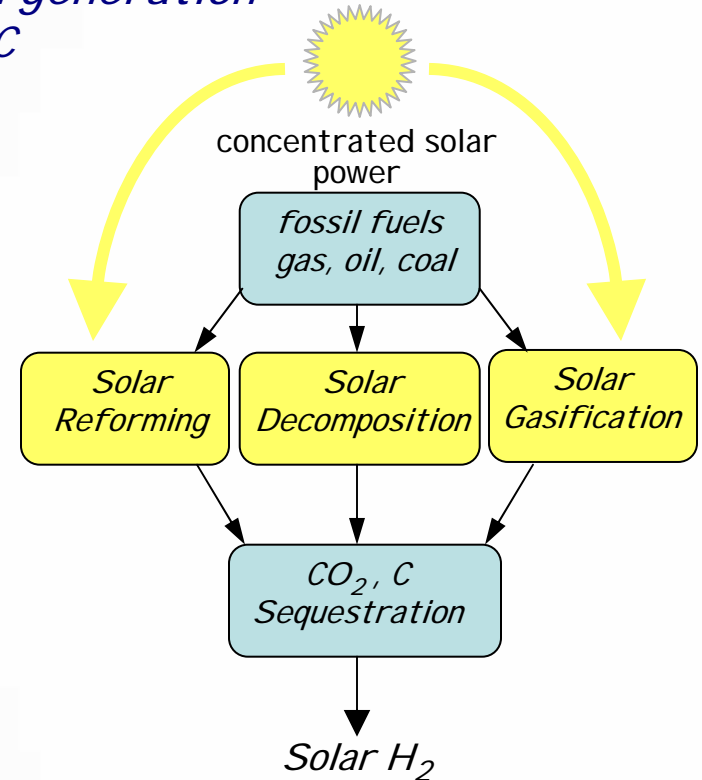
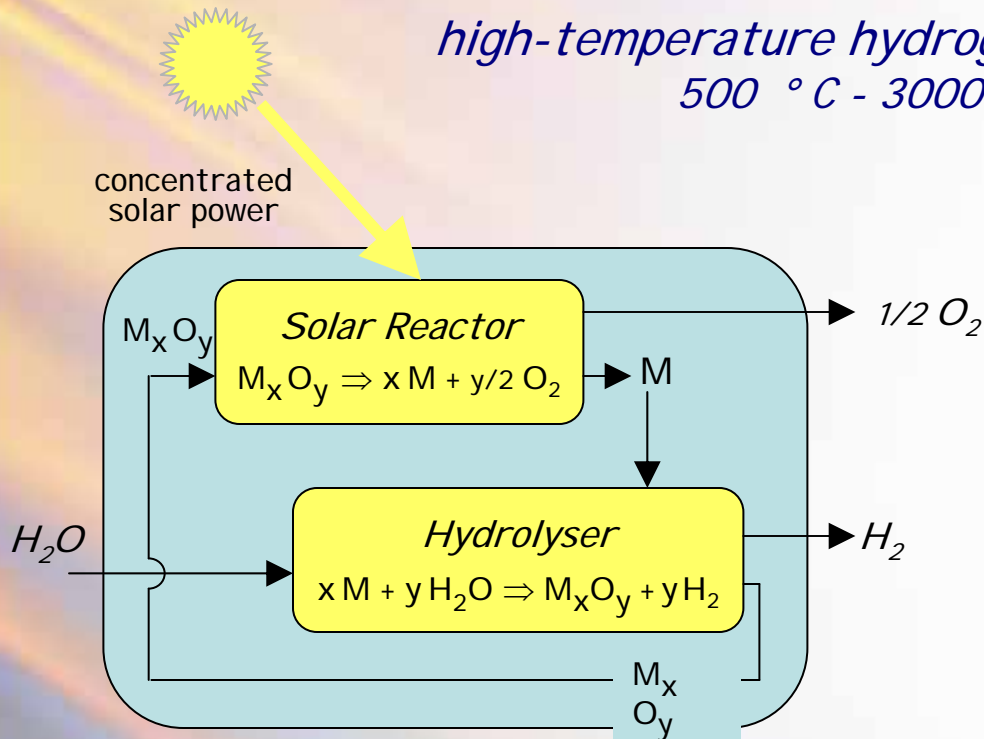
Solar Thermal



- 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

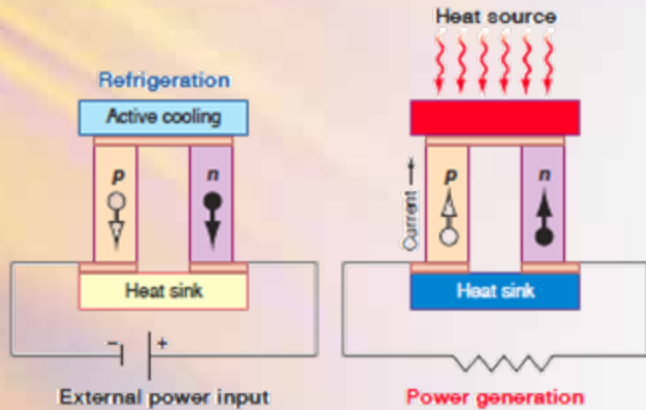


Scientific Challenges

- high temperature reaction kinetics of
 - metal oxide decomposition
 - fossil fuel chemistry

robust chemical reactor designs and materials

Thermoelectric Conversion



thermal gradient \Leftrightarrow electricity

figure of merit: $ZT \sim (\sigma/\kappa) T$

$ZT \sim 3$: efficiency \sim heat engines
no moving parts

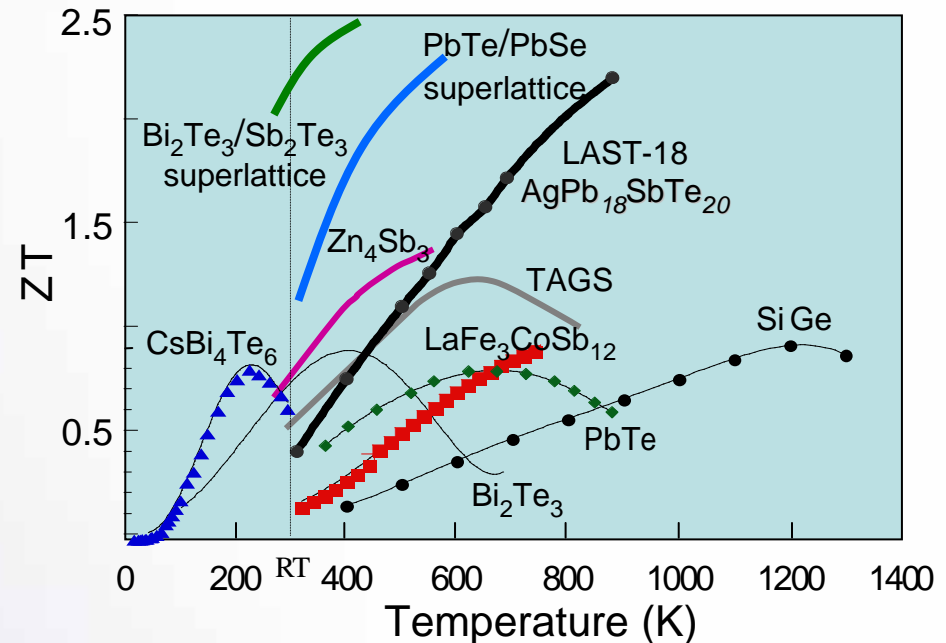
Scientific Challenges

increase electrical conductivity
decrease thermal conductivity



nanowire superlattice

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

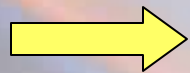


Solar Energy Challenges

Solar electric

Solar fuels

Solar thermal

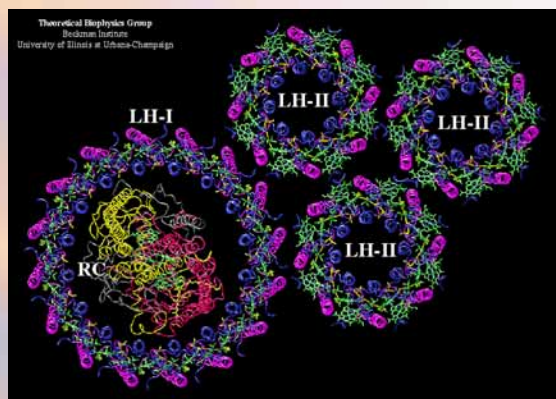


Cross-cutting research

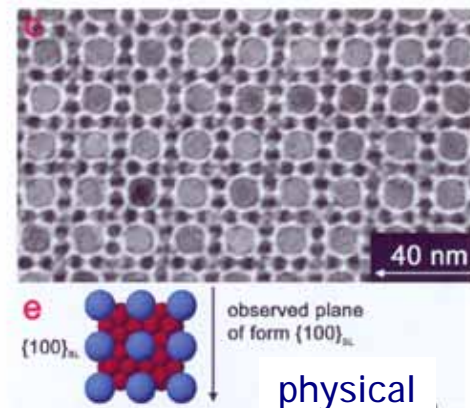
Molecular Self-Assembly at All Length Scales

The major cost of solar energy conversion is materials fabrication

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



biological



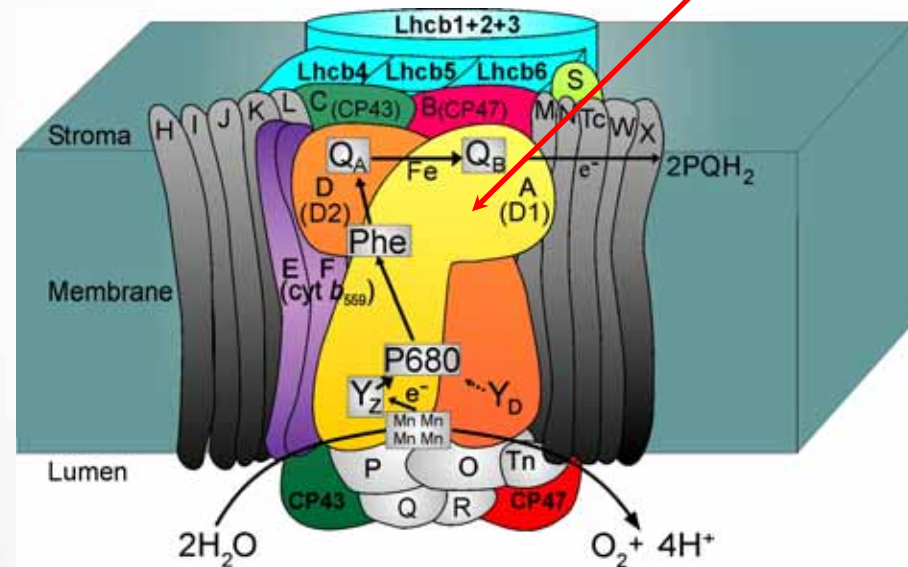
Scientific Challenges

- 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

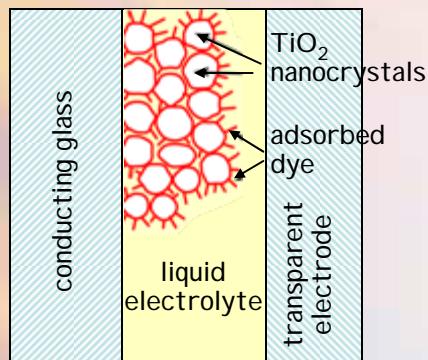
- Understand defect formation in photovoltaic materials and self-repair mechanisms in photosynthesis
- Achieve defect tolerance and active self-repair in solar energy conversion devices, enabling 20–30 year operation

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

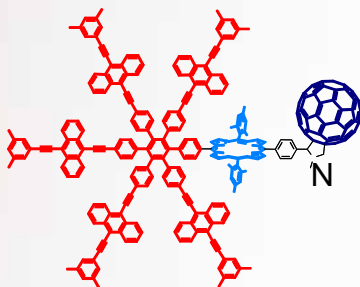


Nanoscience

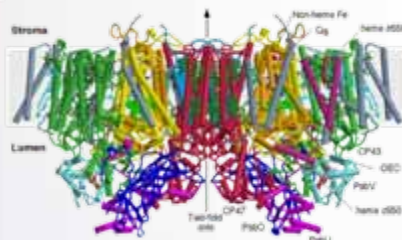
manipulation of photons, electrons, and molecules



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

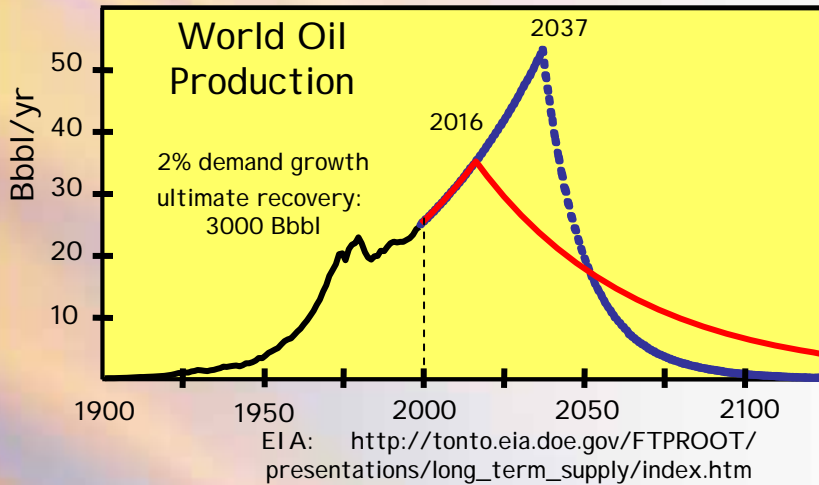
- capacity, environmental impact, geo-political security

Breakthrough research directions for mature solar energy

- solar electric
- solar fuels
- solar thermal

Fossil: Supply and Security

When Will Production Peak?



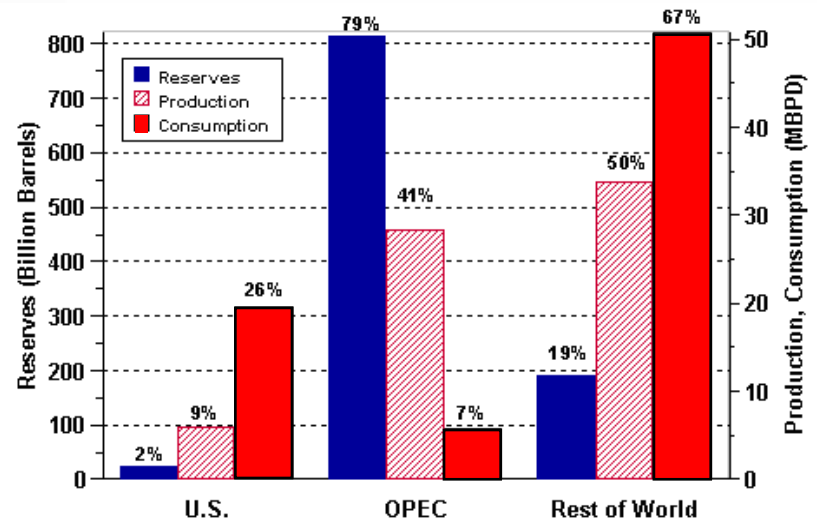
gas: beyond oil
coal: > 200 yrs



production peak
demand exceeds supply
price increases
geo-political restrictions

World Oil Reserves/Consumption 2001

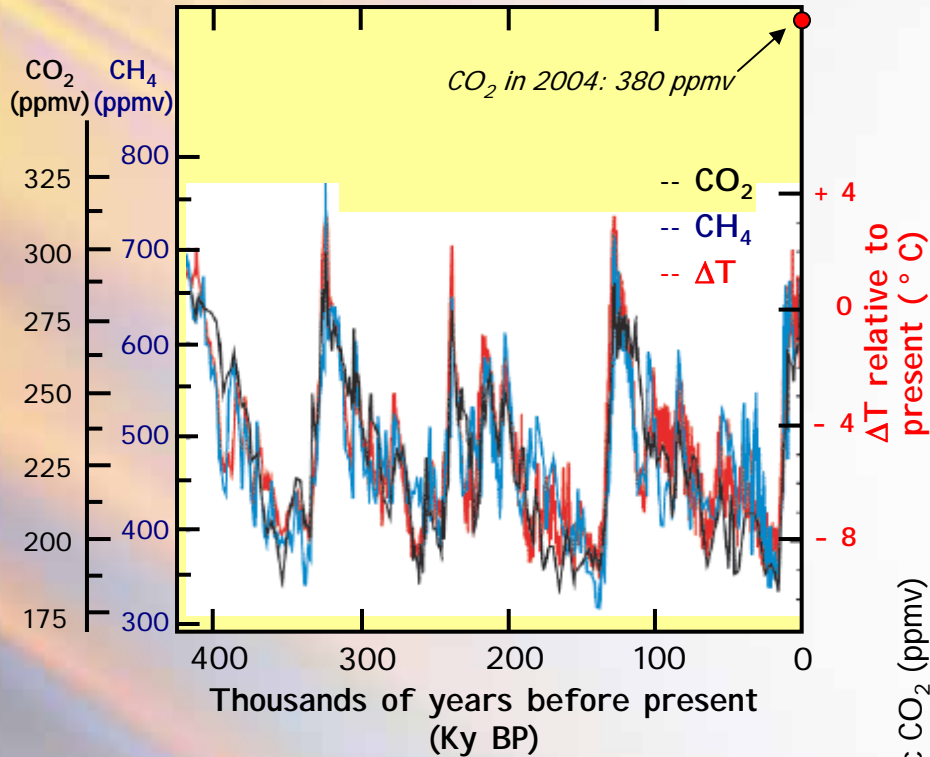
unequal supply ⇒
insecure access



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

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

Fossil: Climate Change

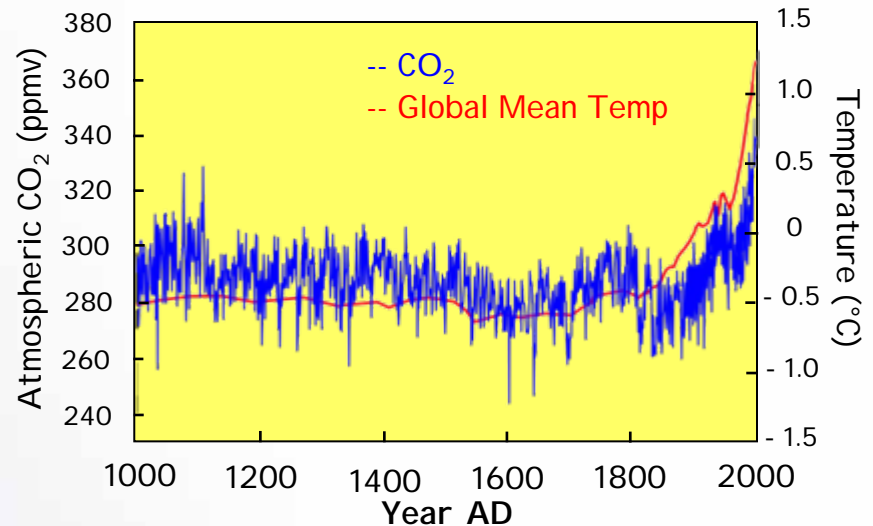


Climate Change 2001: The Scientific Basis, Fig 2.22

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

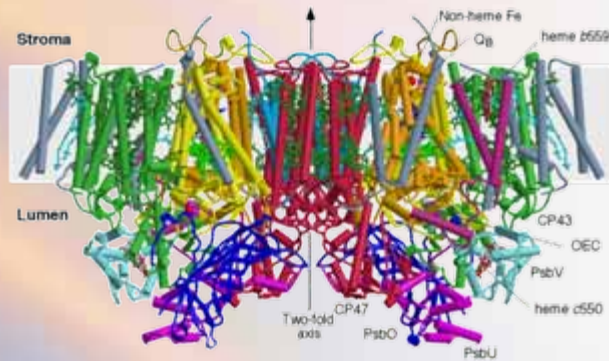
N. Oreskes, Science 306, 1686, 2004
D. A. Stainforth et al, Nature 433, 403, 2005

*Relaxation time
 transport of CO₂ or heat to deep
 ocean: 400 - >3000 years*

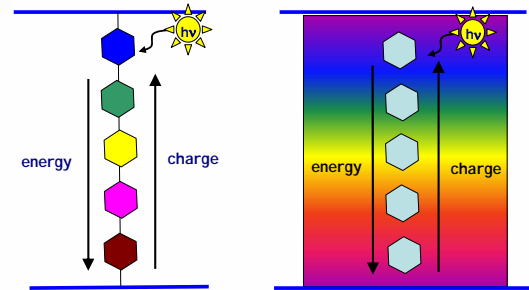


Smart Matrices for Solar Fuel Production

- 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