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U.S. DEPARTMENT OF ENERGY

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The Global Energy Challenge

George Crabtree

Argonne National Laboratory

Fossil Energy Challenges

Production: Solar

Distribution: Electricity

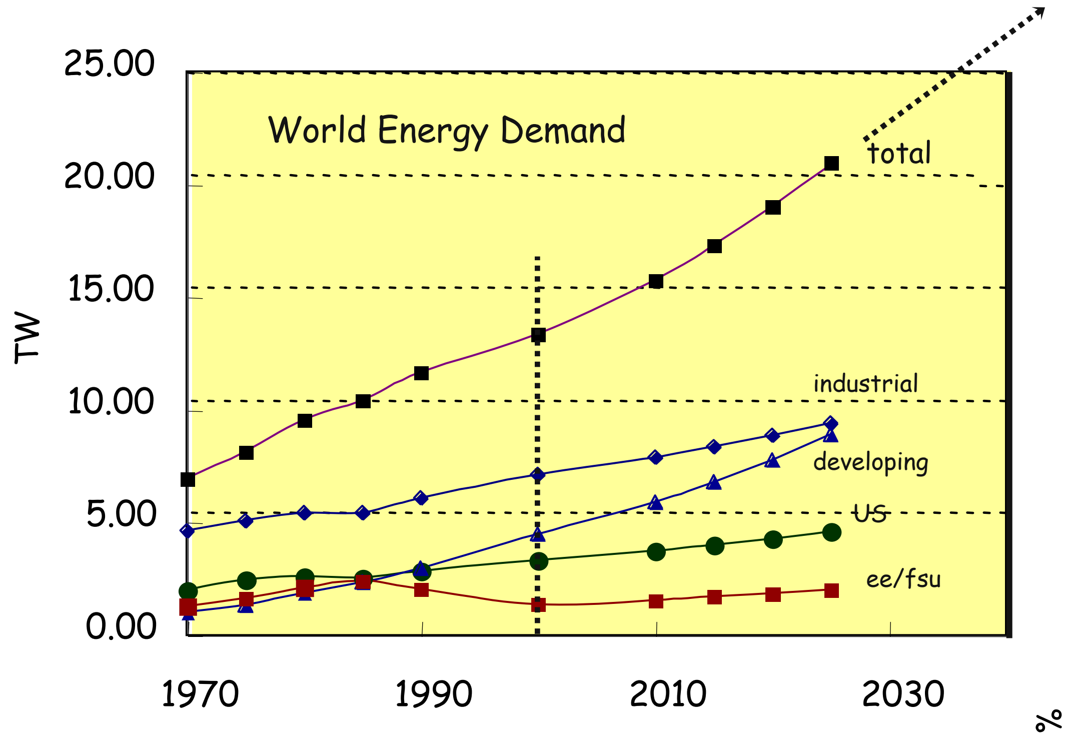
Use: Solid State Lighting

Hydrogen

Search for a Sustainable Energy Future
University of Pennsylvania
March 9, 2007

World Energy Demand

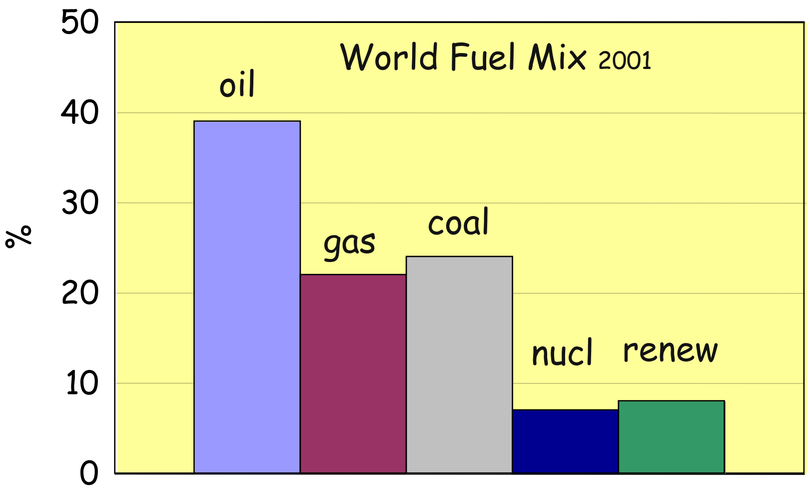
2100: 40-50 TW
2050: 25-30 TW



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

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

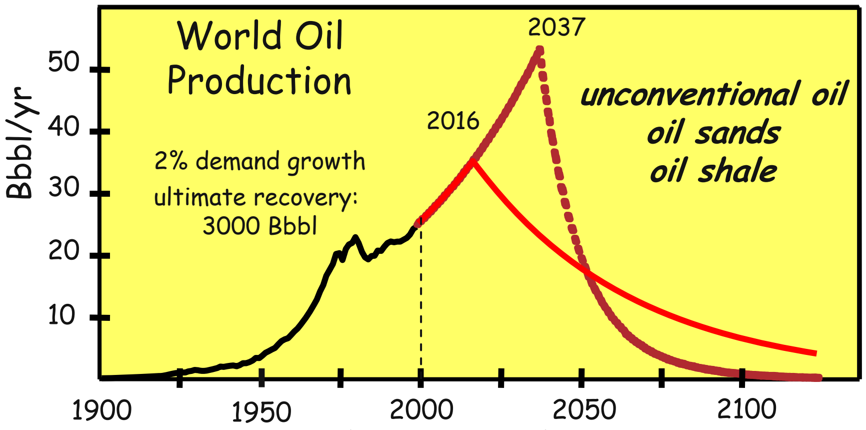
Hoffert et al Nature 395, 883,1998



85% fossil

Fossil: Supply and Security

When Will Production Peak?



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

R. Kerr, Science **310**, 1106 (2005)

gas: beyond oil

coal: > 200 yrs

beyond the peak

new geopolitical relationships

alternative fuels

unconventional oil

break even ~ $30-40 / bbl

50% more CO_2/gallon gasoline

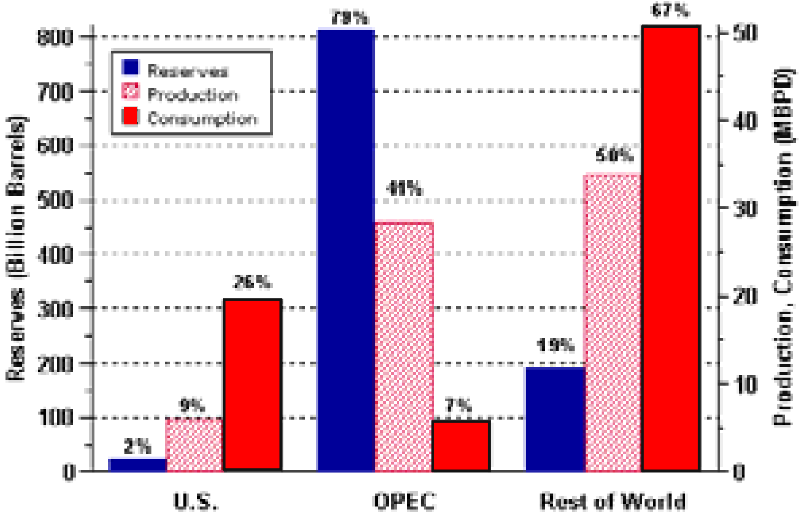
World Oil Reserves/Consumption

2001

uneven distribution

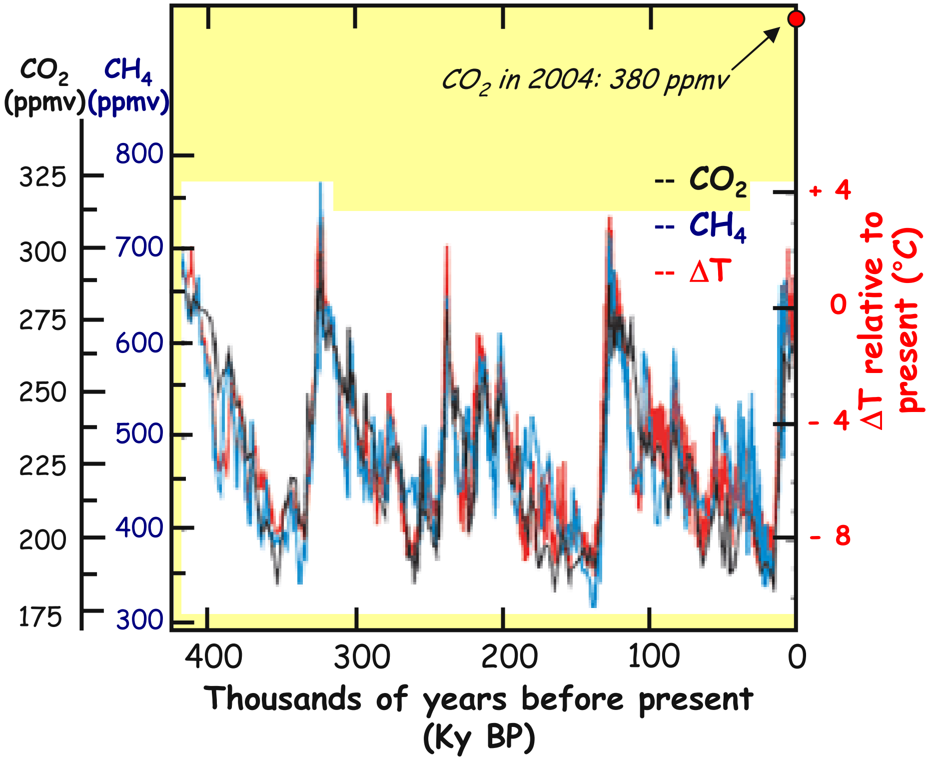
⇒ insecure access

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

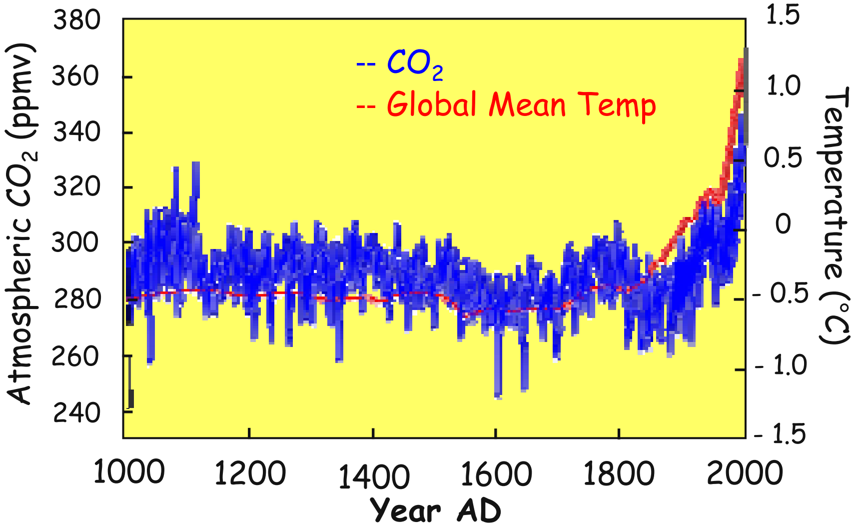
Fossil: Climate Change



Climate Change 2001: The Scientific Basis, Fig 2.22

Relaxation time

transport of CO$_2$ or heat to deep ocean: 400 - 1000 years



J. R. Petit et al, Nature ***399****, 429, 1999*
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*

The Energy Alternatives

Fossil

Nuclear

Renewable

solar, wind, hydroelectric
ocean tides and currents
biomass, geothermal

Fusion

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

10 TW = 10,000 1 GW power plants

1 new power plant/day for 27 years

no single solution

diversity of energy sources required

Assessing Energy Futures

Energy Source: Solar

electricity - fuel- heat

Energy Carrier: Electricity

Energy Carrier: Hydrogen

State of the art today

Future potential

Science challenges

The Energy in Sunlight

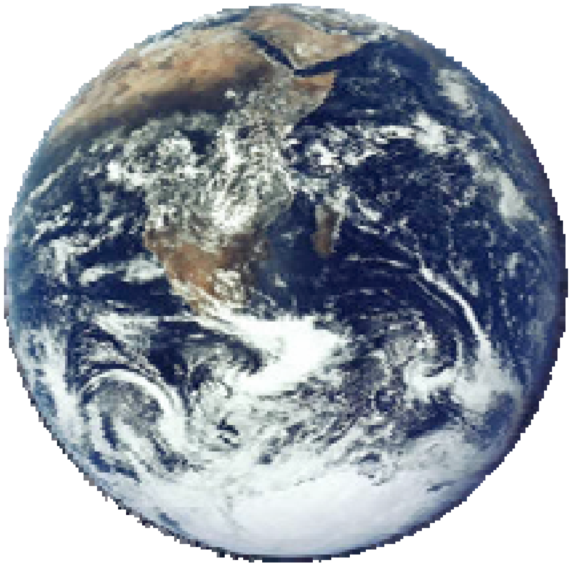
1.2×10^5 TW delivered to Earth
36,000 TW on land (world)
2,200 TW on land (US)

San Francisco Earthquake (1906)

magnitude 7.8

10^{17} Joules

1 second of sunlight



Earth's Ultimate Recoverable Resource of oil

3 Trillion (=Tera) Barrels

1.7×10^{22} Joules

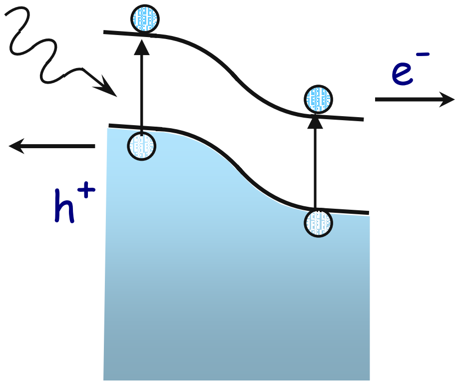
1.5 days of sunlight

Annual Human Production of Energy

4.6×10^{20} Joules

1 hour of sunlight

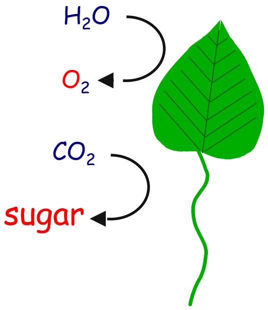
Solar Energy Utilization



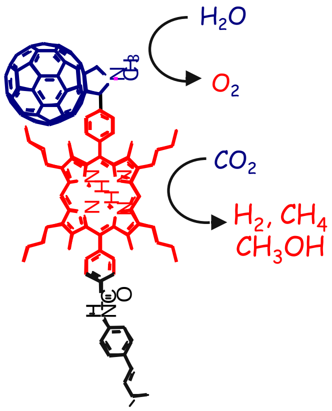
Solar Electric

.0002 TW PV (world)
.00003 TW PV (US)
$0.30/kWh w/o storage

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



natural photosynthesis

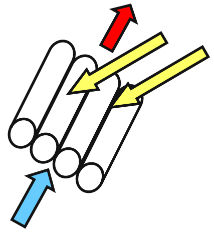


artificial photosynthesis

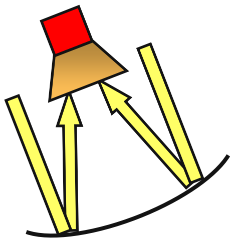
Solar Fuel

1.4 TW biomass (world)
0.2 TW biomass sustainable (world)

11 TW fossil fuel
(present use)



50 - 200 °C
space, water
heating



500 - 3000 °C
heat engines
electricity generation
process heat

Solar Thermal

0.006 TW (world)

2 TW
space and water
heating (world)

~ 14 TW additional energy by 2050

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***

Basic Research Needs for Solar Energy Utilization

http://www.sc.doe.gov/bes/reports/abstracts.html#SEU

Solar Energy Challenges

➡ Solar electric

Solar fuels

Solar thermal

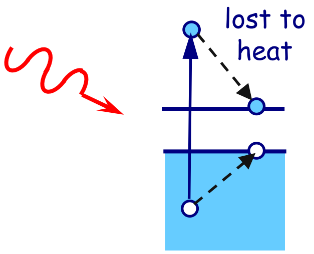
Solar Electric

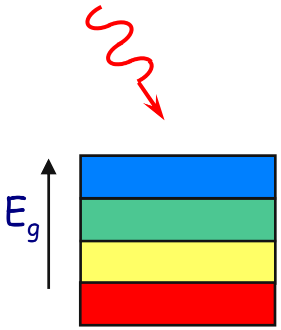
- Despite 30-40% growth rate in installation, photovoltaics generate
  - *less* than 0.02% of world electricity (2001)
  - *less* than 0.002% of world total energy (2001)
- Decrease *cost*/watt by a factor 10 - 25 to be competitive with fossil electricity (without storage)
- Find effective method for *storage* of photovoltaic-generated electricity

Revolutionary Photovoltaics: 50% Efficient Solar Cells

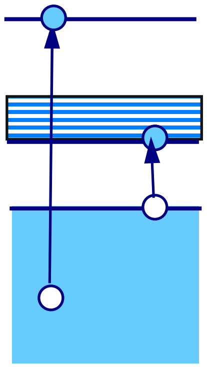
present technology: 32% limit for

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

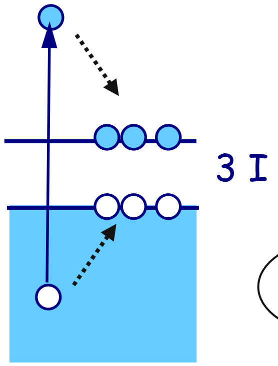




multiple junctions

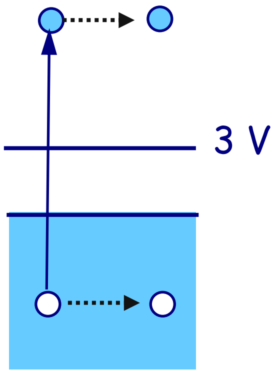


multiple gaps



multiple excitons
per photon

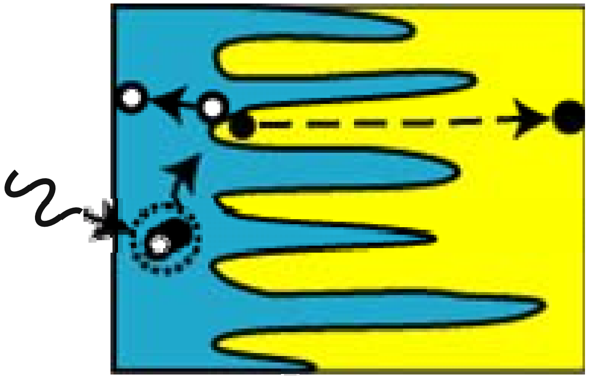
nanoscale
formats



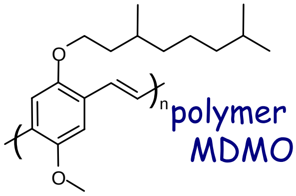
hot carriers

rich variety of new physical phenomena
challenge: understand and implement

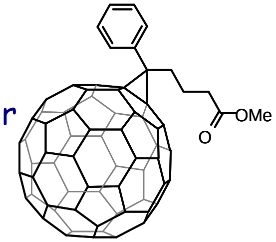
Organic Photovoltaics: Plastic Photocells



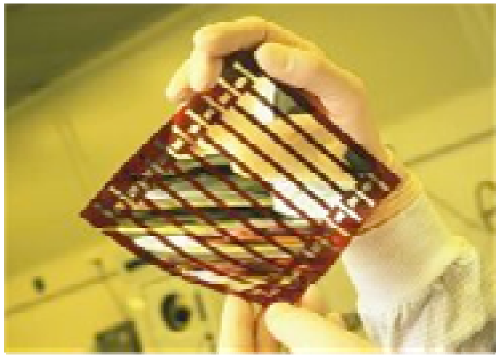
donor-acceptor junction



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

Solar Energy Challenges

Solar electric

➡ Solar fuels

Solar thermal

Solar Fuels: Solving the Storage Problem

- Biomass < 0.3% efficient: 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

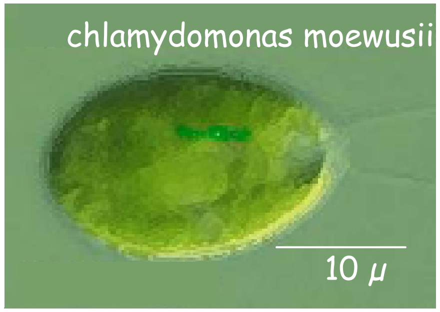
Leveraging Photosynthesis for Efficient Energy Production

- photosynthesis converts ~ 100 TW of sunlight to sugars: nature's fuel
- low efficiency (< 0.3%) 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

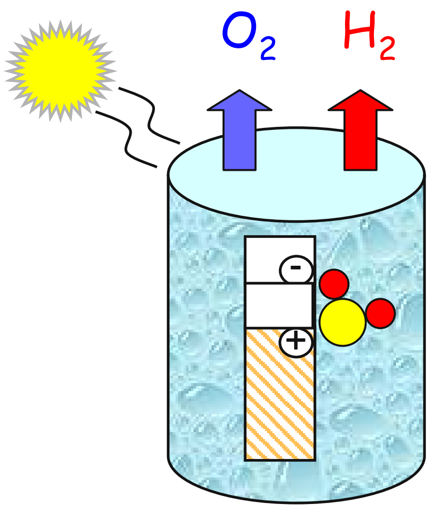


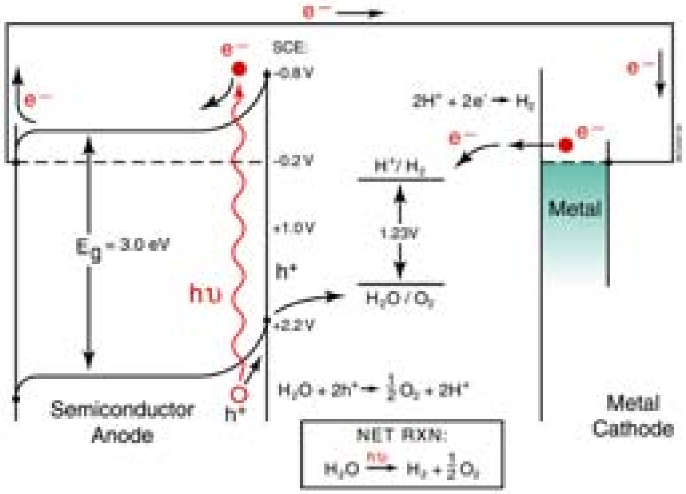
hydrogenase
$2H^+ + 2e^- \Leftrightarrow H_2$

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



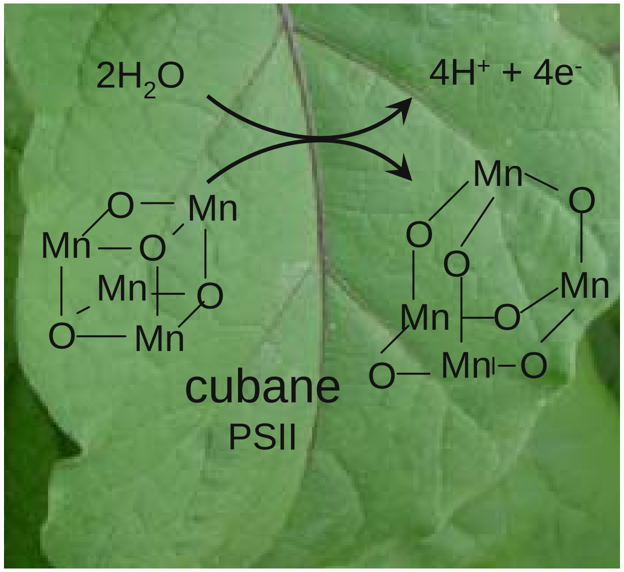


demonstrated efficiencies 10% in laboratory

Scientific Challenges

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

Solar-Powered Catalysts for Fuel Formation



Wu, Dismukes et al, *Inorg, Chem* 43, 5795 (2004)
Ferreira, et al, *Science* 303: 1831 (2004).

plants - photosynthesis

$2H_2O + h\nu \rightarrow 4H^+ + 4e^- + O_2$

$CO_2 + H^+ + e^- \rightarrow$ carbohydrates (~ $H_6C_{12}O_6$)

bio inspired artificial water splitting
fuel production:

artificial photosynthesis

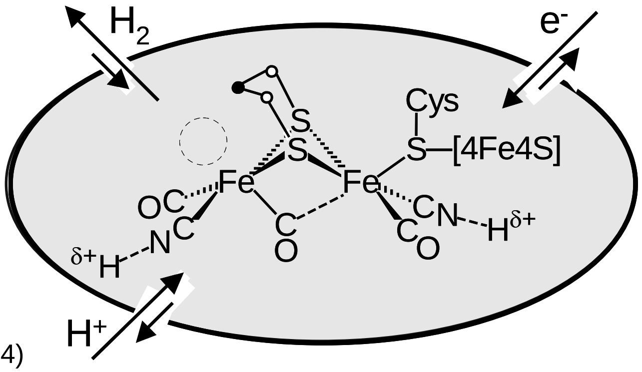
fuel from sunlight, H_2O, CO_2

H_2, CH_4, CH_3OH, C_2H_5OH

bacteria - hydrogenase

catalyst for

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



Tard et al, *Nature* 433, 610 (2005)
Justice, Rauchfuss et al, *J. Am. Chem. Soc.*126, 13214 (2004)
Alper, *Science* 299, 1686 (2003)

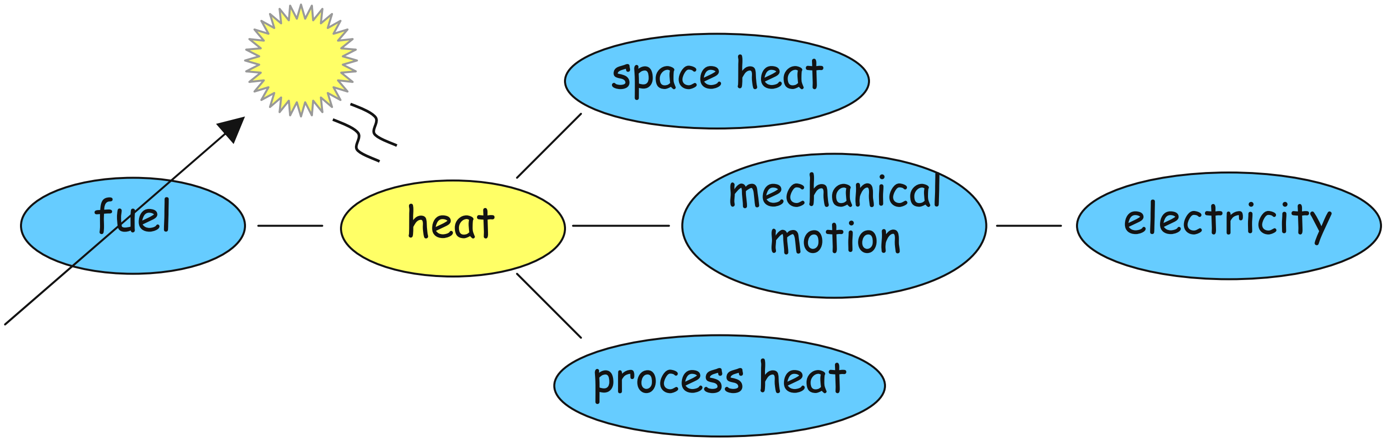
Solar Energy Challenges

Solar electric

Solar fuels

➡ Solar thermal

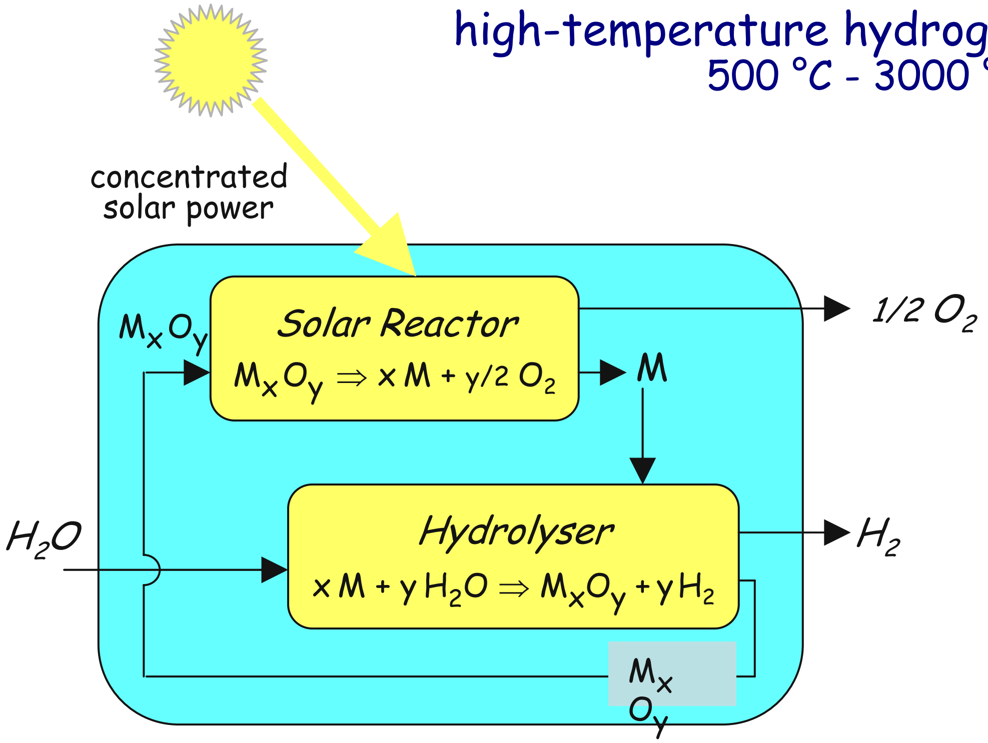
Solar Thermal



- 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



concentrated solar power

Solar Reactor
$M_xO_y \Rightarrow x\,M + y/2\,O_2$

M_xO_y

1/2 O_2

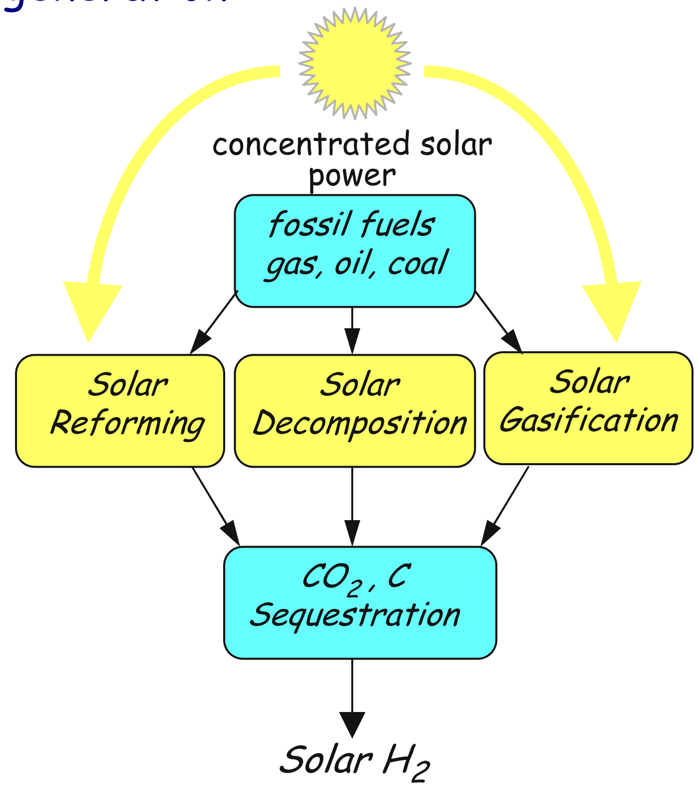
M

H_2O

Hydrolyser
$x\,M + y\,H_2O \Rightarrow M_xO_y + y\,H_2$

H_2

M_xO_y



concentrated solar power

fossil fuels
gas, oil, coal

Solar Reforming

Solar Decomposition

Solar Gasification

CO_2, C
Sequestration

Solar H_2

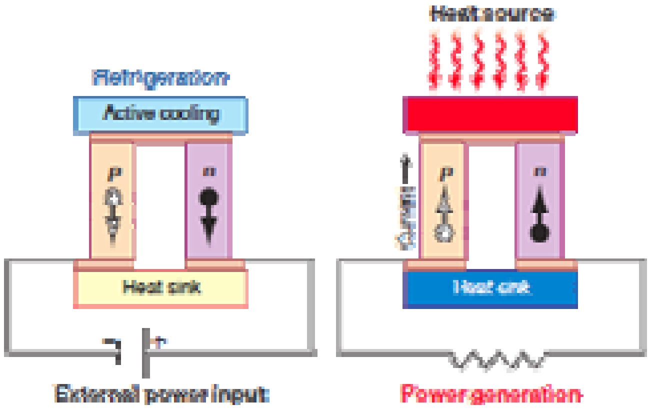
Scientific Challenges

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

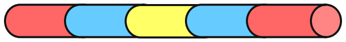


thermal gradient ⇔ electricity

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

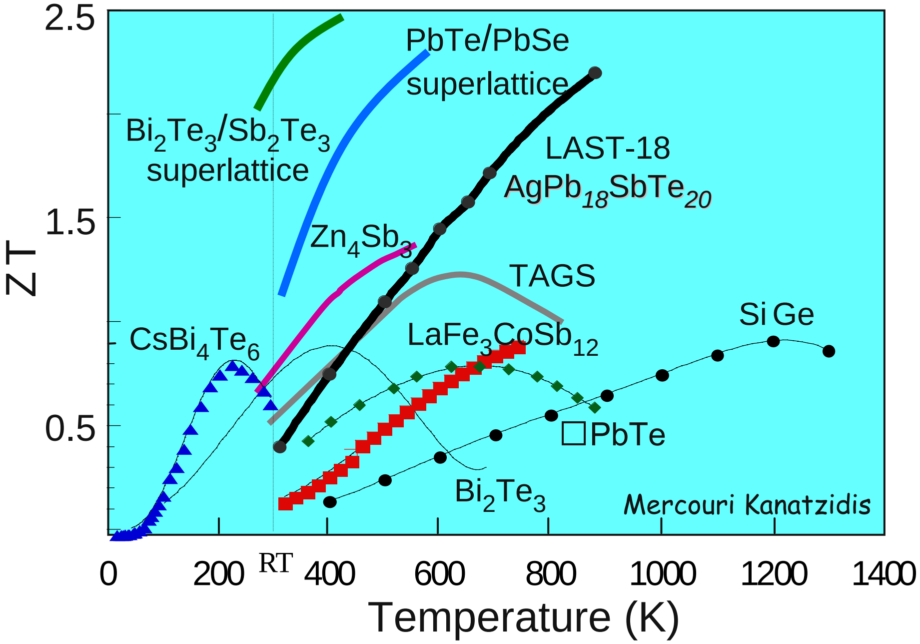
$ZT \sim 3$: efficiency ~ heat engines
no moving parts

Scientific Challenges
increase electrical conductivity
decrease thermal conductivity



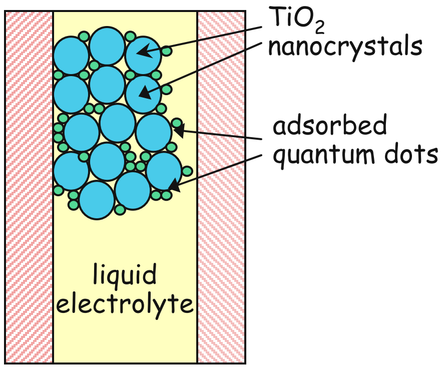
nanowire superlattice

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

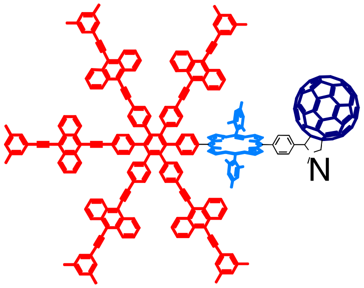


Nanoscience

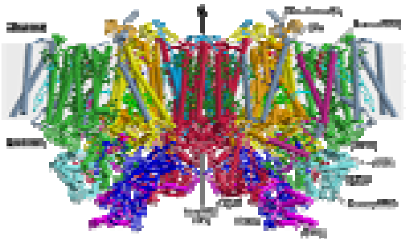
manipulation of photons, electrons, and molecules



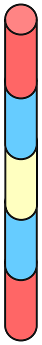
quantum dot solar cells



artificial photosynthesis



natural photosynthesis



nanostructured thermoelectrics

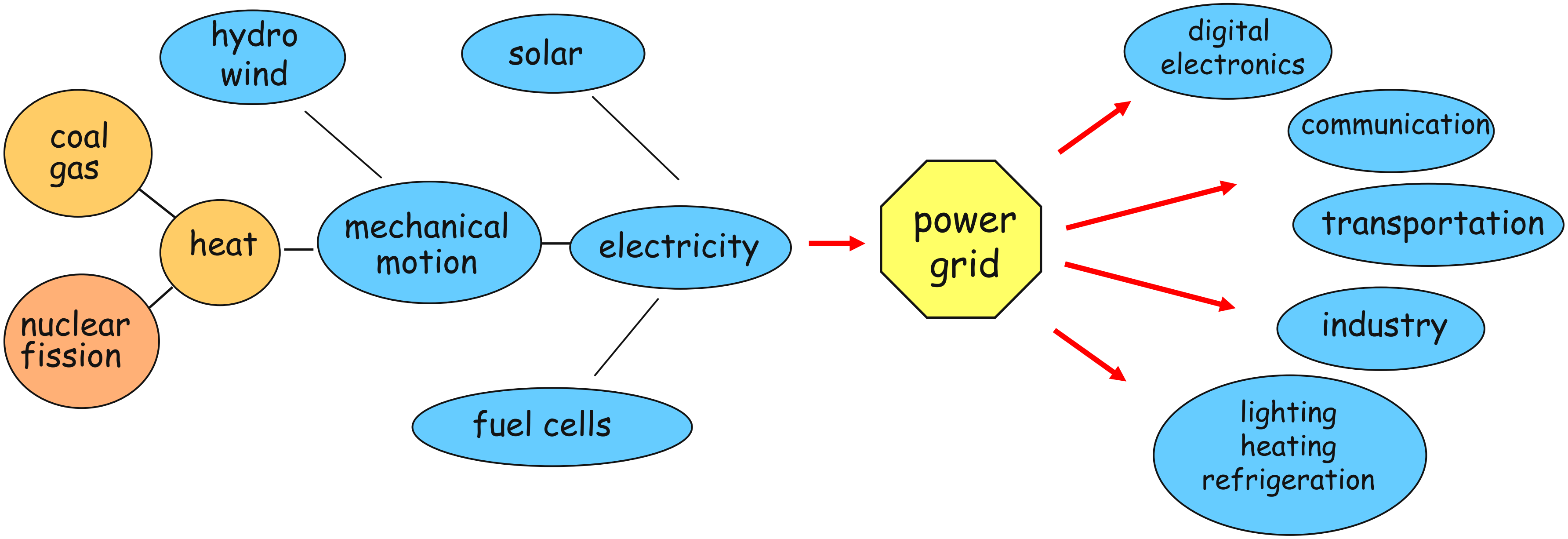
nanoscale architectures
top-down lithography
bottom-up self-assembly
multi-scale integration

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

Electricity as an Energy Carrier



coal
gas

nuclear
fission

heat

hydro
wind

mechanical
motion

solar

electricity

fuel cells

power
grid

digital
electronics

communication

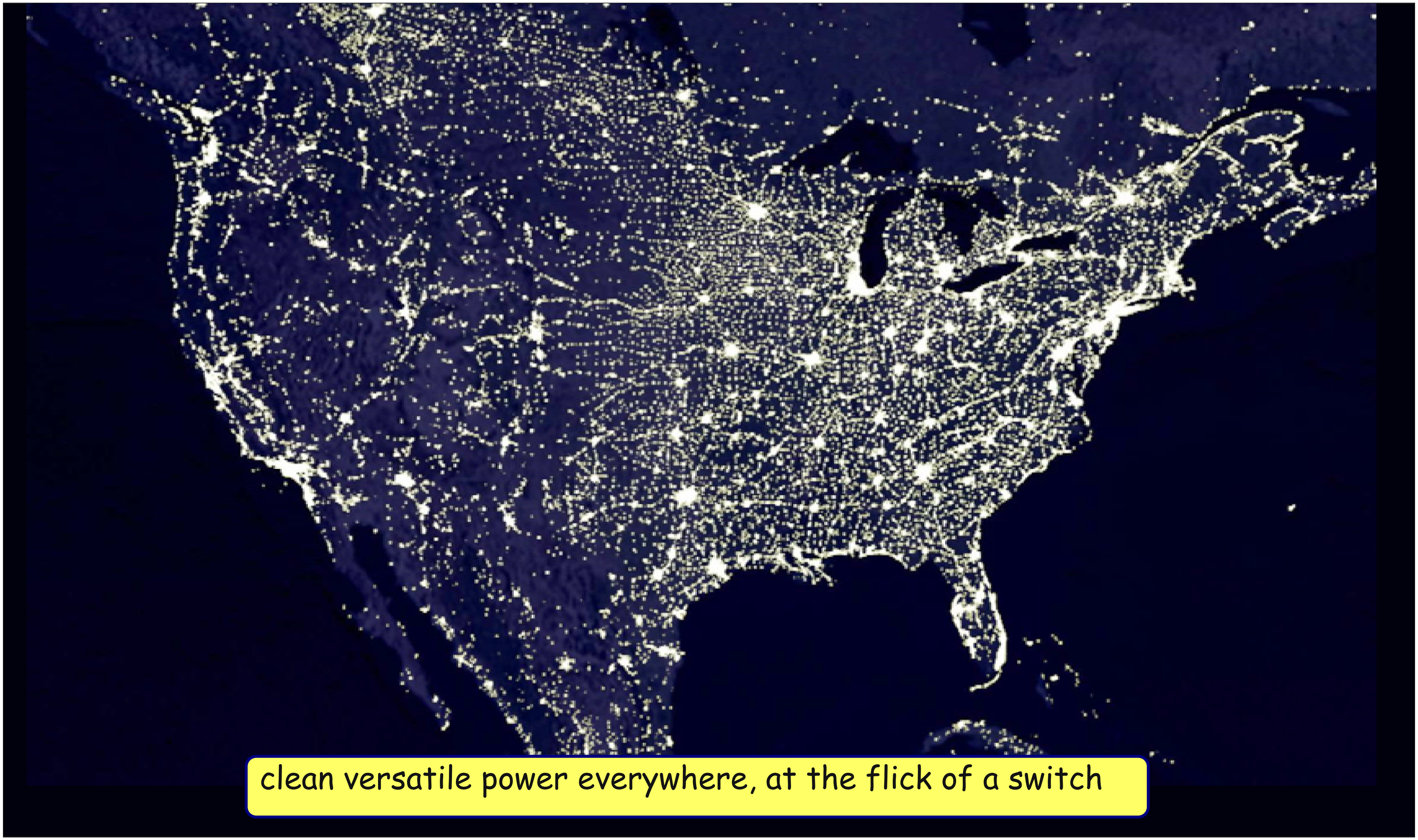
transportation

industry

lighting
heating
refrigeration

35% of primary energy
34% of CO_2 emissions
63% of energy lost

The Grid - the Triumph of 20th Century Engineering

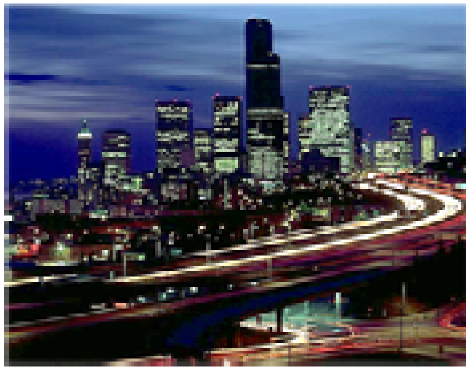


clean versatile power everywhere, at the flick of a switch

The 21st Century: A Different Set of Challenges

capacity

growing electricity uses
growing cities and suburbs
high people / power density
urban power bottleneck

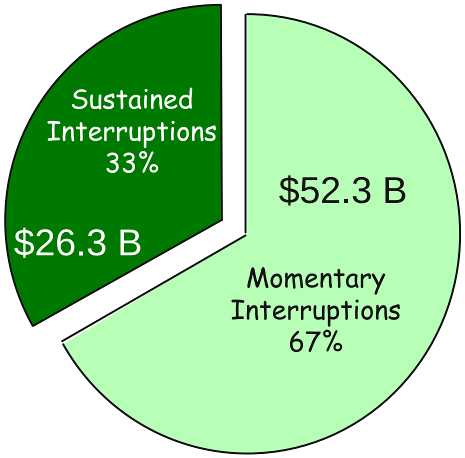


2030
50% demand growth (US)
100% demand growth (world)

reliability
power quality

average
power loss/customer
(min/yr)

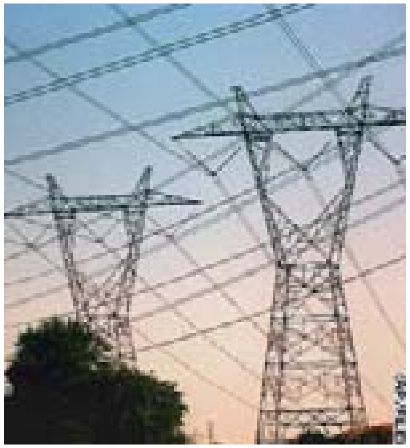
US	214
France	53
Japan	6



$79 B economic loss (US)

LaCommare & Eto, Energy 31, 1845 (2006)

efficiency
lost energy



62% energy lost in production / delivery

8-10% lost in grid

40 GW lost (US)
~ 40 power plants

2030: 60 GW lost (US)
340 Mtons CO_2

Superconductivity for the 21st Century Grid

Superconductors carry electrical current

without resistance or energy loss

capacity ⇒ high current / low voltage

reliability / quality ⇒ smart, self-healing power control

efficiency ⇒ zero resistance (DC)
100 times lower than copper (AC)

BES Superconductivity Workshop Report

Electricity is our most effective energy carrier
  - *Clean, versatile, switchable power anywhere*

Power grid cannot meet 21st century challenges
  - *Capacity, reliability, quality, efficiency*

Superconducting technology is poised to meet the challenge

Present generation materials enable grid-connected cables and demonstrate control technology

Basic and applied research needed to lower cost and raise performance

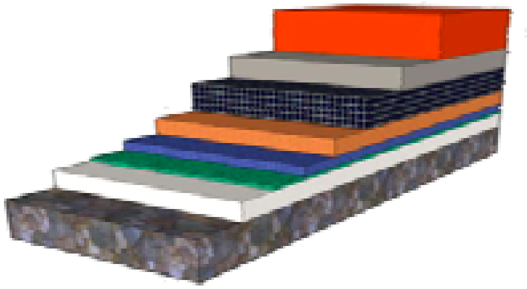
High risk-high payoff discovery research for next-generation superconducting materials
  - *Higher temperature and current capability*
  - *Understand fundamental phenomena of transition temperature and current flow*

BASIC RESEARCH NEEDS FOR
SUPERCONDUCTIVITY

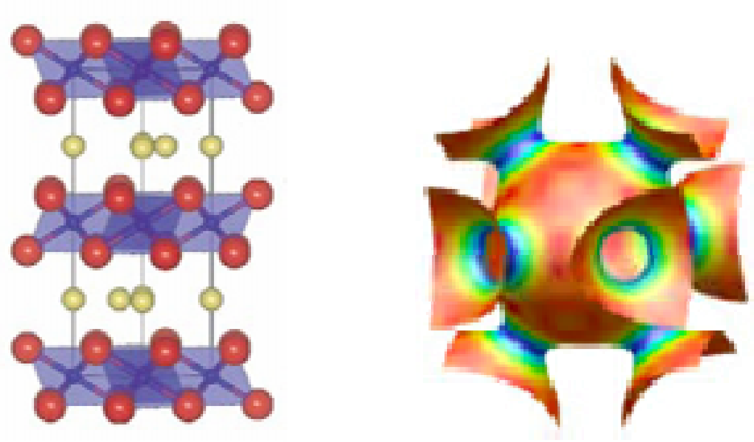
http://www.sc.doe.gov/bes/reports/abstracts.html#SC

Research Challenges and Opportunities

Superconducting Cable



Next Generation Materials



Superconducting Cables

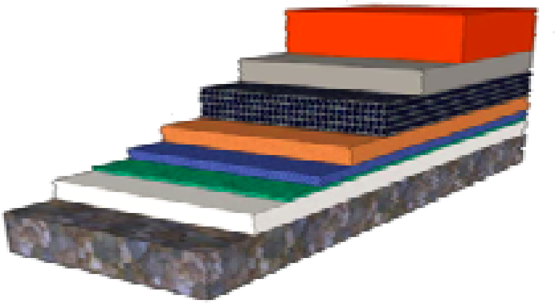
- 5x power capacity of copper in same cross-sectional area
  - Relieve power bottleneck in urban / suburban areas
  - Low loss cross-country power transmission
- Cables operating at 77 K are technically ready
  - in grid demonstrations at Albany,
- Cost must be reduced by factor 10 - 100 to compete with copper
- Reliable multiyear operation must be demonstrated

Superconducting Cable Demonstration

200 meters, 13.2 kV, 3kA, American Electric Power, Columbus, OH, in service Sept 06

Superconducting Cable

$YBa_2Cu_3O_{7-x}$ coated conductor
transition temperature = 92 K
operating temperature = 77 K (LN_2)
cheap materials
high performance
complex multilayer architecture



Research Challenges
Lower cost by factor 10 - 100
simplify architecture
new dual function materials eliminate layers
simplify layer deposition methods

Next Generation Materials

operate at higher transition temperatures

~ 50 copper oxide superconductors

Highest Tc = 164 K under pressure

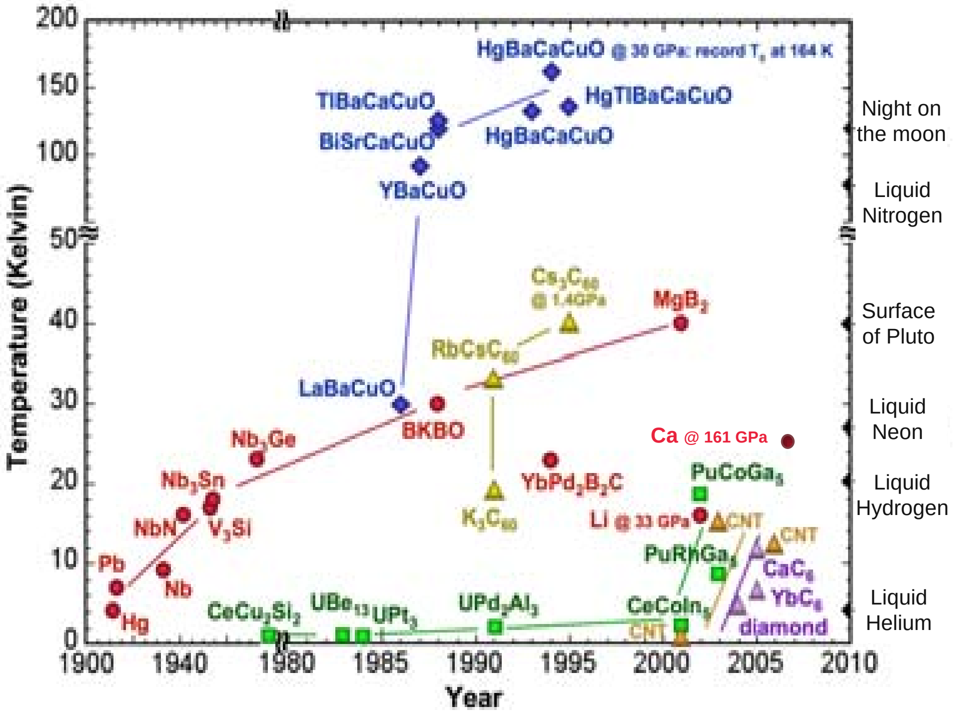
(1/2 Room Temp)

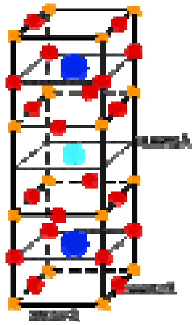
Only class of high T_c superconductors ?

High T_c superconductors $\geq$ 4 elements

55 superconducting elements

-> 55^4 ~ 10 million quaternaries





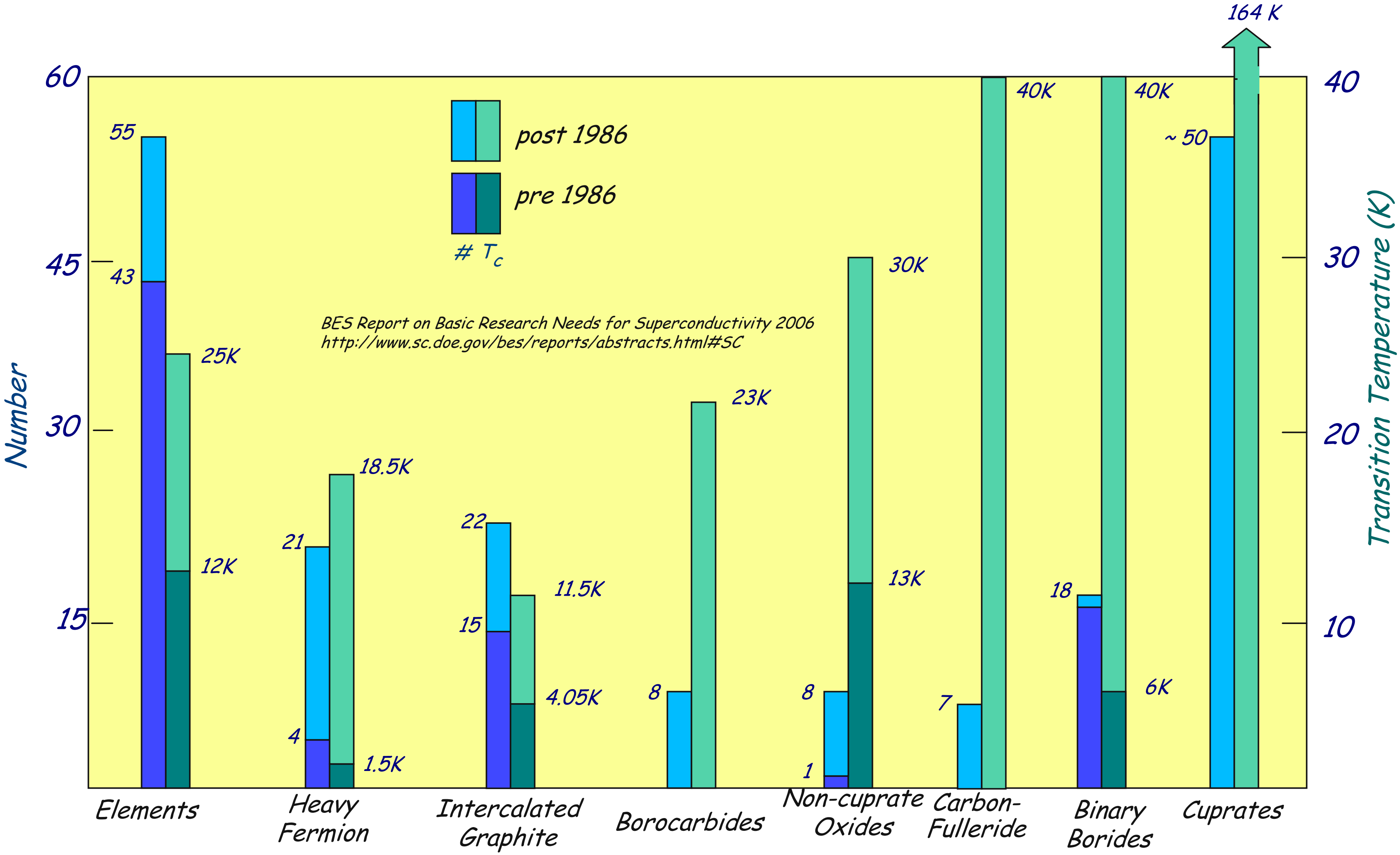
Search strategies for new superconductors

- Quaternary and higher compounds
- Layered structures
- Highly correlated normal states
- Competing high temperature ordered phases

Challenge

Discover next generation complex superconductors

New Materials: Recent Superconductor Discoveries

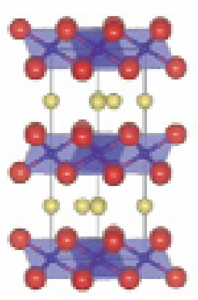


BES Report on Basic Research Needs for Superconductivity 2006
http://www.sc.doe.gov/bes/reports/abstracts.html#SC

Superconductors by Design

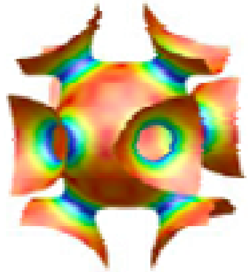
Discovery by serendipity: Hg (1911), copper oxides (1986), MgB_2 (2001), $NaCoO_2{:}H_2O$ (2003)

Discovery by empirical guidelines: competing phases, layered structures, light elements, . . .
B-doped diamond (2004), CaC_6 (2005)



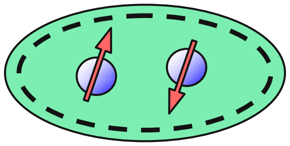
Crystal Structure
Composition

+



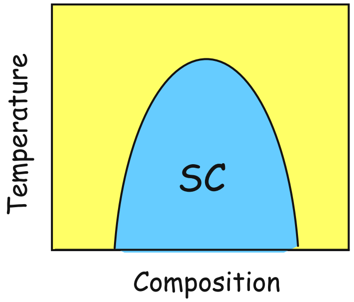
Electronic Structure
Density functional theory

+



Pairing Mechanism
phonons (classical BCS)
spin fluctuations
valence fluctuations

=



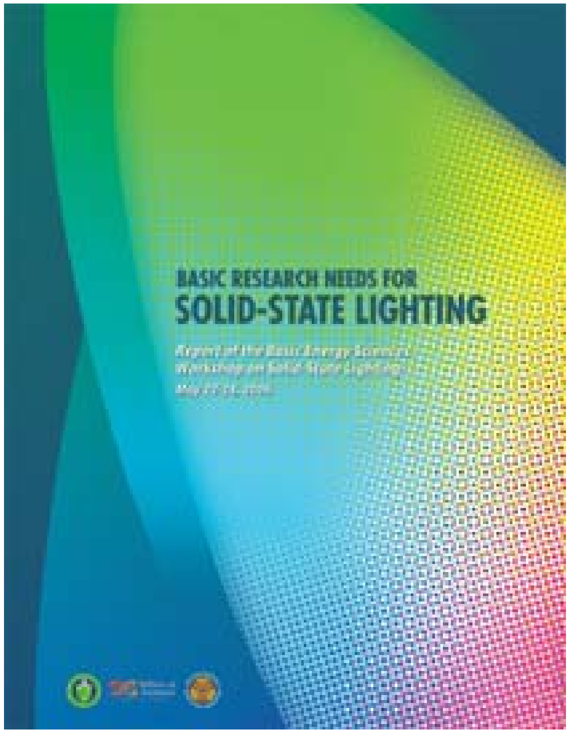
Superconductivity

Computationally designed superconductors

- Electronic structure calculation by density functional theory
- Large scale phonon calculations in nonlinear, anharmonic limit
- Formulate “very strong” electron-phonon coupling (beyond Eliashberg)
- Determine quantitative pairing mechanisms for high temperature SC

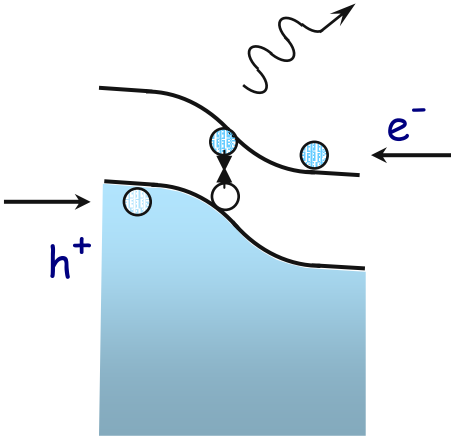
Challenge: Create a paradigm shift to superconductors by design

Electricity Use: Solid State Lighting



BASIC RESEARCH NEEDS FOR
SOLID-STATE LIGHTING

http://www.sc.doe.gov/bes/reports/abstracts.html#SSL

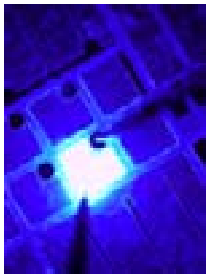


wide bandgap
compound semicondutors
GaN InGaN AlGaN
color: control bandgap
efficiency: control defects
white light: mix 3 or 4 colors

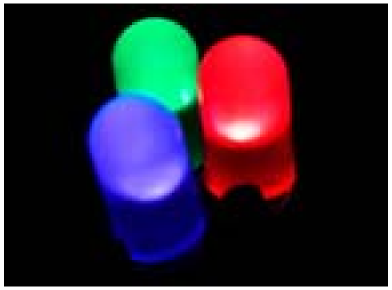
Research Challenges
new materials
doping and defect control
white light at 50% efficiency

Lighting ~ 22%
of electricity use

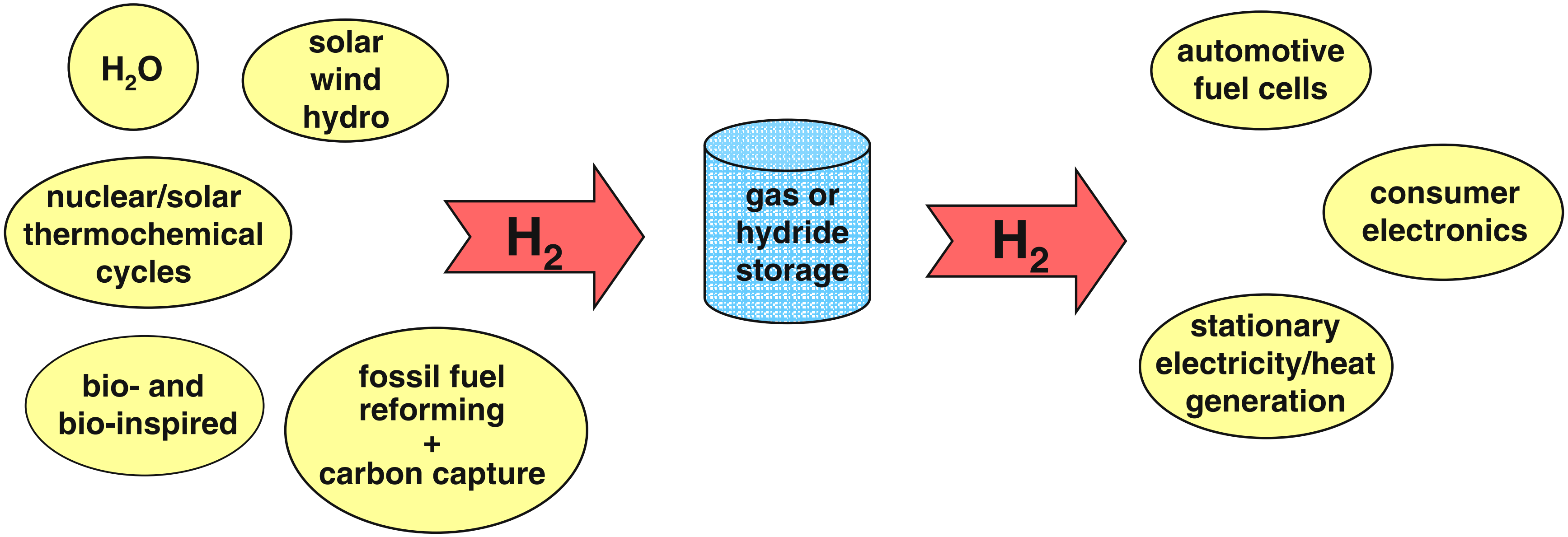
incandescent
~ 5% efficient



Solid state
> 50% efficient



Hydrogen as an Energy Carrier



H_2O

solar
wind
hydro

nuclear/solar
thermochemical
cycles

bio- and
bio-inspired

fossil fuel
reforming
+
carbon capture

H_2

gas or
hydride
storage

H_2

automotive
fuel cells

consumer
electronics

stationary
electricity/heat
generation

production

9M tons/yr

↓

150 M tons/yr
(light trucks and cars in 2040)

storage

4.4 MJ/L (Gas, 10,000 psi)
8.4 MJ/L (LH2)

↓

9.72 MJ/L
(2015 FreedomCAR Target)

use
in fuel cells

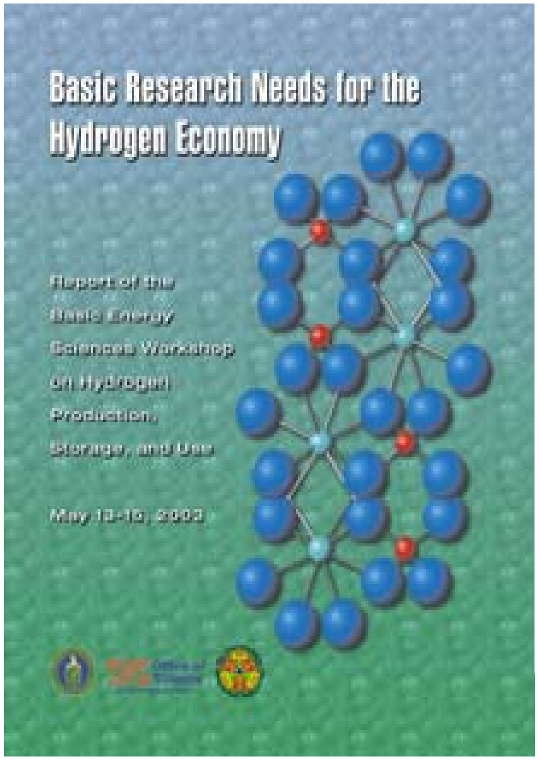
$3000/kW

↓

$300/kW
mass production

$30/kW
(Internal Combustion Engine)

Hydrogen Studies



Basic Research Needs for the Hydrogen Economy

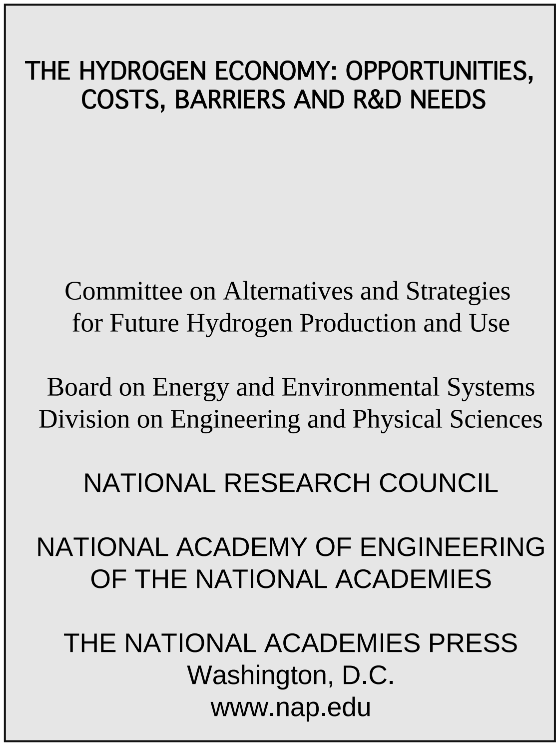
Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use

May 13-15, 2003

Basic Energy Sciences
Department of Energy

July 2003/February 2004

http://www.sc.doe.gov/bes/hydrogen.pdf



THE HYDROGEN ECONOMY: OPPORTUNITIES, COSTS, BARRIERS AND R&D NEEDS

Committee on Alternatives and Strategies
for Future Hydrogen Production and Use

Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF ENGINEERING
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

National Research Council
National Academy of Sciences

February 2004

http://www.nap.edu/catalog/10922.html

December 2004
PHYSICS TODAY

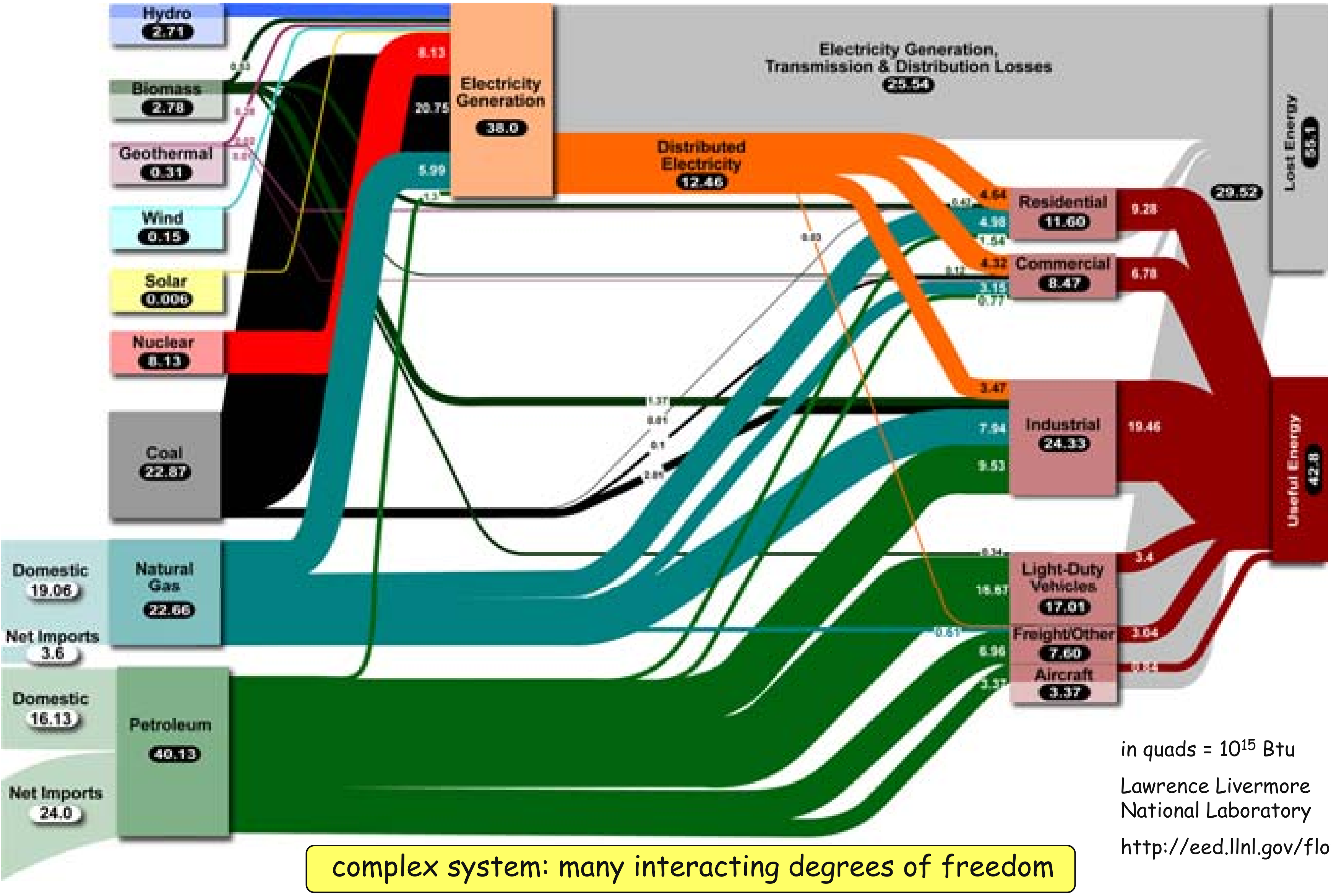
The Hydrogen Economy

G. W. Crabtree, M. S. Dresselhaus,
M. V. Buchanan

Physics Today **57**(12), 39-44, 2004

http://www.physicstoday.org/vol-57/iss-12/p39.html

Energy Flows in 2005



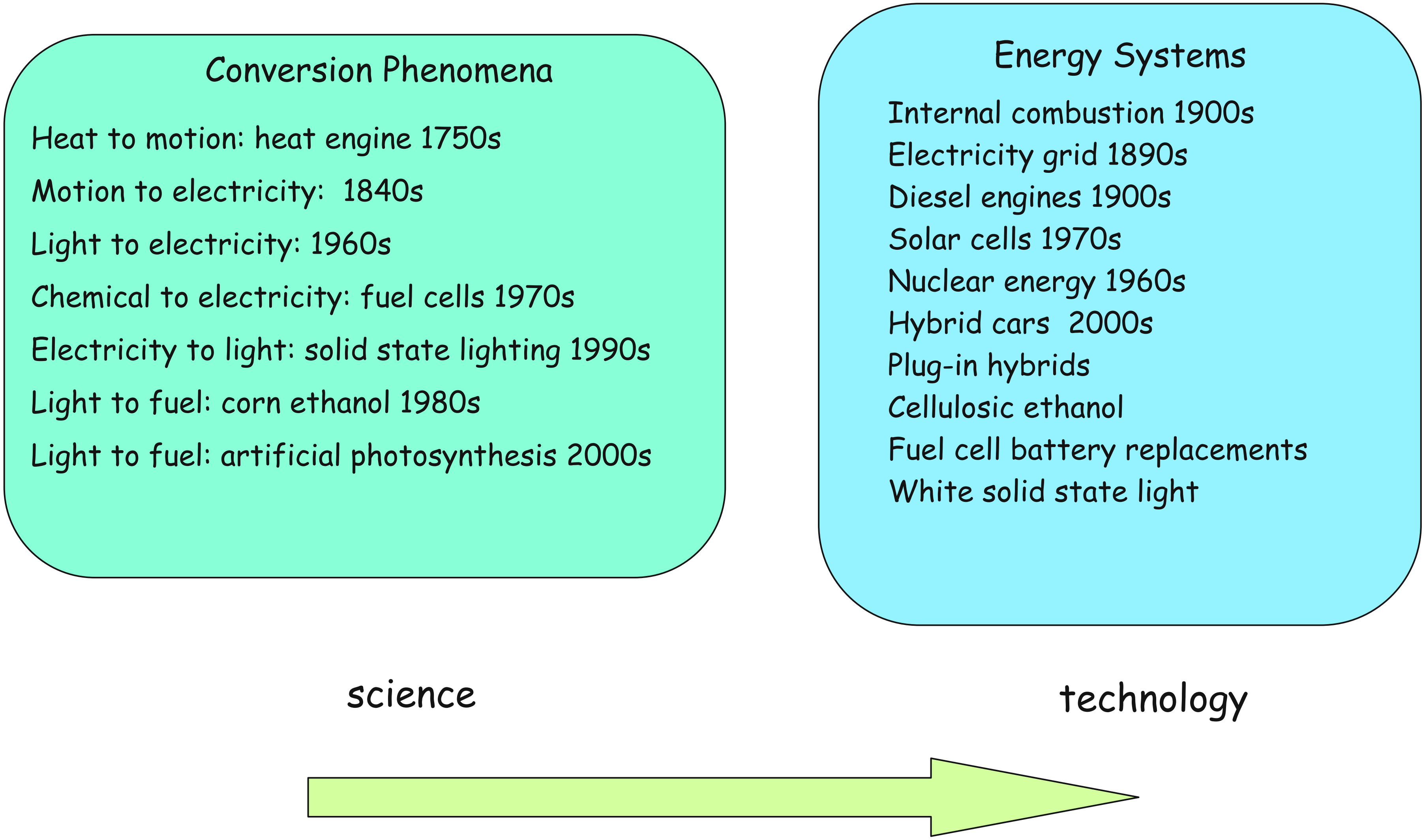
complex system: many interacting degrees of freedom

in quads = 10^{15} Btu

Lawrence Livermore
National Laboratory

http://eed.llnl.gov/flow/

The Technical Challenges



Conversion Phenomena

Heat to motion: heat engine 1750s

Motion to electricity: 1840s

Light to electricity: 1960s

Chemical to electricity: fuel cells 1970s

Electricity to light: solid state lighting 1990s

Light to fuel: corn ethanol 1980s

Light to fuel: artificial photosynthesis 2000s

Energy Systems

Internal combustion 1900s
Electricity grid 1890s
Diesel engines 1900s
Solar cells 1970s
Nuclear energy 1960s
Hybrid cars 2000s
Plug-in hybrids
Cellulosic ethanol
Fuel cell battery replacements
White solid state light

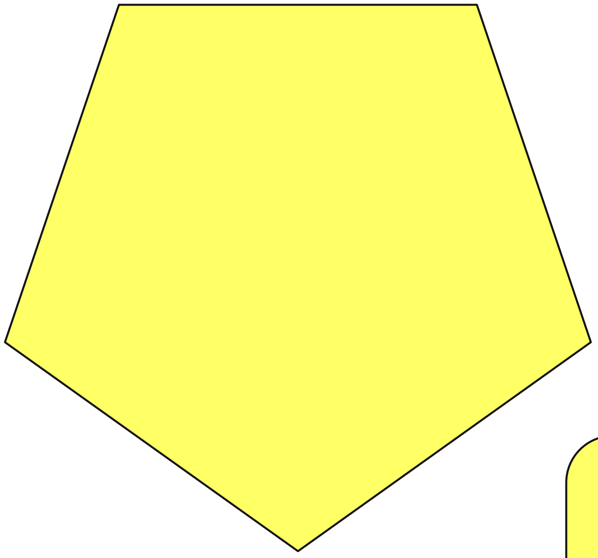
science

technology

Energy Conversion Efficiency

conversion	*efficiency*	*practical target*
chemical bonds ⇒ electrons	30% (fossil electricity)	> 60%
chemical bonds ⇒ motion	28% (gasoline engine)	> 60%
photons ⇒ electrons	18% (market) / 28% (lab)	> 60%
photons ⇒ chemical bonds	0.3% (biomass)	> 20%
electrons ⇒ photons	5-25%	> 50%

Energy: a BIG Complex System



Science

Technology

Economics

Sociology

Politics

Emergent behavior

reactions of a thousand players
unanticipated events

Distant outcomes are unpredictable

no one dimensional solutions

change requires confluence of all elements

Perspective

- Grand energy challenge
  - Double by 2050, triple by 2100
  - Supply, security, pollution, climate
  - Complex emergent system- cannot predict distant outcomes
- Efficient energy conversion is key for production, storage and use
- Materials and nanoscience are key to energy conversion
- Discovery science is needed, incremental advances not sufficient
- Basic research investments today create energy alternatives tomorrow