

The Global Energy Challenge

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Fossil Energy Challenges

Fossil Alternatives:

Energy Production: Solar

Energy Carrier: Electricity

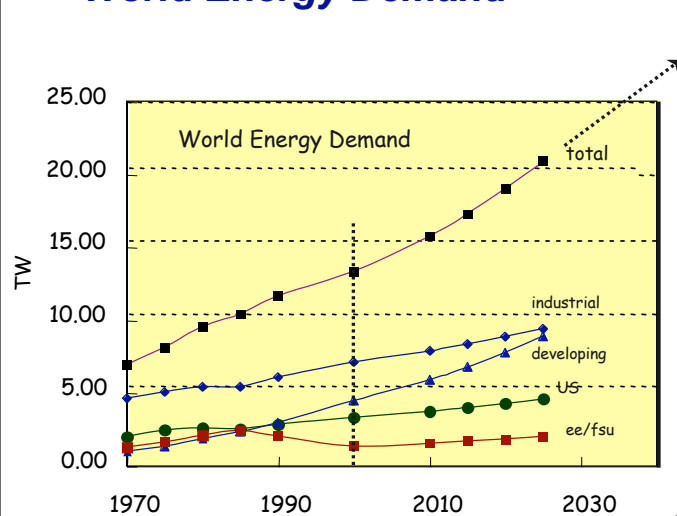
Energy Carrier: Hydrogen

Perspective

Kansas Energy Symposium

October 10-11, 2007

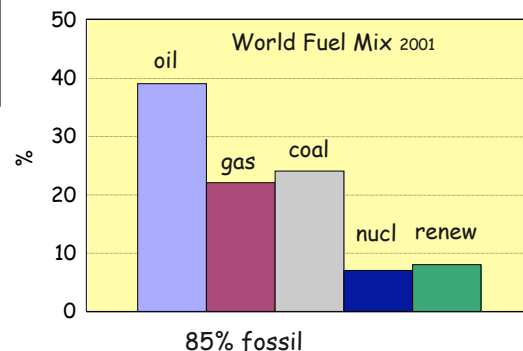
World Energy Demand



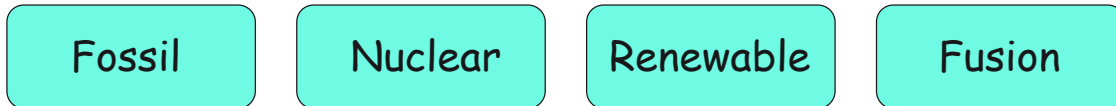
EIA Intl Energy Outlook 2004
<http://www.eia.doe.gov/oiaf/ieo/index.html>
Hoffert et al Nature 395, 883,1998

Fossil challenges

- Finite supply
- Secure access
- Environmental pollution
- Greenhouse gases



The Energy Alternatives



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

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

China: 1 GW / week

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 x 10⁵ TW delivered to Earth
 36,000 TW on land (world)
 2,200 TW on land (US)

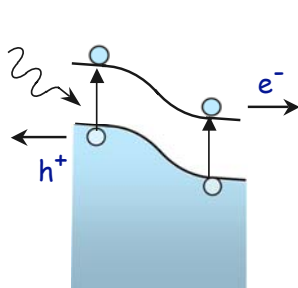
San Francisco Earthquake
 (1906)
 magnitude 7.8
 10¹⁷ Joules
 1 second of sunlight



Earth's
 Ultimate Recoverable Resource
 of oil
 3 Trillion (=Tera) Barrels
 1.7 x 10²² Joules
 1.5 days of sunlight

Annual Human Production of Energy
 4.6 x 10²⁰ Joules
 1 hour of sunlight

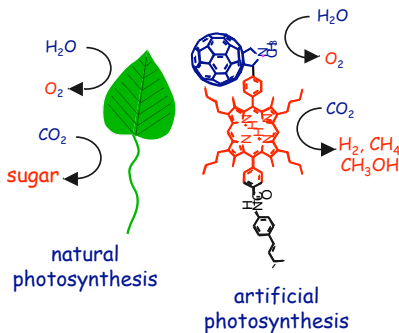
Solar Energy Utilization



Solar Electric

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

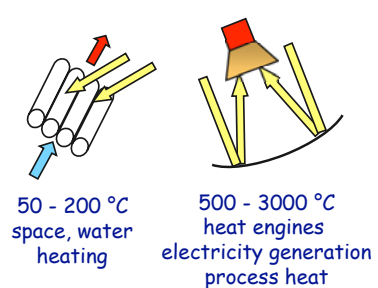
1.5 TW electricity (world)
 \$0.03-\$0.06/kWh (fossil)



Solar Fuel

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

11 TW fossil fuel
 (present use)



Solar Thermal

0.006 TW (world)

2 TW
 space and water
 heating (world)

~ 14 TW additional energy by 2050

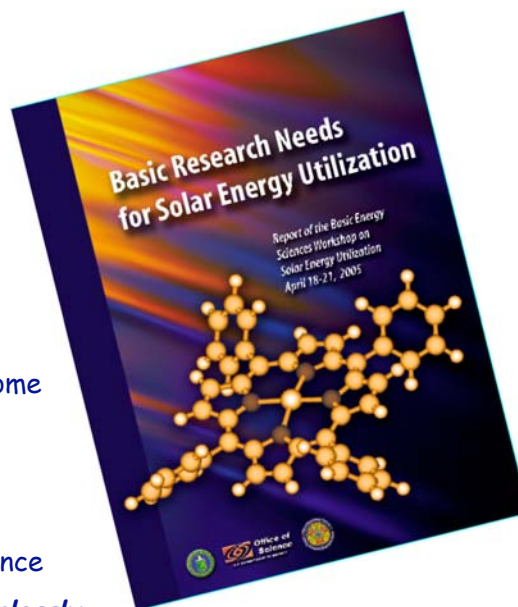
Basic Research Needs for Solar Energy

- *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

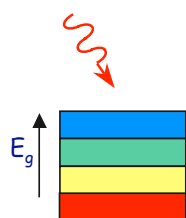
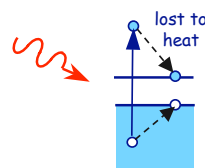
- *Basic and applied science should couple seamlessly*



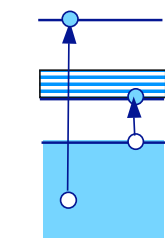
<http://www.sc.doe.gov/bes/reports/abstracts.html#SEU>

Revolutionary Photovoltaics: 50% Efficient Solar Cells

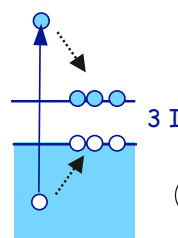
- present technology: 32% limit for
- single junction
 - one exciton per photon
 - relaxation to band edge



multiple junctions

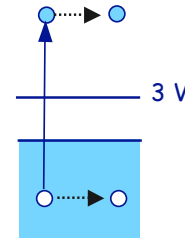


multiple gaps



multiple excitons per photon

nanoscale formats



hot carriers

rich variety of new physical phenomena
challenge: understand and implement

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, H₂, CH₄

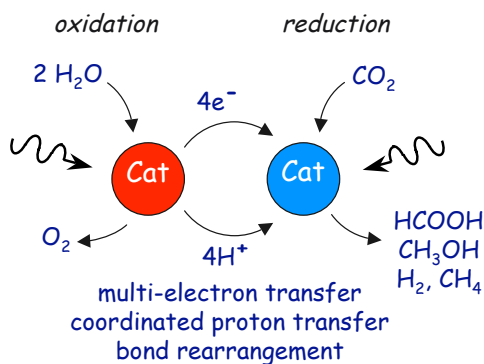


hydrogenase
 $2\text{H}^+ + 2\text{e}^- \rightleftharpoons \text{H}_2$

Scientific Challenges

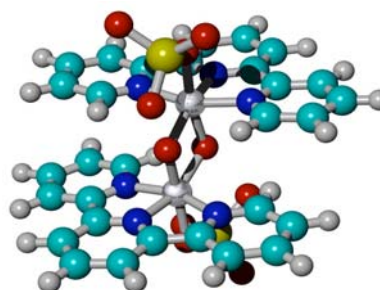
- understand and modify genetically controlled biochemistry that limits growth
- elucidate plant cell wall structure and its efficient conversion to ethanol or other fuels
- capture high efficiency early steps of photosynthesis to produce fuels like ethanol and H₂
- modify bacteria to more efficiently produce fuels
- improved catalysts for biofuels production

Solar-Powered Catalysts for Fuel Formation



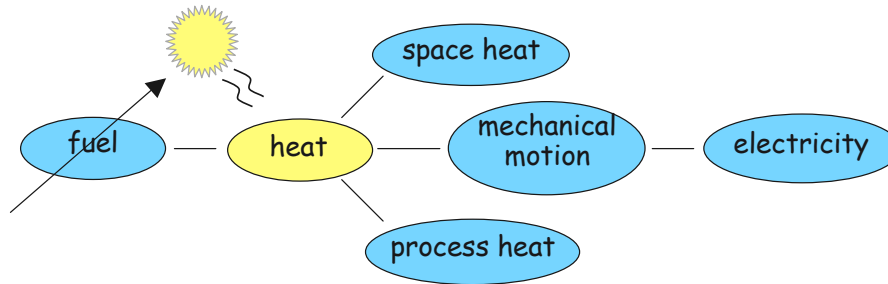
"uphill" reactions enabled by sunlight
 simple reactants, complex products
 spatial-temporal manipulation of electrons, protons, geometry

new catalysts targeted for
 H₂, CH₄, methanol and ethanol
 are needed



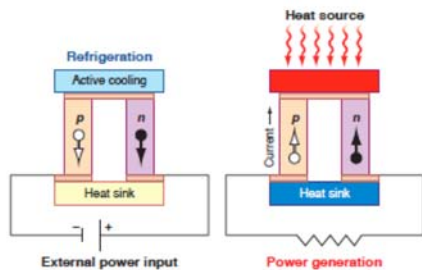
Prototype Water Splitting Catalyst

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

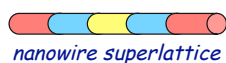
Thermoelectric Conversion



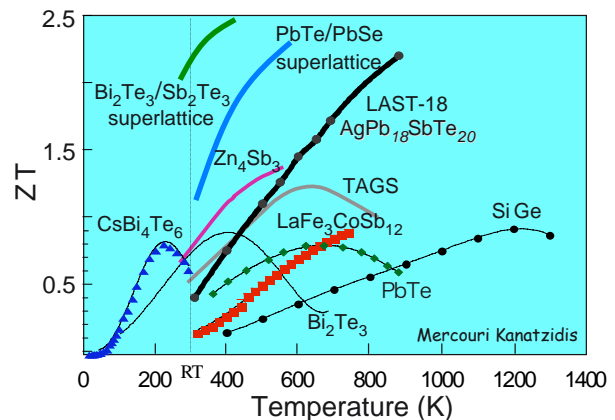
thermal gradient \Leftrightarrow electricity

figure of merit: $ZT = S^2 (\sigma/\kappa) T$
 $ZT \sim 3$: efficiency \sim heat engines
 no moving parts

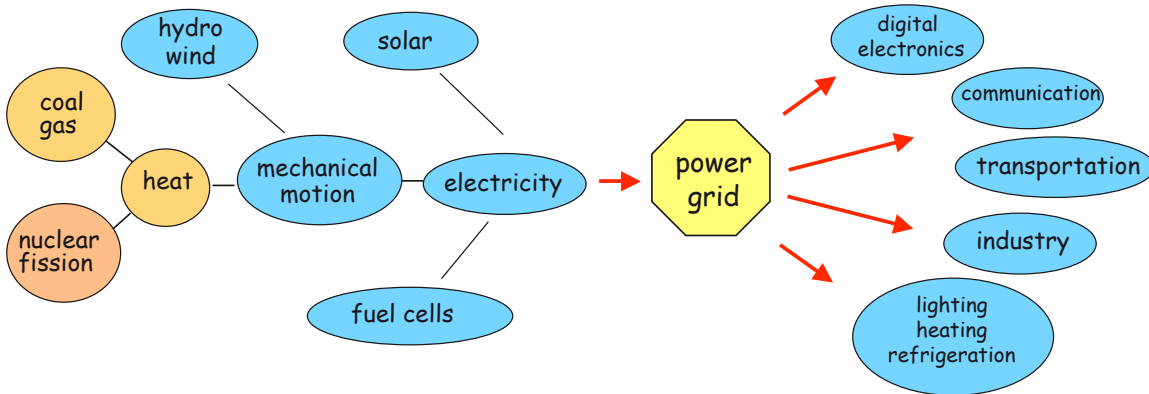
Scientific Challenges
 increase electrical conductivity
 decrease thermal conductivity



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

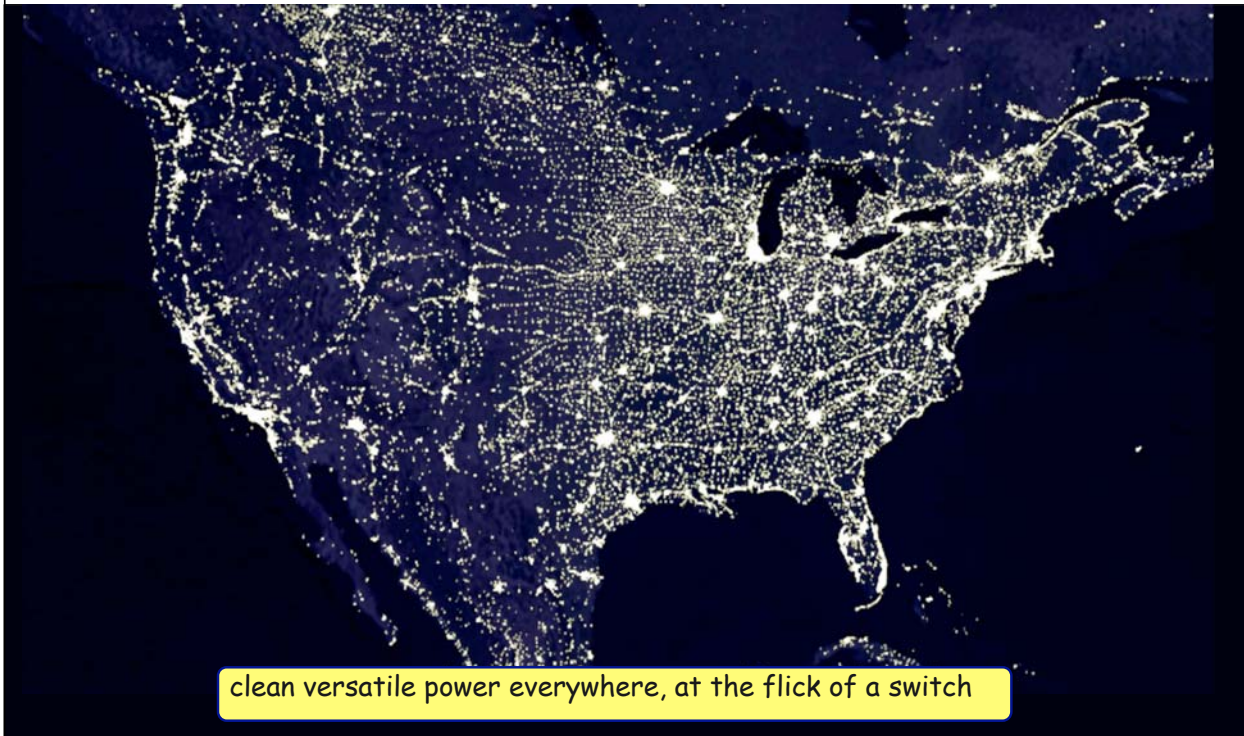


Electricity as an Energy Carrier



35% of primary energy
34% of CO₂ 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

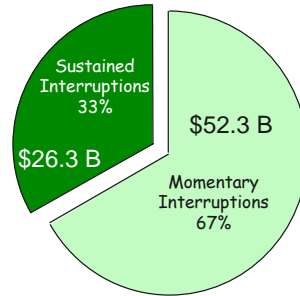


2030
50% demand growth (US)
100% demand growth (world)

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 CO₂

Superconductivity for the 21st Century Grid

*Superconductors carry electrical current
without resistance or energy loss*

capacity \Rightarrow high current / low voltage

reliability / quality \Rightarrow smart, self-healing power control

efficiency \Rightarrow 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

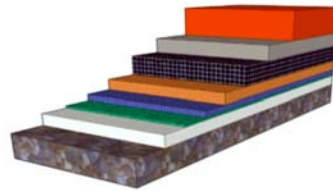
- *Higher temperature and current capability*
- *Understand fundamental phenomena of transition temperature and current flow*



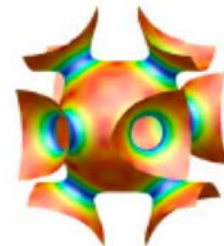
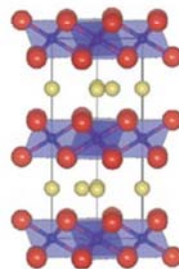
<http://www.sc.doe.gov/bes/reports/abstracts.html#SC>

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 NY, Long Island NY, Columbus OH
- Cost must be reduced by factor 10 - 100 to compete with copper
- Reliable multiyear operation must be demonstrated

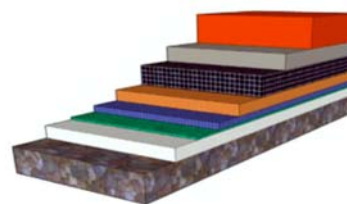
Superconducting Cable Demonstration



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

Superconducting Cable

YBa₂Cu₃O_{7-x} coated conductor
 transition temperature = 92 K
 operating temperature = 77 K (LN₂)
 cheap materials
 high performance
 complex multilayer architecture



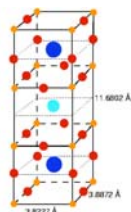
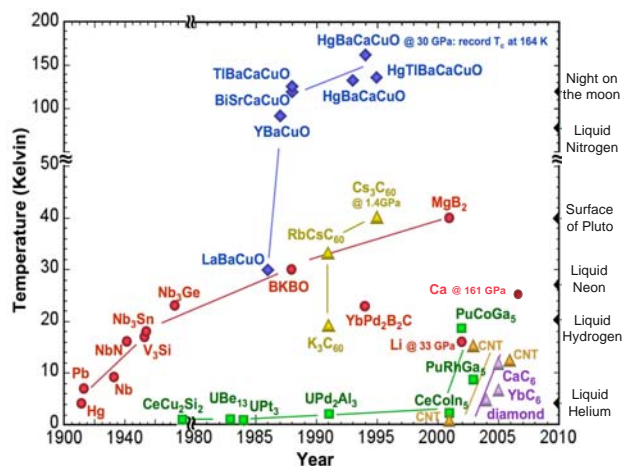
Research Challenges
 Lower cost by factor 10 - 100
simplify architecture
 new dual function materials eliminate layers
simplify layer deposition methods

Next Generation Materials

operate at higher transition temperatures

- ~ 50 copper oxide superconductors
- Highest T_c = 164 K under pressure (1/2 Room Temp)
- Only class of high T_c superconductors ?

High T_c superconductors ≥ 4 elements
 55 superconducting elements
 → 55⁴ ~ 10 million quaternaries

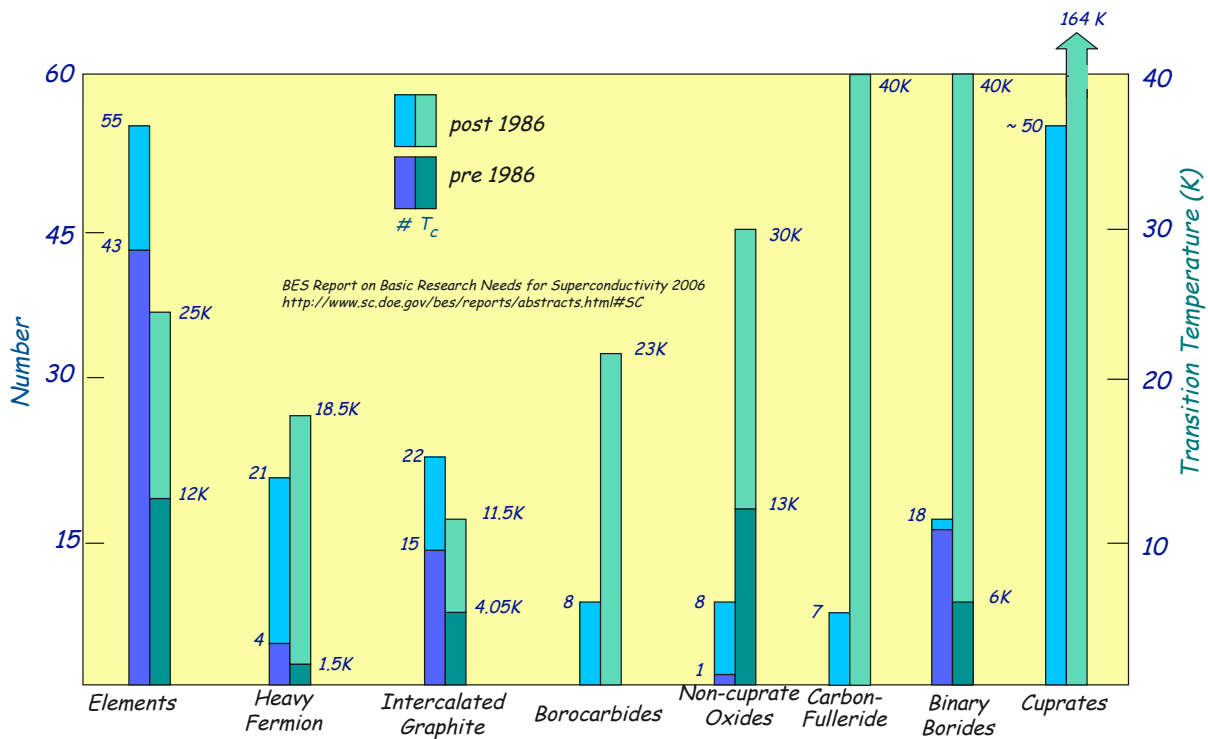


Search strategies for new superconductors

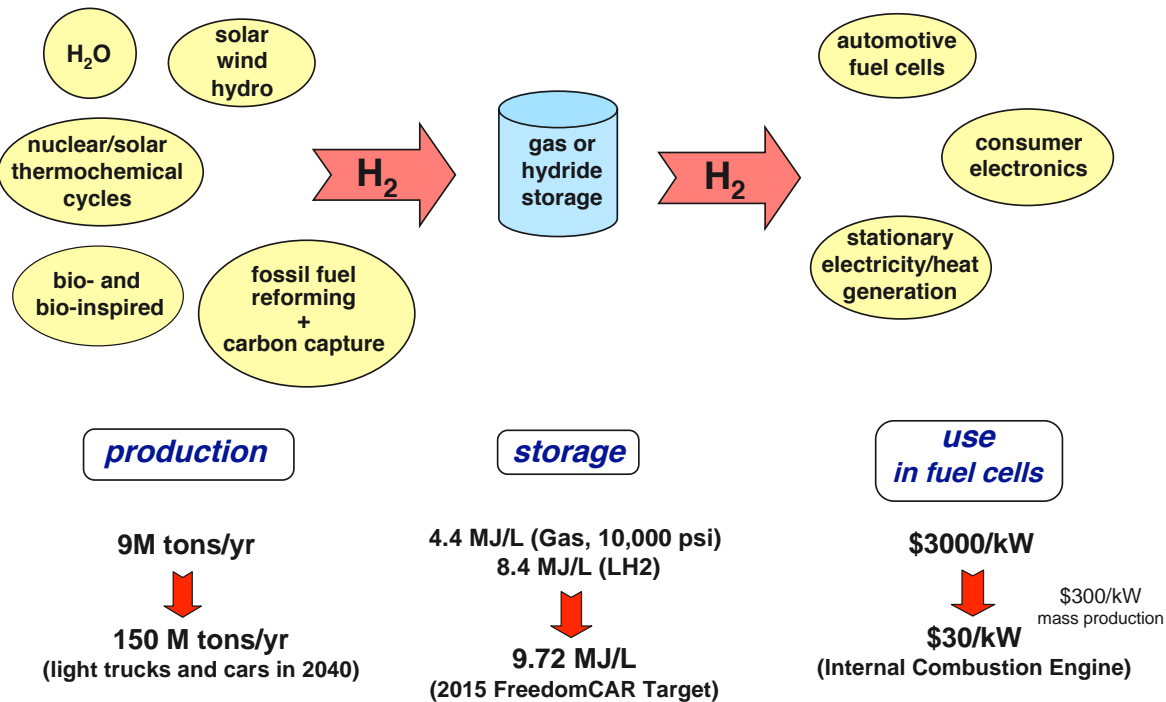
- Quaternary and higher compounds
- Layered structures
- Highly correlated normal states
- Competing high temperature ordered phases

Challenge
 Discover next generation complex superconductors

New Materials: Recent Superconductor Discoveries



Hydrogen as an Energy Carrier



Hydrogen Use Tomorrow: Fuel Cells



transportation
30 buses/10 cities in Europe

<http://www.fuel-cell-bus-club.com/>

battery replacement
longer time/vol-wt

R. Service, Science 296, 1222, 2002

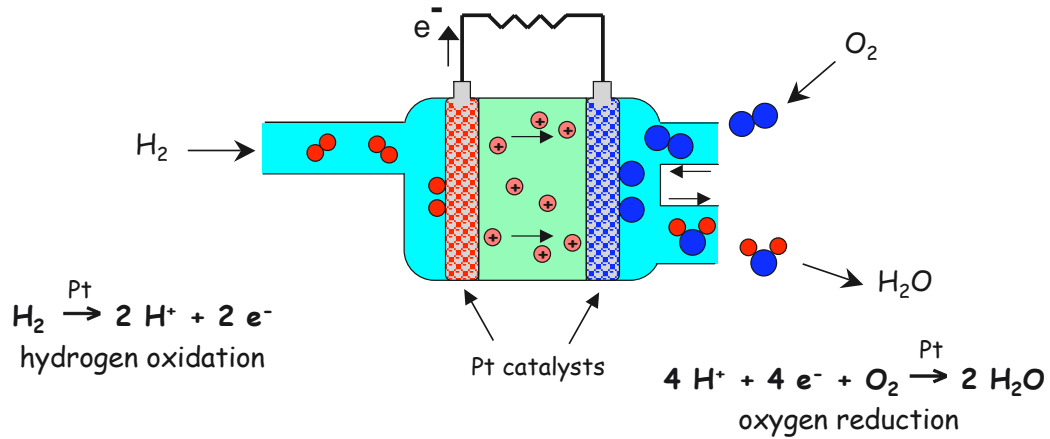


stationary power/heat
250 kW Solid Oxide Fuel Cell



Fuel Cell Principles

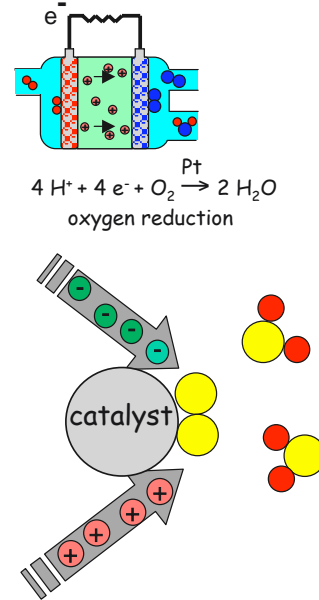
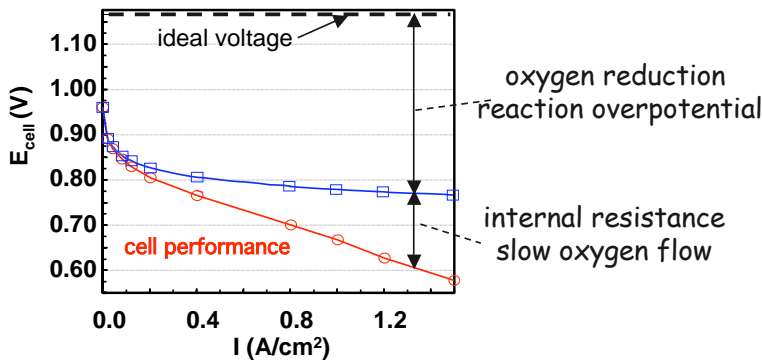
proton exchange membrane fuel cell



*a chemical engine, not a heat engine
chemical energy to electrical energy
~ twice the efficiency of a heat engine*

Fuel Cell Challenges: Oxygen Reduction Reaction

cathode "overpotential"



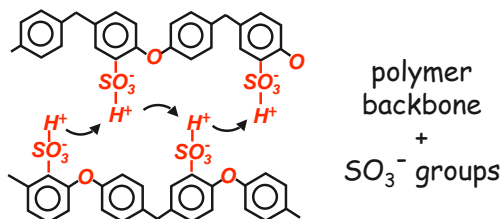
slow kinetics at the cathode
more active catalysts

complex spatial/temporal
coordination

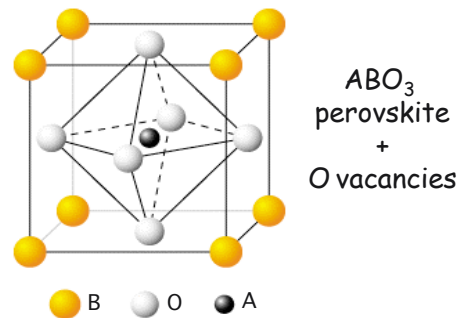
Basic Research Needs for the Hydrogen Economy,
DOE Office of Science/Basic Energy Sciences (2004)
<http://www.sc.doe.gov/bes/reports/list.html>

Markovic and Ross, Surface Science Rep 45,117 (2003)

Fuel Cell Challenges: Ion Conducting Membranes



proton exchange membranes
 H_2O assists proton transport $\sim 80^\circ C$
active electrode catalysts required
higher temperature membranes needed



solid oxide fuel cells
 O^{2-} exchange membranes
vacancies $\sim 800^\circ C$
charge deficient substitution A, B
dense vacancies - structural instability
lower temperature membranes needed

R. Rajendran, MRS Bulletin 30, 587, 2005
G. Marsh, Materials Today 6(3), 28, 2003
Q. Li et al, Chem Mater 15, 4896, 2003

H. Yokokawa, MRS Bulletin 30, 591, 2005
Z. Shao and S. Haile, Nature 431, 170, 2004
Skinner and Kilner, Materials Today 6(3), 30, 2003

Hydrogen Storage Today: Gas and Liquid



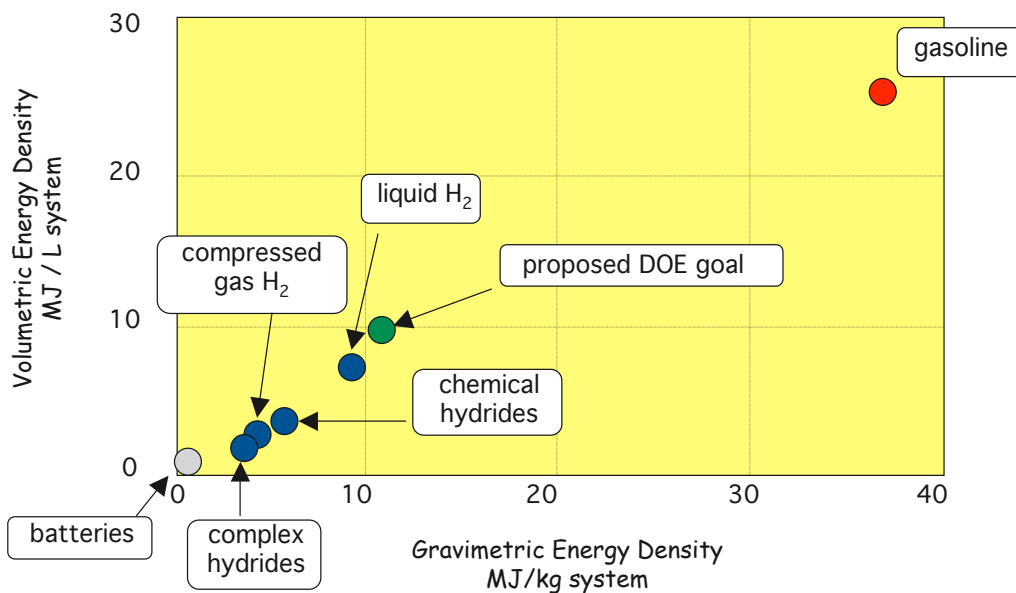
gaseous storage
 5000 psi = 350 bar
 10000 psi = 700 bar
 fiber reinforced
 composite containers

liquid storage
 standard in stationary applications
 portable cryogenics for auto
 30-40% energy lost to liquifaction

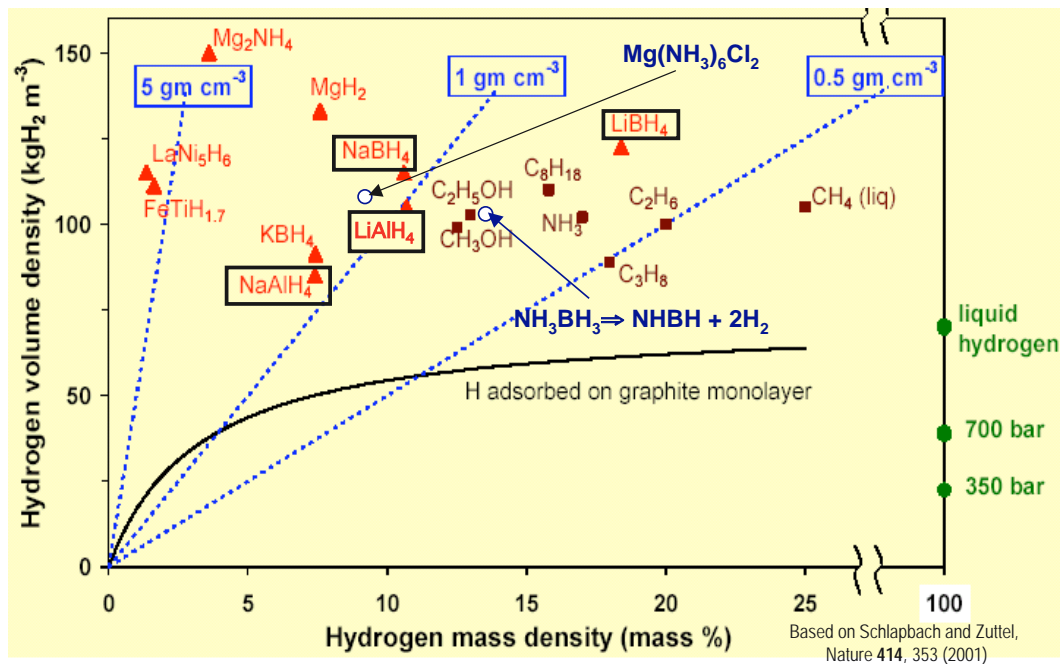
within technological reach

Storage Challenges: Energy Density

Energy Density of Fuels



Hydrogen Storage Tomorrow: Hydride Materials



Energy Conversion Efficiency

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

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