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The Sustainable Energy Challenge

George Crabtree

Argonne National Laboratory

Fossil Energy Challenges

Sustainable Alternatives

Electricity

Hydrogen

Today's Workshop Program

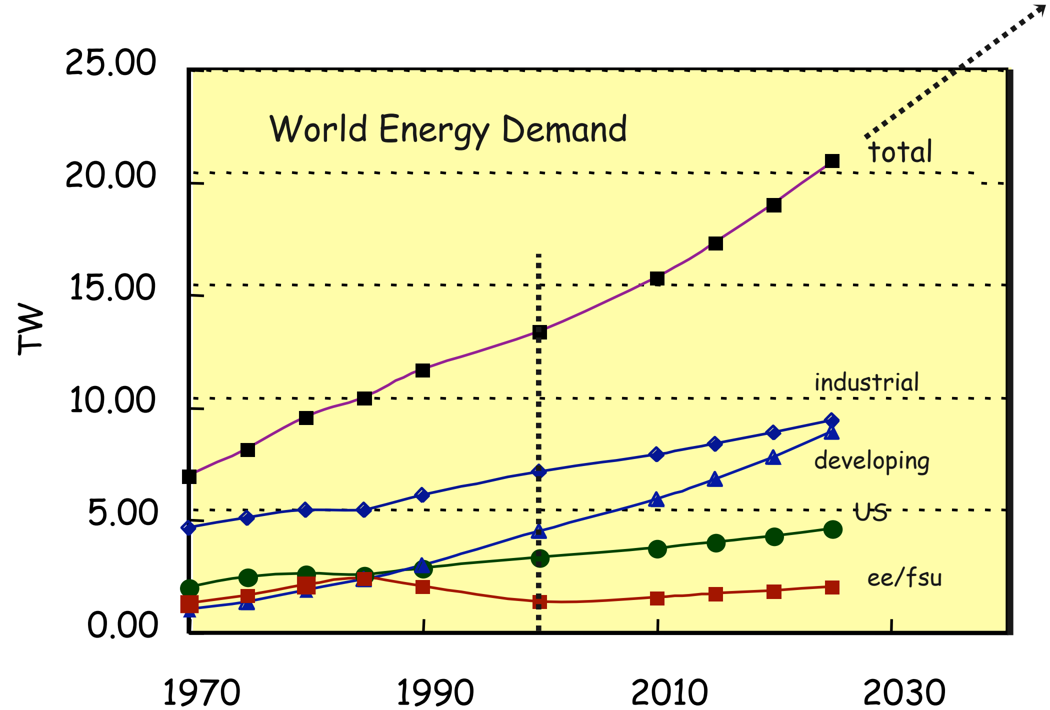
APS Energy Research Workshop

Pittsburgh PA

March 15, 2009

World Energy Demand

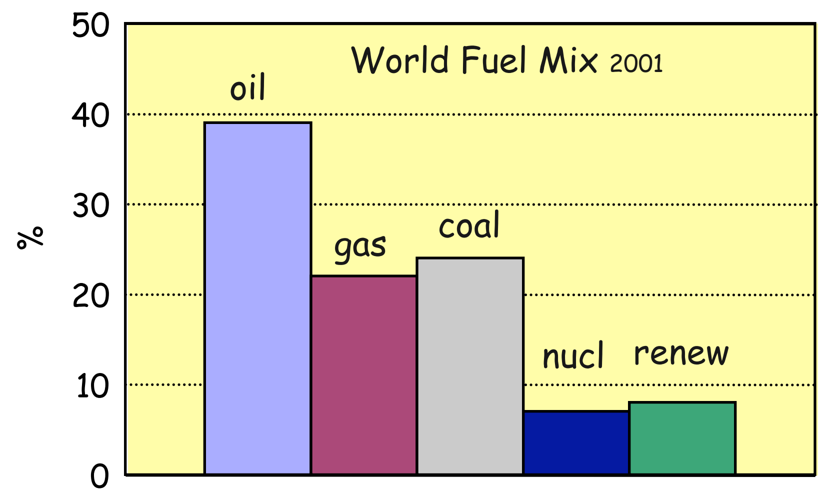
2100: 40-50 TW
2050: 25-30 TW



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

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

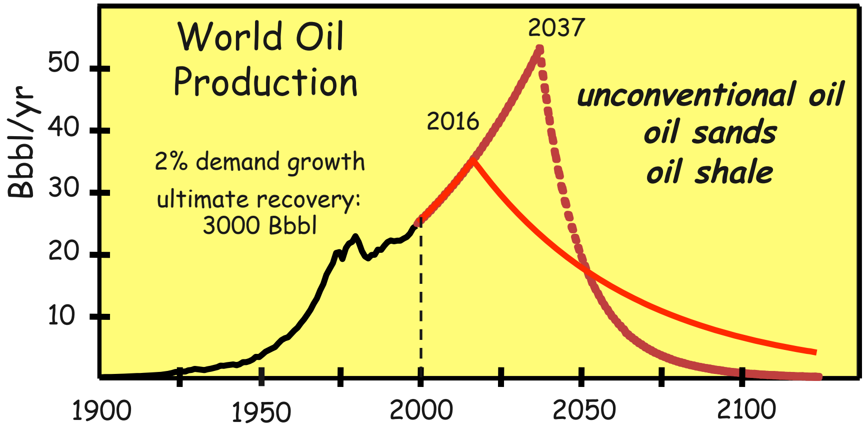
Hoffert et al Nature 395, 883,1998



85% fossil

Energy Challenges: Supply and Security

When Will Production Peak?



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

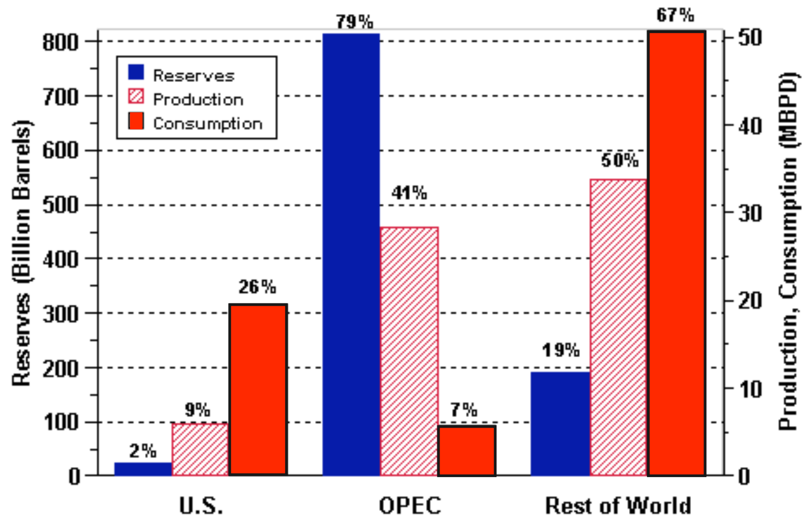
R. Kerr, Science **310**, 1106 (2005)

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



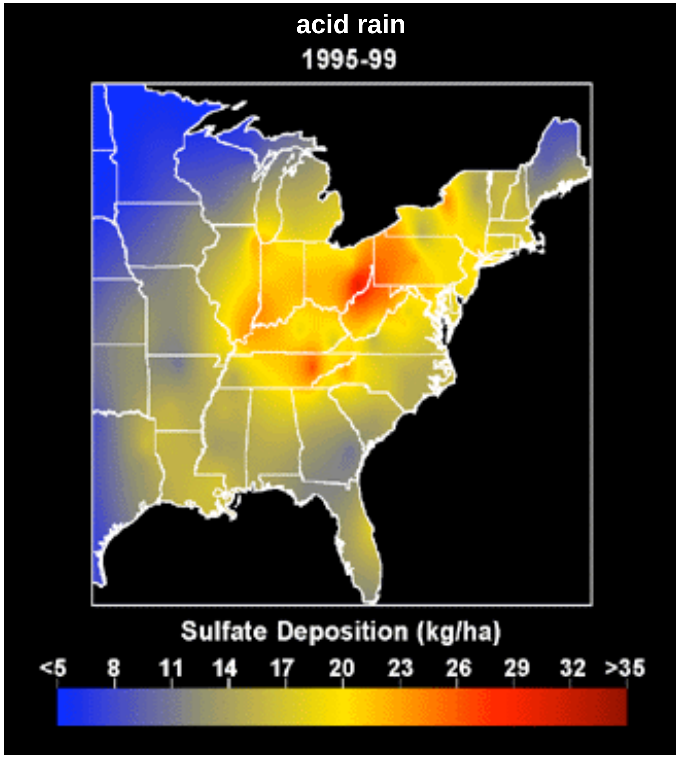
OPEC: Venezuela, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, United Arab Emirates, Algeria, Libya, Nigeria, and Indonesia

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

Energy Challenges: Pollution

acid rain in the US

Auto exhaust in Los Angeles

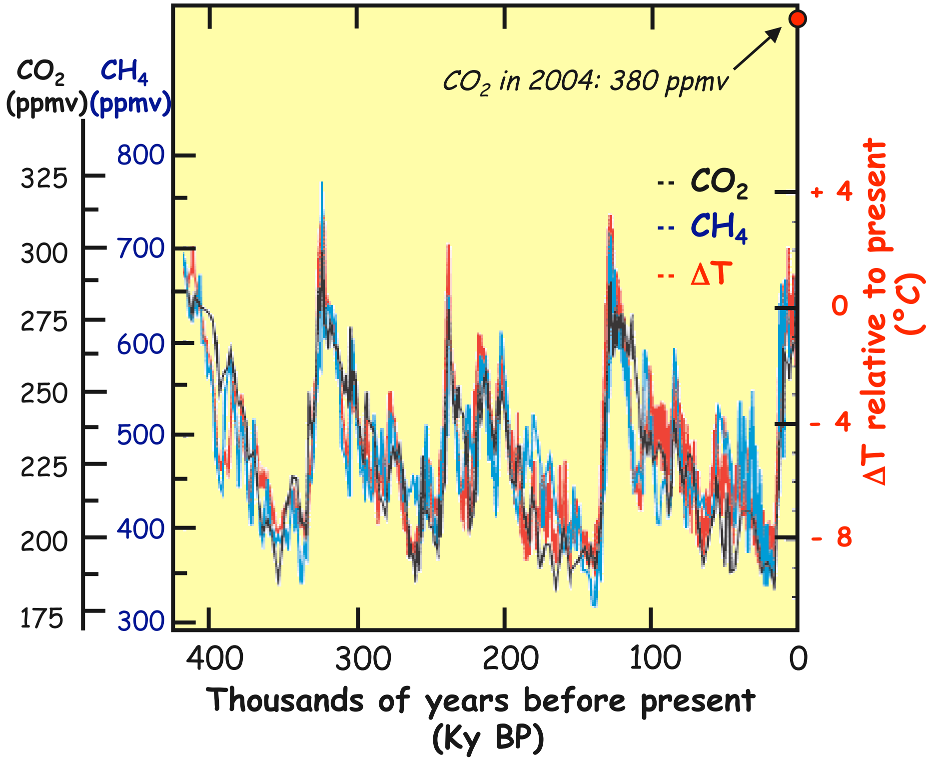


pollution collects in high auto density basins

pollution zones near sources urban areas, power plants

http://www.epa.gov/air/urbanair/6poll.html

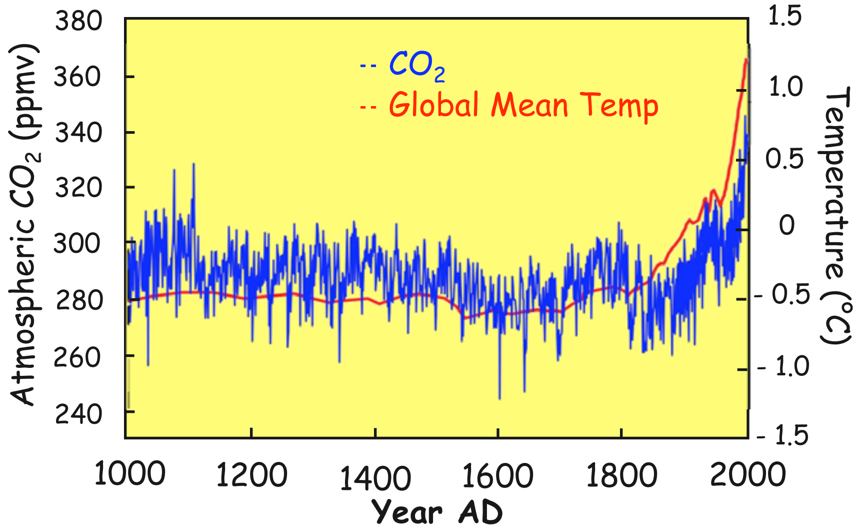
Energy Challenges: Climate Change



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 | Fission | Renewable | Fusion | Efficiency

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

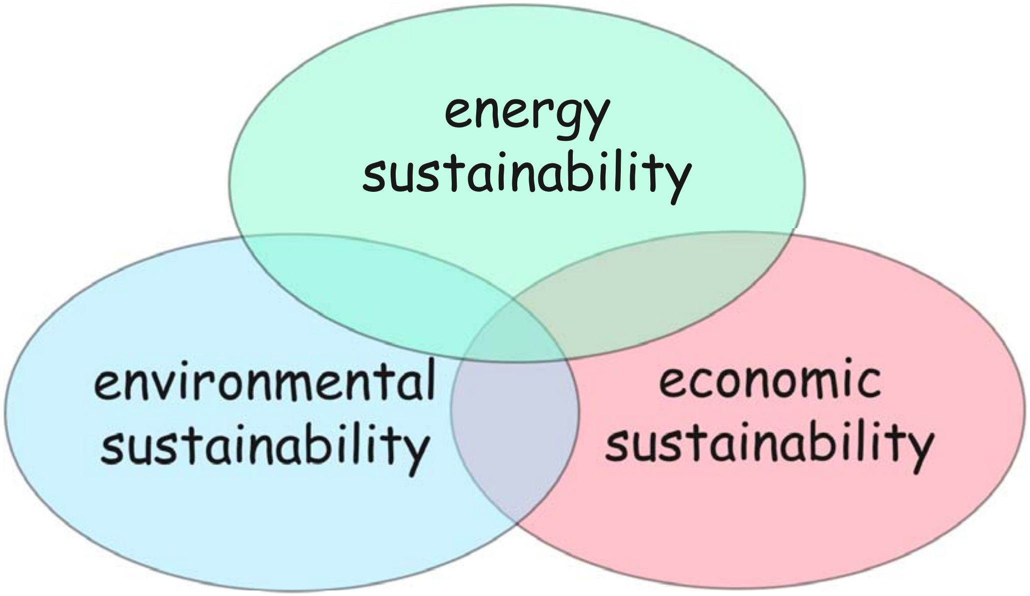
1 new power plant/day for 27 years

China: 1 GW / week

no single solution

diversity of energy sources required

The Goal: Sustainability



a multidimensional, interactive challenge

What is Sustainability?

Lasts a long time

Oil in 1900

Coal in 2008

Does no harm

Nuclear electricity: no CO_2

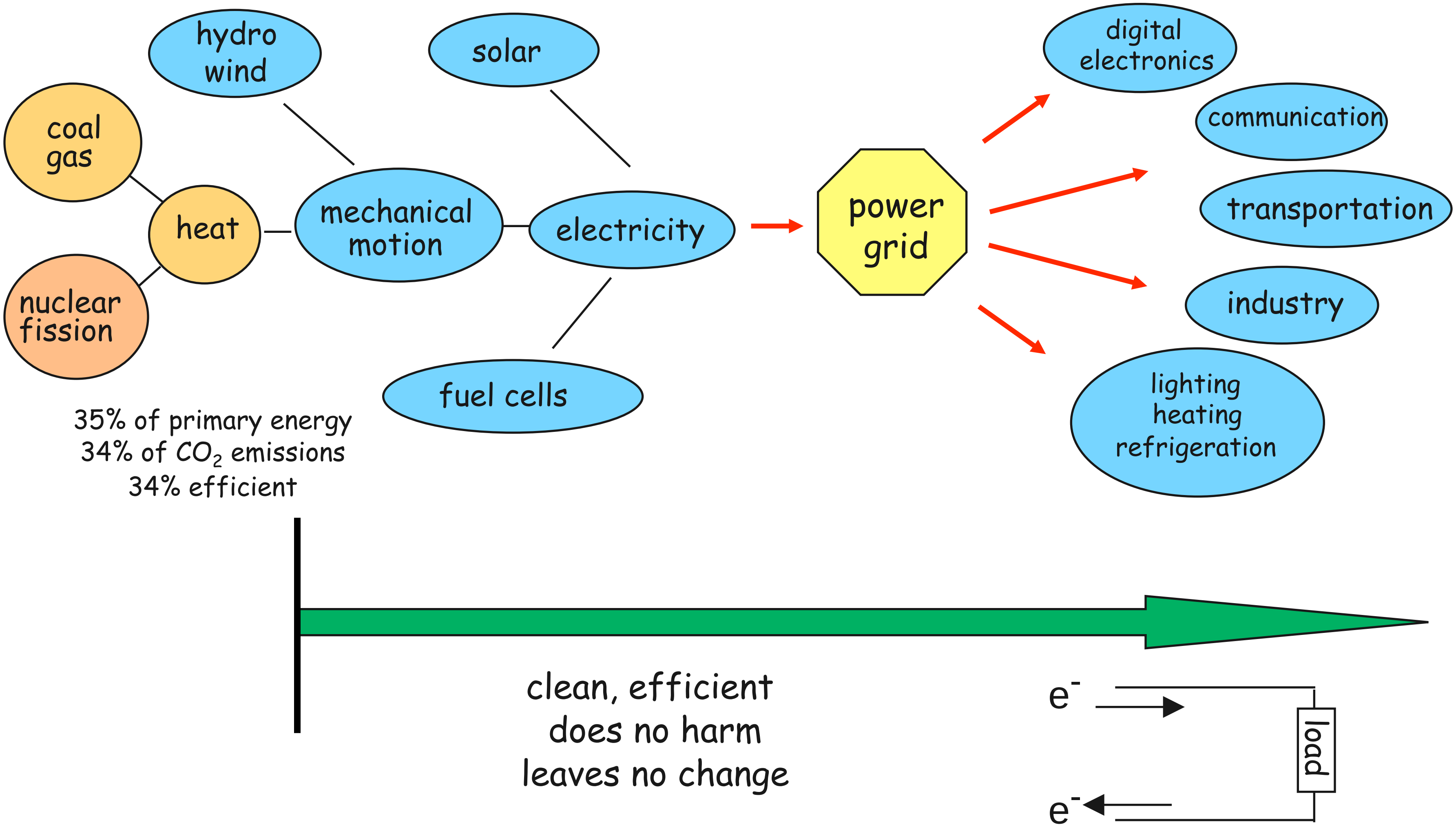
Ethanol: reduced CO_2

Leaves no change

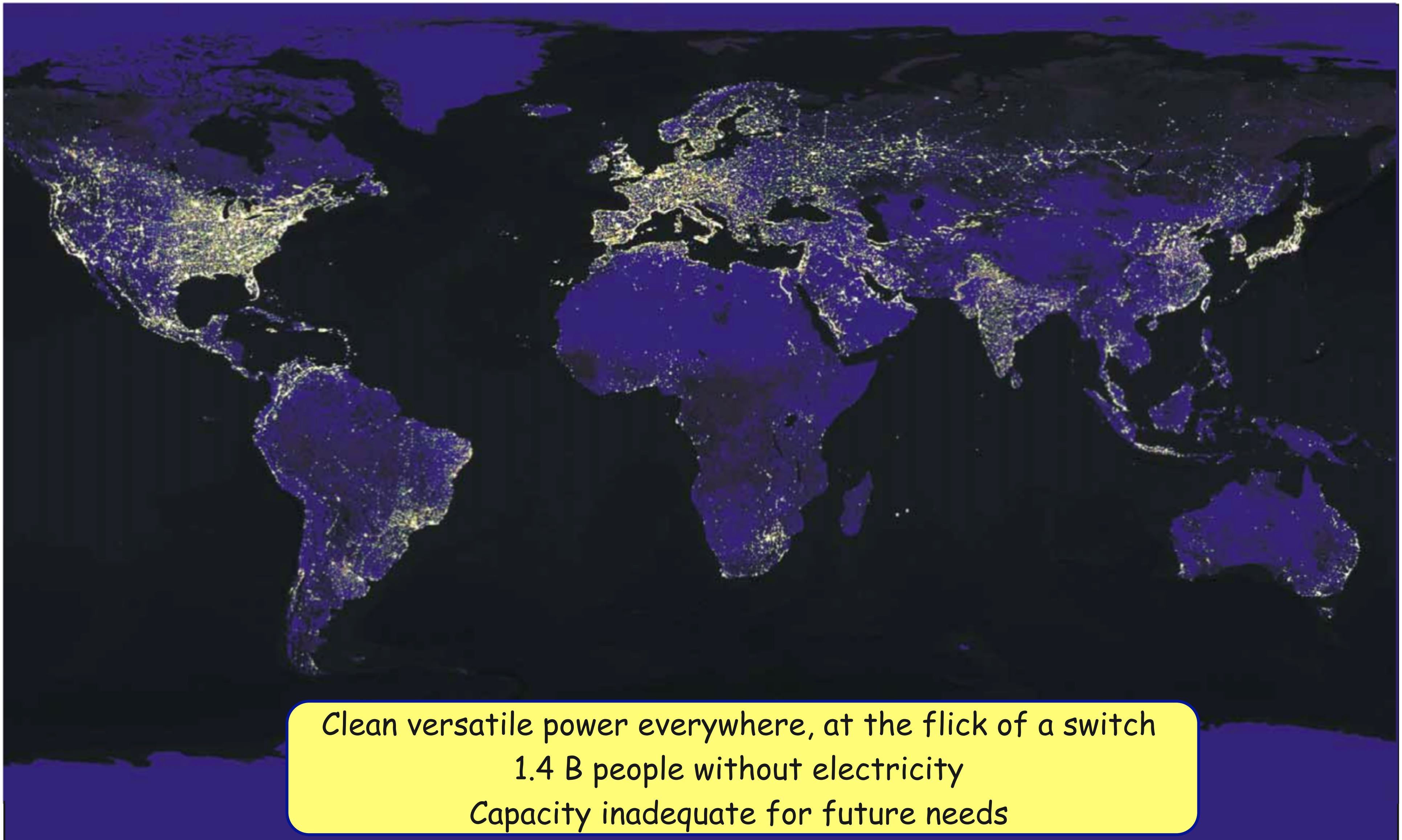
Closed chemical cycle

Electricity, hydrogen

Electricity as an Energy Carrier

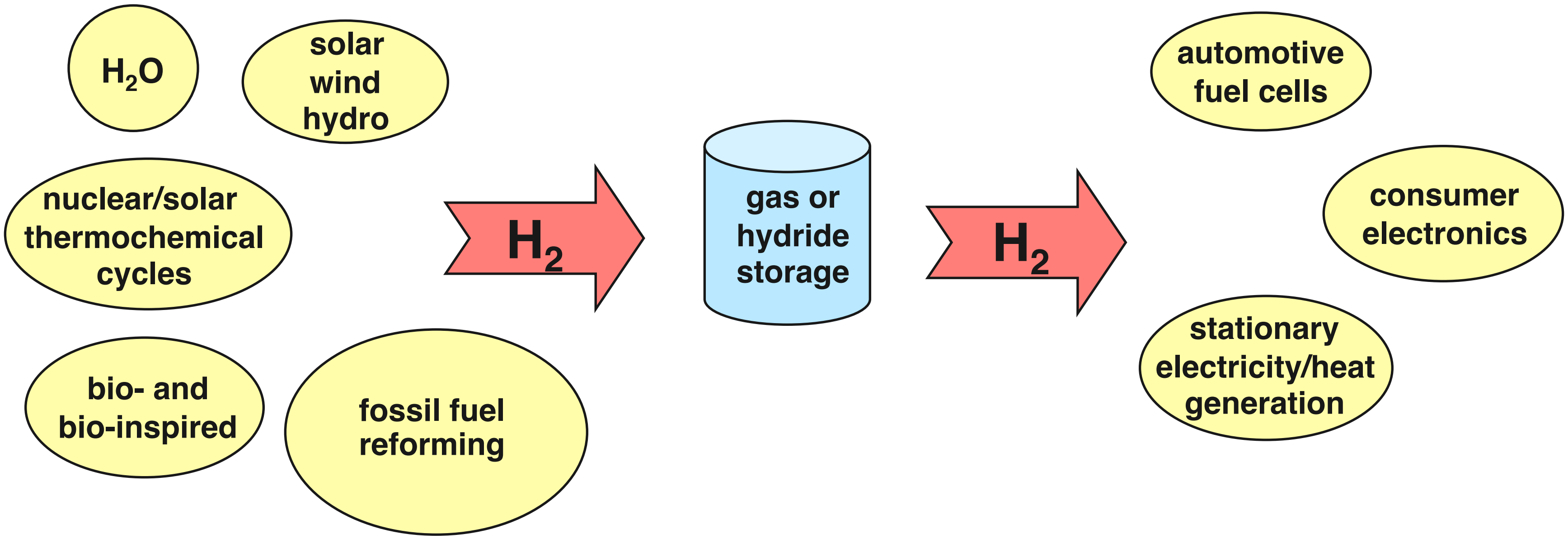


The Grid - the Triumph of 20th Century Engineering



Clean versatile power everywhere, at the flick of a switch
1.4 B people without electricity
Capacity inadequate for future needs

Hydrogen as an Energy Carrier



90% of hydrogen produced in US by reforming CH_4

$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

clean, efficient
does no harm
leaves only H_2O

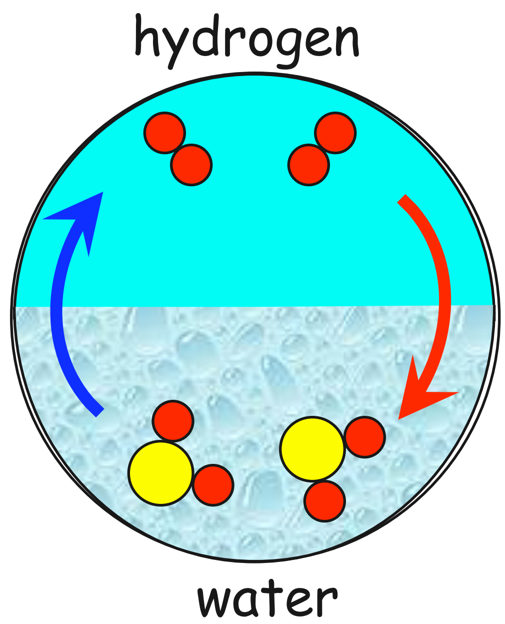
$2\,H_2 + O_2 \rightarrow 2\,H_2O$

The Appeal of Hydrogen: Closing the Cycle

Energy in

Solar or Wind Electricity

Sunlight



Energy out

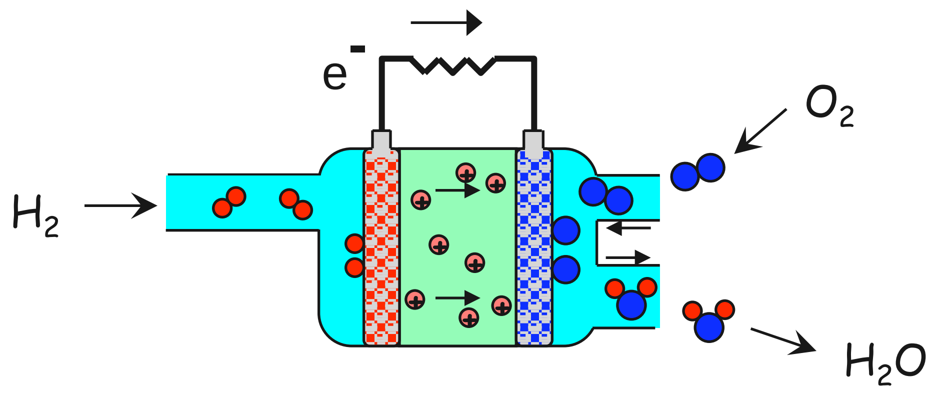
Electricity in fuel cells

hydrogen: a clean carrier of energy

water: a clean carrier of hydrogen

The hydrogen - water cycle can be closed to leave no chemical change

The Appeal of Hydrogen: Conversion to Electricity



hydrogen can be exchanged for electricity in a fuel cell

natural partners

hydrogen: stable, storable energy carrier

electricity: versatile, disposable energy carrier

electric transportation: hydrogen + fuel cell

renewable electricity: hydrogen as local storage media

The Sustainable 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

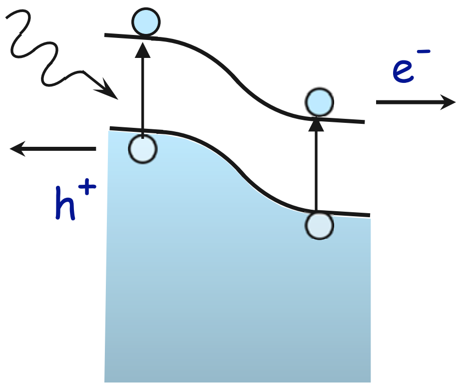
1.5 days of sunlight

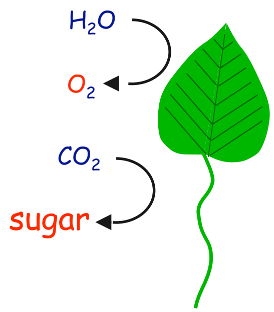
Annual Human Production of Energy

4.6×10^{20} Joules

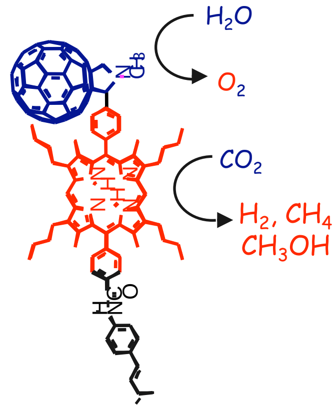
1 hour of sunlight

Solar Energy Utilization

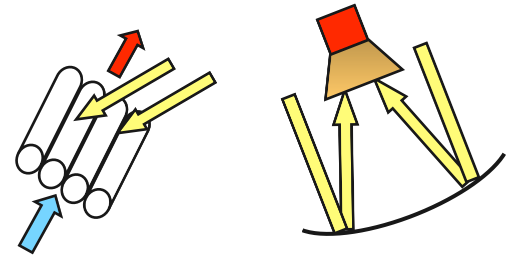




natural
photosynthesis



artificial
photosynthesis



50 - 200 °C
space, water
heating

500 - 3000 °C
heat engines
electricity generation
process heat

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)

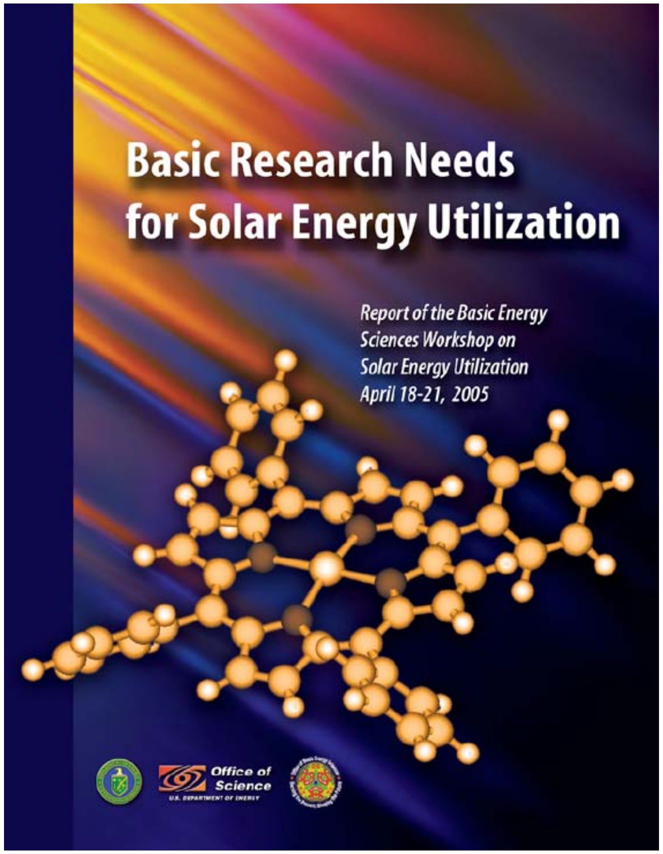
Solar Thermal

0.006 TW (world)

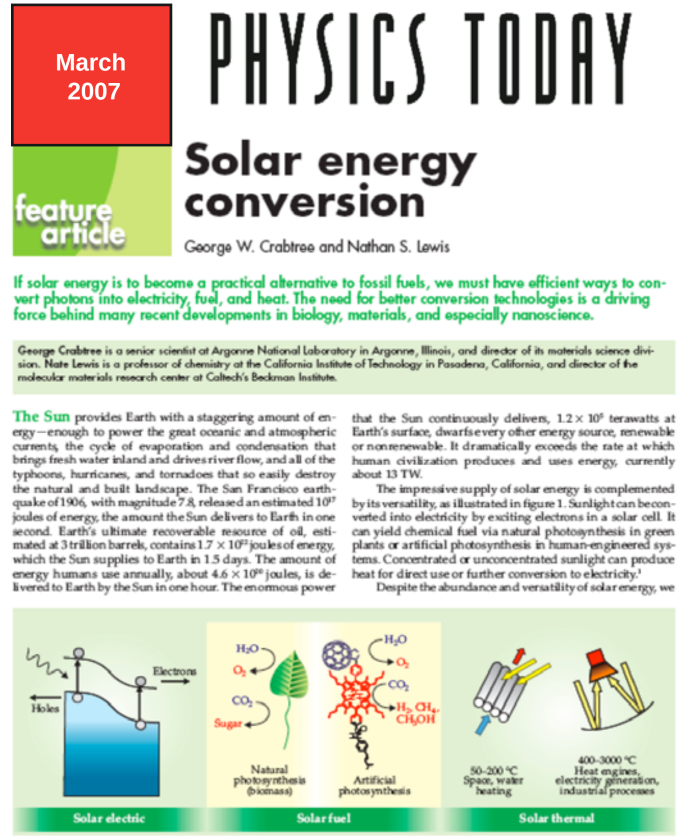
2 TW
space and water
heating (world)

~ 14 TW additional energy by 2050

Solar Energy Challenges and Opportunities



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



March 2007

PHYSICS TODAY

feature article

Solar energy conversion

George W. Crabtree and Nathan S. Lewis

If solar energy is to become a practical alternative to fossil fuels, we must have efficient ways to convert photons into electricity, fuel, and heat. The need for better conversion technologies is a driving force behind many recent developments in biology, materials, and especially nanoscience.

George Crabtree is a senior scientist at Argonne National Laboratory in Argonne, Illinois, and director of its materials science division. Nate Lewis is a professor of chemistry at the California Institute of Technology in Pasadena, California, and director of the molecular materials research center at Caltech's Beckman Institute.

The Sun provides Earth with a staggering amount of energy—enough to power the great oceanic and atmospheric currents, the cycle of evaporation and condensation that brings fresh water inland and drives river flow, and all of the typhoons, hurricanes, and tornadoes that so easily destroy the natural and built landscape. The San Francisco earthquake of 1906, with magnitude 7.8, released an estimated 10^{17} joules of energy, the amount the Sun delivers to Earth in one second. Earth's ultimate recoverable resource of oil, estimated at 3 trillion barrels, contains 1.7×10^{22} joules of energy, which the Sun supplies to Earth in 1.5 days. The amount of energy humans use annually, about 4.6×10^{20} joules, is delivered to Earth by the Sun in one hour. The enormous power that the Sun continuously delivers, 1.2×10^{5} terawatts at Earth's surface, dwarfs every other energy source, renewable or nonrenewable. It dramatically exceeds the rate at which human civilization produces and uses energy, currently about 13 TW.

The impressive supply of solar energy is complemented by its versatility, as illustrated in figure 1. Sunlight can be converted into electricity by exciting electrons in a solar cell. It can yield chemical fuel via natural photosynthesis in green plants or artificial photosynthesis in human-engineered systems. Concentrated or unconcentrated sunlight can produce heat for direct use or further conversion to electricity.[1]

Despite the abundance and versatility of solar energy, we

George Crabtree and Nathan Lewis
Physics Today **60**(3), 37 (2007)

http://ptonline.aip.org/dbt/dbt.jsp
?KEY=PHTOAD&Volume=60&Issue=3#MAJOR1

Storing the Energy We Produce

- Store intermittent solar and wind electricity
- Electrify transportation with plug-in hybrids and electric cars

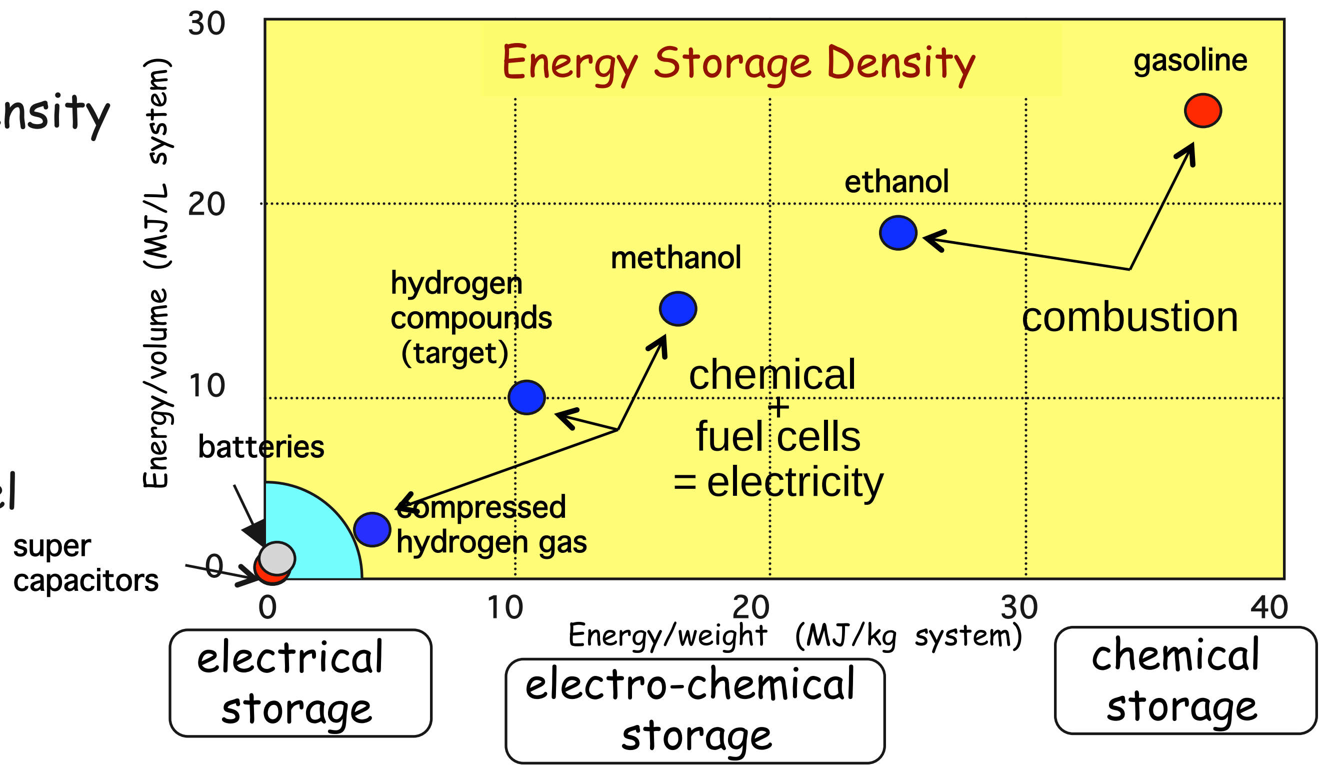
batteries:

30-50x less energy density than gasoline

impossible dream: x10 improvement

beyond batteries:

chemical storage + fuel cells = electricity



breakthroughs needed

x2-5 increase in battery energy density

x10-20 increase through chemical storage + fuel cells

Research Challenges for Sustainable Alternatives to Fossil

Electricity

- *Renewable production: solar photovoltaics, thermoelectrics*
- *Storage: bridging cycles of supply and demand*
- *Distribution: grid capacity saturated - superconductivity*
- *Use: efficient solid state lighting*

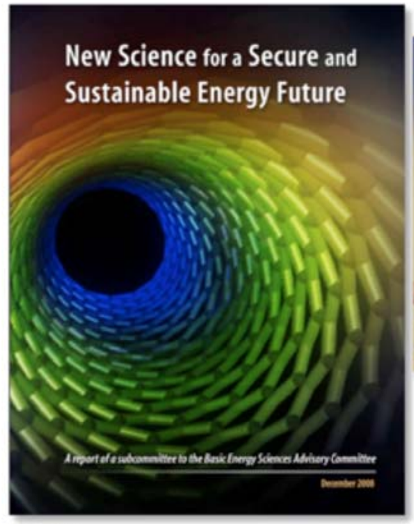
Hydrogen

- *Renewable production: splitting water from solar photons or heat*
- *Storage: high density storage media for transportation*
- *Use: performance, durability and lowering cost of fuel cells*

The Energy and Science Grand Challenges

BESAC and BES Reports

- Secure Energy Future, 2002
- Hydrogen Economy, 2003
- Solar Energy Utilization, 2005
- Superconductivity, 2006
- Solid-state Lighting, 2006
- Advanced Nuclear Energy Systems, 2006
- Clean and Efficient Combustion of Fuels, 2006
- Electrical Energy Storage, 2007
- Catalysis for Energy, 2007
- Geosciences: Facilitating 21st Century Energy Systems, 2007
- Materials Under Extreme Environments, 2007
- Directing Matter and Energy: Five Grand Challenges for Science and the Imagination, 2007
- New Science for a Secure and Sustainable Energy Future, 2008



http://www.sc.doe.gov/bes/reports/list.html

Energy: Interdisciplinary Science of the 21st Century

Transforming the Energy Chain

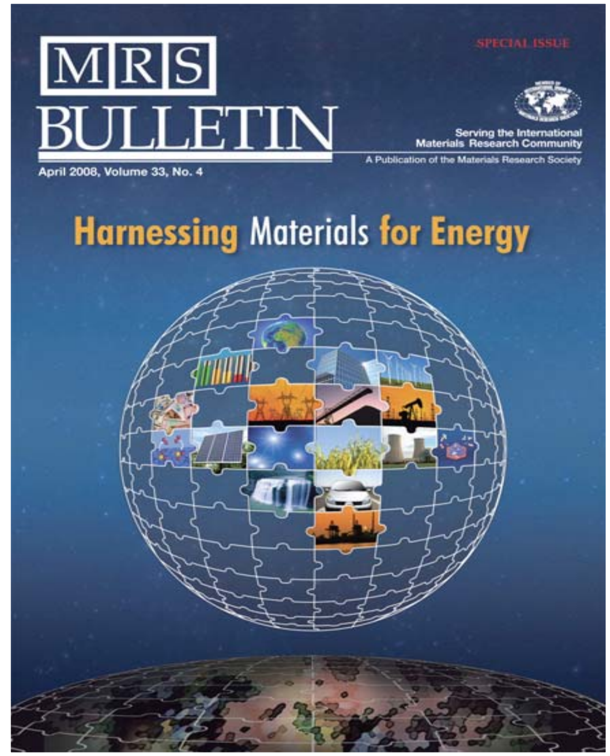
Resources ⇒ Carriers ⇒ Storage ⇒ Use

Sustainability

Environment Climate Economy

Materials

the critical links in the energy chain



April 2008
www.mrs.org/bulletin_energy

Today's APS Energy Research Workshop Program

Compound Semiconductor and Multijunction Solar Cells
Harry Atwater – Caltech

Recent advances in organic photovoltaics
Gary Rumbles – NREL

Batteries for transportation
Mark Verbrugge – General Motors

Vehicular Hydrogen Storage with Sorbent Materials
Channing Ahn - Caltech

Solid State Lighting
Jeff Tsao - Sandia National Lab

Superconductivity: Challenges and Opportunities for Our Energy Future
John Sarrao – Los Alamos

Panel Discussion on Careers and Research Funding
Art Nozik – *National Renewable Energy Laboratory*
Jeff Tsao– *Sandia National Laboratory*
Jan Herbst – *General Motors*
Vivek Mohta – *Massachusetts Department of Energy Resources*

5:30 - 6:30 Reception and Informal Discussion