Argonne NATIONAL LABORATORY

... for a brighter future

U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

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The Sustainable Energy Challenge

George Crabtree

Argonne National Laboratory

Fossil Energy Challenges

Sustainable Alternatives

Electricity

Hydrogen

Research Challenges

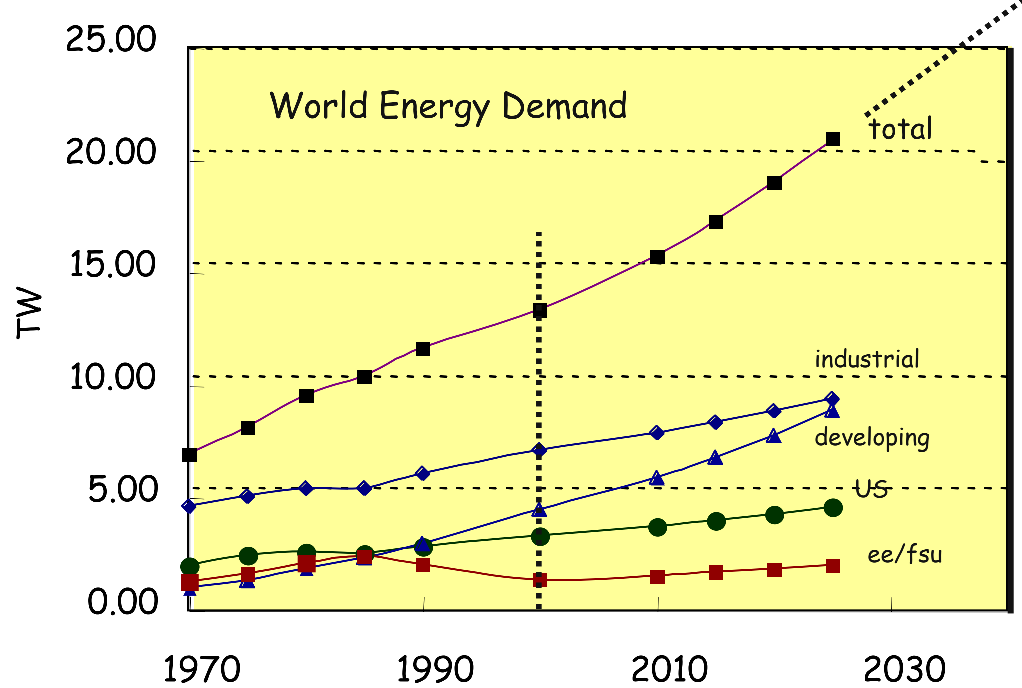
NSLS-CFN Users Meeting

Brookhaven National Laboratory

May 20, 2008

World Energy Demand

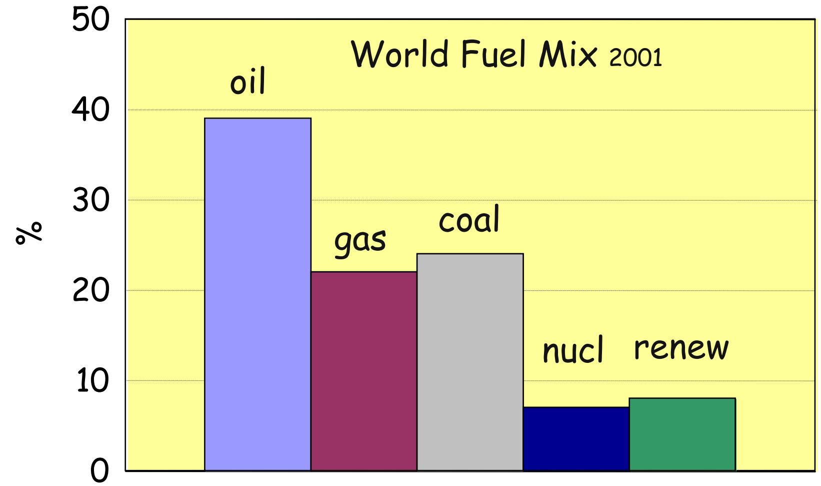
2100: 40-50 TW
2050: 25-30 TW



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

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

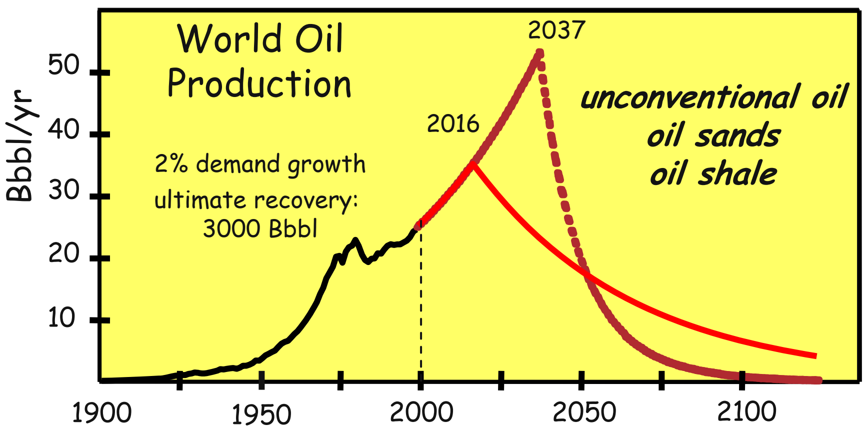
Hoffert et al Nature 395, 883,1998



85% fossil

Energy Challenges: Supply and Security

When Will Production Peak?



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

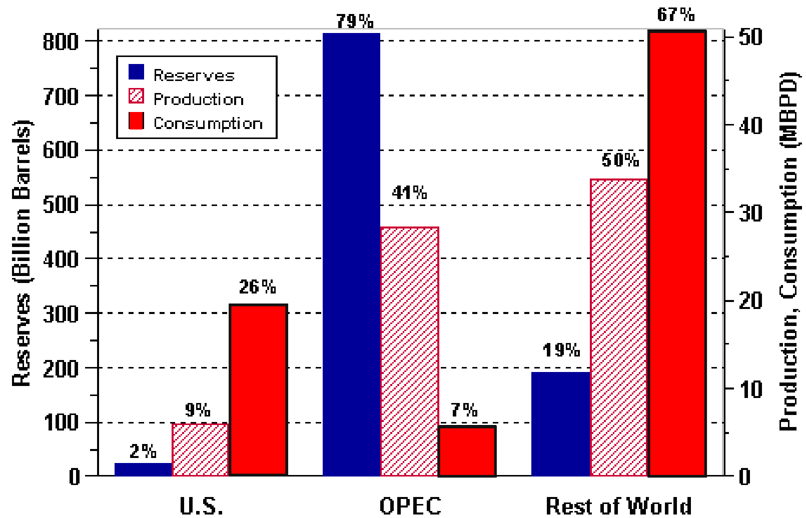
R. Kerr, Science **310**, 1106 (2005)

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

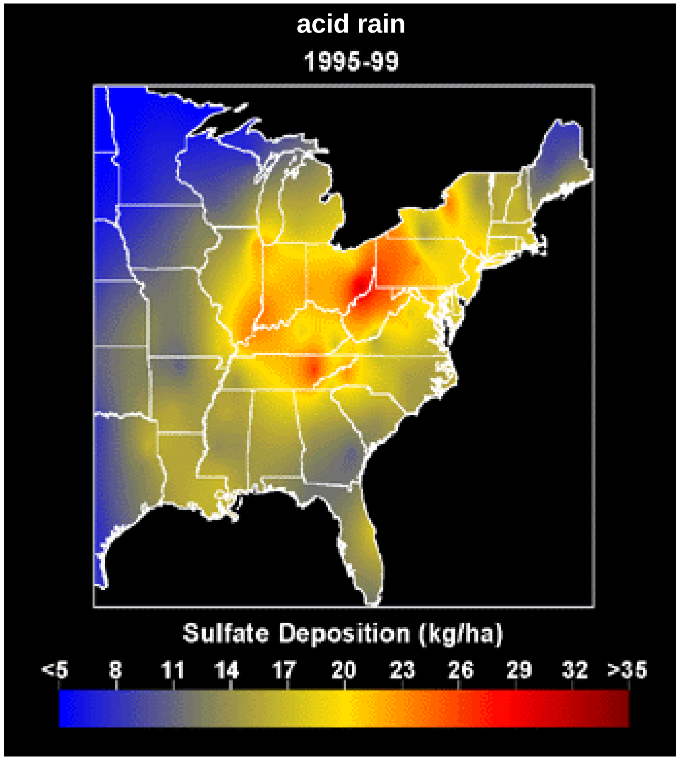
Energy Challenges: Pollution

acid rain in the US

air pollution in Beijing

99% of urban dwellers in China
breathe unsafe air
by European Union standards

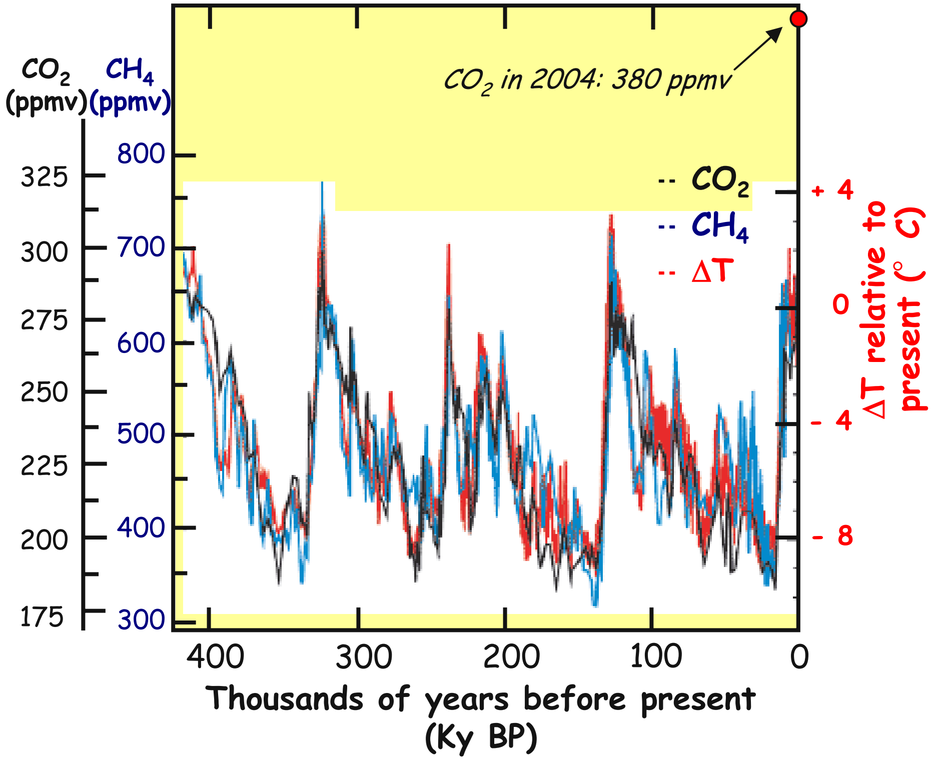
http://www.nytimes.com/2007/08/26/world/asia/26china.html



pollution zones near sources
urban areas, power plants

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

Energy Challenges: Climate Change

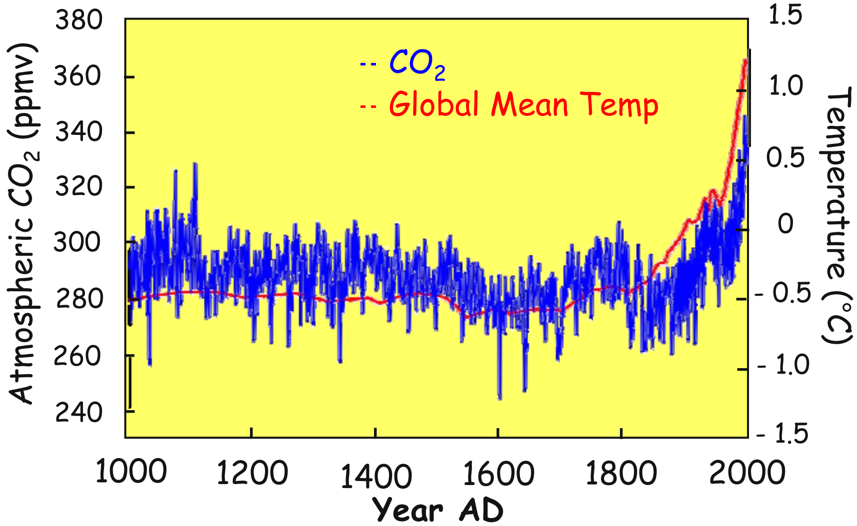


Climate Change 2001: The Scientific Basis, Fig 2.22

*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*

Relaxation time

transport of CO_2 or heat to deep ocean: 400 - 1000 years



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

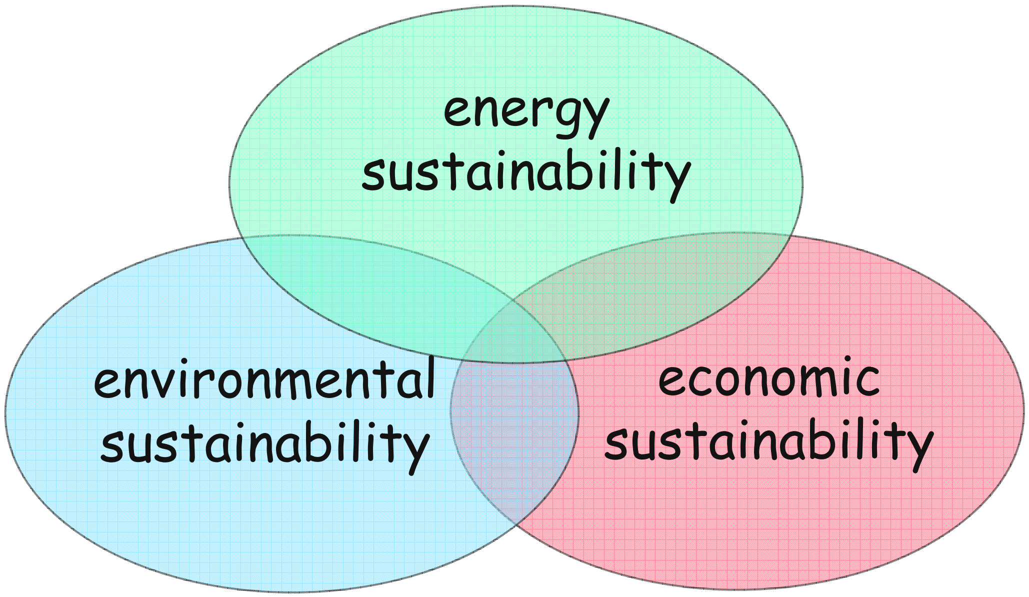
1 new power plant/day for 27 years

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

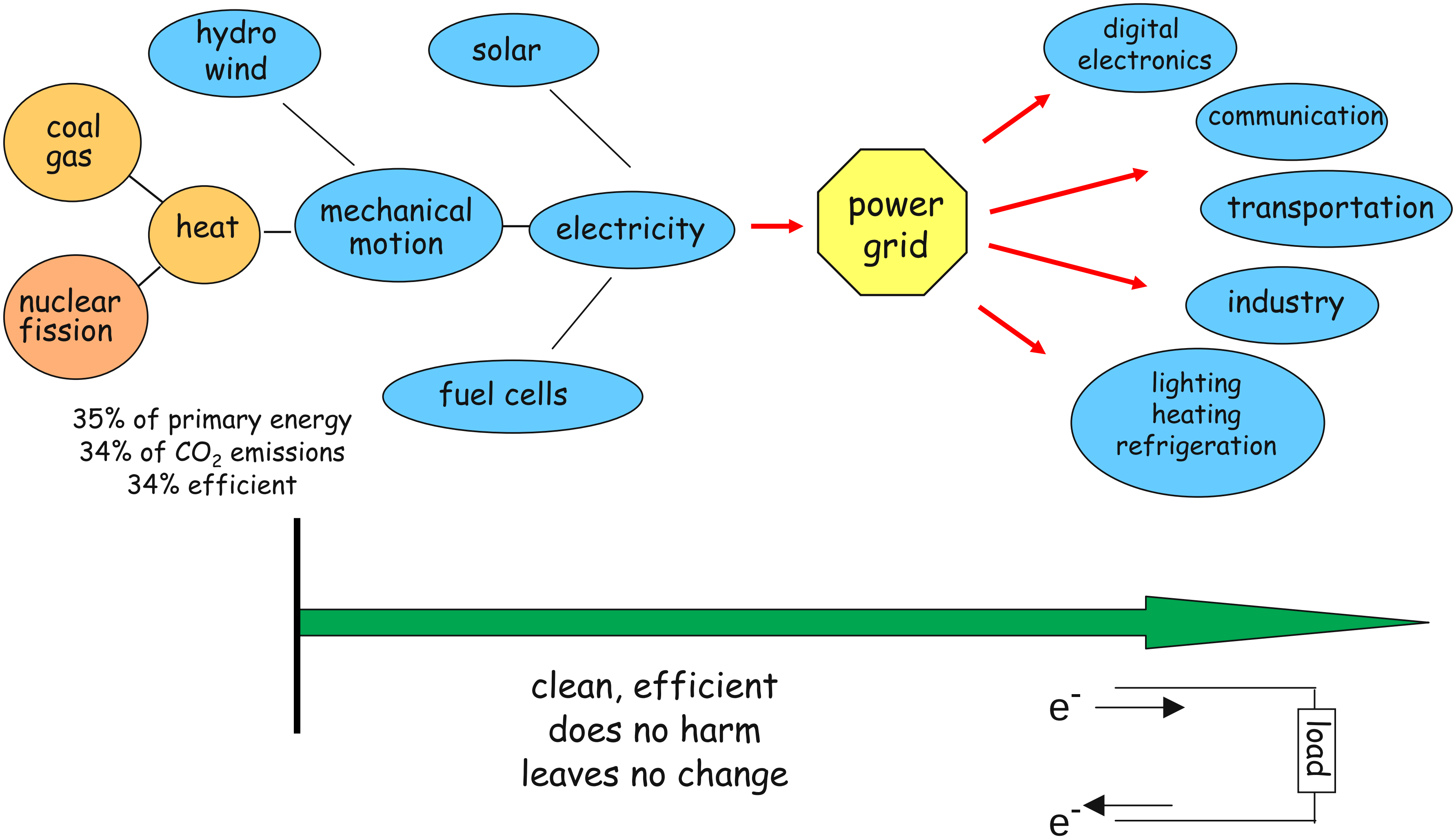
Ethanol: reduced CO_2

Leaves no change

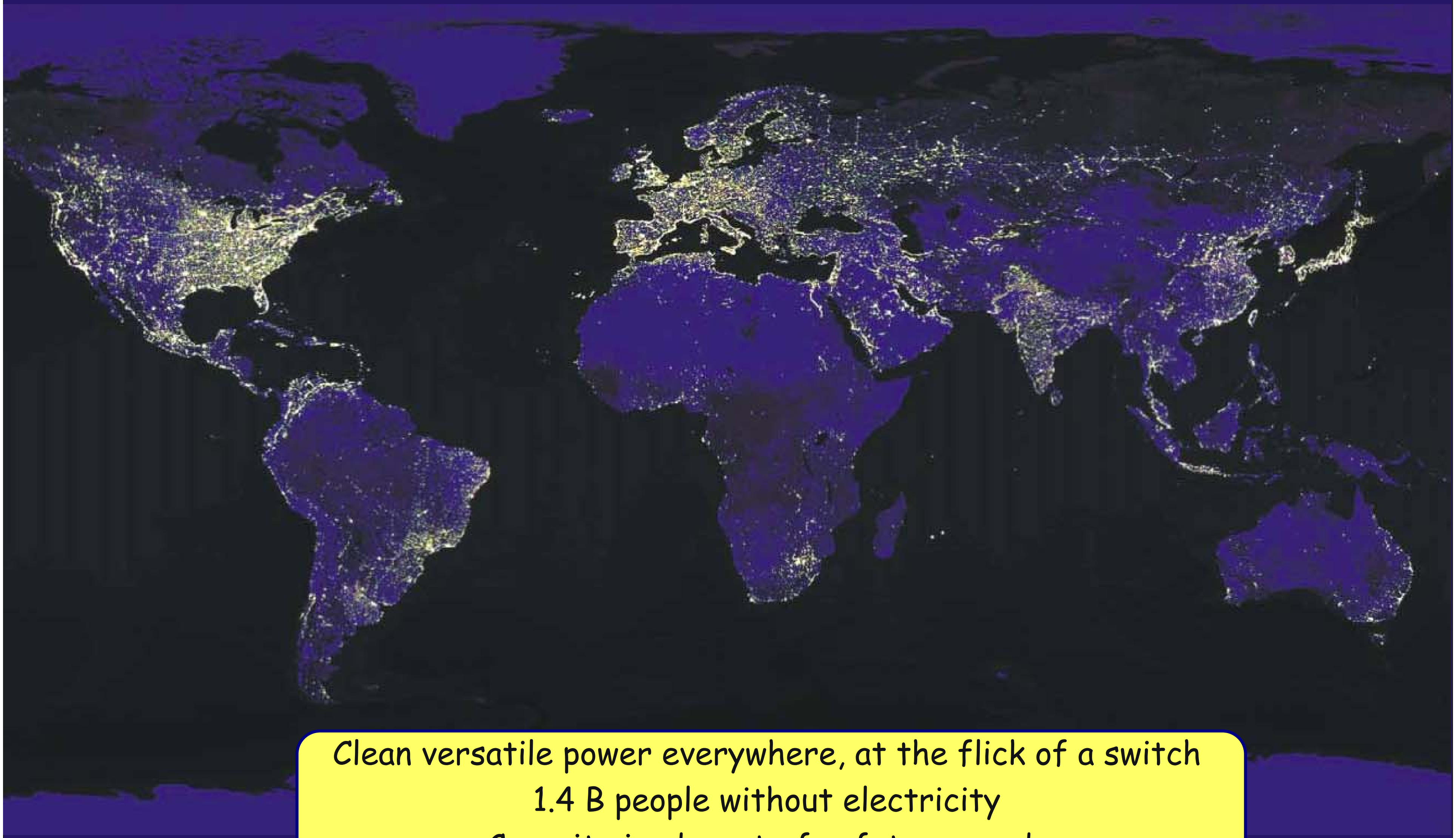
Closed chemical cycle

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

The 21st Century: A Different Set of Challenges

capacity

electric power concentrated
in cities and suburbs

33% of power used
in top 22 metro areas

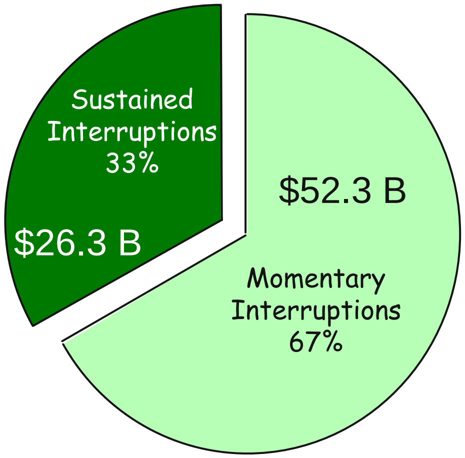
urban power bottleneck

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

reliability
power quality

average
power loss/customer
(min/yr)

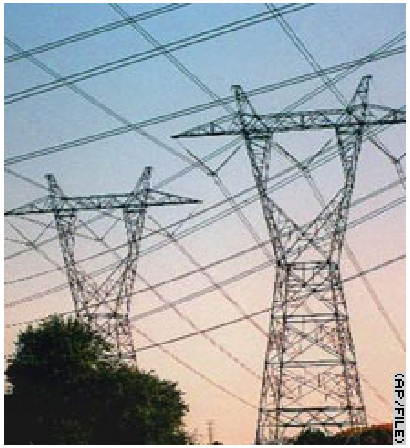
US	214
France	53
Japan	6



$79 B economic loss (US)

LaCommare & Eto, Energy 31, 1845 (2006)

efficiency
lost energy



63% energy lost in
production / delivery

8-10% lost in grid

40 GW lost (US)
~ 40 power plants

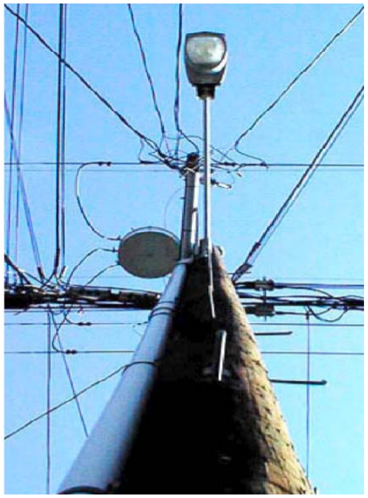
2030: 60 GW lost (US)
340 Mtons CO_2

Superconductivity: A 21st Century Solution

Relieve Urban Power Bottleneck

Replace saturated underground cables and overhead lines with superconductor

⇒ 5x capacity



- Lower voltage
- No heating
- No stray fields
- No impact on underground infrastructure
- Easier permitting

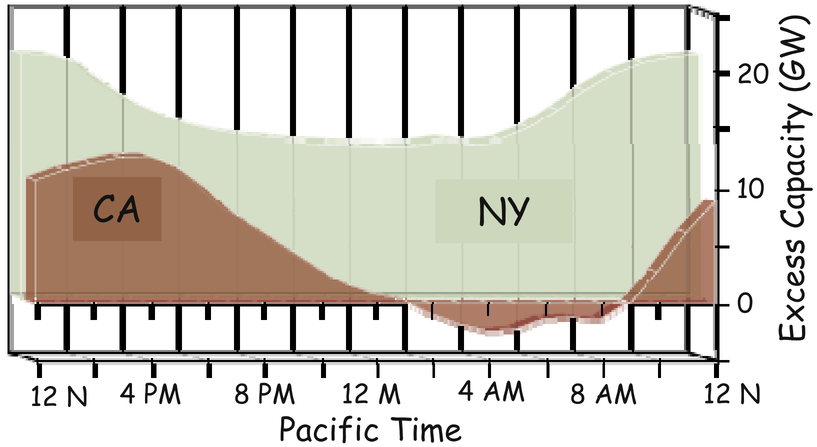
Long Distance Superconducting Grid

Intercity transmission cables

Transcontinental power and load sharing

Cross weather boundaries / generation zones

Generation at fuel source for distant use



Transcontinental diurnal leveling

Increase efficiency and capacity

Only superconductors can achieve this

Next Generation Materials

~ 50 copper oxide superconductors

Highest Tc = 164 K under pressure

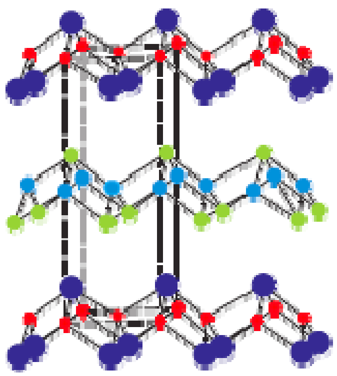
(1/2 Room Temp)

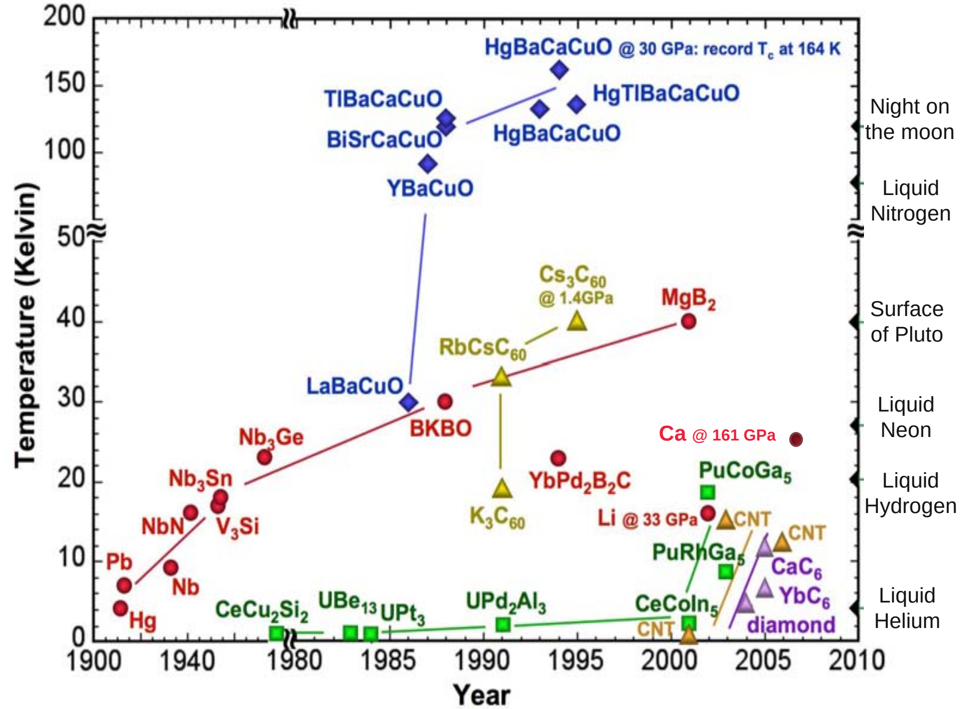
Only class of high T_c superconductors ?

High T_c superconductors $\geq$ 4 elements

55 superconducting elements

-> 55^4 ~ 10 million quaternaries





LaO

FeAs

LaOFeAs

Tc ~ 55K

Search strategies for new superconductors

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

Challenge

Discover next generation complex superconductors

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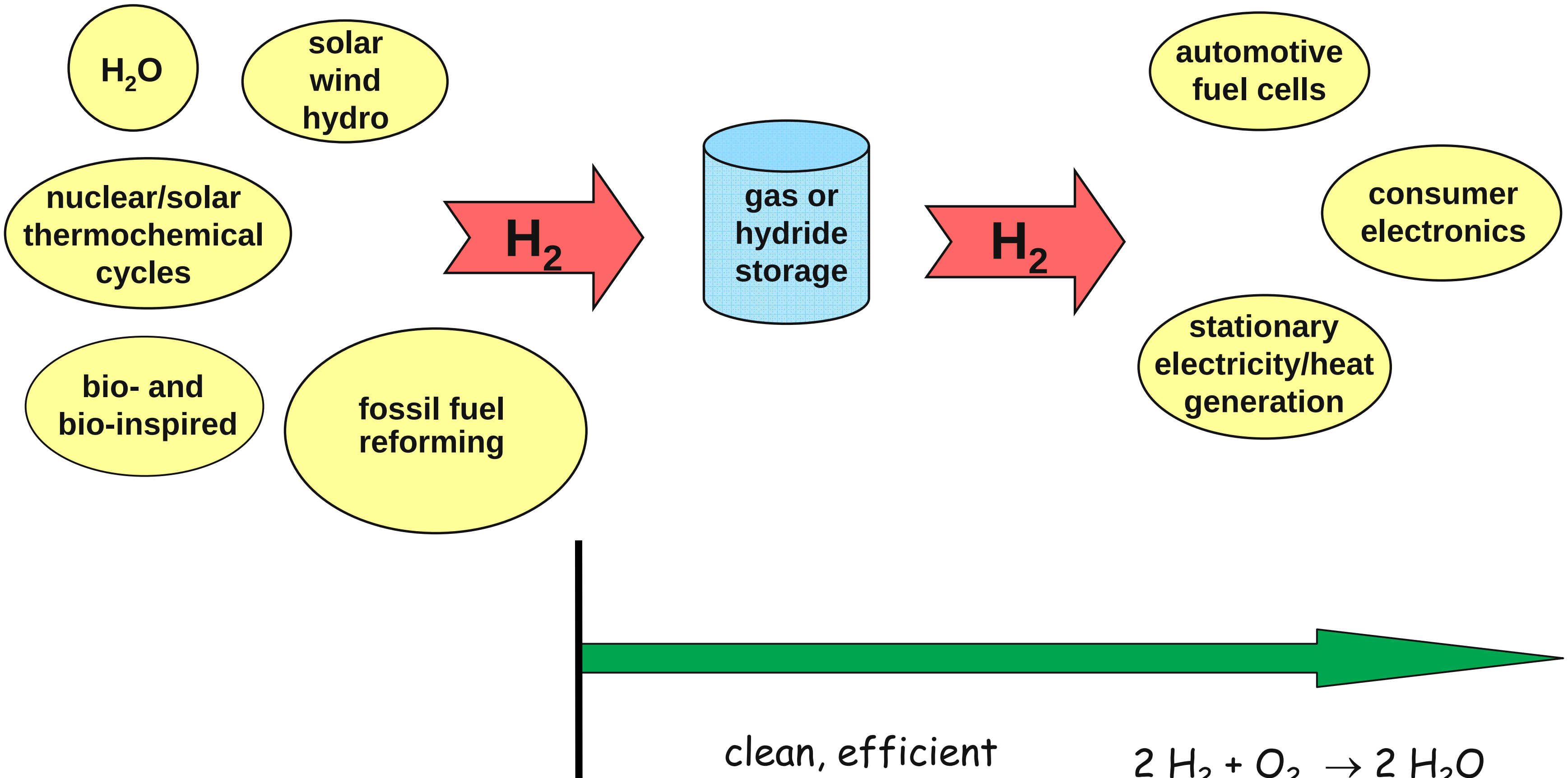
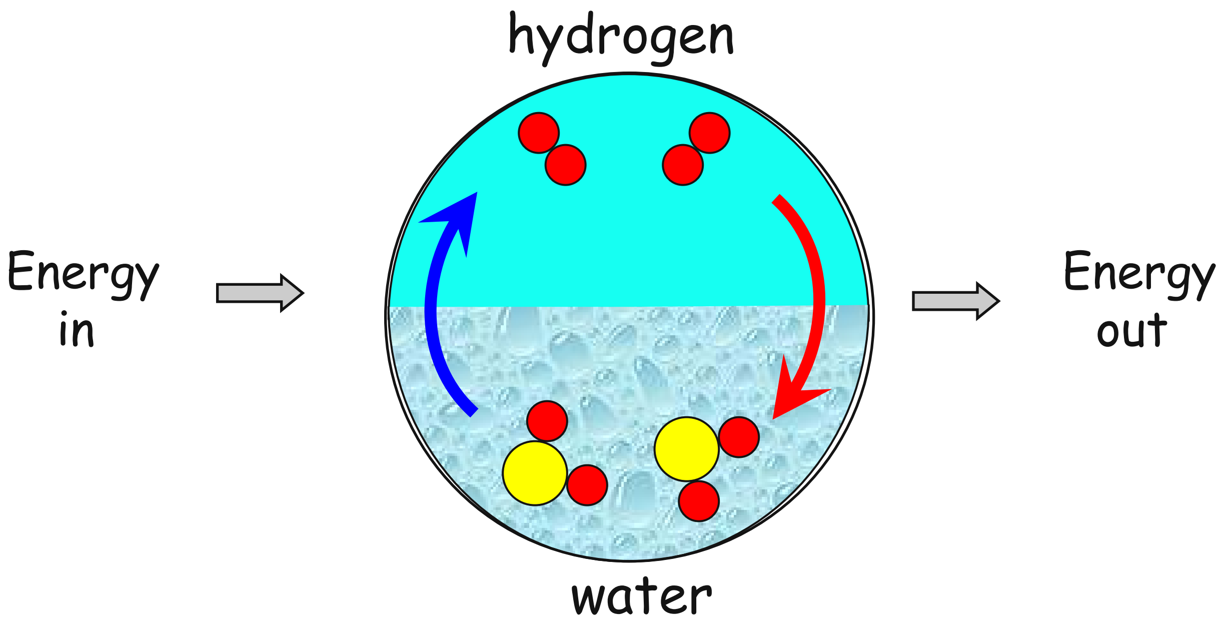
Hydrogen as an Energy Carrier



clean, efficient
does no harm
leaves only H_2O

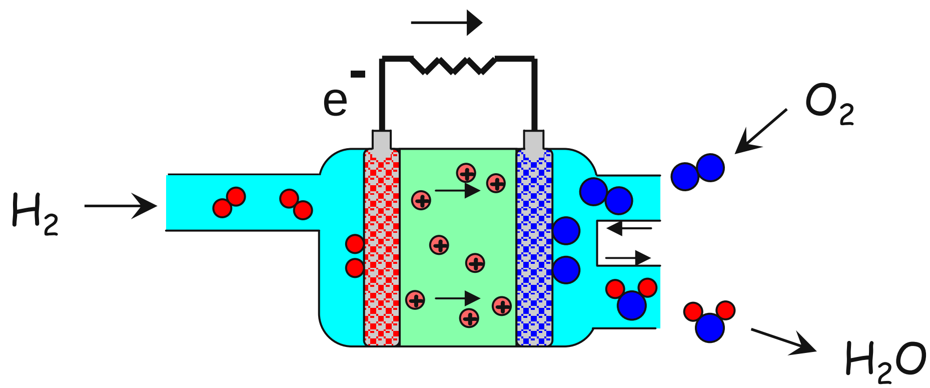
$$2\ H_2 + O_2 \rightarrow 2\ H_2O$$

The Appeal of Hydrogen: Closing the Cycle



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

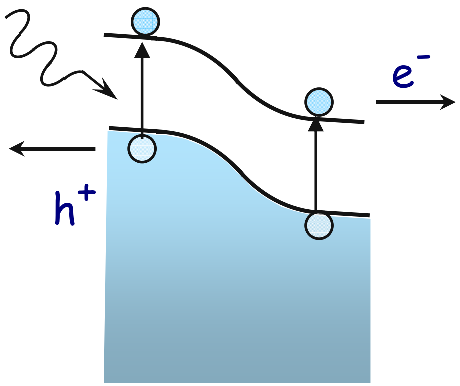
1.5 days of sunlight

Annual Human Production of Energy

4.6×10^{20} Joules

1 hour of sunlight

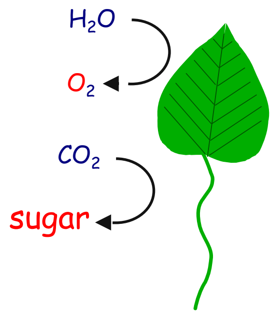
Solar Energy Utilization



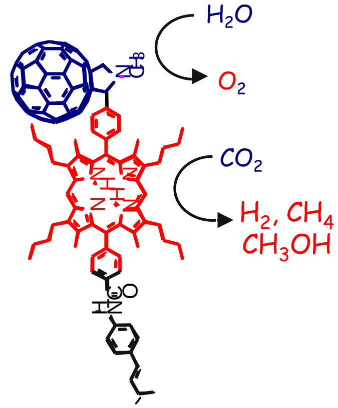
Solar Electric

.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

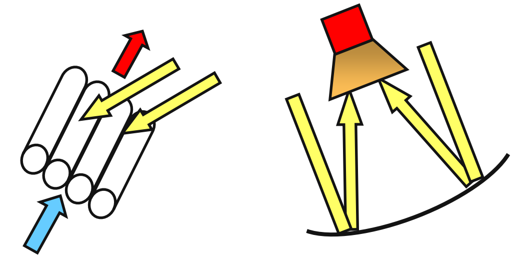


artificial photosynthesis

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

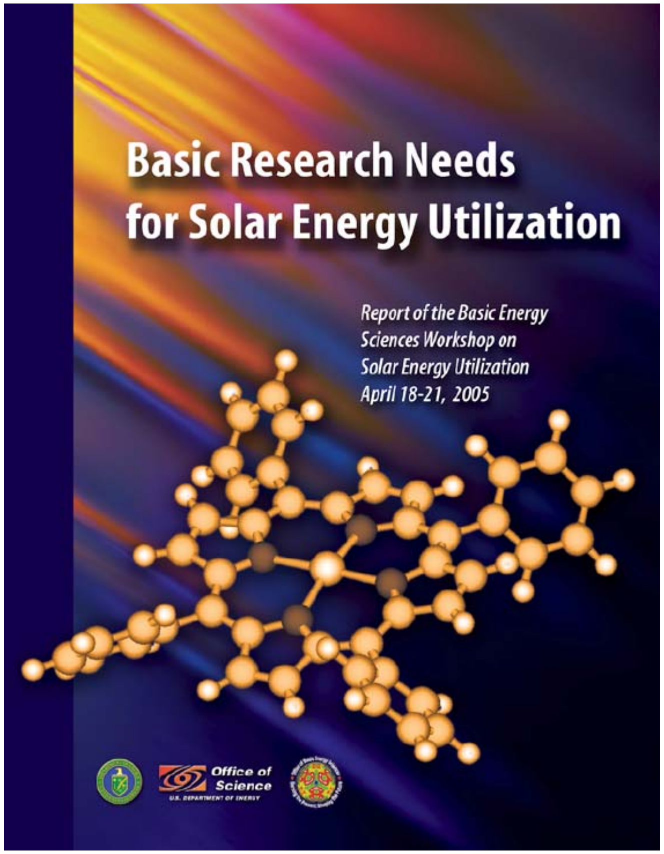
Solar Thermal

0.006 TW (world)

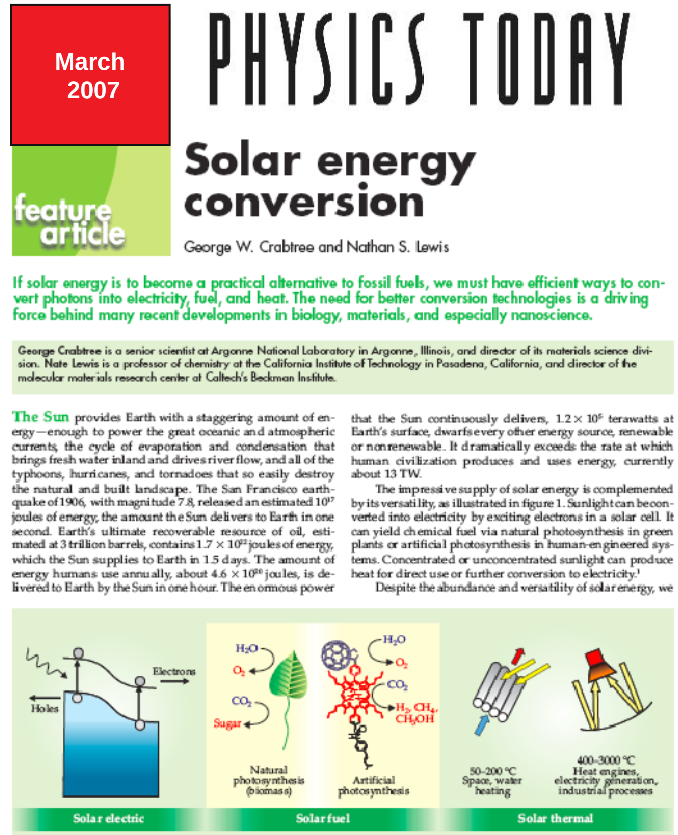
2 TW
space and water heating (world)

~ 14 TW additional energy by 2050

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.

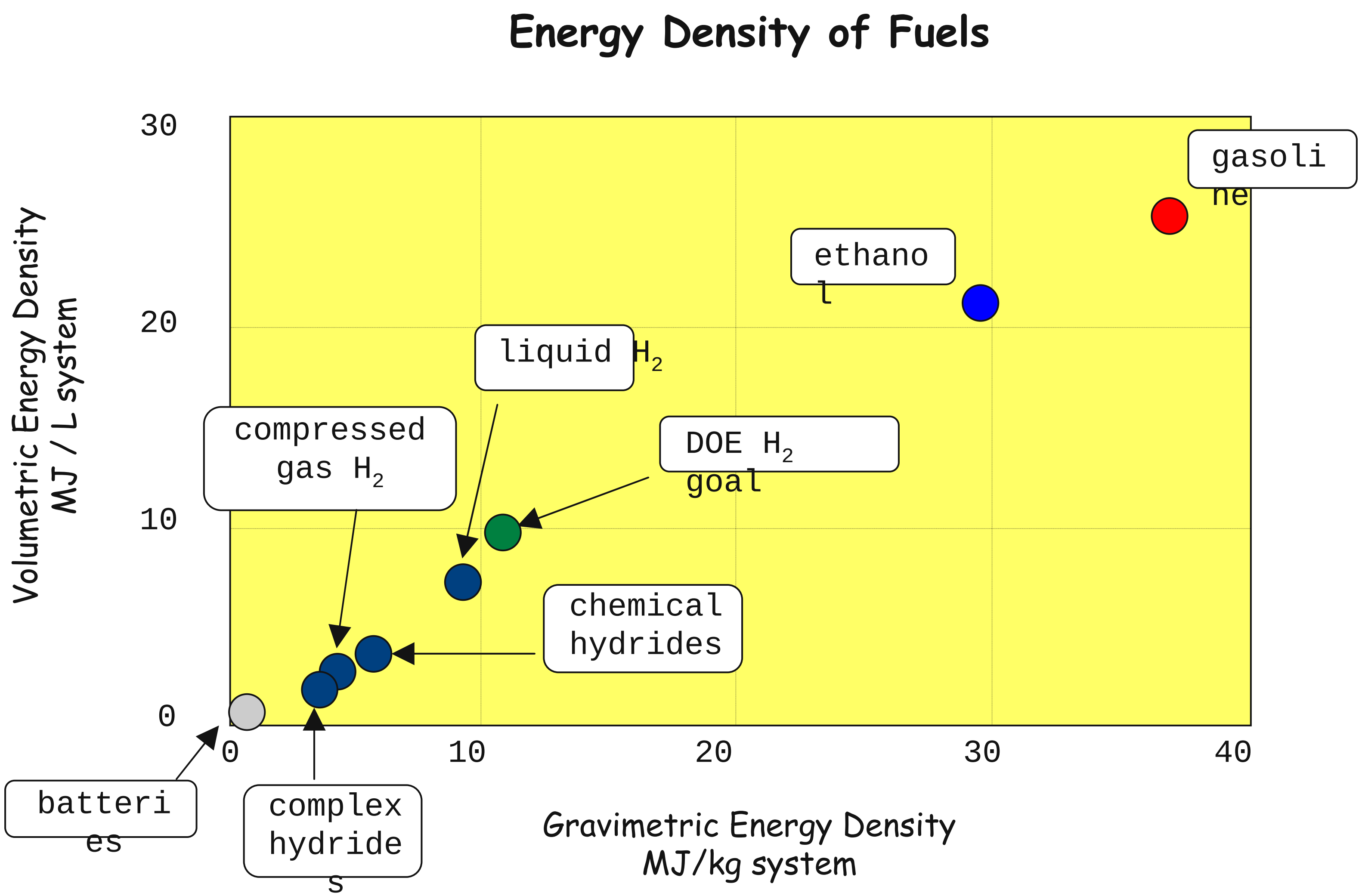
The impressive supply of solar energy is complemented by its versatility, as illustrated in figure 1. Sunlight can be converted into electricity by exciting electrons in a solar cell. It can yield chemical fuel via natural photosynthesis in green plants or artificial photosynthesis in human-engineered 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



Research Challenges for Sustainable Alternatives to Fossil

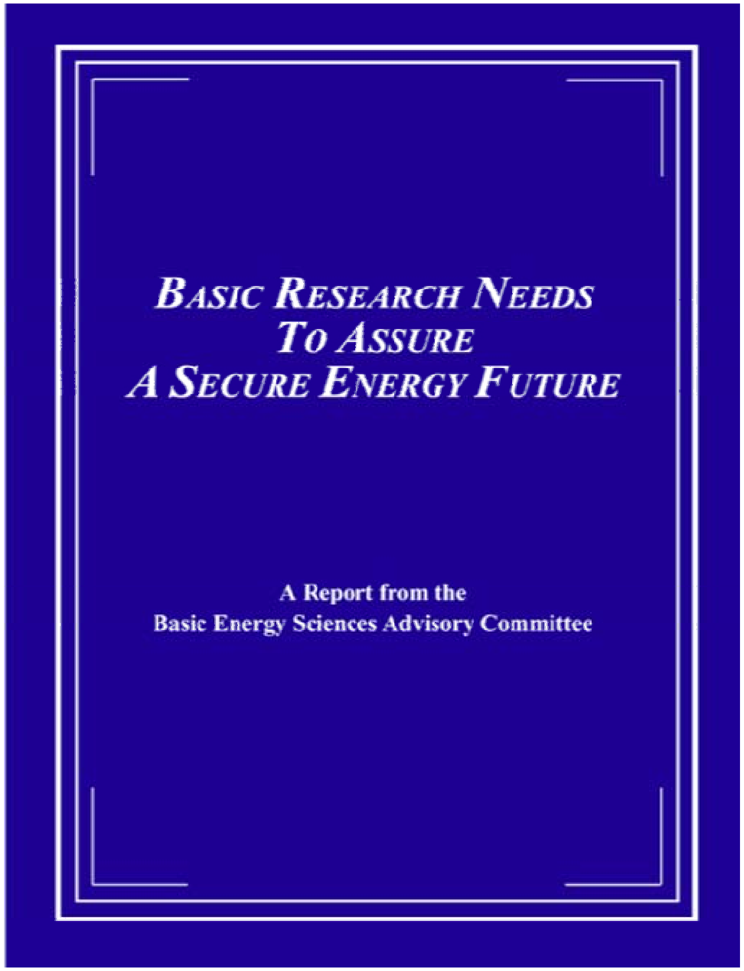
Electricity

- *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*

BES Basic Research Needs Workshops



"Considering the urgency of the energy problem, the magnitude of the needed scientific breakthroughs, and the historic rate of scientific discovery, current efforts will likely be too little, too late. Accordingly, BESAC believes that ***a new national energy research program is essential and must be initiated with the intensity and commitment of the Manhattan Project, and sustained until this problem is solved."***

BESAC Report, February 2003

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

The Basic Research Needs Workshops

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

Basic Research in Support of the DOE Missions

- Basic Research Needs to Assure a Secure Energy Future
  BESAC Workshop, October 21–25, 2002
  The foundation workshop that set the model for the focused workshops that follow
- Basic Research Needs for the Hydrogen Economy
  BES Workshop, May 13–15, 2003
- Basic Research Needs for Solar Energy Utilization
  BES Workshop, April 18–21, 2005
- Basic Research Needs for Superconductivity
  BES Workshop, May 8–10, 2006
- Basic Research Needs for Solid-state Lighting
  BES Workshop, May 22–24, 2006
- Basic Research Needs for Advanced Nuclear Energy Systems
  BES Workshop, July 31–August 3, 2006
- Basic Research Needs for the Clean and Efficient Combustion of 21st Century Transportation Fuels
  BES Workshop, October 30–November 1, 2006
- Basic Research Needs for Electrical Energy Storage
  BES Workshop, April 2007
- Basic Research Needs for Geosciences: Scientific Challenges for Measurement, Monitoring, and Verification
  BES Workshop, Spring 2007
- Basic Research Needs for Materials Under Extreme Environments
  BES Workshop, June 11-13, 2007

Energy: Emergent Science of the 21st Century

APS Energy Workshop: Sunday preceding March Meeting

MRS Energy Forum: Monday preceding the Spring Meeting

Transforming the Energy Chain

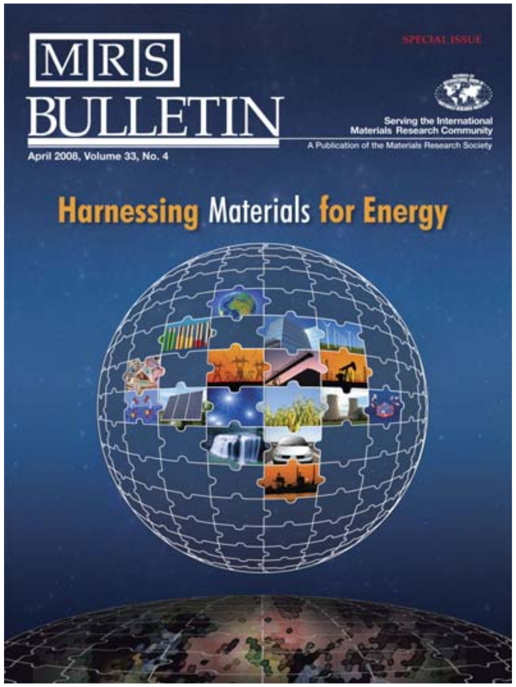
Resources ⇒ Carriers ⇒ Storage ⇒ Use

Sustainability

Environment Climate Economy

Materials

the critical links in the energy chain



April 2008
www.mrs.org/bulletin_energy