
The Sustainable Energy Challenge

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Outline

- the challenges: oil and carbon dioxide
- sustainable energy alternatives and roadblocks
- what is sustainability?
- controlling materials and phenomena

Background Reading

The energy puzzle: Sustainability



physicsworld.com
October 2009

The road to sustainability

George Crabtree and John Sarrao

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The oil shock of the 1970s triggered worldwide awareness of oil dependency and launched a search for alternative sources of energy. But three decades on, these efforts have barely had an impact: oil still accounts for almost 40% of global energy use, and fossil fuels make up 85%. The US, for example, imported 20% of its oil in 1970; today the figure is 60%, and other countries import even larger fractions of the oil they consume. The problem of oil dependency is compounded by cost. Before the current recession, the price of oil peaked at \$140 a barrel – five times its price in 2002 and 10 times its price in 1975 – rewriting the economics of transportation, food, manufacturing and trade that underlie the operation of society. In addition to dependency and

higher than they were before the Industrial Revolution, and they are rising at an accelerating pace, driven by the human combustion of fossil fuels. The potential implications for global warming and climate change are sobering. Left unchecked, climate change could produce dislocations in the agricultural, trade and demographic patterns that define global economic and social structures. A particularly worrying feature of global warming is the timescale involved. It takes 400–1000 years for carbon dioxide in the atmosphere to equilibrate in the deep ocean. Hence, the carbon dioxide that we have already added – and continue to add – to the atmosphere will affect not only our grandchildren but also

Controlling the Functionality of Materials for Sustainable Energy

George Crabtree
John Sarrao



ANNUAL REVIEW OF
CONDENSED MATTER
PHYSICS

October 2010

<http://www.annualreviews.org/journal/conmatphys>

RISING ABOVE THE GATHERING STORM, REVISITED

Rapidly Approaching Category 5

By Members of the 2005 "Rising Above the Gathering Storm" Committee

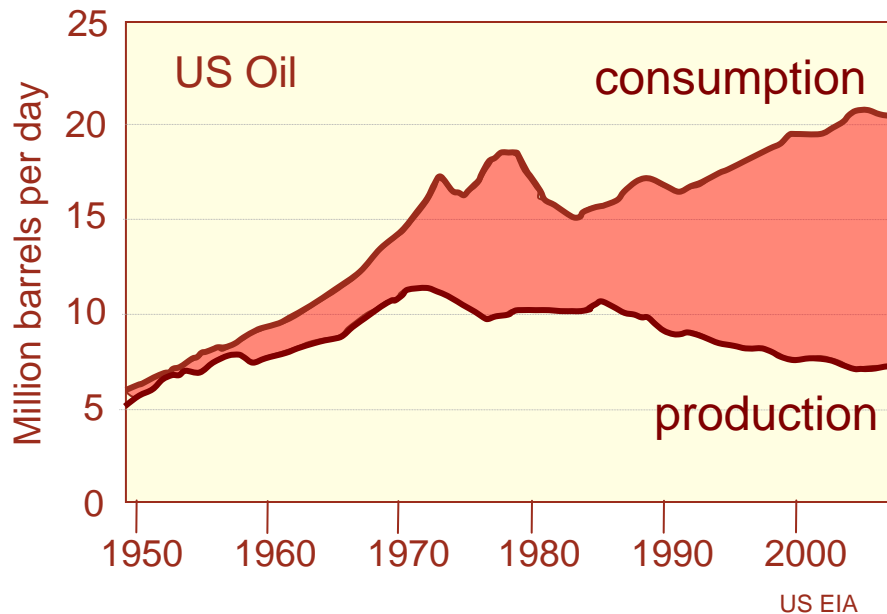
Prepared for the Presidents of the
National Academy of Sciences
National Academy of Engineering
Institute of Medicine

National Academy of Sciences
National Academy of Engineering
Institute of Medicine

http://www.nap.edu/catalog.php?record_id=12999

<http://physicsworld.com/ews/article/print/40527>

The Problem: Dependence on Imported Oil



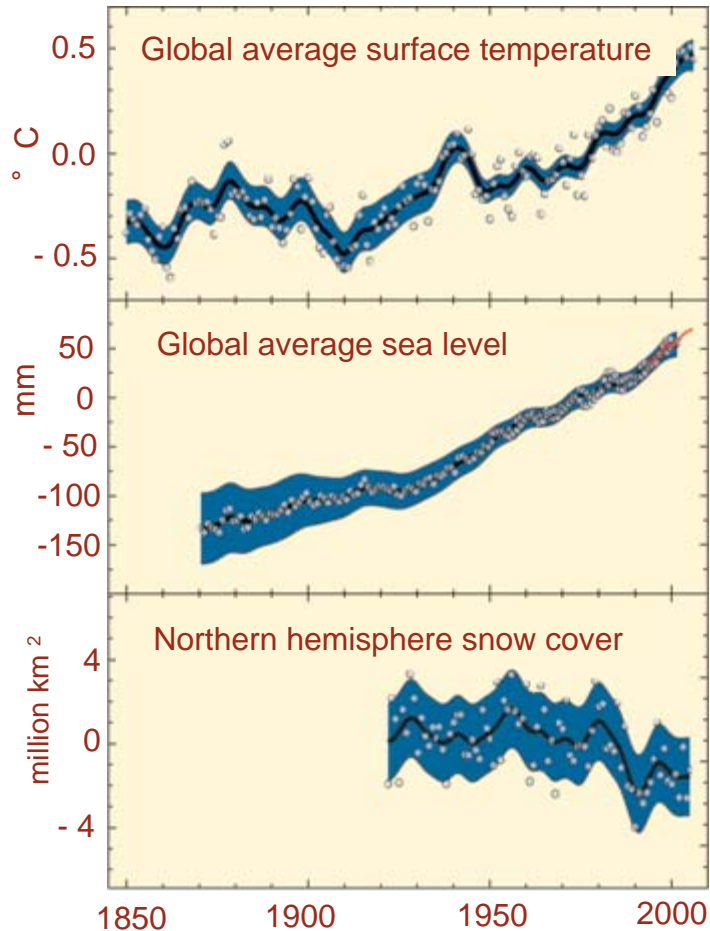
Unpredictable supply
threatens
economy, lifestyle, national security

find alternatives to imported oil
biofuels, electricity, solar fuels

Cost to economy
\$350 B/yr at current prices
transferred to foreign oil
producers



The Problem: Greenhouse Gases and Climate Change



IPCC Fourth Assessment 2007
<http://www.ipcc.ch/graphics/gr-ar4-syr.htm> SPM1



2/3 of carbon dioxide emissions come from power plants and autos

Permanent changes in weather patterns, agricultural networks and coastal geography

Cost of accommodation may be higher than preventive cost of reducing emissions

Roadblocks to Sustainable Energy Technologies

Performance: fossil is cheaper

Sustainable energy technologies are in their infancy.
They perform far below their ultimate potential.

Dramatic improvements are needed -
incremental tuning of the present state of the art
is not sufficient

Breakthroughs needed
understand and control materials and chemistry
at molecular and nanoscale levels

What is Sustainability?

Lasts a long time

Oil in 1900

Coal in 2010

Does no harm

Nuclear electricity: no CO_2

Ethanol: reduced CO_2

Leaves no change

Closed chemical cycle

Electricity, hydrogen

Sustainable Next-Generation Energy Technologies

Sustainability Profile

lasts a long time ☺

does no harm ☺

leaves no change ☺



Solar electricity: a fully sustainable energy chain
manufacture and end-of-life impact must be considered

breakthroughs needed
lower cost, higher efficiency photovoltaics
third generation materials and nanostructures
electricity storage

Carbon Sequestration

Sustainability Profile

lasts a long time



emissions

does no harm



leaves no change



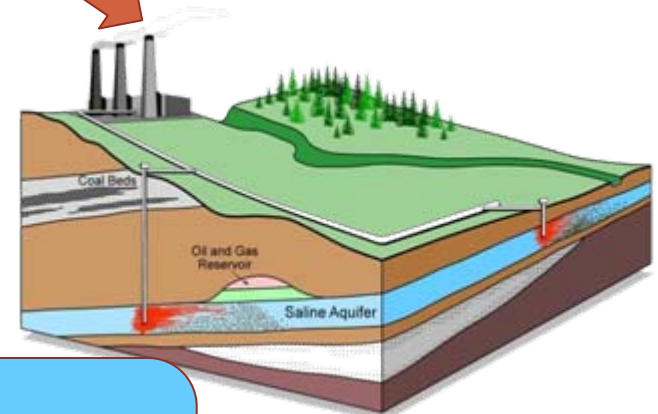
sequestration



depletes coal resource
100s of years



carbon dioxide



~ 1000 years

breakthroughs needed
chemical reactivity with rocks in extreme environments
migration through porous rocks
geologic monitoring and predictive modeling
leakage routes to atmosphere

Nuclear Electricity

Sustainability Profile

lasts a long time

does no harm

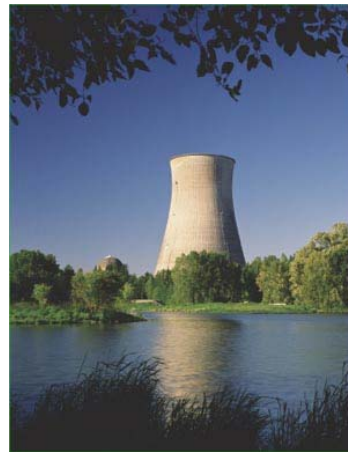
leaves no change



emissions

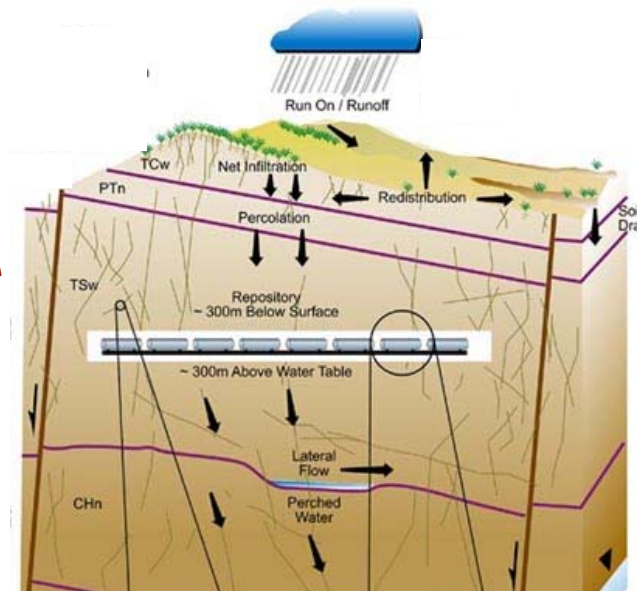


nuclear waste



depletes uranium resource
100s of yrs

breakthroughs needed
materials for extreme environments
high temperature, high radiation flux
high corrosivity
geologic monitoring and modeling



nuclear waste
100 000s yrs

usgs

Replace Conventional Oil

cellulosic biofuel
solar chemical fuel

lasts a long time 😊

does no harm 😊

leaves no change 😊



switchgrass

oil sands and shale
coal to liquid

lasts a long time 😞

does no harm 😞

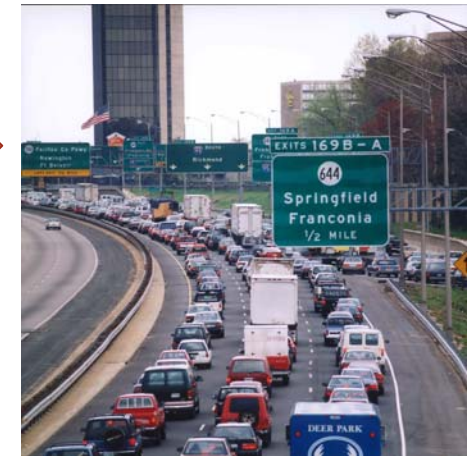
leaves no change 😞



ethanol plant



recycles CO₂ ↗



cellulosic biofuel: recycles carbon dioxide

solar fuel without biology: thermo- or photo-chemistry

oil sands and shale, coal to liquid: → 50% more carbon dioxide

→ more pollutants

breakthroughs needed

cellulosic breakdown to sugar or fuel
chemistry of carbon dioxide to fuel

Electrify Transportation

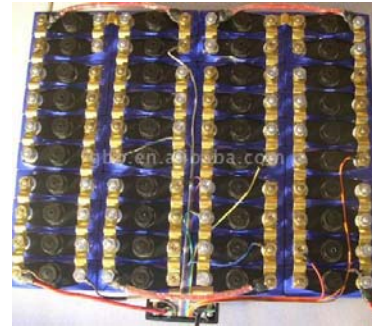
Sustainability Profile

lasts a long time ☺

does no harm ☺

leaves no change ☺

renewable
electricity
production



battery

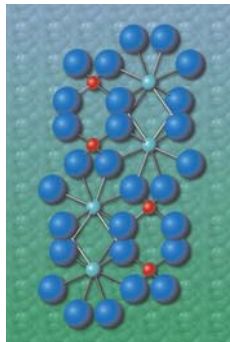


electric motor
replaces
gasoline engine

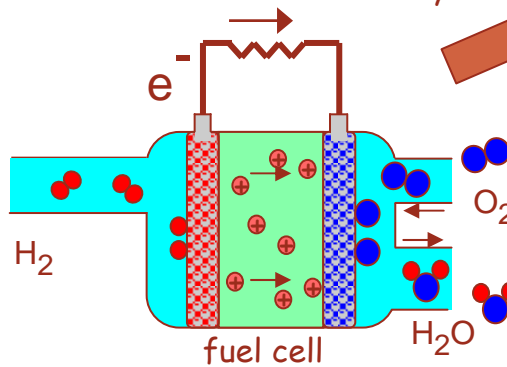


tesla motors

renewable
hydrogen
production

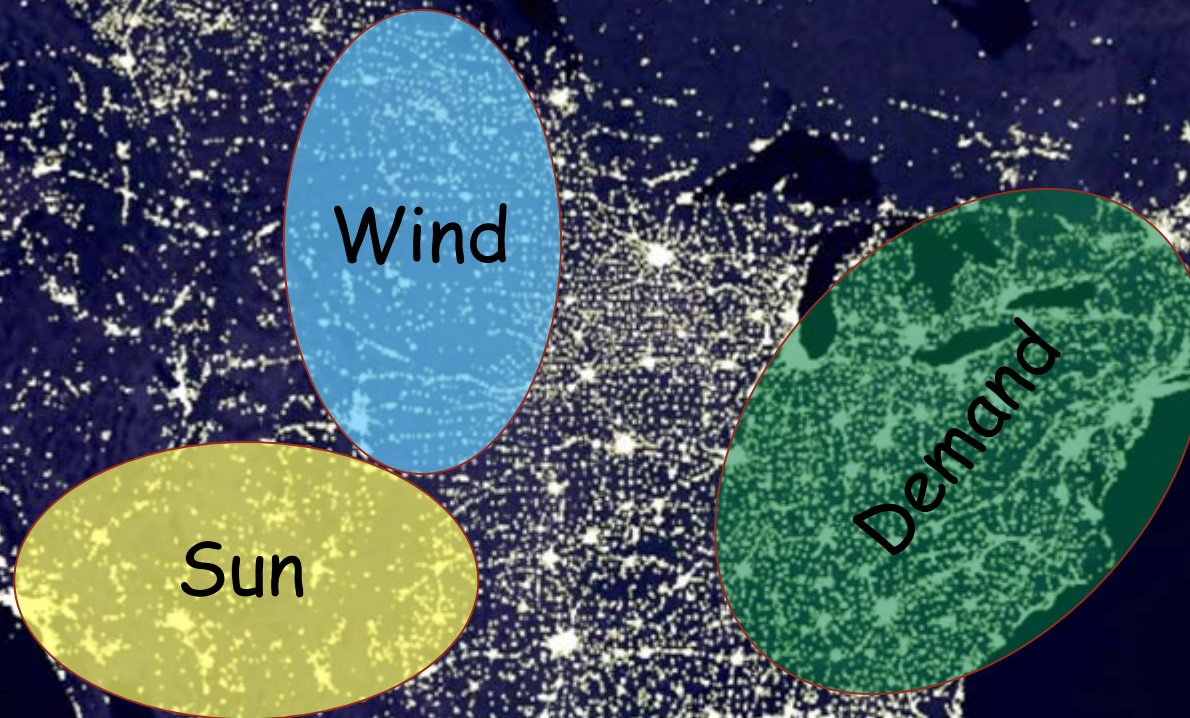


hydrogen
storage



breakthroughs needed
x2-5 higher energy density in batteries
catalysts, membranes and electrodes in fuel cells

Sustainable Energy Enabling Technologies: The Grid



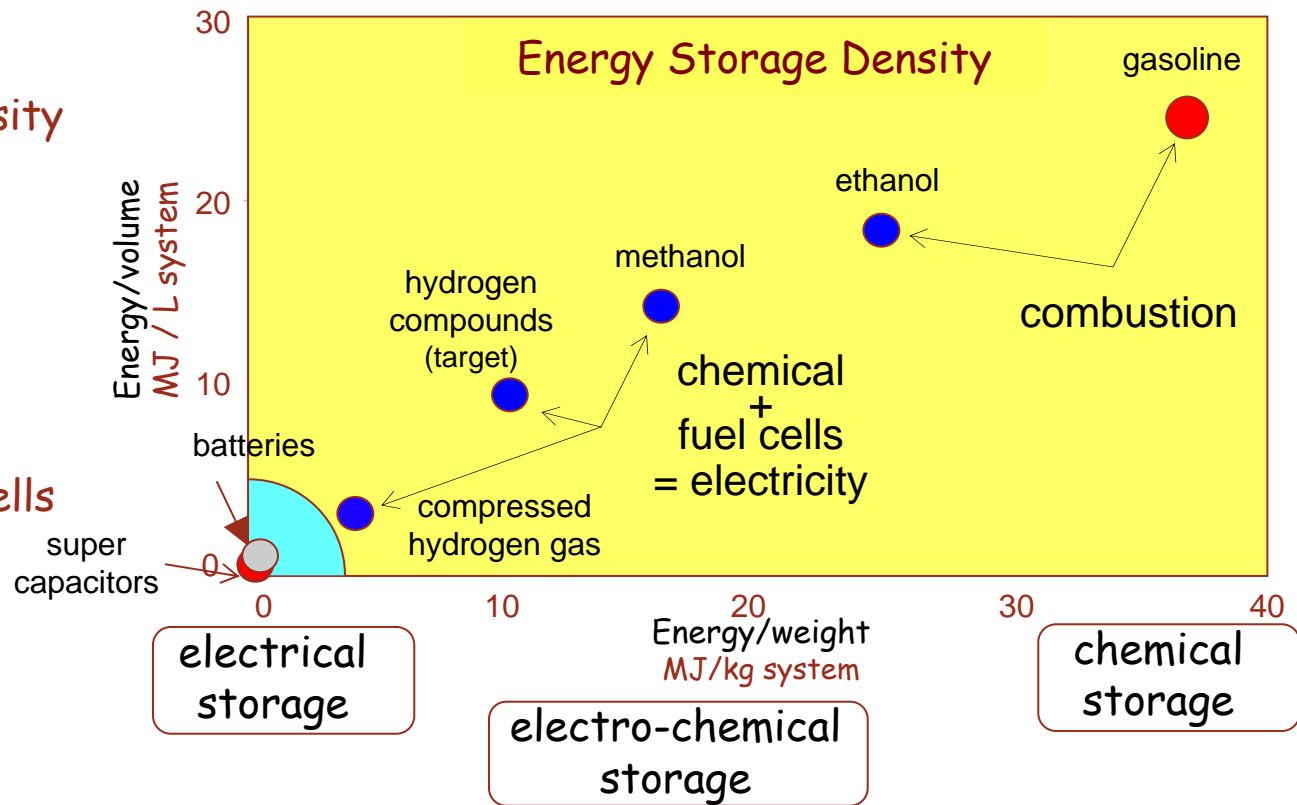
breakthroughs needed
long distance reliable, efficient delivery of electricity

Enabling Technologies: Storing Energy

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

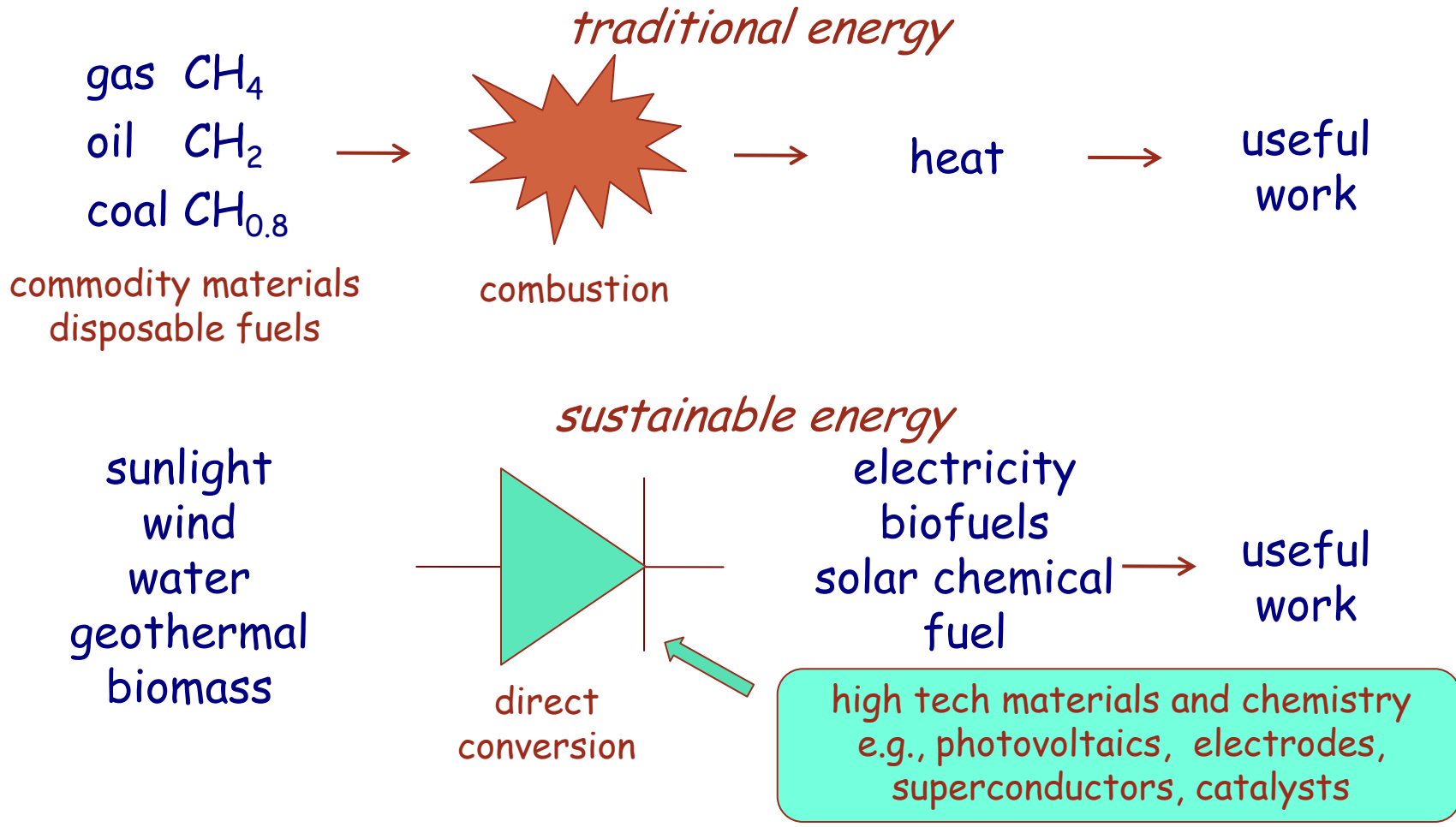
batteries:
30-50x less energy density
than gasoline
impossible dream: x10
improvement

beyond batteries:
chemical storage + fuel cells
= electricity



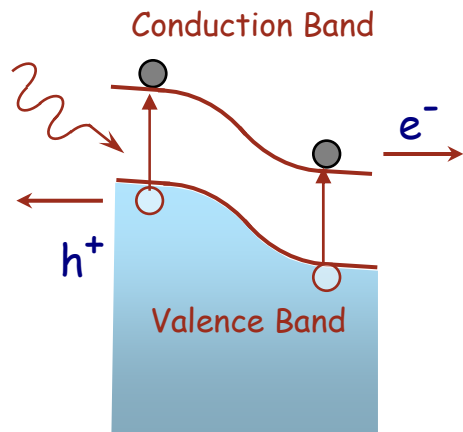
breakthroughs needed
x2-5 increase in battery energy density
x10-20 increase through chemical storage + fuel cells

The Transition to Sustainable Energy: High Tech Materials and Chemistry



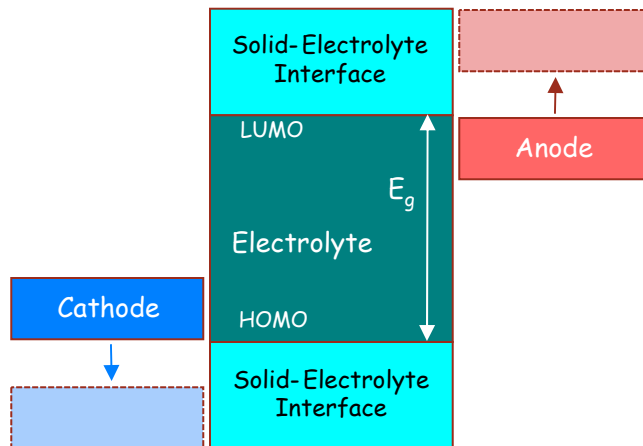
sustainable energy requires controlling complex, functional, high tech materials and chemistry

Quantum Energy Conversion



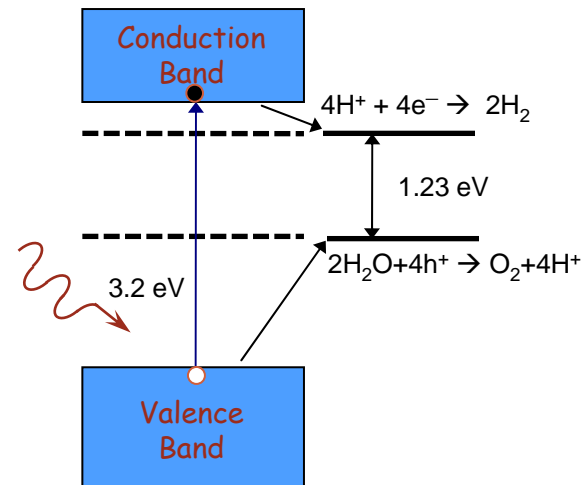
Silicon
Photovoltaic
Cell

Crabtree and Lewis
Solar Energy Conversion
Physics Today 60(3), 37 (2007)



Li ion
Battery
Fuel Cell

Goodenough and Kim
Challenges for Rechargeable Li Batteries
Chemistry of Materials 22, 587 (2010)

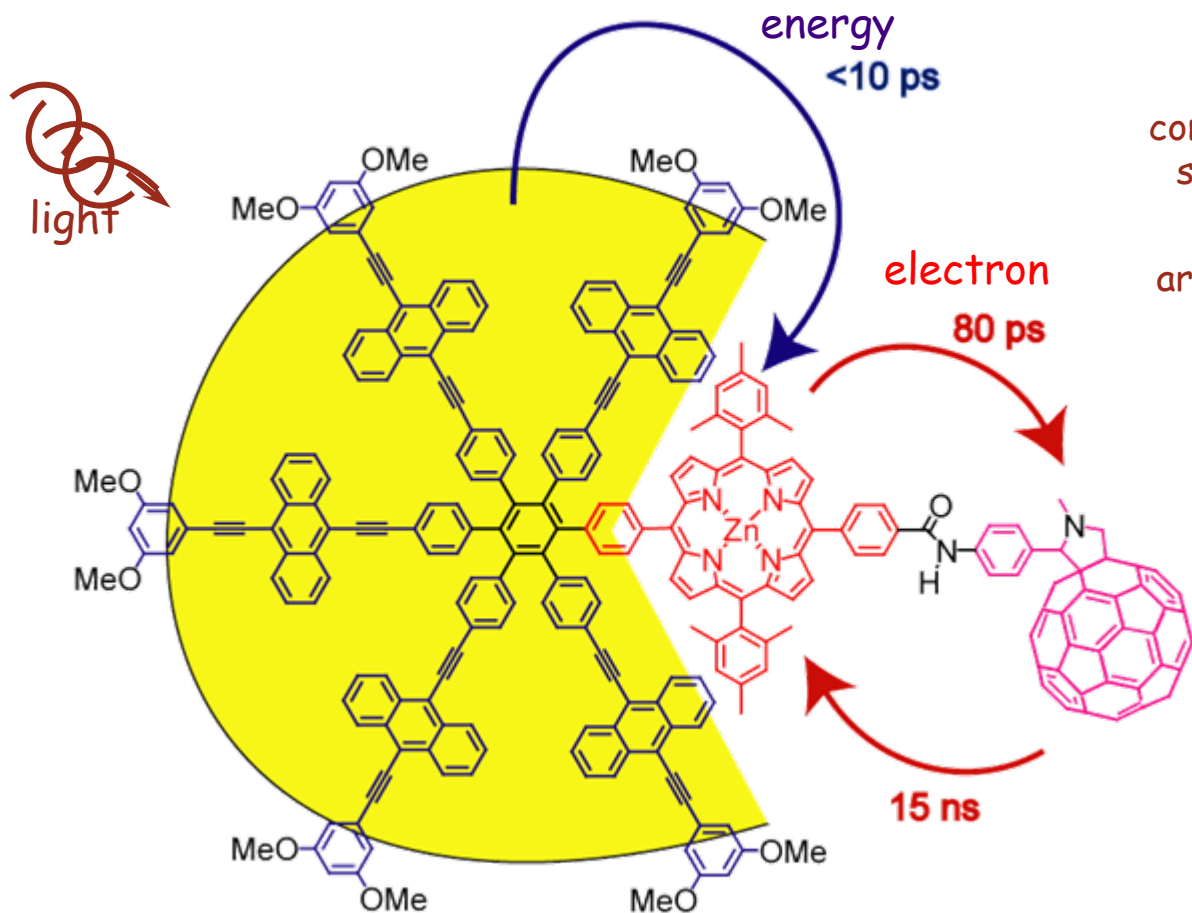


Solar chemistry
TiO₂ / water splitting
Photo-electrochemical
Cell

Crabtree and Sarrao
*Controlling the Functionality of Materials
for Sustainable Energy*
Annual Review of Condensed Matter
Physics October 2010

Sustainable Energy is Quantum Energy Conversion

Complexity Equals Functionality



Levels of Complexity

- compositional structural \longrightarrow functional unit
- architectural \longrightarrow connecting functional units
- temporal \longrightarrow connecting sequential steps

many interacting degrees of freedom

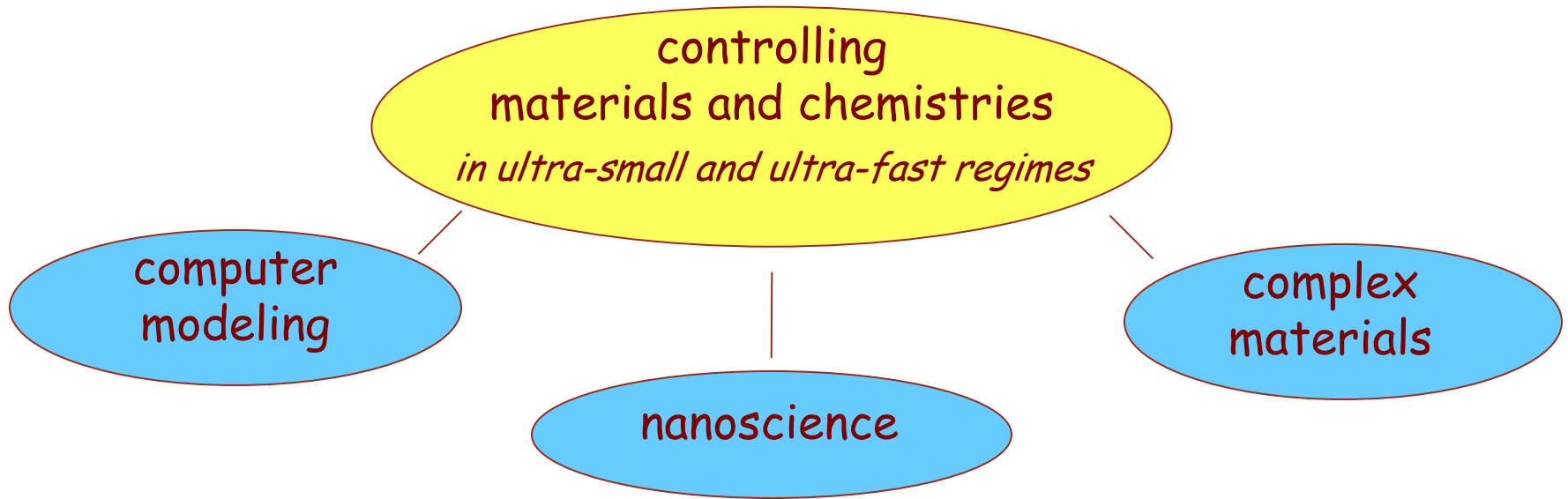
synthesis
characterization
theory and
modeling

Artificial light-gathering and reaction center complex

Kodis et al, JACS 128, 1818 (2006)

Crabtree and Lewis, *Solar Energy Conversion*, Physics Today 60(3), 37 (2007)

New Science: Controlling Complexity



We are at the dawn of a new era

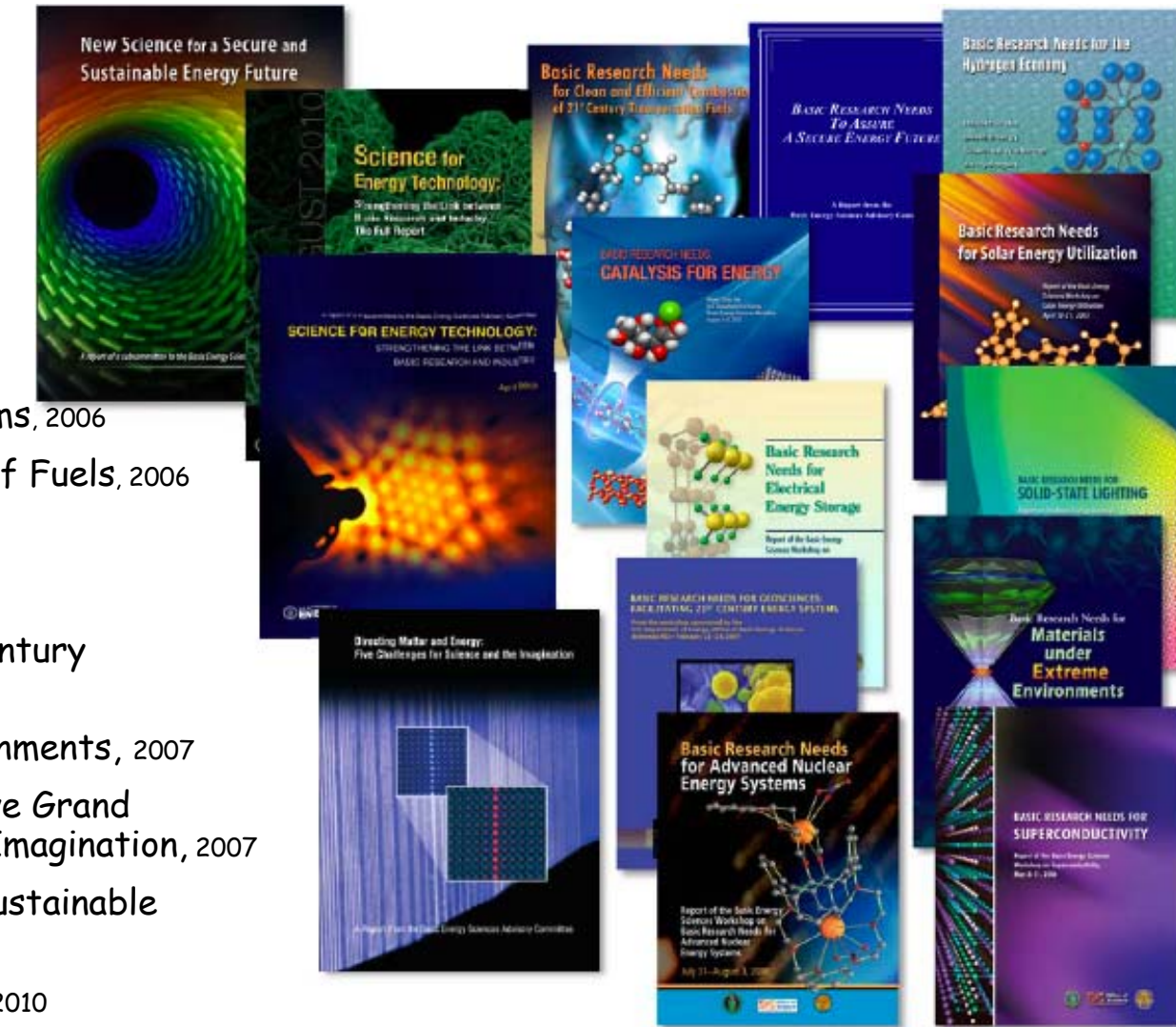
- build materials with atom-by-atom chemical precision
- predict behavior of materials that have not been made
- design new materials and chemistries for specific tasks

breakthroughs to next-generation sustainable energy technologies are within reach

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
- Science for Energy Technology, 2010



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

Perspective

Energy is making an historic transition
fossil to alternative, clean, sustainable

The transition will take decades

Alternative energies are in their infancy
breakthrough research and development
define the "big picture" energy landscape

High tech materials and chemistry are key
complexity = functionality
synthesis, characterization, theory and modeling
