The Sustainable Energy Challenge

George Crabtree

Materials Science Division
Argonne National Laboratory

Departments of Physics, Electrical and Mechanical Engineering
University of Illinois at Chicago

Outline

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

Background Reading

physicsworld.com
October 2009

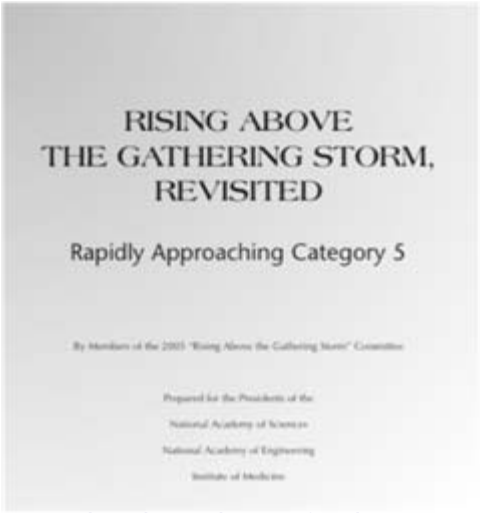
http://physicsworld.com/cws/article/print/40527

Controlling the Functionality of Materials for Sustainable Energy

George Crabtree
John Sarrao

ANNUAL REVIEW OF CONDENSED MATTER PHYSICS
October 2010

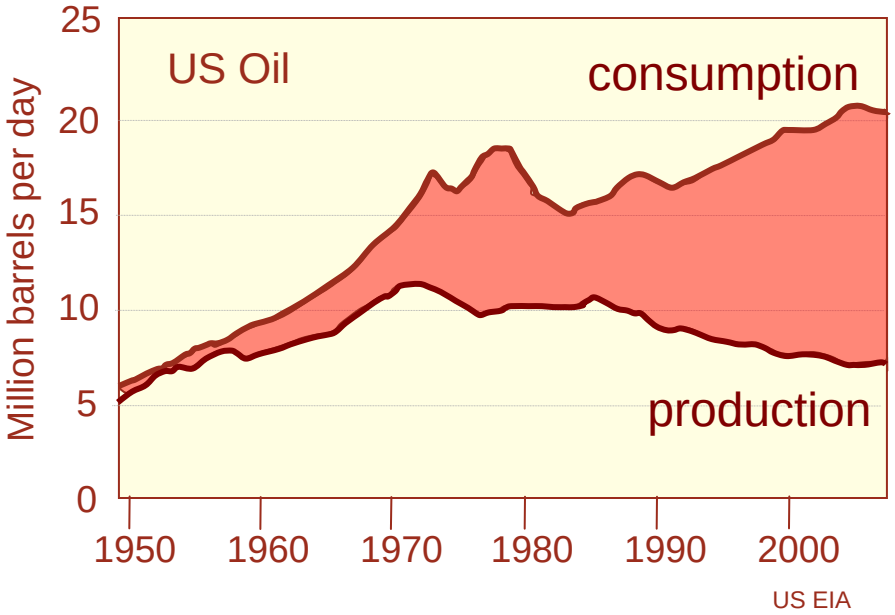
http://www.annualreviews.org/journal/conmatphys



National Academy of Sciences
National Academy of Engineering
Institute of Medicine

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

The Problem: Dependence on Imported Oil



Cost to economy

$350 B/yr at current prices

transferred to foreign oil producers

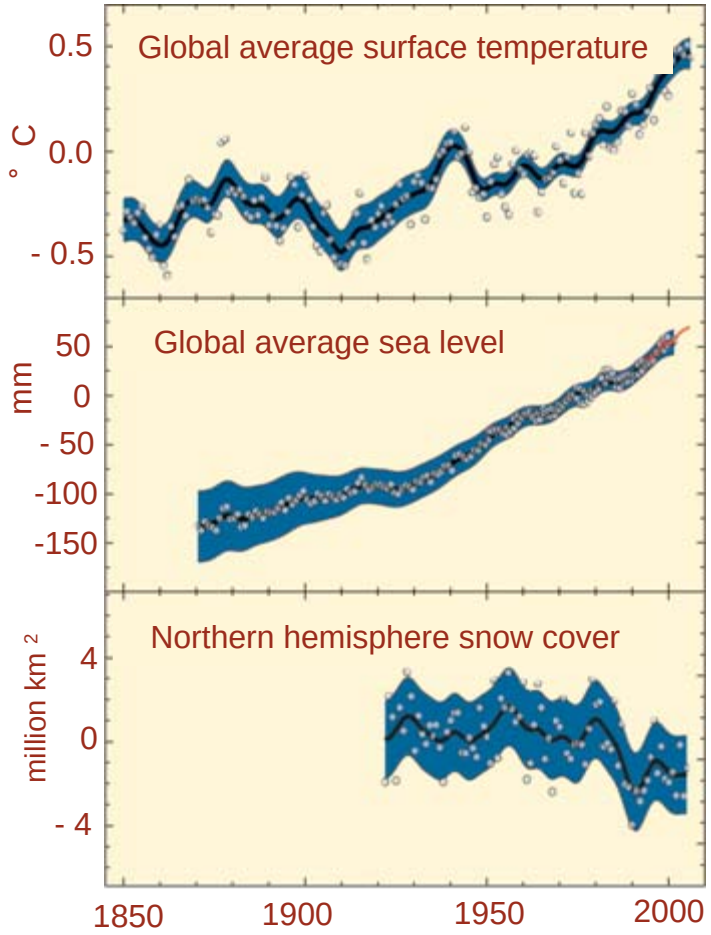
Unpredictable supply threatens economy, lifestyle, national security

find alternatives to imported oil

biofuels, electricity, solar fuels

http://tonto.eia.doe.gov/energy_in_brief/foreign_oil_dependence.cfm

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

does no harm

leaves no change

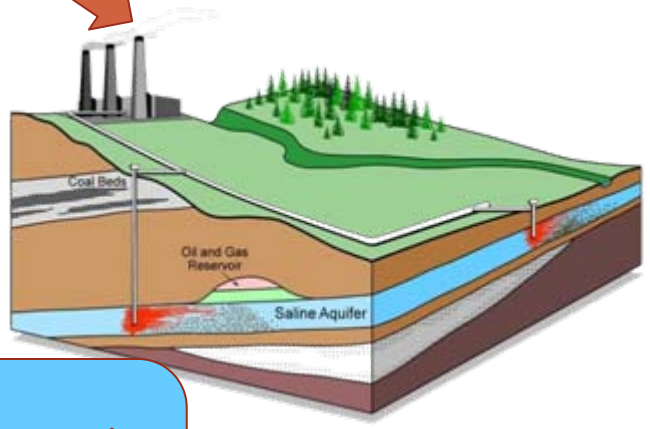
emissions

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

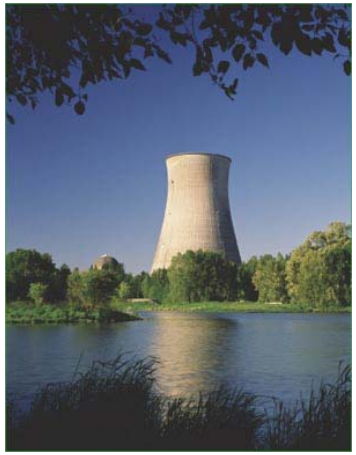
does no harm

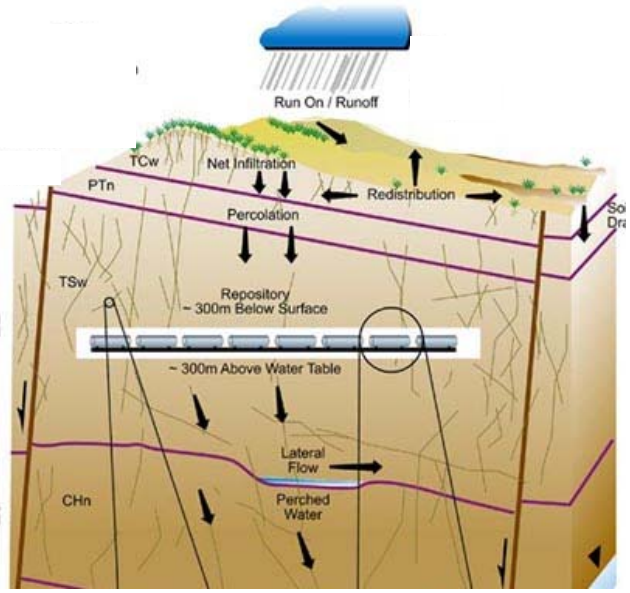
leaves no change

emissions

nuclear waste

depletes uranium resource
100s of yrs





nuclear waste
100 000s yrs

usgs

breakthroughs needed

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

Replace Conventional Oil

cellulosic biofuel
solar chemical fuel

lasts a long time ☺
does no harm ☺
leaves no change ☺

oil sands and shale
coal to liquid

lasts a long time 😐
does no harm ☹
leaves no change ☹

recycles CO_2

switchgrass

ethanol plant

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

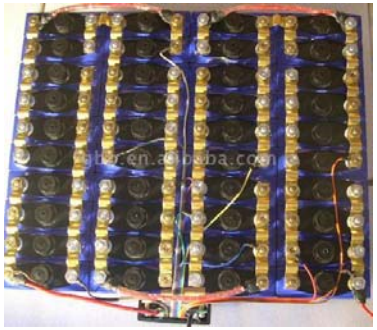
Sustainability Profile

lasts a long time ☺

does no harm ☺

leaves no change ☺

renewable electricity production

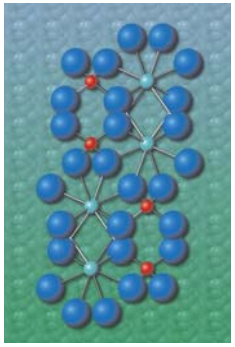


battery

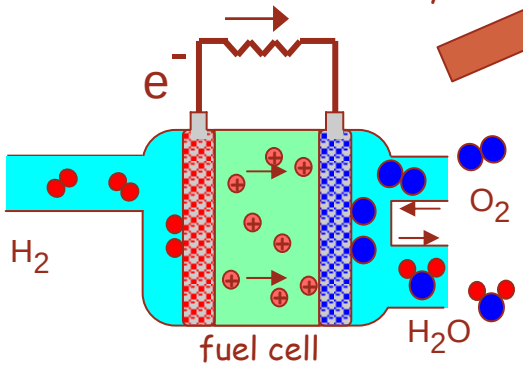
electric motor replaces gasoline engine

tesla motors

renewable hydrogen production



hydrogen storage

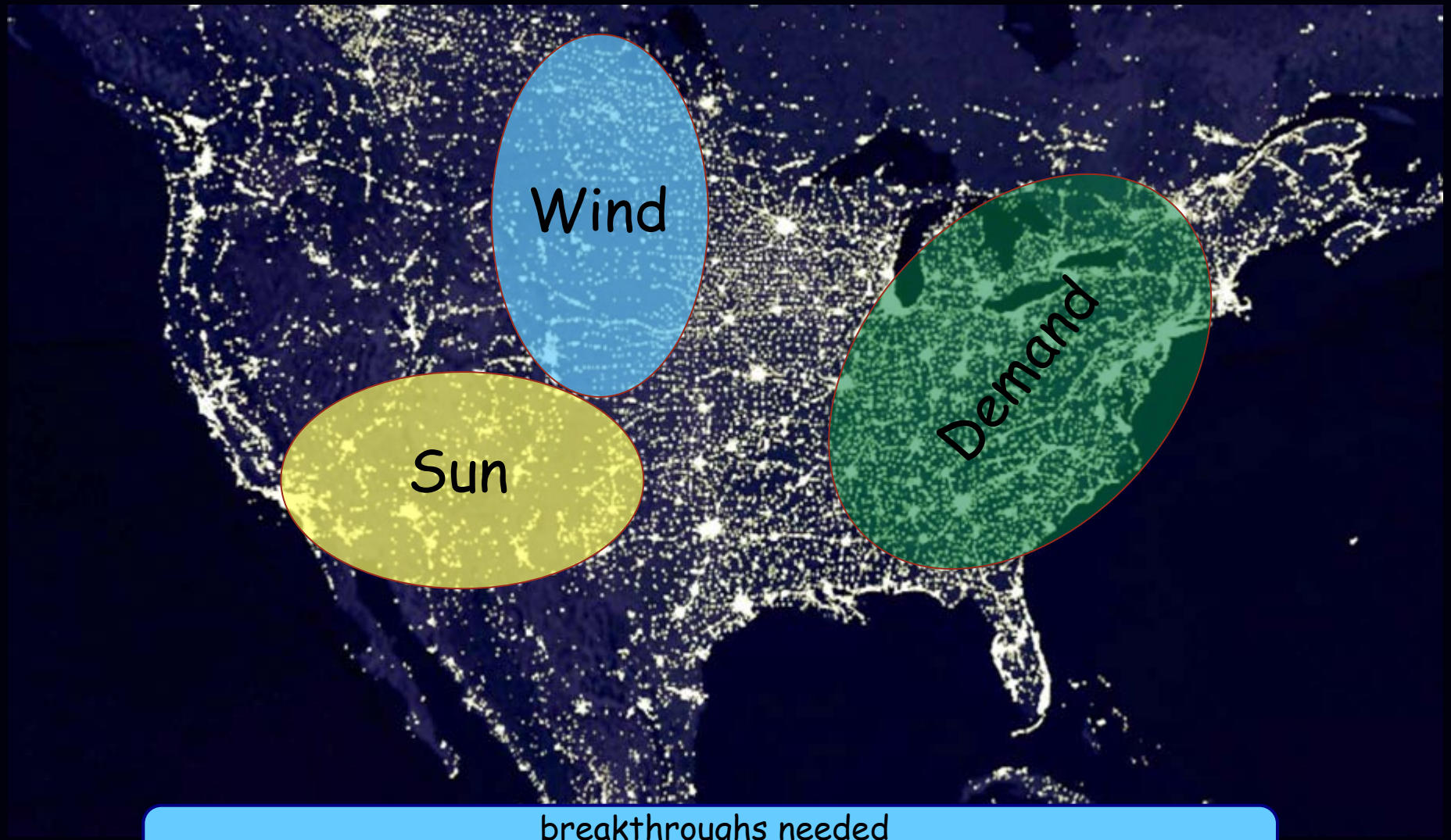


breakthroughs needed

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

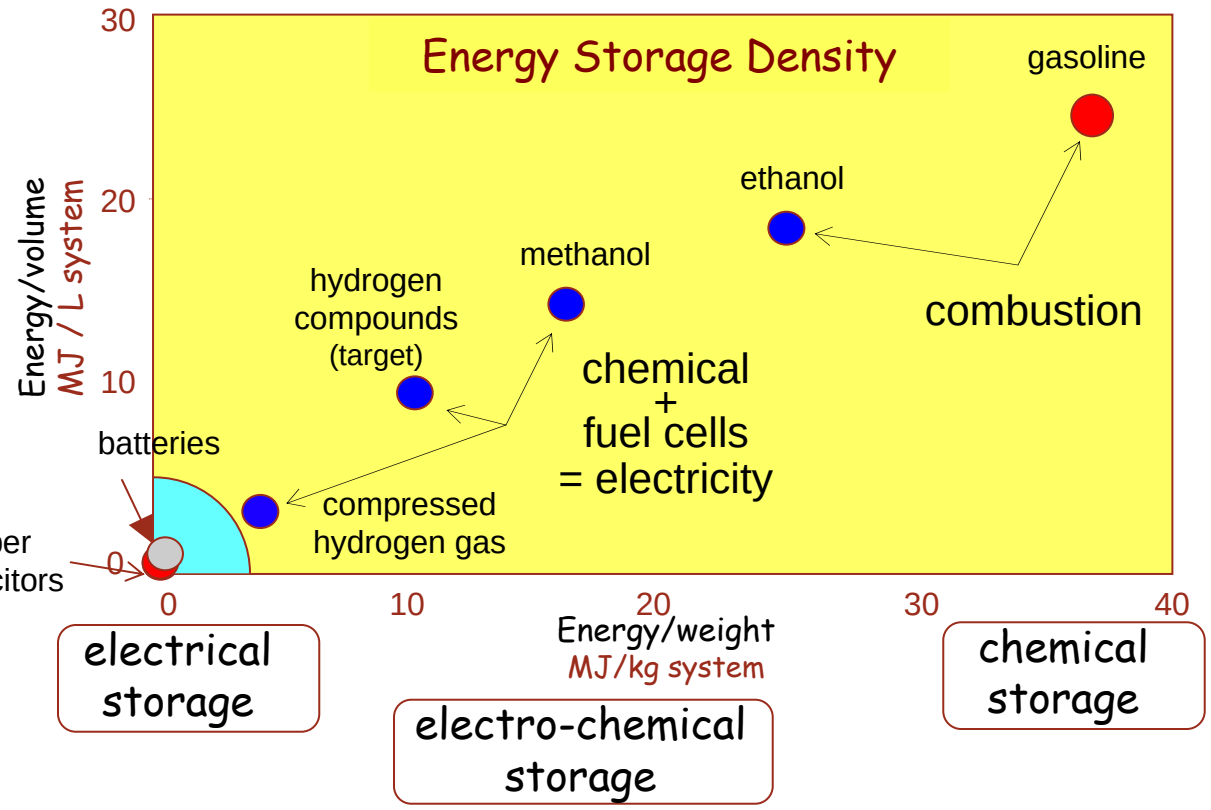
Enabling Technologies: Storing Energy

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

batteries:
30-50x less energy density than gasoline

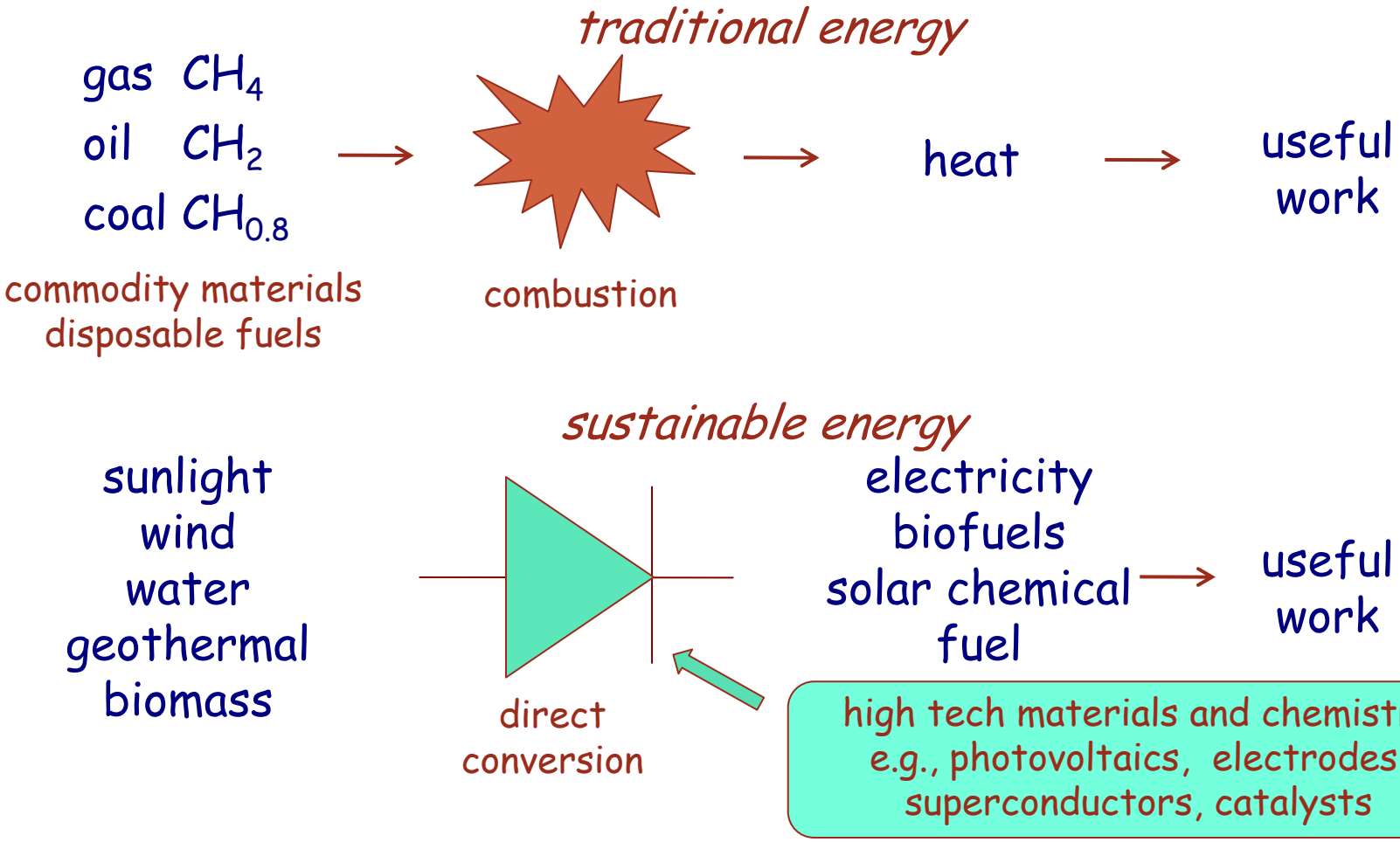
impossible dream: x10 improvement

beyond batteries:
chemical storage + fuel cells = electricity



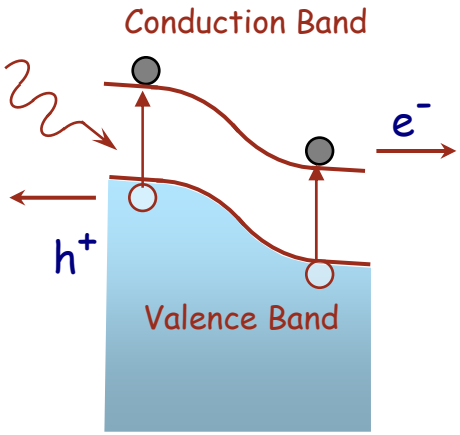
breakthroughs needed
x2-5 increase in battery energy density
x10-20 increase through chemical storage + fuel cells

The Transition to Sustainable Energy: High Tech Materials and Chemistry



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

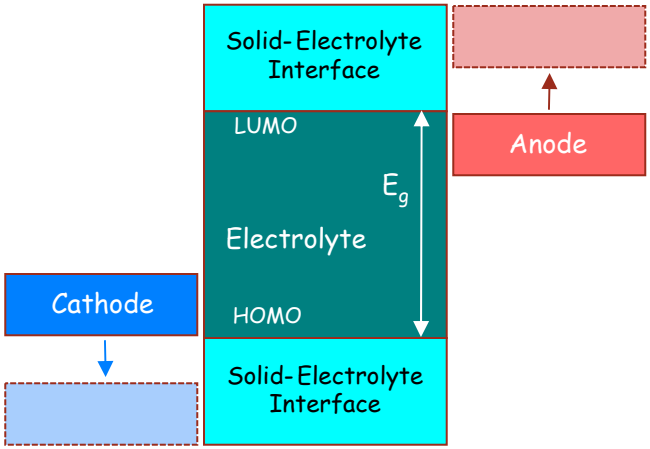
Quantum Energy Conversion



Silicon

Photovoltaic Cell

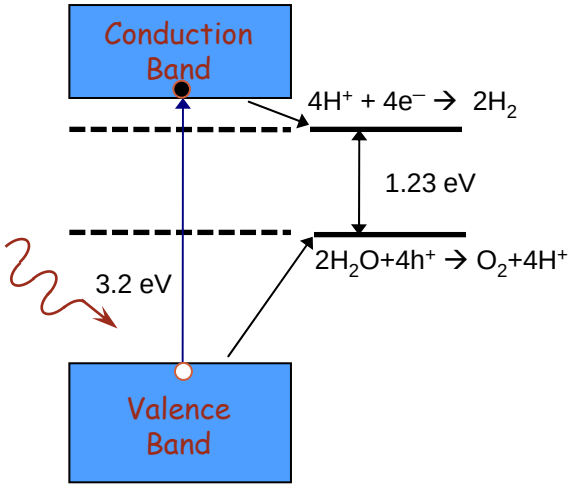
Crabtree and Lewis
Solar Energy Conversion
Physics Today 60(3), 37 (2007)



Li ion

Battery Fuel Cell

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



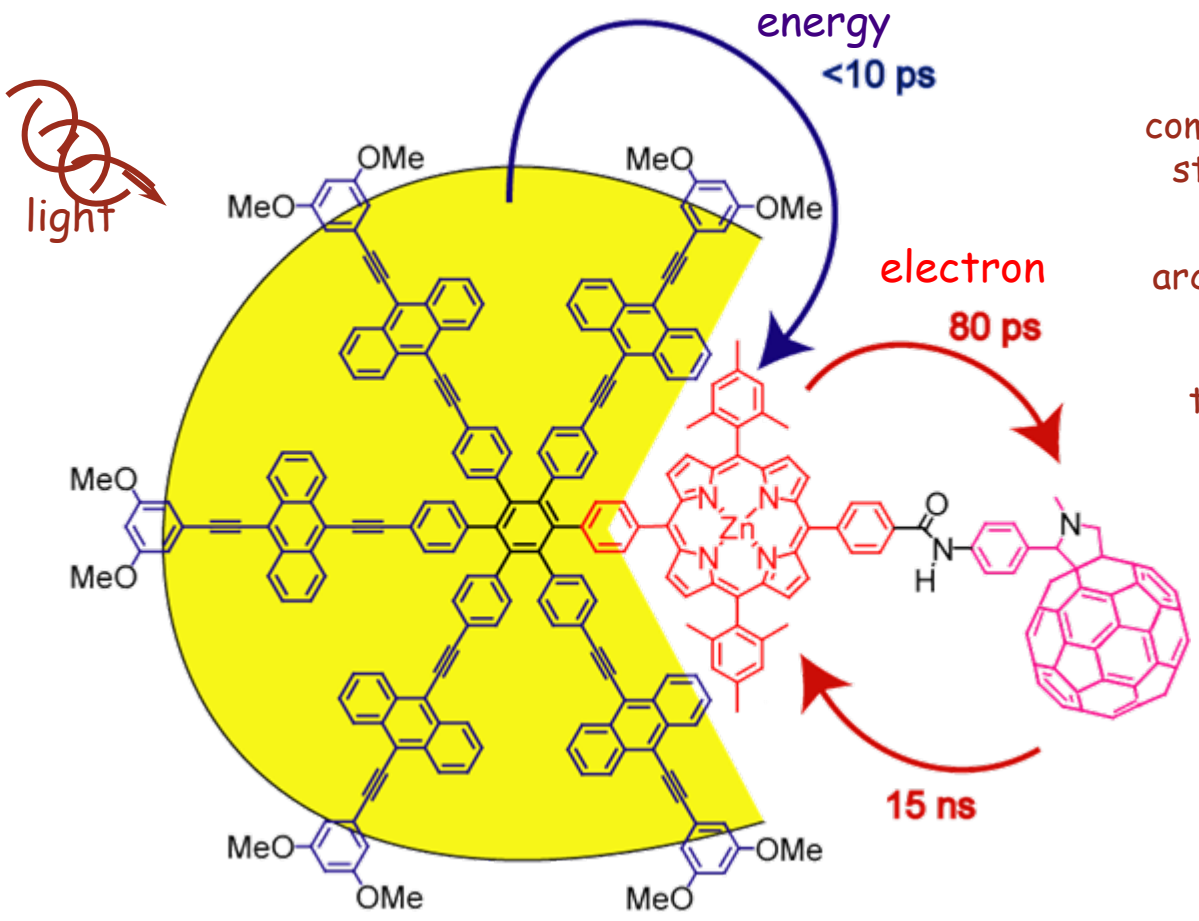
Solar chemistry
TiO_2 / water splitting

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



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)

Levels of Complexity

compositional structural → functional unit

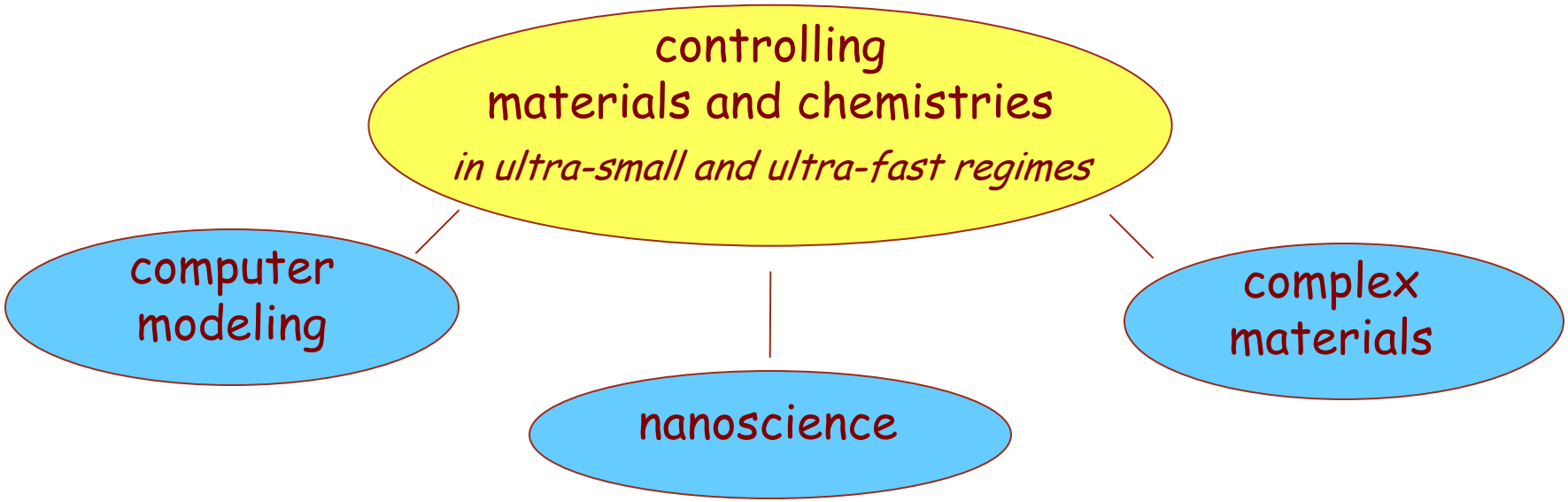
architectural → connecting functional units

temporal → connecting sequential steps

many interacting degrees of freedom

synthesis characterization theory and modeling

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