March 2007

The Global Energy Challenge

George Crabtree
Argonne National Laboratory

Follow this and additional works at: http://repository.upenn.edu/pennergy_presentations

http://repository.upenn.edu/pennergy_presentations/2


This paper is posted at ScholarlyCommons. http://repository.upenn.edu/pennergy_presentations/2
For more information, please contact libraryrepository@pobox.upenn.edu.
The Global Energy Challenge

Abstract
The expected doubling of global energy demand by 2050 and its impact on supply, security, environment and climate challenge our traditional patterns of energy production, distribution and use. New routes are needed for the efficient conversion of energy from chemical fuel, sunlight, and heat to electricity or hydrogen as an energy carrier and finally to end uses like transportation, lighting, communication and information processing. Opportunities for efficient new energy conversion routes based on nanoscale materials will be presented, with emphasis on the sustainable energy technologies they enable.

Comments

This presentation is available at ScholarlyCommons: http://repository.upenn.edu/pennergy_presentations/2
The Global Energy Challenge

George Crabtree
Argonne National Laboratory

Fossil Energy Challenges
Production: Solar
Distribution: Electricity
Use: Solid State Lighting
Hydrogen

Search for a Sustainable Energy Future
University of Pennsylvania
March 9, 2007
World Energy Demand

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

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

World Fuel Mix 2001

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

Argonne National Laboratory
**Fossil: Supply and Security**

**When Will Production Peak?**

- **World Oil Production**
  - 2% demand growth
  - Ultimate recovery: 3000 Bbbl
  - 2016 peak

- **unconventional oil**
  - oil sands
  - oil shale

**EIA:** [http://tonto.eia.doe.gov/FTPROOT/presentations/long_term_supply/index.htm](http://tonto.eia.doe.gov/FTPROOT/presentations/long_term_supply/index.htm)


**World Oil Reserves/Consumption 2001**

- Uneven distribution
  - \( \Rightarrow \) Insecure access

**Beyond the peak**

- New geopolitical relationships
- Alternative fuels
- Unconventional oil
  - Break even ~ $30-40 / bbl
  - 50% more \( CO_2 \)/gallon gasoline


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

Relaxation time
transport of CO$_2$ or heat to deep ocean: 400 - 1000 years

Climate Change 2001: The Scientific Basis, Fig 2.22

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

Atmospheric CO$_2$ (ppmv)

- 8 - 4 0 + 4 + 8

ΔT relative to present (°C)

Thousands of years before present (Ky BP)

Year AD

Temperature (°C)

CO$_2$ in 2004: 380 ppmv
The Energy Alternatives

Fossil  Nuclear  Renewable  Fusion

- 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

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 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 x 10^{22} Joules
1.5 days of sunlight

Annual Human Production of Energy
4.6 x 10^{20} Joules
1 hour of sunlight
Solar Energy Utilization

Solar Electric

- 0.0002 TW PV (world)
- 0.00003 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
Solar Energy Challenges

- Solar electric
- Solar fuels
- Solar thermal
Solar Electric

- Despite 30-40% growth rate in installation, photovoltaics generate
  
  *less than 0.02% of world electricity (2001)*
  
  *less than 0.002% of world total energy (2001)*

- Decrease *cost/watt* by a factor 10 - 25 to be competitive with fossil electricity (without storage)

- Find effective method for *storage* of photovoltaic-generated electricity
Revolutionary Photovoltaics: 50% Efficient Solar Cells

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

rich variety of new physical phenomena
challenge: understand and implement
Organic Photovoltaics: Plastic Photocells

opportunities
inexpensive materials, conformal coating, self-assembling fabrication, wide choice of molecular structures, “cheap solar paint”

challenges
low efficiency (2-5%), high defect density, low mobility, full absorption spectrum, nanostructured architecture
Solar Energy Challenges

Solar electric

Solar fuels

Solar thermal
Solar Fuels: Solving the Storage Problem

- Biomass < 0.3% efficient: too much land area
  Increase efficiency 5 - 10 times

- Designer plants and bacteria for designer fuels:
  $H_2$, $CH_4$, methanol and ethanol

- Develop artificial photosynthesis
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

Modify the biochemistry of plants and bacteria
- improve efficiency by a factor of 5–10
- produce a convenient fuel: methanol, ethanol, H₂, CH₄

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

hydrogenase

$2H^+ + 2e^- \Leftrightarrow H_2$

switchgrass

chlamydomonas moewusii

10 µ
Efficient Solar Water Splitting

demonstrated efficiencies 10% in laboratory

Scientific Challenges

- cheap materials that are robust in water
- catalysts for the redox reactions at each electrode
- nanoscale architecture for electron excitation ⇒ transfer ⇒ reaction
Solar-Powered Catalysts for Fuel Formation

plants - photosynthesis

\[ 2H_2O + hv \rightarrow 4H^+ + 4e^- + O_2 \]

\[ CO_2 + H^+ + e^- \rightarrow \text{carbohydrates} \ (\sim H_6C_{12}O_6) \]

bio inspired artificial water splitting
fuel production:

artificial photosynthesis
fuel from sunlight, \( H_2O, CO_2 \)
\( H_2, CH_4, CH_3OH, C_2H_5OH \)

bacteria - hydrogenase
catalyst for

\[ 2H^+ + 2e^- \Leftrightarrow H_2 \]


Solar Energy Challenges

- Solar electric
- Solar fuels
- Solar thermal
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
Solar Thermochemical Fuel Production

high-temperature hydrogen generation
500 °C - 3000 °C

Scientific Challenges
high temperature reaction kinetics of
- metal oxide decomposition
- fossil fuel chemistry
robust chemical reactor designs and materials

A. Streinfeld, Solar Energy, 78,603 (2005)
Thermoelectric Conversion

$ZT = \frac{\sigma}{\kappa} T$

$ZT \sim 3$: efficiency ~ 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

thermal gradient $\Leftrightarrow$ electricity

$\text{AgPb}_{18}\text{SbTe}_{20}$

$\text{LAST-18}$

$\text{Zn}_4\text{Sb}_2$

$\text{Bi}_2\text{Te}_3$/$\text{Sb}_2\text{Te}_3$

$\text{PbTe}$/$\text{PbSe}$

$\text{Bi}_2\text{Te}_3$

$\text{SiGe}$

$\text{Mercuri Kanatzidis}$

Argonne National Laboratory
Nanoscience

manipulation of photons, electrons, and molecules

nanostructured thermoelectrics

nanoscale architectures
  top-down lithography
  bottom-up self-assembly
  multi-scale integration

characterization
  scanning probes
  electrons, neutrons, x-rays
  smaller length and time scales

theory and modeling
  multi-node computer clusters
  density functional theory
  10,000 atom assemblies

Solar energy is interdisciplinary nanoscience
Electricity as an Energy Carrier

- coal
- gas
- nuclear fission
- hydro
- wind
- solar
- mechanical motion
- electricity
- fuel cells

> power grid

- digital electronics
- communication
- transportation
- industry
- lighting
- heating
- refrigeration

35% of primary energy
34% of CO\(_2\) 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

reliability
power quality
- average power loss/customer (min/yr)
  - US: 214
  - France: 53
  - Japan: 6

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

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

$79 B economic loss (US)

$26.3 B
Sustained Interruptions 33%

$52.3 B
Momentary Interruptions 67%

LaCommare & Eto, Energy 31, 1845 (2006)
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)
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
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,

- 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

YBa$_2$Cu$_3$O$_{7-x}$ coated conductor
transition temperature = 92 K
operating temperature = 77 K (LN$_2$)
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 Tc = 164 K under pressure
  (1/2 Room Temp)
  Only class of high Tc superconductors?

High Tc superconductors ≥ 4 elements
55 superconducting elements
  → $55^4 \approx 10$ 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

http://www.sc.doe.gov/bes/reports/abstracts.html#SC
Superconductors by Design

Discovery by serendipity: Hg (1911), copper oxides (1986), MgB₂ (2001), NaCoO₂·H₂O (2003)
Discovery by empirical guidelines: competing phases, layered structures, light elements, . . .
B-doped diamond (2004), CaC₆ (2005)

Crystal Structure
Composition

Electronic Structure
Density functional theory

Pairing Mechanism
phonons (classical BCS)
spin fluctuations
valence fluctuations

Temperature

Composition
Superconductivity

Computationally designed superconductors

- Electronic structure calculation by density functional theory
- Large scale phonon calculations in nonlinear, anharmonic limit
- Formulate “very strong” electron-phonon coupling (beyond Eliashberg)
- Determine quantitative pairing mechanisms for high temperature SC

Challenge: Create a paradigm shift to superconductors by design
Electricity Use: Solid State Lighting

Lighting ~ 22% of electricity use

incandescent ~ 5% efficient
Solid state > 50% efficient

wide bandgap compound semiconductors
GaN InGaN AlGaN
color: control bandgap
efficiency: control defects
white light: mix 3 or 4 colors

Research Challenges
new materials
doping and defect control
white light at 50% efficiency

http://www.sc.doe.gov/bes/reports/abstracts.html#SSL
Hydrogen as an Energy Carrier

Production:
- H₂O
- solar wind hydro
- nuclear/solar thermochemical cycles
- bio- and bio-inspired
- fossil fuel reforming + carbon capture

Storage:
- H₂
- gas or hydride storage

Use in fuel cells:
- automotive fuel cells
- consumer electronics
- stationary electricity/heat generation

- 9M tons/yr
- 150 M tons/yr (light trucks and cars in 2040)

- 4.4 MJ/L (Gas, 10,000 psi)
- 8.4 MJ/L (LH2)

- 9.72 MJ/L (2015 FreedomCAR Target)

- $3000/kW
- $30/kW (mass production)

($300/kW mass production)
Hydrogen Studies

Basic Energy Sciences Department of Energy
July 2003/February 2004

National Research Council National Academy of Sciences
February 2004
http://www.nap.edu/catalog/10922.html

G. W. Crabtree, M. S. Dresselhaus, M. V. Buchanan
Physics Today 57(12), 39-44, 2004
http://www.physicstoday.org/vol-57/iss-12/p39.html
Energy Flows in 2005

in quads = 10^{15} \text{ Btu}

Lawrence Livermore
National Laboratory
http://eed.llnl.gov/flow/

complex system: many interacting degrees of freedom
The Technical Challenges

Conversion Phenomena
Heat to motion: heat engine 1750s
Motion to electricity: 1840s
Light to electricity: 1960s
Chemical to electricity: fuel cells 1970s
Electricity to light: solid state lighting 1990s
Light to fuel: corn ethanol 1980s
Light to fuel: artificial photosynthesis 2000s

Energy Systems
Internal combustion 1900s
Electricity grid 1890s
Diesel engines 1900s
Solar cells 1970s
Nuclear energy 1960s
Hybrid cars 2000s
Plug-in hybrids
Cellulosic ethanol
Fuel cell battery replacements
White solid state light

science ➔ technology
# Energy Conversion Efficiency

<table>
<thead>
<tr>
<th>conversion</th>
<th>efficiency</th>
<th>practical target</th>
</tr>
</thead>
<tbody>
<tr>
<td>chemical bonds $\Rightarrow$ electrons</td>
<td>30% (fossil electricity)</td>
<td>$&gt; 60%$</td>
</tr>
<tr>
<td>chemical bonds $\Rightarrow$ motion</td>
<td>28% (gasoline engine)</td>
<td>$&gt; 60%$</td>
</tr>
<tr>
<td>photons $\Rightarrow$ electrons</td>
<td>18% (market) / 28% (lab)</td>
<td>$&gt; 60%$</td>
</tr>
<tr>
<td>photons $\Rightarrow$ chemical bonds</td>
<td>0.3% (biomass)</td>
<td>$&gt; 20%$</td>
</tr>
<tr>
<td>electrons $\Rightarrow$ photons</td>
<td>5-25%</td>
<td>$&gt; 50%$</td>
</tr>
</tbody>
</table>
Energy: a **BIG** Complex System

- Science
- Technology
- Economics
- Sociology
- Politics

no one dimensional solutions
change requires confluence of all elements

Emergent behavior
reactions of a thousand players
unanticipated events
Distant outcomes are unpredictable
**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**