The Sustainable Energy Challenge

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Fossil Energy Challenges
Sustainable Alternatives
Electricity
Hydrogen
Today’s Workshop Program

APS Energy Research Workshop
Pittsburgh PA
March 15, 2009
World Energy Demand

- EIA Intl Energy Outlook 2004

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**World Energy Demand**

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

**Energy Gap**
- ~ 14 TW by 2050
- ~ 33 TW by 2100

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**World Fuel Mix 2001**

- 85% fossil

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- Total
- Industrial
- Developing
- US
- EE/FSU
**Energy Challenges: Supply and Security**

**When Will Production Peak?**

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

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

**World Oil Reserves/Consumption 2001**

- Uneven distribution ⇒ insecure access

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

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

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Beyond the peak
- New geopolitical relationships
- Alternative fuels
- Unconventional oil
- Coal: > 200 yrs
- Gas: beyond oil
- Break even ~ $30-40 / bbl
- 50% more CO₂/gallon gasoline

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**World Oil Reserves/Consumption**

Energy Challenges: Pollution

Auto exhaust in Los Angeles

pollution collects in high auto density basins

acid rain in the US

pollution zones near sources urban areas, power plants

http://www.epa.gov/air/urbanair/6poll.html
**Energy Challenges: Climate Change**

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

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

solar, wind, hydroelectric
ocean tides and currents
biomass, geothermal
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

- coal
- gas
- nuclear fission
- hydro
- wind
- solar
- heat
- mechanical motion
- electricity
- fuel cells
- digital electronics
- communication
- transportation
- industry
- lighting heating refrigeration

- 35% of primary energy
- 34% of CO₂ emissions
- 34% efficient

- clean, efficient
  - does no harm
  - leaves no change

- e⁻
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

- Nuclear/solar thermochemical cycles
- Solar, wind, hydro
- Bio- and bio-inspired
- Fossil fuel reforming
- Gas or hydride storage
- Automotive fuel cells
- Consumer electronics
- Stationary electricity/heat generation

90% of hydrogen produced in US by reforming CH₄

\[ CH₄ + 2H₂O \rightarrow CO₂ + 4H₂ \]

Clean, efficient, does no harm, leaves only H₂O

\[ 2H₂ + O₂ \rightarrow 2H₂O \]
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 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**
- .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

Basic Research Needs for Solar Energy Utilization
Report of the Basic Energy Sciences Workshop on Solar Energy Utilization
April 19-21, 2005

March 2007

PHYSICS TODAY

Solar energy conversion
George Crabtree and Nathan Lewis

If solar energy is to become a practical alternative to fossil fuel, 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.

The Sun provides Earth with a staggering amount of energy—enough to power the great oceanic and atmospheric systems, the cycle of evaporation and condensation that brings fresh water inland, the current flows, 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 10^12 joules of energy, the amount the Sun delivers to Earth in one second. Earth's ultimate renewable resource of oil, estimated at 3.5 x 10^12 barrels, contains 17 x 10^12 joules of energy, which the Sun supplies to Earth in 1.5 days. The amount of energy humans use annually, about 4.4 x 10^12 joules, is delivered to Earth by the Sun in one hour.

Despite the abundance and versatility of solar energy, we...
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
- Materials Under Extreme Environments, 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