Energy: the Next Fifty Years

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Messages
Energy determines the aspirations and limitations of society

Vibrant global society in fifty years requires strategic energy decisions now

Top priorities for energy and society in fifty years

Discovery science is the low cost engine of innovation for energy and society
Energy Determines Aspirations and Limitations of Life

Energy
the prime mover of society
The World in Fifty Years... depends on the energy choices we develop now...

Steven Chu and Arun Majumdar, Nature 488, 294 (2012)
Planning for the Energy Future

Conventional approach
Project energy futures based on today’s technologies
Extrapolate trends in efficiency and cost
The energy future is a continuous extension of the present

Proactive approach
Define the global society we want in fifty years
Identify the strategic energy outcomes needed to enable that society
Target R&D to obtain those energy outcomes

Fifty years is long enough for energy R&D to work
Steer the energy–society nexus toward strategic global targets
The Global Society We Want in Fifty Years

- rapid growth of developing economies
- steady growth of developed economies
- aggressive pursuit of discovery science and innovation
- rapid deployment of innovative technologies
- lively communication, trade and exchange of people and ideas across national and regional boundaries
- globalization of opportunity and participation in scientific, technological, economic, social and cultural advances

“a vibrant, interactive, inclusive and rapidly advancing global society”
Energy Outcomes for a Vibrant Global Society in Fifty Years

Top Three Energy Outcomes

Energy security: adequate, affordable, sustainable, predictable
  basic to personal, social, professional, civic and commercial life

Stable climate
  Global discretionary resources are finite – after food, shelter, public health
  Cost of climate change depletes discretionary resources for advancing society
    e.g., discovery science, new technologies and improving the quality of life
  Curb carbon emissions to avoid the human and economic costs of climate change

Economic development and growth
  the natural aspiration of people and countries, the source of discretionary resources
  requires inexpensive, abundant energy
Energy Science for Society in Fifty Years

On the road

• Replace fossil with wind and solar electricity

On the road but not sustainable

• Replace coal and gas electricity with nuclear electricity
• Replace coal and oil with abundant, safe and inexpensive shale gas

Not on the road

• Mitigate carbon emissions: mineralize carbon dioxide to rocks
• Develop electricity storage for cars and the grid
• Make chemical fuel a sustainable energy carrier
Wind and Solar Electricity

- Stable climate
- Energy security

Viable technologies on deployment path

Remaining science challenges improve efficiency lower cost

**US Wind and Solar Electricity**

Cumulative Installed Capacity

- Ave output: 17 GW
- US ave use: 450 GW (~ 3.8% of US electricity)

15% growth/yr → 40% wind and solar electricity by 2030

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Safe, Higher Performing Nuclear Electricity

Heat without combustion or carbon dioxide
Established experience curve

Now: 35% efficiency
2050: 50%

Materials for
- Higher temperature
- Higher radiation damage
- Corrosive environments

Challenges
- Safety
- 1960s technology
- Spent fuel

Reprocessing for
- More electricity/fuel
- Less spent fuel storage
- Shorter storage time

4 to 10 times smaller volume
Thousands of years instead of hundreds of thousands of years

CuNb interfaces
Michael Demkowicz-MIT
Shale Gas and Hydraulic Fracturing

Abundant worldwide sources
Inexpensive
Lower carbon emissions than coal or oil

$/MBTU
peak 05-08: $12
non-peak 05-08: $8
Since Jan 2012: $2 - $4

US Natural Gas Production

Source: EIA

Potential Game Changer
lower carbon emissions
energy security
diversity of sources and uses
replace coal for power production
oil for transportation

EIA World Shale Gas Resources
http://www.eia.gov/analysis/studies/worldshalegas/
Hydraulic Fracturing Challenges – Science Needed

Operation
- Distant horizontal drilling into thin shale layers
- Local explosions fracture rock
- High pressure hydraulic fluid opens fissures
- Sand driven into fissures to prop open
- Gas and oil flow out

Challenges
- Flow of fluids in mesoporous rock
- Contamination of water, air
- Initial rush of gas
- Sharp decline in first year
- Only 20% of shale gas recovered

Science Challenges
- Understand and control fracture mechanics, pore formation, fluid flow in fractured rock

Carbon Dioxide Mineralization

MO + CO₂ → MCO₃ + energy

\[ \text{Mg}_2\text{Si}_2\text{O}_4 + 2\text{CO}_2 \rightarrow 2\text{MgCO}_3 + \text{SiO}_2 + ~1.4 \text{ MJ/kg CO}_2 \]

Also Ca, Fe, . . .

- Permanent, benign storage
- No follow up monitoring
- Capacity >> emissions

Carbon Dioxide Mineralization

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Gigatons Carbon</th>
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<tbody>
<tr>
<td>Atmosphere</td>
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<tr>
<td>Surface Ocean</td>
<td>670</td>
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<tr>
<td>Deep Ocean</td>
<td>36,730</td>
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<td>Carbonate Rocks</td>
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</tr>
<tr>
<td>Fossil fuels</td>
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</tr>
</tbody>
</table>

challenges / science solutions

- Slow reaction kinetics - find catalysts
- Non-reactive coating - control surface chemistry

Tannock Hall of Education, University of Notre Dame, Australia 2010
Electricity Storage

Two Biggest Energy Uses Poised for Transformational Change

Transportation 29%
- Foreign oil → domestic electricity
- Reduce carbon emissions
- Reduce energy use
- Moving energy in space

Electricity 40%
- Coal → Gas → Wind and Solar
- Reduce carbon emissions
- Greater flexibility, reliability, resiliency
- Moving energy in time

The bottleneck for both transitions is inexpensive, high performance electrical energy storage

EIA Annual Energy Review 2009
Joint Center for Energy Storage Research (JCESR)

**Vision**
Transform transportation and the electricity grid with high performance, low cost energy storage

**Mission: 5-5-5**
Deliver electrical energy storage with five times the energy density and one-fifth the cost of today’s commercial batteries within five years

**Legacies**
- A library of the fundamental science of the materials and phenomena of energy storage at atomic and molecular levels
- Two prototypes, one for transportation and one for the electricity grid, that, when scaled up to manufacturing, have the potential to meet JCESR’s 5-5-5 goals
- A new paradigm for battery R&D that integrates discovery science, battery design, research prototyping and manufacturing collaboration in a single highly interactive organization
JCESR Creates a New Paradigm for Battery R&D
Beyond Lithium Ion Space is Large, Unexplored and Rich

Materials

- Graphite, LiCoO₂, LiFePO₄, LiMnO₂
- Li, Mg, Bi, Sn, Oxysulfides
- Quinoxaline Metal Coordination Complexes
- Triflate, Tetraborate
- Oxide, Phosphate-based ceramics, Block Co-polymer
- Spinel, Layered, Li-S, Na-S, Quinoxoline, Polysulfides

Systems

- Intercalant electrodes
- Catholyte
- Chemical Transformation
- Intercalant
- Solid
- Liquid
- Anolyte
- Intercalant/Alloy
- Metal

Beyond Li-ion

mostly unknown

transformational advances

mostly known

Li-ion
incremental improvements
Develop Chemical Fuel as a Sustainable Energy Carrier

Hydrogen
requires infrastructure, storage, renewable production
2003 →

Cellulosic biofuels
requires land, low efficiency, limited capacity
2007 →

Carbon dioxide + water (hydrogen)
recycled chemical fuels
Significant science breakthrough

Graves, Ebbesen, Mogensen, Lackner
Renewable and Sustainable Energy Reviews 15,1 (2011)

Drop-in replacement for fossil
Incremental change to established combustion infrastructure
Promotes carbon mitigation, energy security
Develop Chemical Bonds as a Sustainable Energy Carrier

\[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{many opportunities for sustainable chemical fuel} \]
The Cost of Doing Things

discovery

development

deployment
Why Discovery Science?

• The cost is low
• It stimulates innovation - the lifeblood of economic competitiveness and growth
• It tells you what will fail before you attempt to develop it
• It pays back more than it costs in economic return
• It primes the innovation ecosystem
The world is undergoing an historic transition. Get on board.

An intense immersion in sustainable energy.

- lectures
- panel discussions
- energy tours
- career counseling
- networking opportunities
- collaborative research projects

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http://sise.phy.uic.edu
Perspective

Energy determines the aspirations and limitations of society

A vibrant, interactive, inclusive and rapidly advancing global society in fifty years requires strategic energy outcomes

- adequate, affordable, sustainable, predictable energy
- stable climate
- global economic development and growth

Discovery science targets for strategic energy outcomes

- wind and solar electricity
- safe, high performing nuclear electricity
- safe, inexpensive shale gas to replace coal and oil
- mineralization of carbon emissions to carbonate rocks
- electricity storage for transportation and the grid
- sustainable chemical energy carriers

Discovery science is the low cost engine of innovation for energy and society

George Crabtree, Elizabeth Kocs, Thomas Lipsmeyer, Energy, Society and Science: the Fifty Year Scenario to appear in Futures and available at http://ei.phy.uic.edu/res_publications.html