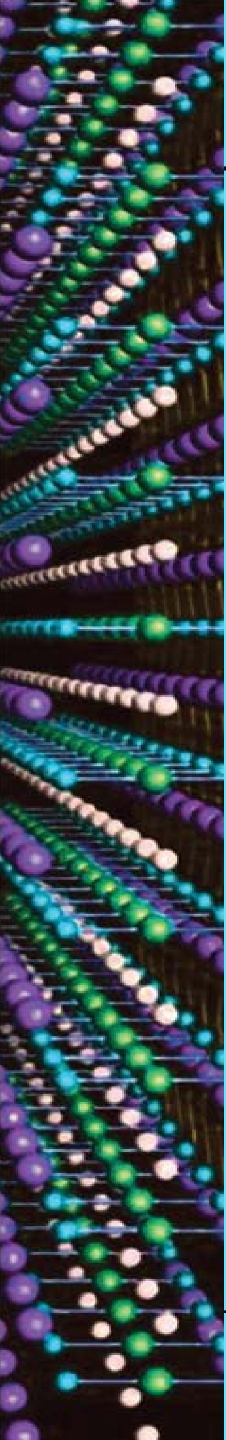

Energy: the Next Fifty Years

George Crabtree

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and
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Argonne National Laboratory

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

American Physical Society
Energy Workshop
Denver CO, March 2, 2014

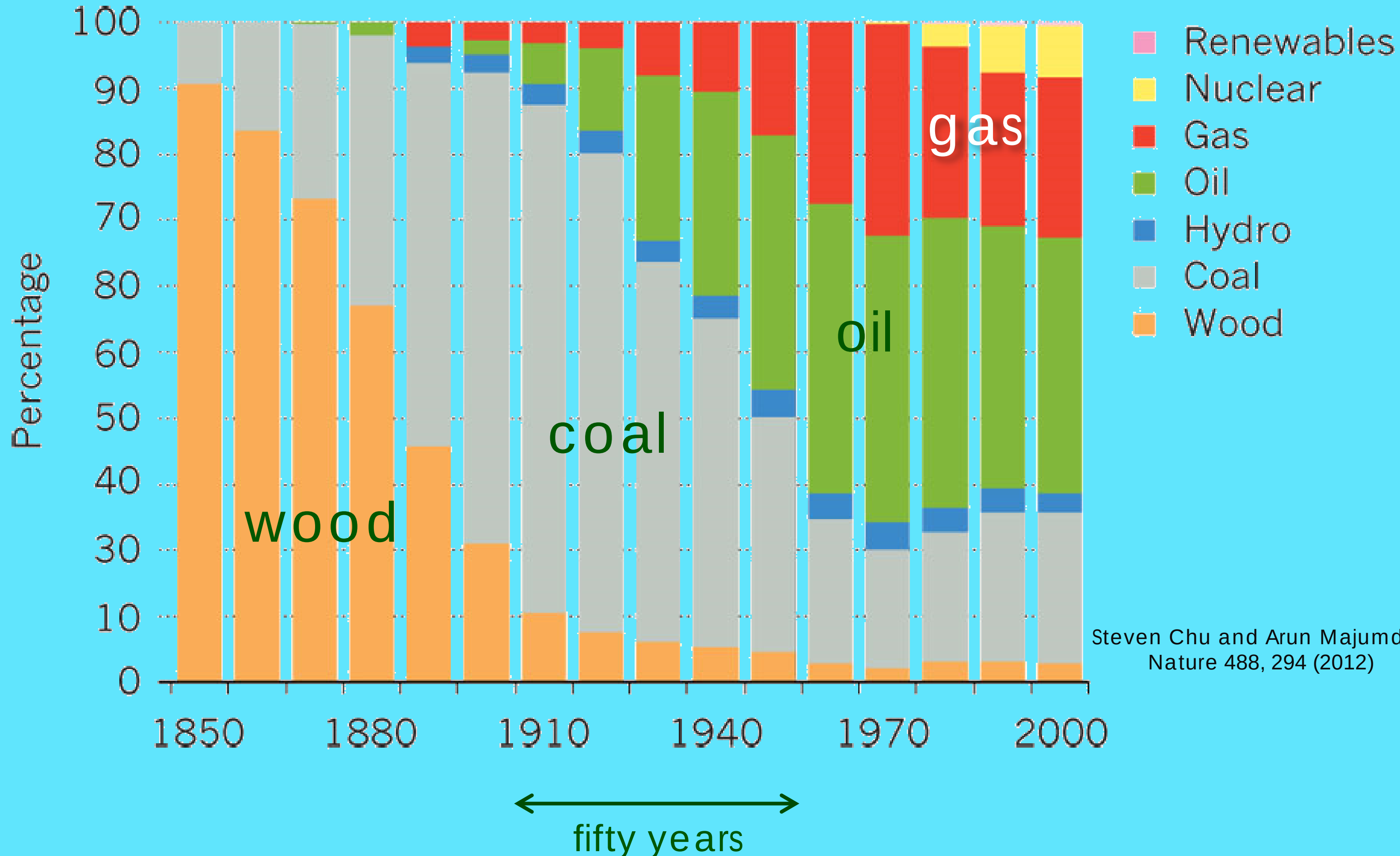
Energy Determines Aspirations and Limitations of Life

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

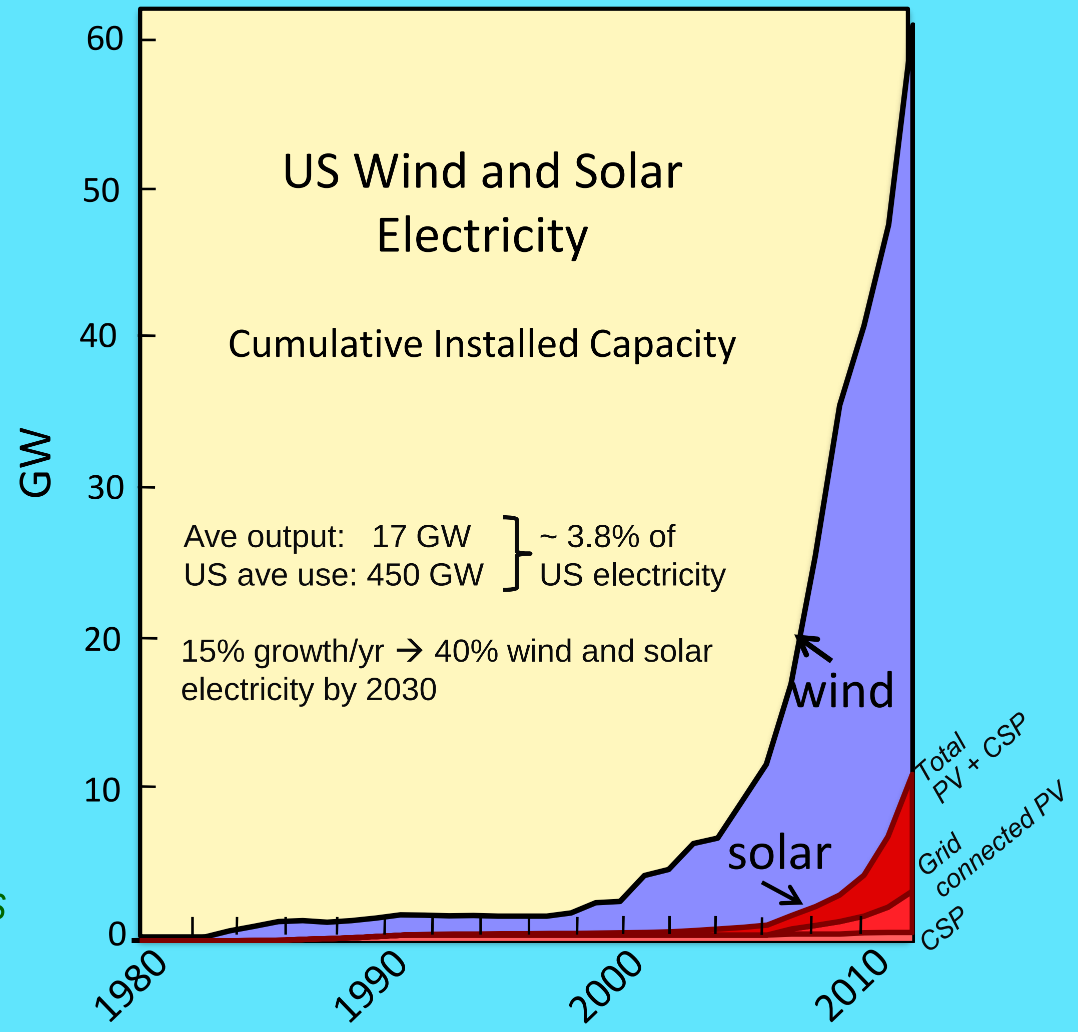
Viable technologies

on deployment path

Remaining science challenges

improve efficiency

lower cost

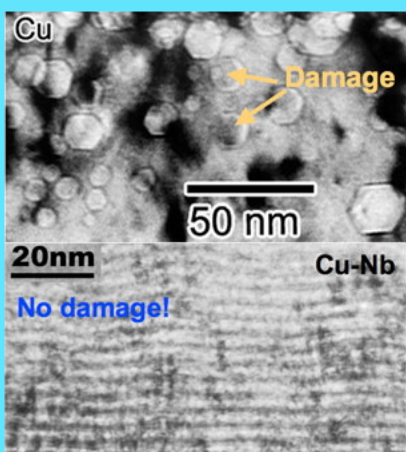


Safe, Higher Performing Nuclear Electricity

Heat without combustion or carbon dioxide

Established experience curve

Challenges
Safety
1960s technology
Spent fuel

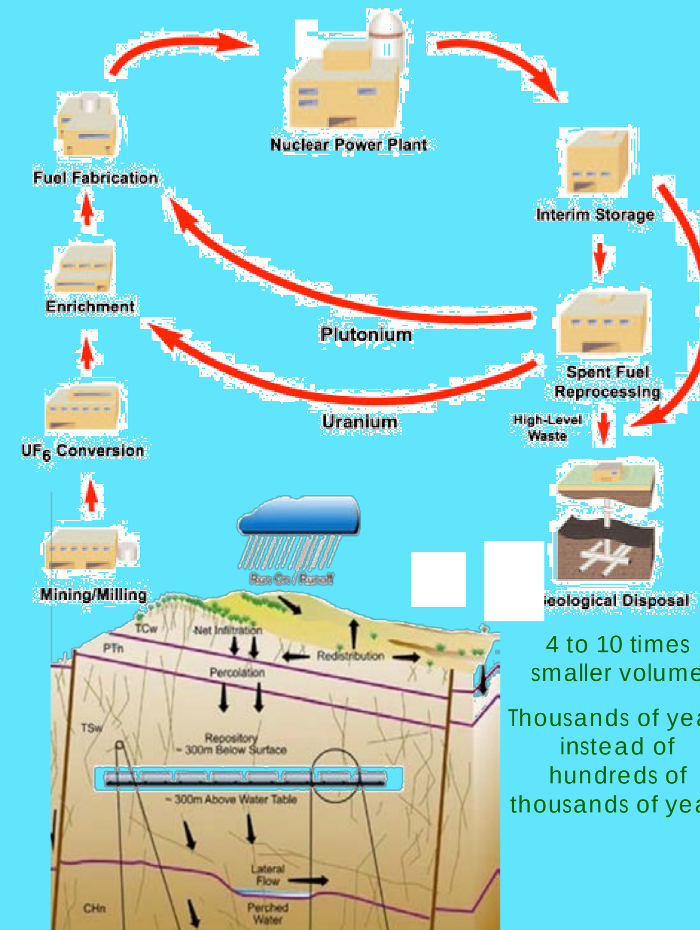


CuNb interfaces
Michael Demkowicz-MIT

Now: 35% efficiency
2050: 50%

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

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

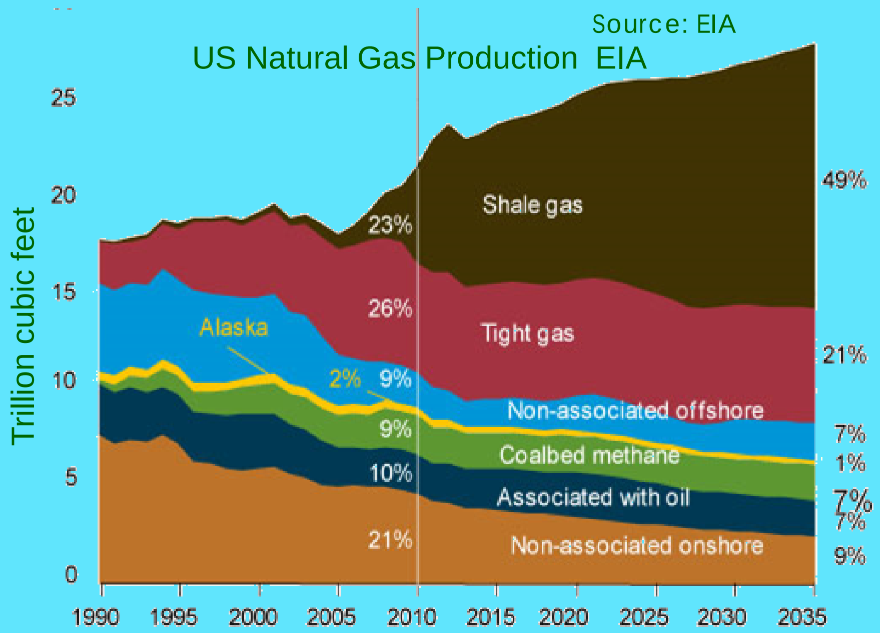
Shale Gas and Hydraulic Fracturing

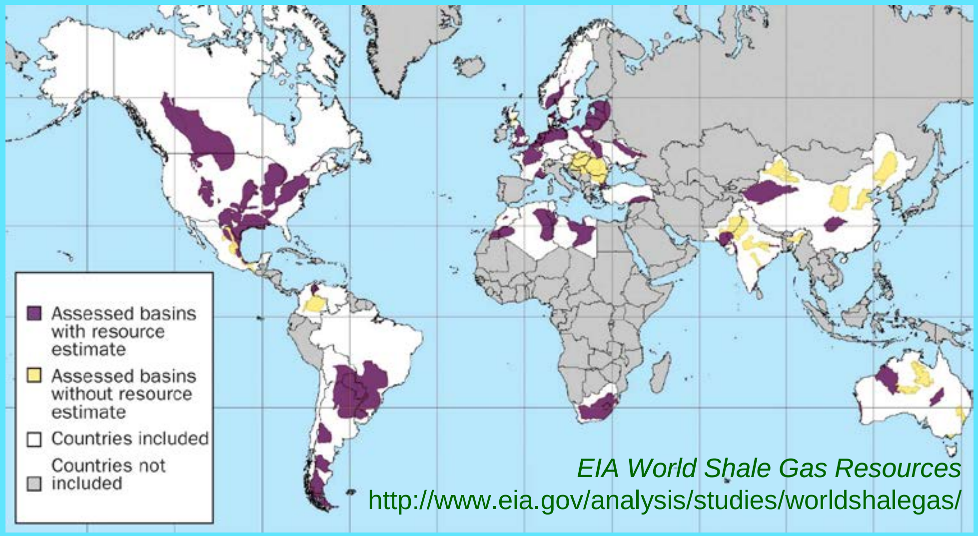
Abundant world wide sources

Inexpensive

Lower carbon emissions
than coal or oil

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





EIA World Shale Gas Resources
http://www.eia.gov/analysis/studies/worldshalegas/

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

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

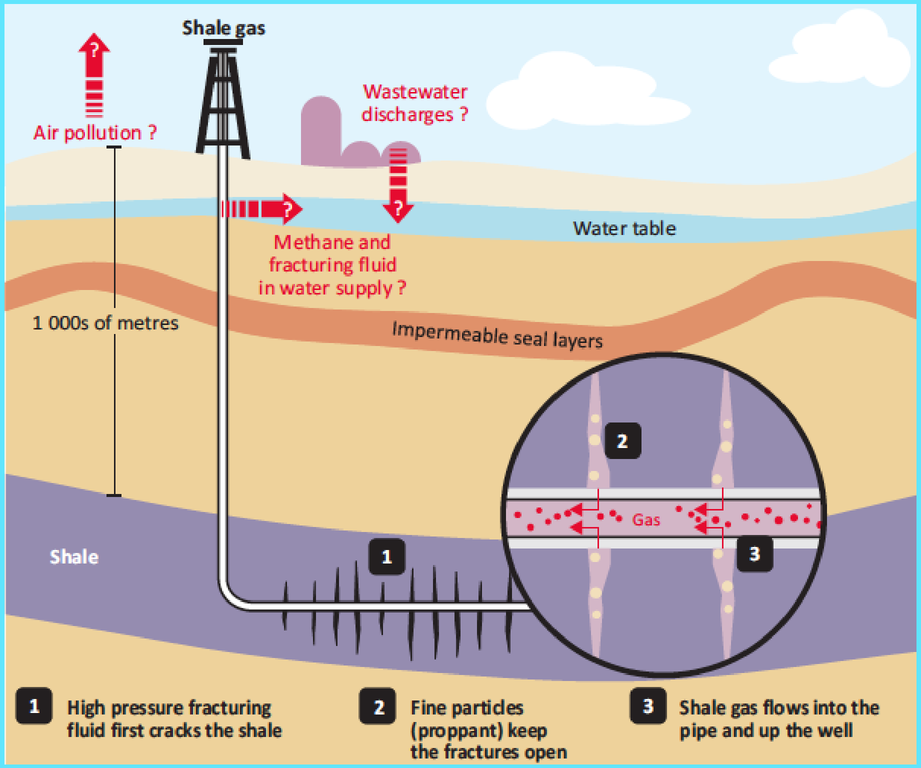
Flow of fluids in mesoporous rock

contamination of water, air

initial rush of gas

sharp decline in first year

Only 20% of shale gas recovered



IEA, Golden Rules for a Golden Era of Gas (2012)
Rachel Ehrenberg, Science News 182, 20 (2012)

Science Challenges

Understand and control

fracture mechanics, pore formation, fluid flow in fractured rock

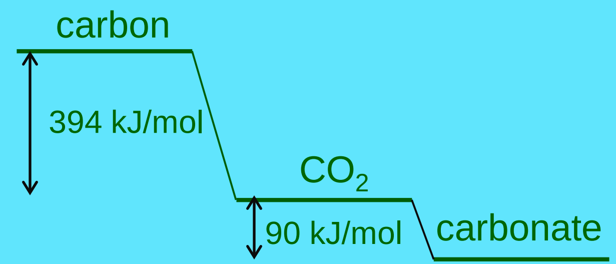
Carbon Dioxide Mineralization

$$MO + CO_2 \rightarrow MCO_3 + \text{energy}$$

$$Mg_2Si_2O_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2 + \sim 1.4 \text{ MJ/kg } CO_2$$

Also Ca, Fe, . . .

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



Reservoir	Gigatons Carbon
Atmosphere	720
Surface Ocean	670
Deep Ocean	36,730
Carbonate Rocks	>60,000,000
Fossil fuels	4,130

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

carbonate powder

challenges / science solutions

Slow reaction kinetics – find catalysts

Non-reactive coating – control surface chemistry

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%

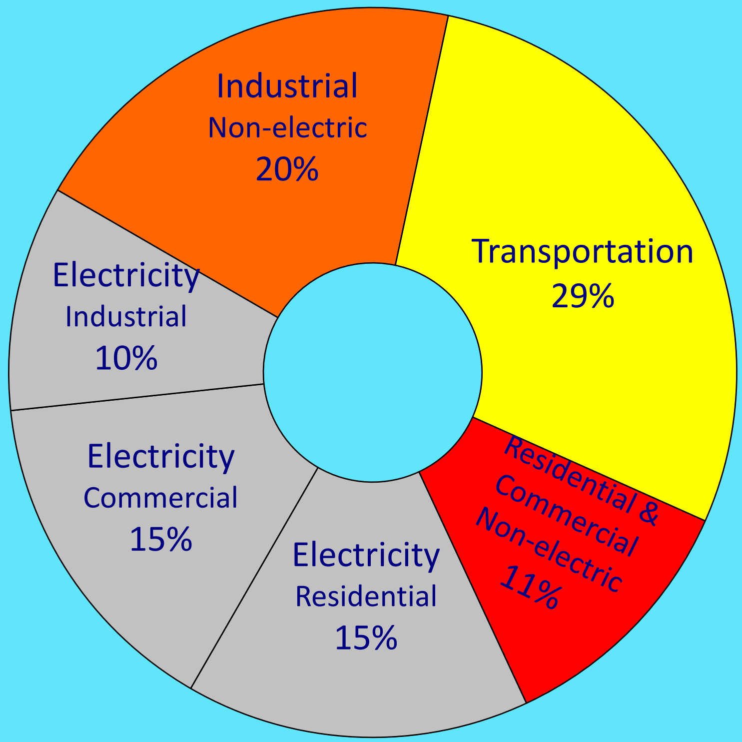
Coal → Gas → Wind and Solar

Reduce carbon emissions

Greater flexibility, reliability, resiliency

Moving energy in time

Energy Demand



EIA Annual Energy Review 2009

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

Joint Center for Energy Storage Research (JCESR)

TRANSPORTATION

$100/kWh

400 Wh/kg 400 Wh/L

800 W/kg 800 W/L

1000 cycles

80% DoD C/5

15 yr calendar life

EUCAR

GRID

$100/kWh

95% round-trip efficiency at C/5 rate

7000 cycles C/5

20 yr calendar life

Safety equivalent to a natural gas turbine

Vision

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

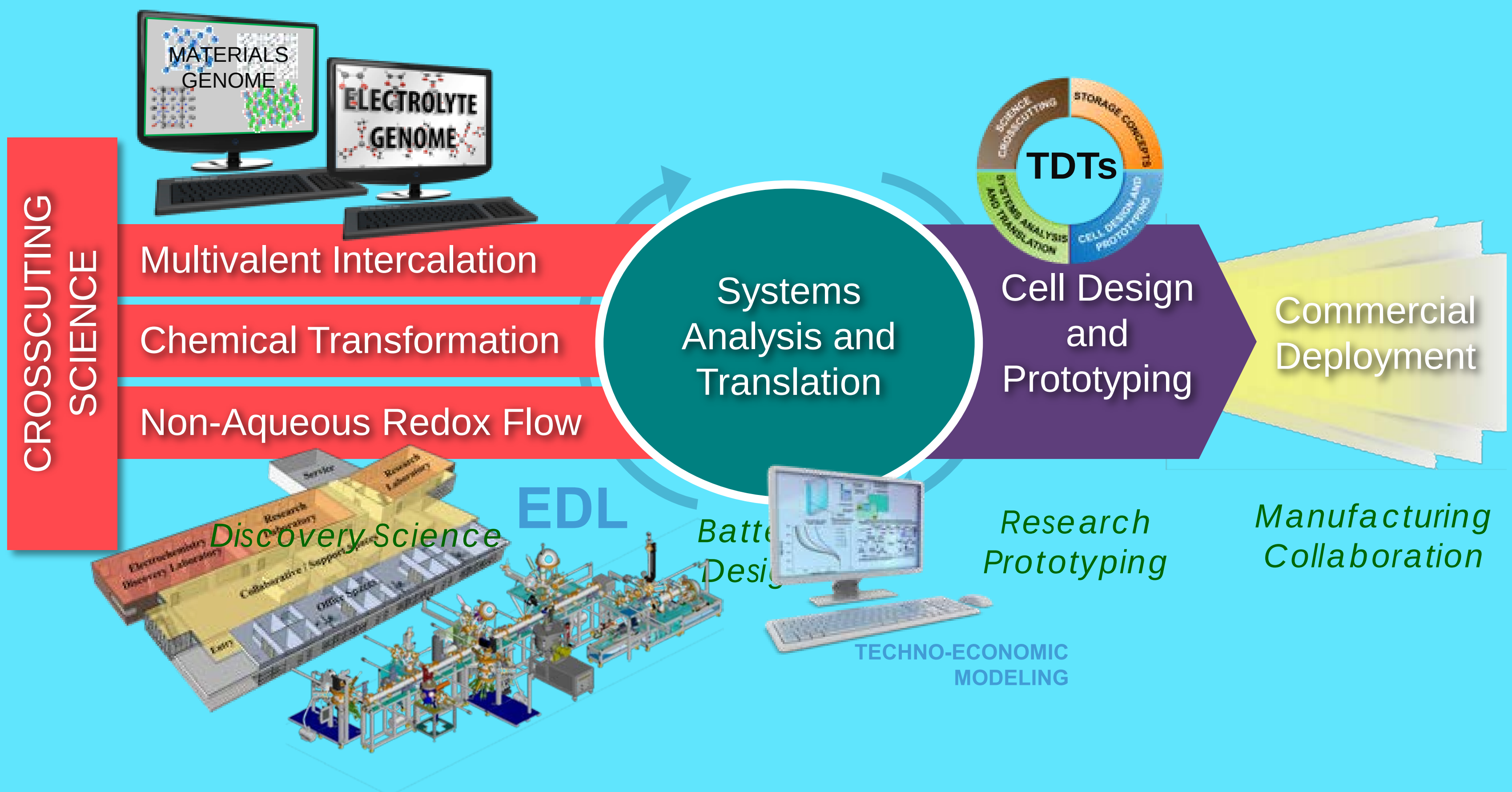
Mission: *5-5-5*

Deliver electrical energy storage with five times the energy density and one-fifth the cost of today's commercial batteries within five years

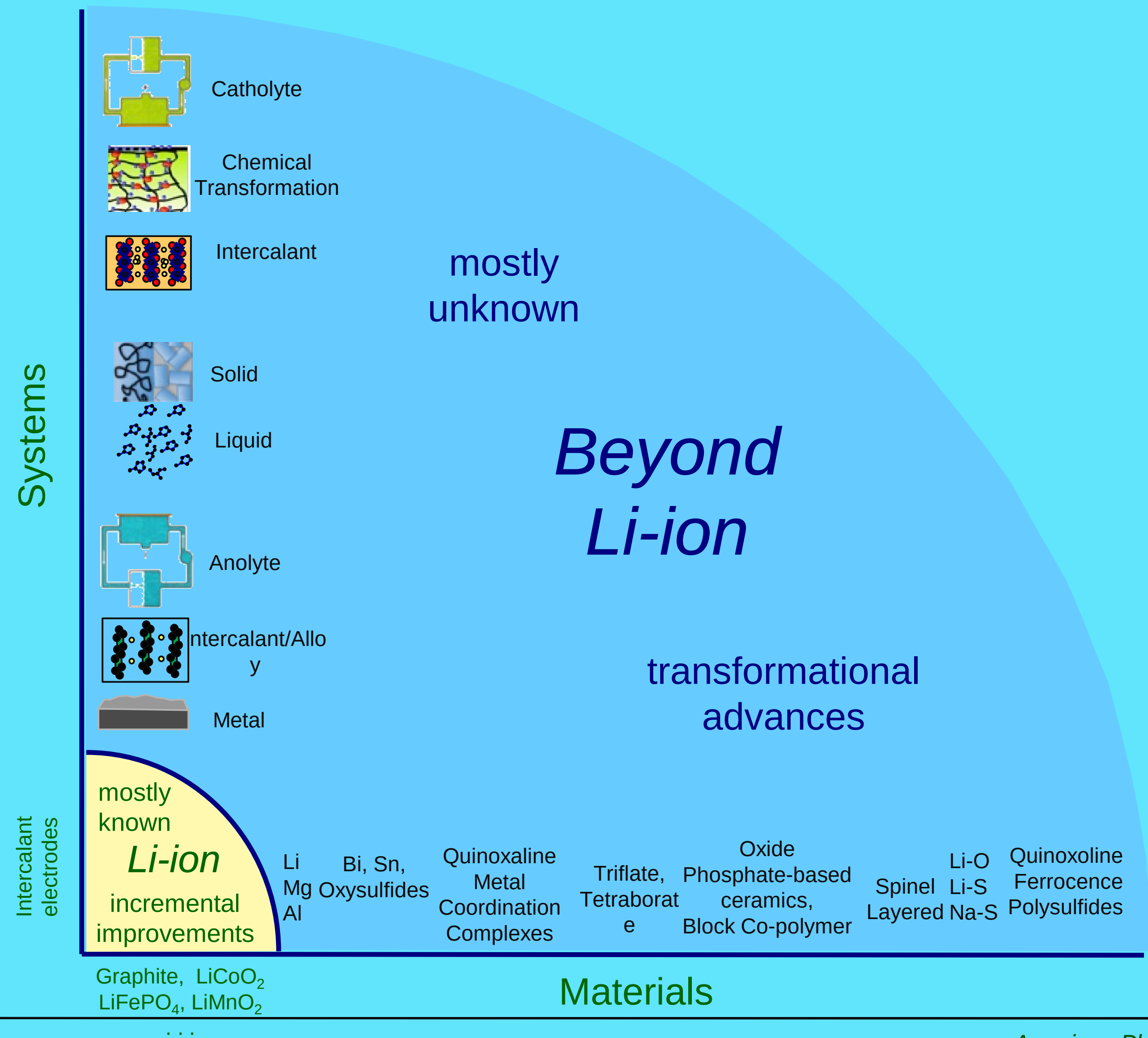
Legacies

- **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



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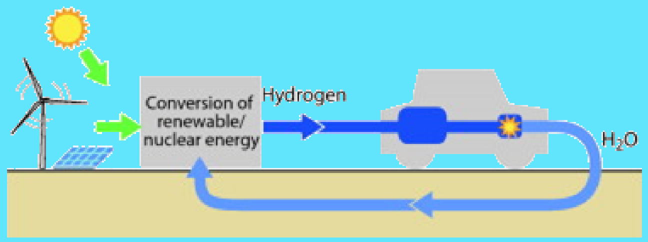
Develop Chemical Fuel as a Sustainable Energy Carrier

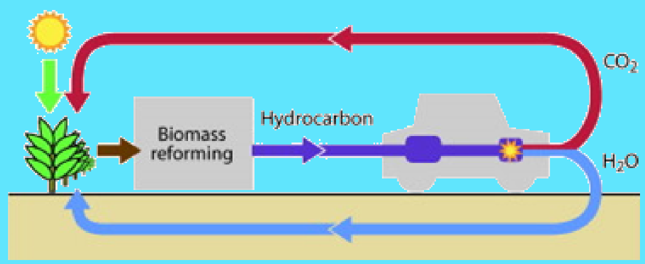


Hydrogen

requires infrastructure, storage,

renewable production

2003 →



Cellulosic biofuels

requires land, low efficiency,

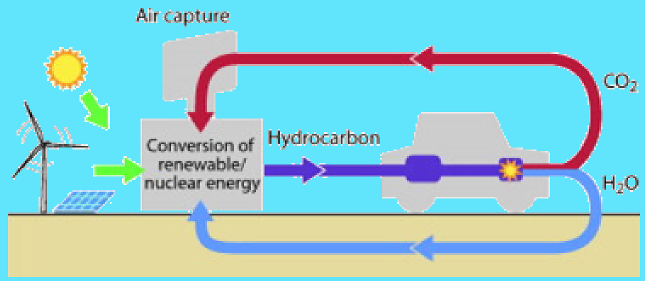
limited capacity

2007 →

Drop-in replacement for fossil

Incremental change to established combustion infrastructure

Promotes carbon mitigation, energy security



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

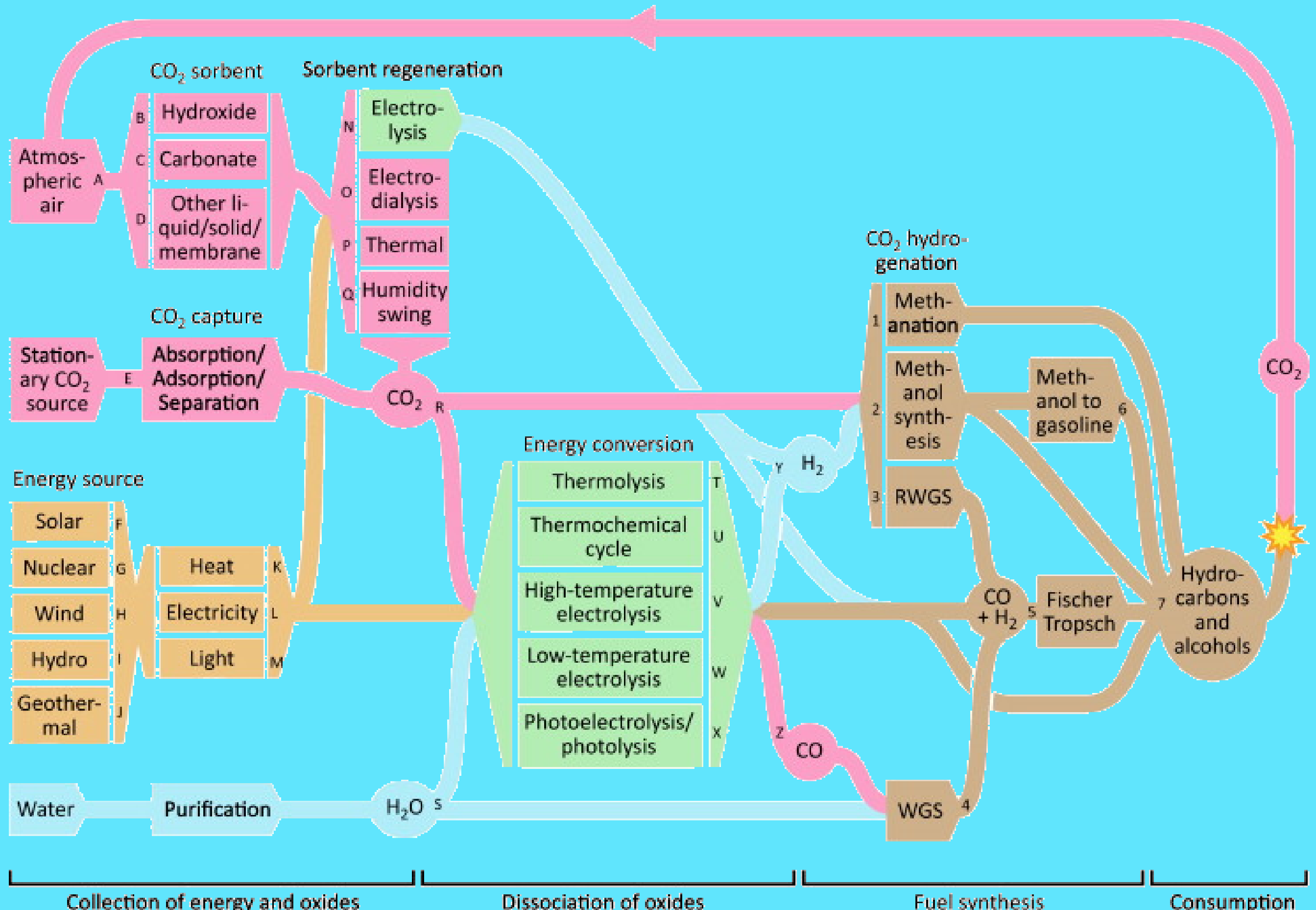
Carbon dioxide + water (hydrogen)

recycled chemical fuels

Significant science breakthrough

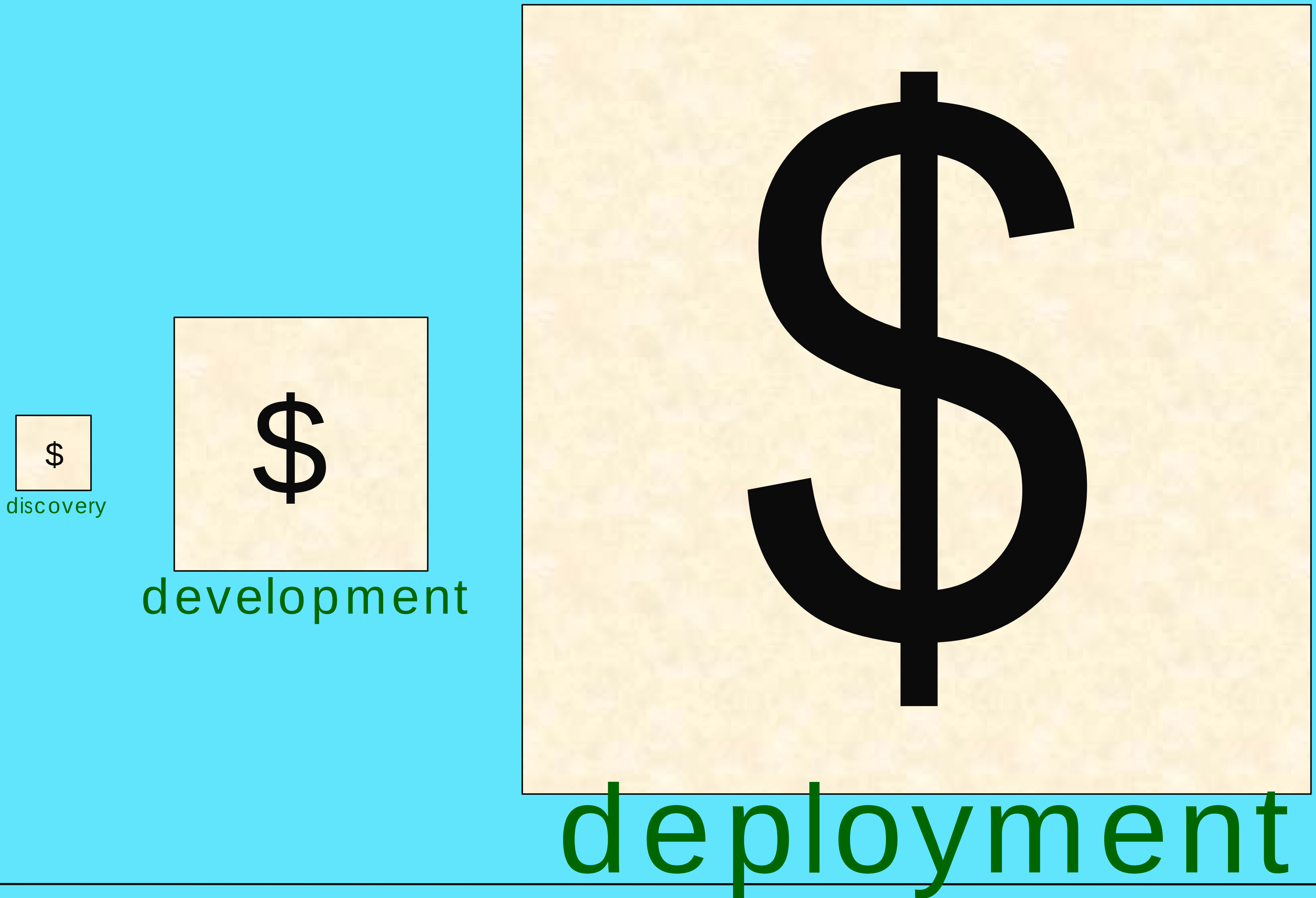
Develop Chemical Bonds as a Sustainable Energy Carrier

$CO_2 + H_2O$ → many opportunities for sustainable chemical fuel



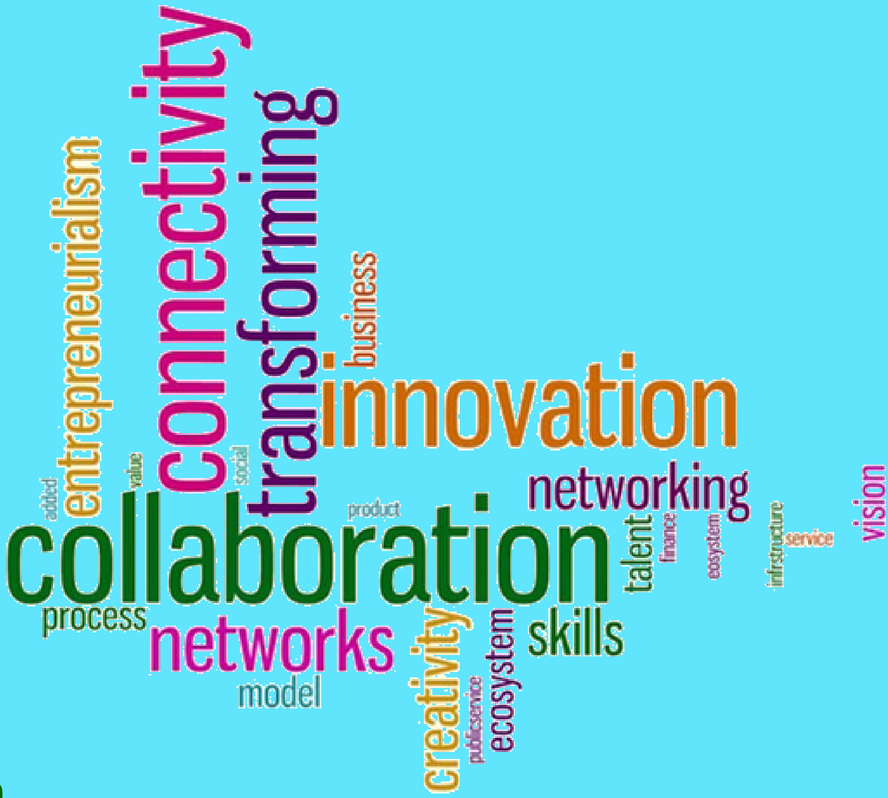
Graves, Ebbesen, Mogensen, Lackner
Renewable and Sustainable Energy Reviews 15,1 (2011)

The Cost of Doing Things



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



SISE

Summer Institute on Sustainable Energy

The world is undergoing an historic transition.

Get on board.

An intense immersion in sustainable energy.

UIC
UNIVERSITY OF ILLINOIS AT CHICAGO

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

August 6-21, 2014

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