EUROPEAN COMMISSION
European Research Area

U.S. DEPARTMENT OF
ENERGY

Significant Science Breakthrough Scenario

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Societal issues

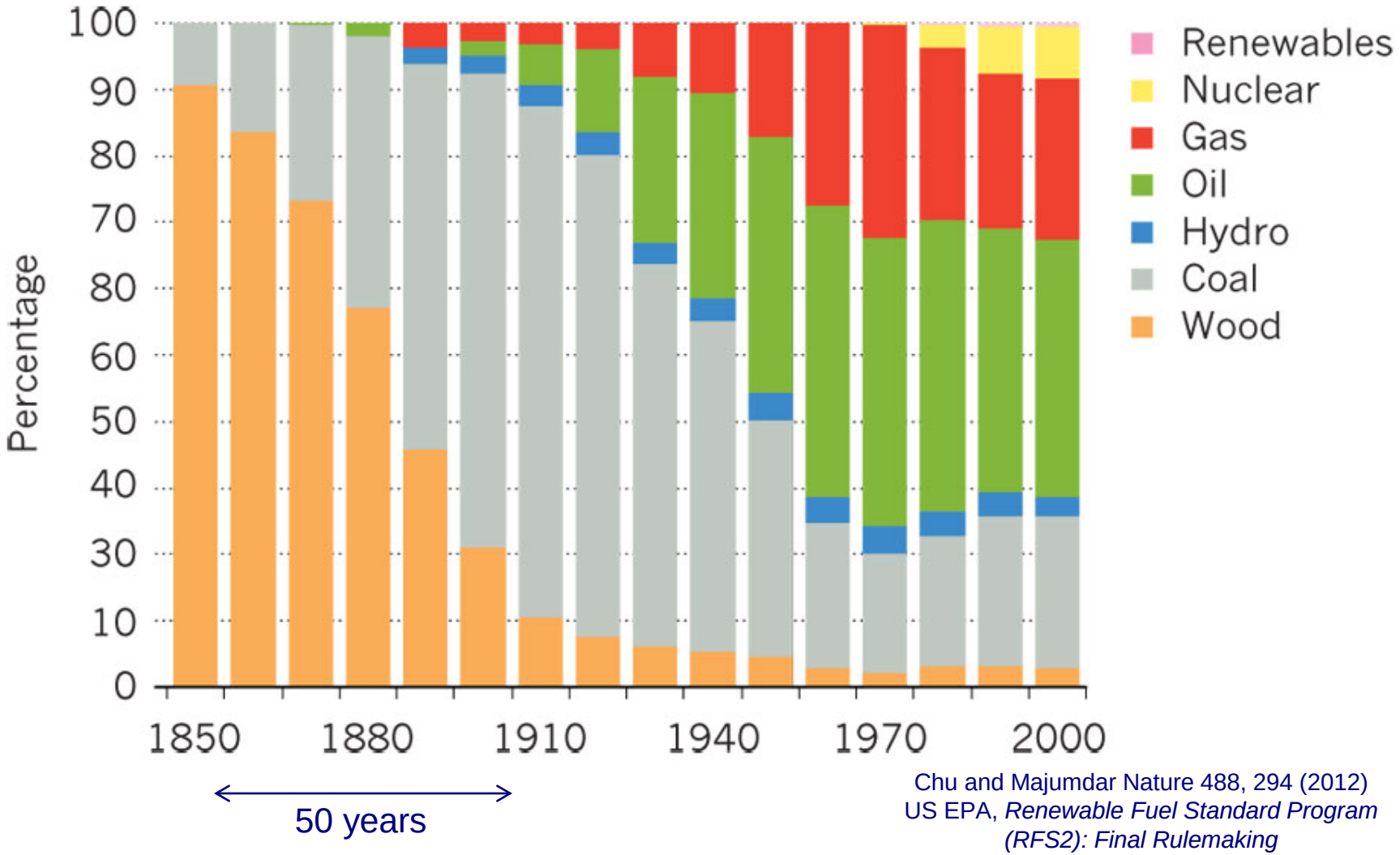
Energy security and predictability
Climate change and carbon emissions
Economic development and growth

Science breakthroughs

Hydraulic fracturing – shale gas
Mineralize carbon dioxide
Electricity storage beyond Li-ion
Recycle carbon dioxide to fuel
Safe, higher performing nuclear electricity

Interchangeable energy carriers
electricity, chemical bonds, photons

Energy Transformation Takes Time



Chu and Majumdar Nature 488, 294 (2012)
US EPA, *Renewable Fuel Standard Program (RFS2): Final Rulemaking*

Societal Concerns to 2050

Energy security, sustainability and predictability

basic to personal, social, professional and civic life

Climate change and carbon emissions

avoid the human and economic cost

Economic development and growth

the natural aspiration of people and countries

inexpensive, abundant energy

International market to mediate across countries, regions and forms of energy

regulates supply, demand and price

provides interchangeable energy alternatives

oil, gas, coal, biofuel, geothermal, solar, wind, and the means to produce them

Independent of geopolitical control over supply and price

Science Breakthroughs to Address Societal Concerns

Replace/displace coal and oil with abundant, cheap shale gas

Mitigate carbon emissions: mineralize carbon dioxide to, e.g., $MgCO_3$

Safe, higher performing nuclear electricity

Offshore wind with high capacity superconducting turbines

Sustainable energy carriers

- *Storage and transmission of electricity, for transportation and the grid*
- *Recycle carbon dioxide to chemical fuel*

Break down barriers between energy carriers

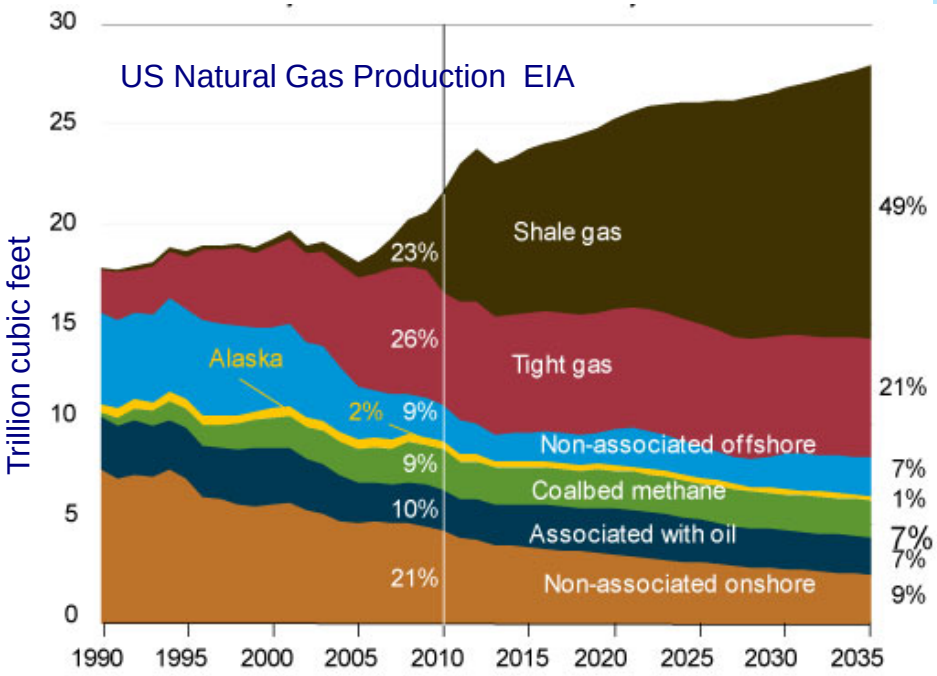
- *Facile, efficient conversion among electricity, chemical fuel, photons*
- *Flexibility, versatility among energy sources and uses*

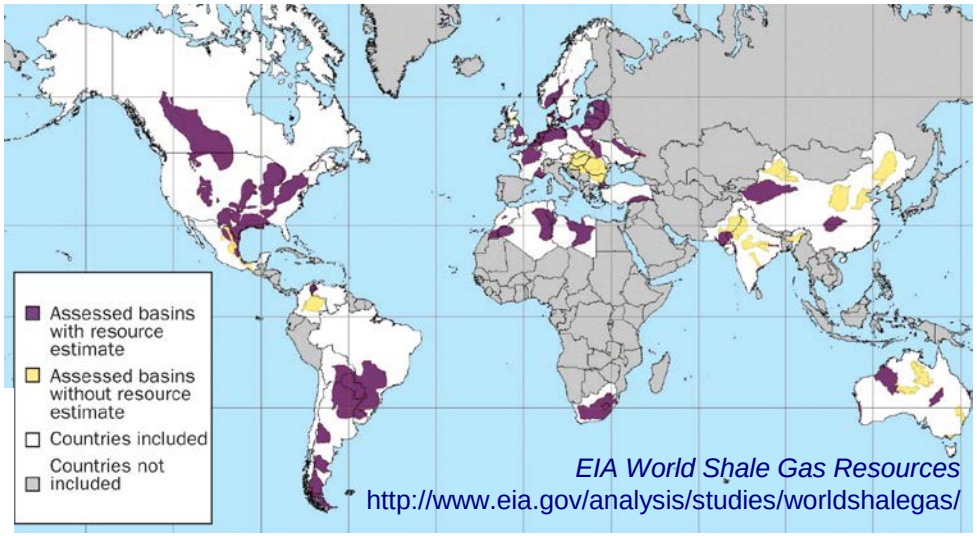
Shale Gas and Hydraulic Fracturing

Abundant
Inexpensive

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

Source: EIA





Potential Game Changer
carbon emissions
energy security
diversity of sources and uses

Hydraulic Fracturing Science Challenges

Operation

Distant horizontal drilling into thin shale layers

Local explosions fracture rock

High pressure hydraulic fluid opens fissures

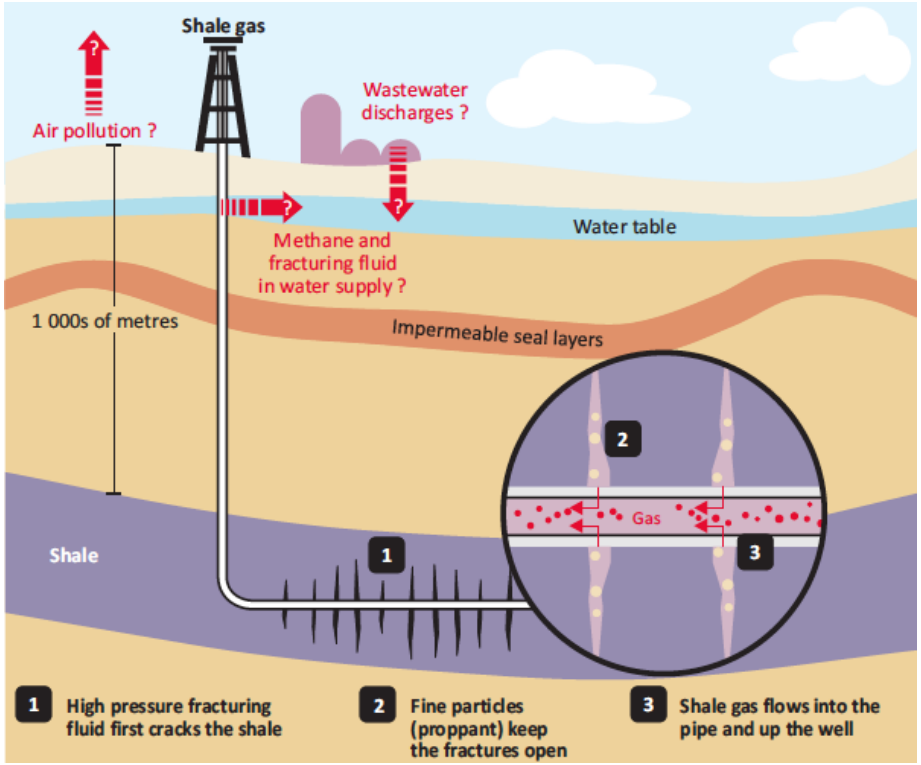
Sand driven into fissures to prop open

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 15% of shale gas recovered



Source: Rachel Ehrenberg, Science News 182, 20 (2012)

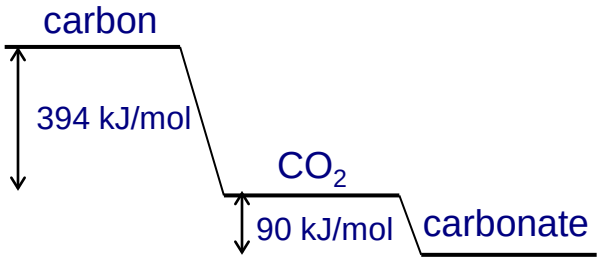
Understand fissure mechanics, pore formation, fluid flow in fractured rock

Carbon Dioxide Mineralization

$MO + CO_2 \rightarrow MCO_3 + energy$

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

Also Ca, Fe, . . .

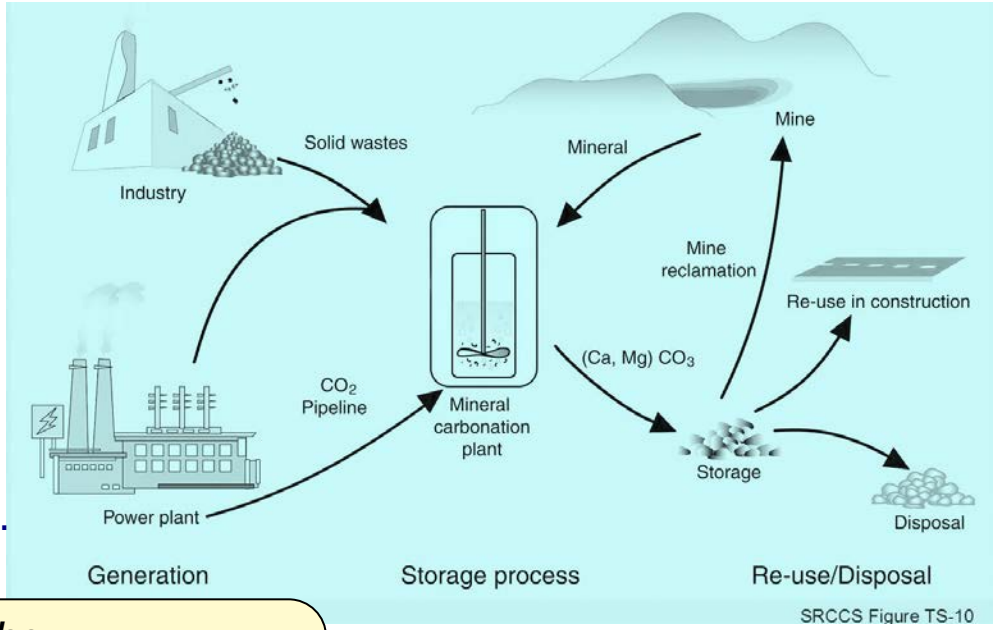


- Spontaneous reaction
- Permanent storage
- No follow up monitoring
- Theoretical capacity >> emissions

In situ: react underground

Ex situ: react in industrial plant
transport reactants and products

Reduce cost - market carbonate products
Roads, buildings, land reclamation, . . .



IPCC Special Report on Carbon Dioxide Capture and Storage (2005)

Zevenhoven, Fagerlund and Songok, Greenhouse Gas Sci Technol 1, 48 (2011)

Sanna, Hall and Maroto-Valer Energy Environ Sci 5, 7781 (2012)

Science Breakthroughs

Slow kinetics – find catalysts

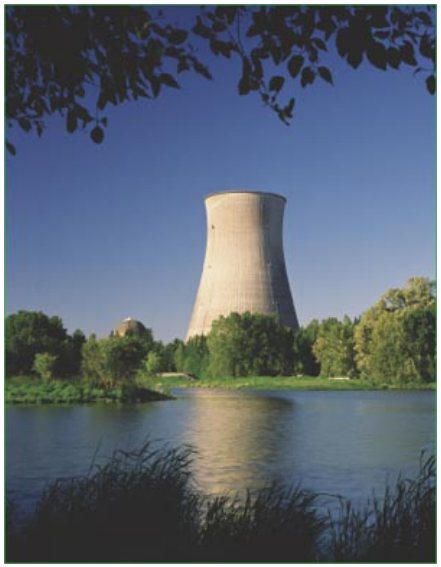
Passivating layer – control surface chemistry

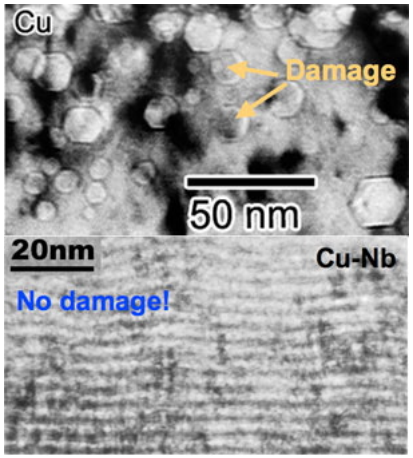
Safe, Higher Performing Nuclear Electricity

Heat without combustion or carbon dioxide

Established experience curve

Challenges
- Safety
- 1960s technology
- Spent fuel



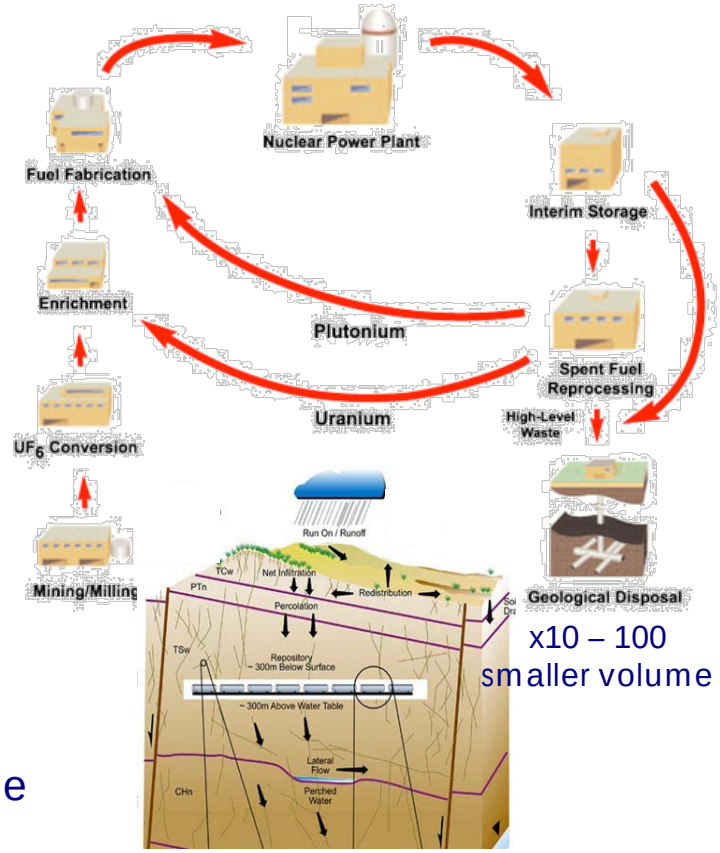


CuNb interfaces
Michael Demkowicz-MIT

Now: 35% efficiency
2050: 50%

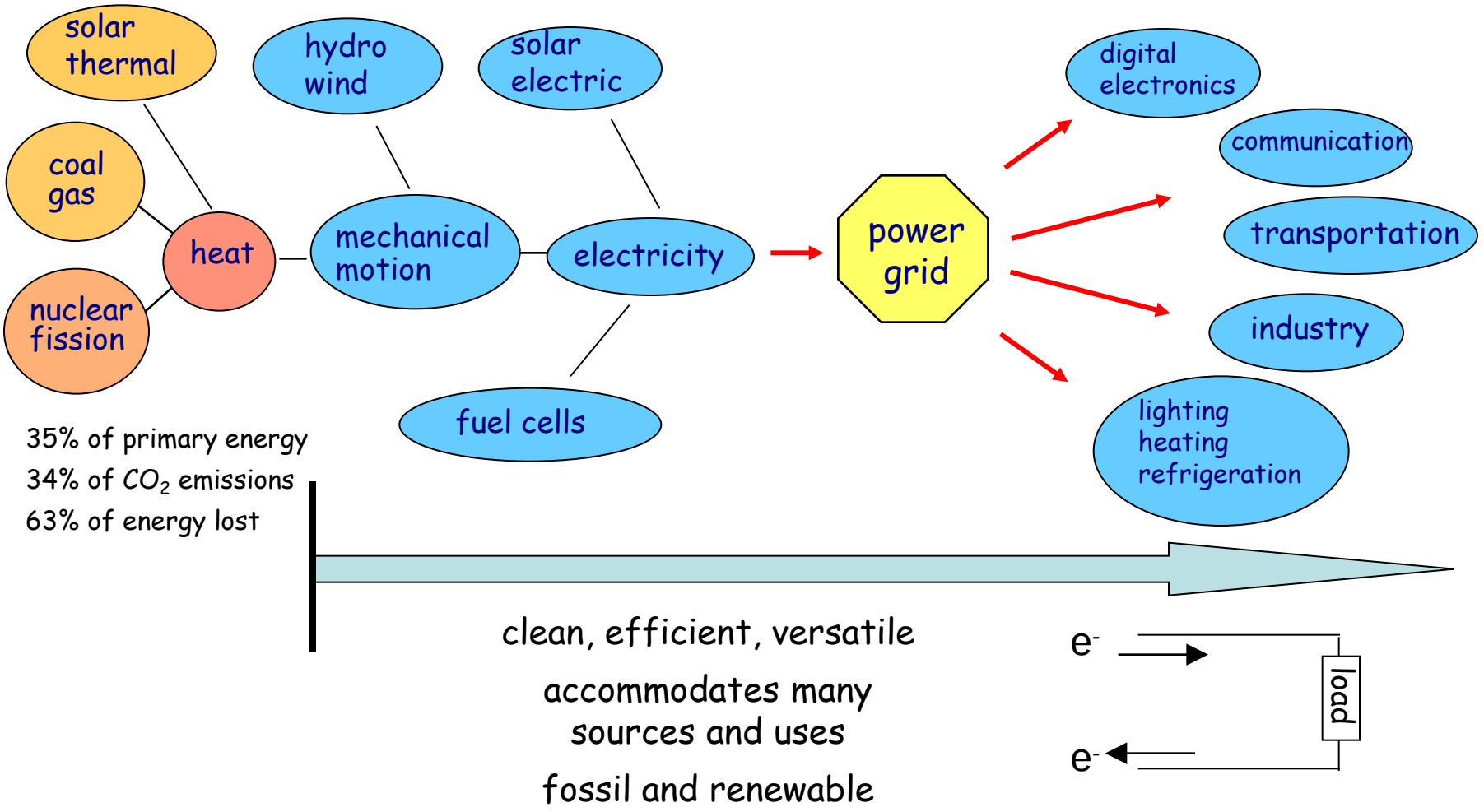
Science Challenges
Materials for
- Higher temperature
- Higher radiation damage

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



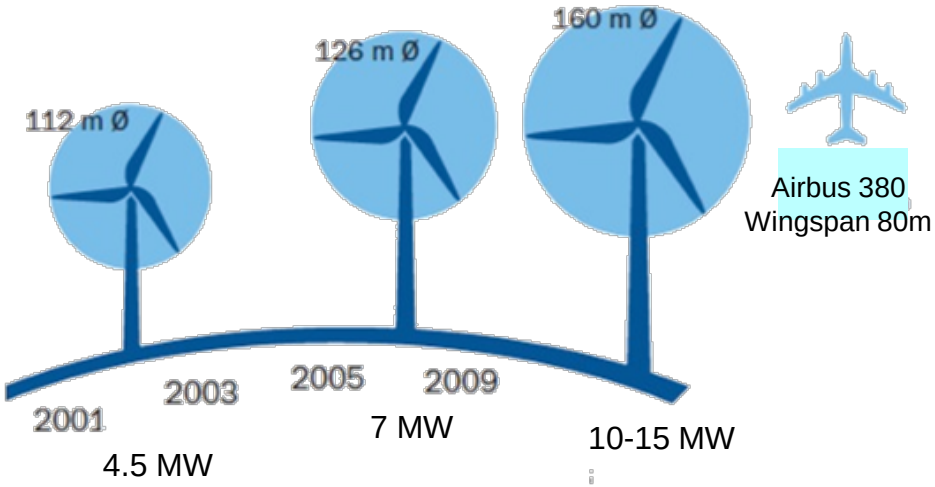
x10 – 100 smaller volume

Develop Electricity as a Sustainable Energy Carrier



Superconducting Offshore Wind Generation

Source: http://webberenergyblog.wordpress.com/2010/02/13/offshore-wind-energy-cape-wind-vs-visual-impacts/



Wind turbine output limited by weight supported on the tower

Science Breakthrough

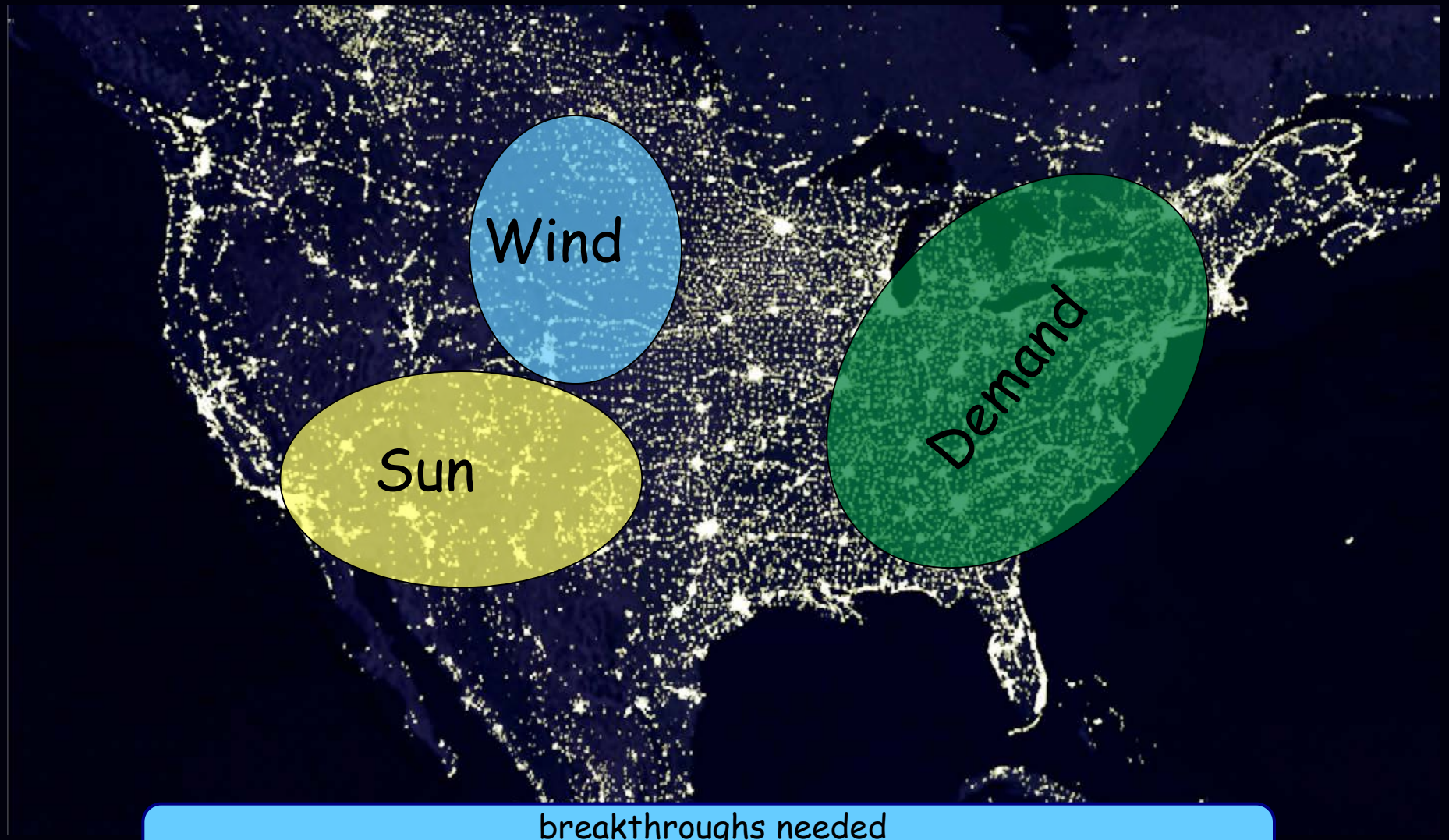
Superconducting wind generator

Double the output for same size and weight

capacity limit: 15-20 MW

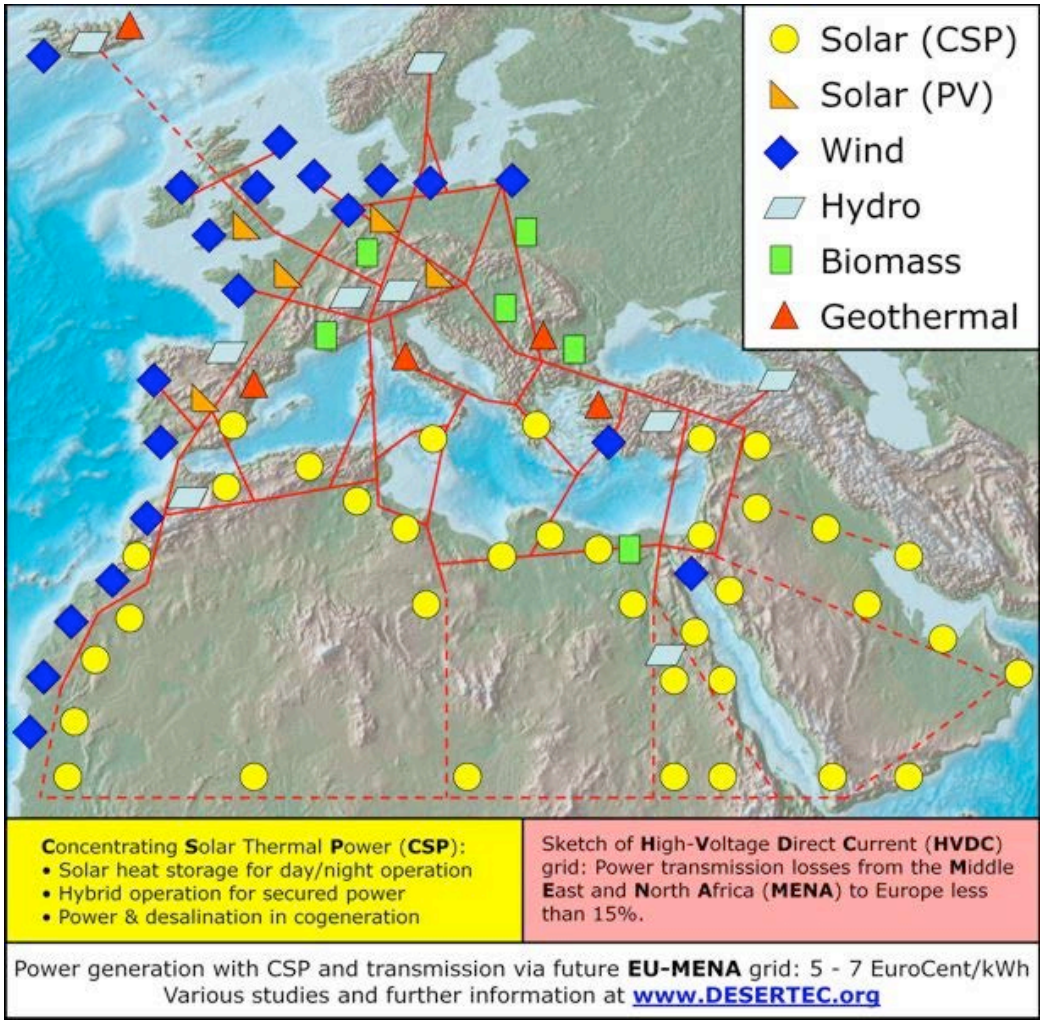
→ offshore wind

Long Distance Electricity Transmission - US



breakthroughs needed
long distance reliable, efficient delivery of electricity

Long Distance Electricity Transmission - Europe



Desertec

connect North Africa with Europe

15% of European power by 2050

thermal storage for power after sunset

http://www.dii-eumena.com/dii-answers/technologies-and-costs.html

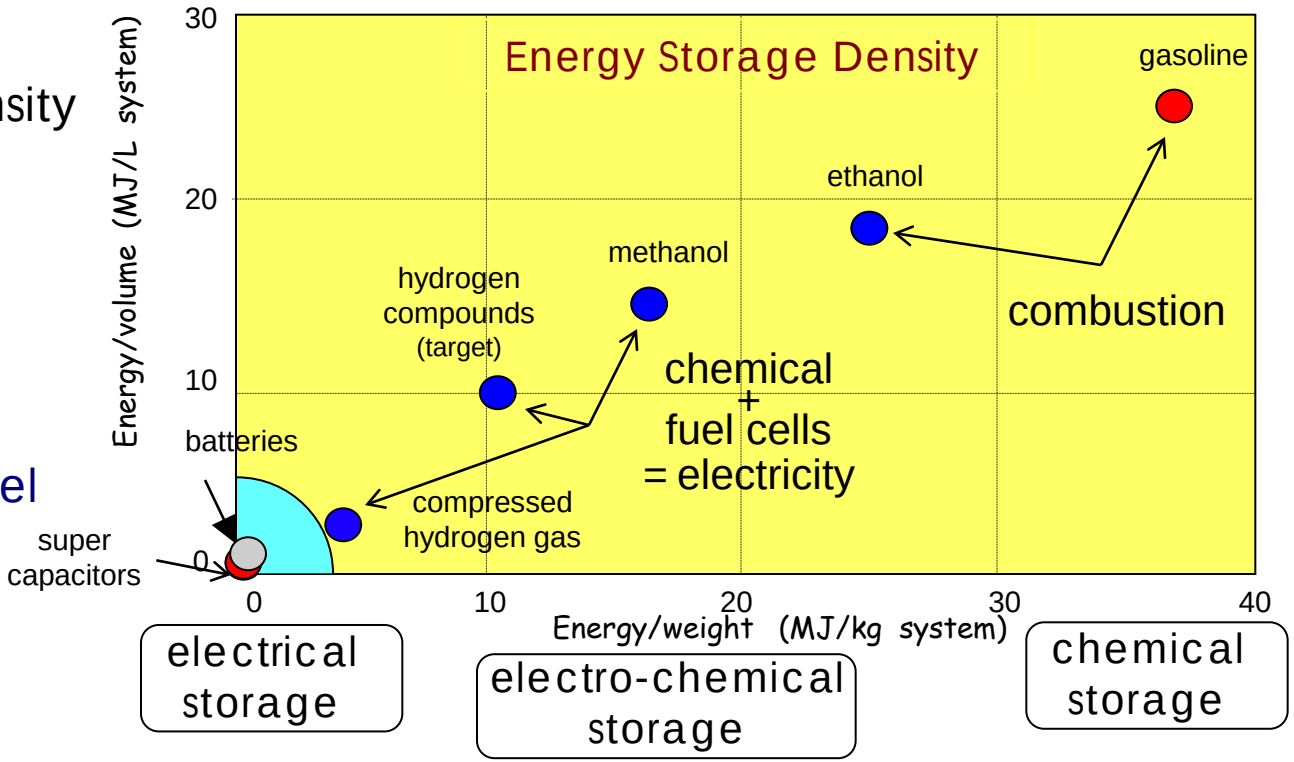
Storing the Energy We Produce

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

batteries:
30-50x less energy density than gasoline

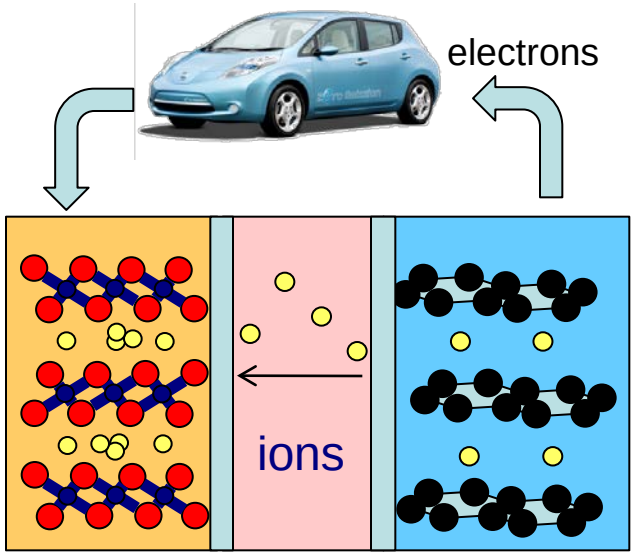
impossible dream:
x10 improvement

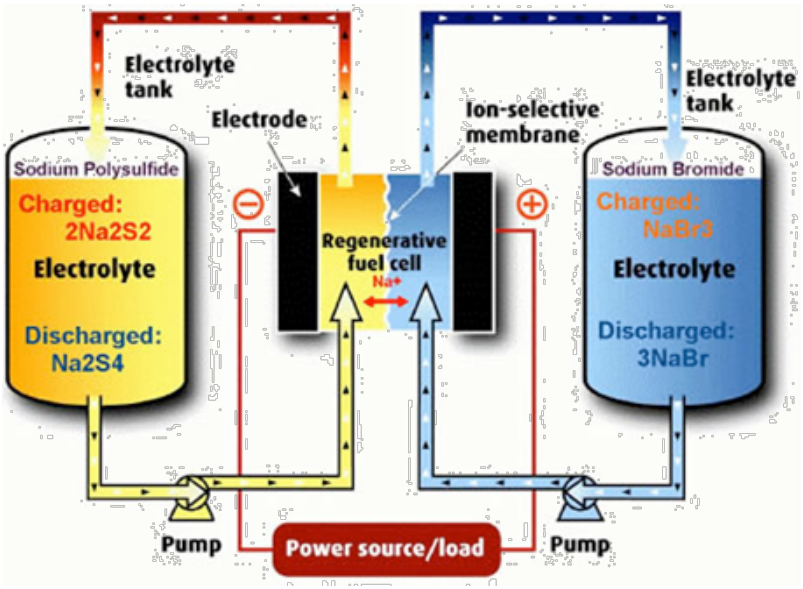
beyond batteries:
chemical storage + fuel cells = electricity



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

Electrical Energy Storage Beyond Li-ion





$Li^{+} \rightarrow Mg^{++}, Y^{+++}$
multivalent intercalation

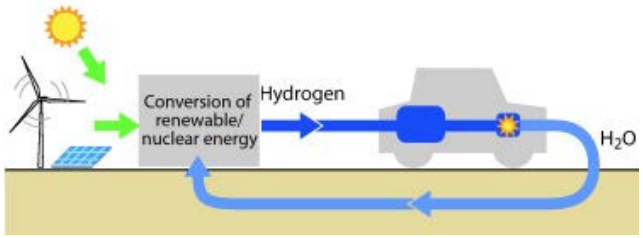
Intercalation → chemical reaction
Li-O_2, Li-S, Na-S

Flow batteries

High capacity, efficient, inexpensive

Many unexplored redox couples

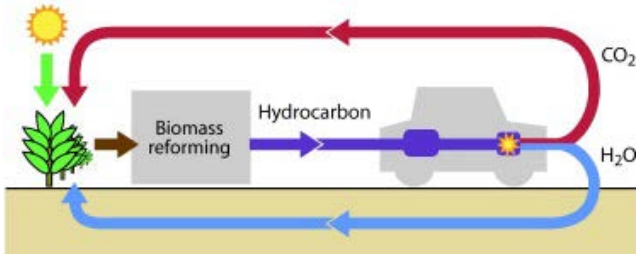
Develop Chemical Bonds as a Sustainable Energy Carrier



Hydrogen

requires infrastructure, storage, renewable production

2003 →



Cellulosic biofuels

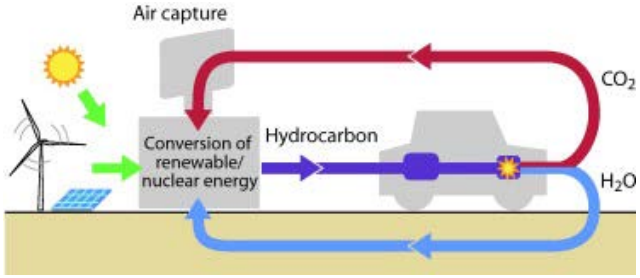
requires land, low efficiency, limited capacity

2007 →

Drop-in replacement for fossil

Incremental change to established combustion infrastructure

Promotes carbon mitigation, energy security



Carbon dioxide + water (hydrogen)

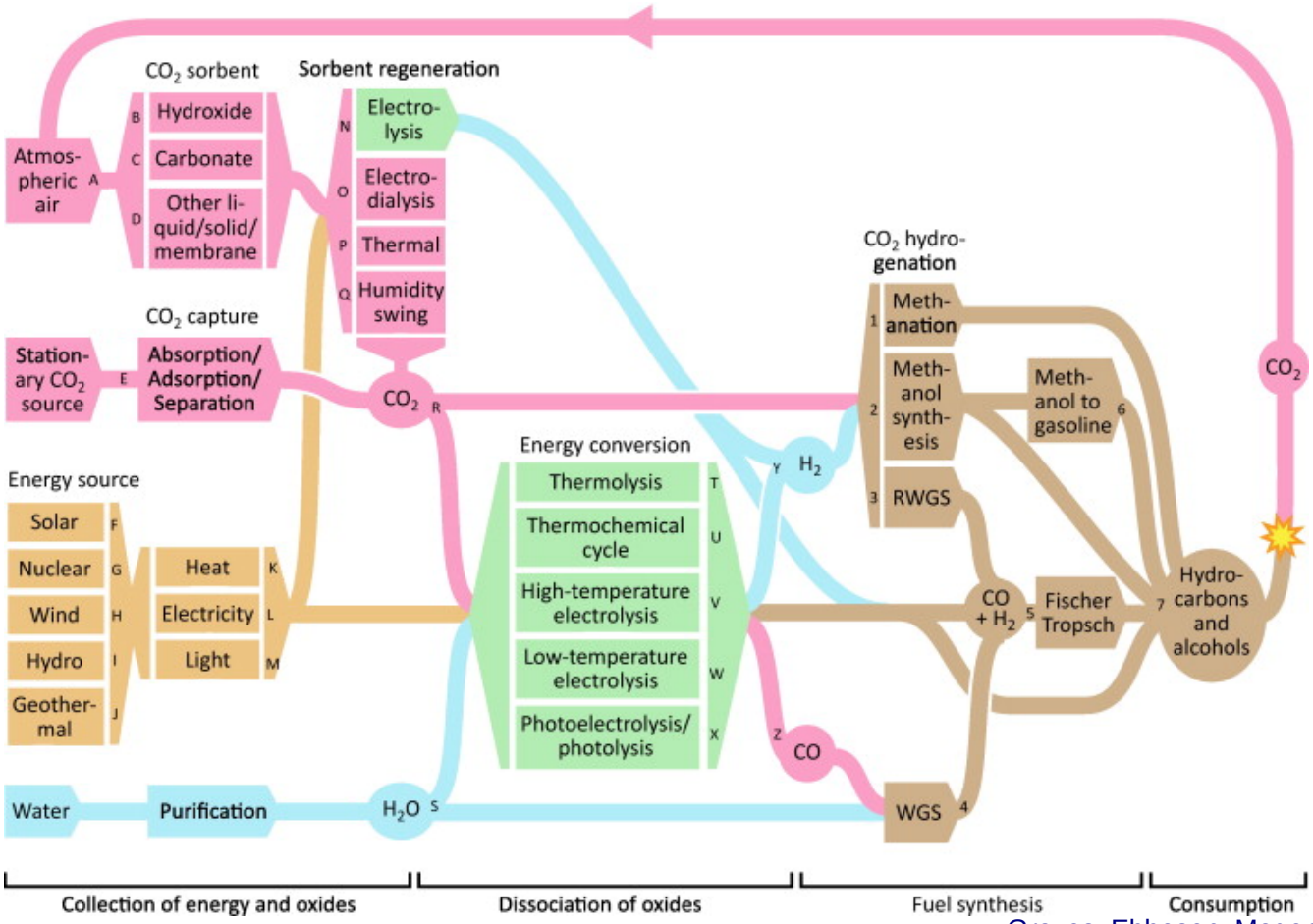
recycled chemical fuels

Significant science breakthrough

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

Develop Chemical Bonds as a Sustainable Energy Carrier

$CO_2 + H_2O \rightarrow$ many opportunities for sustainable chemical fuel



Graves, Ebbesen, Mogensen, Lackner
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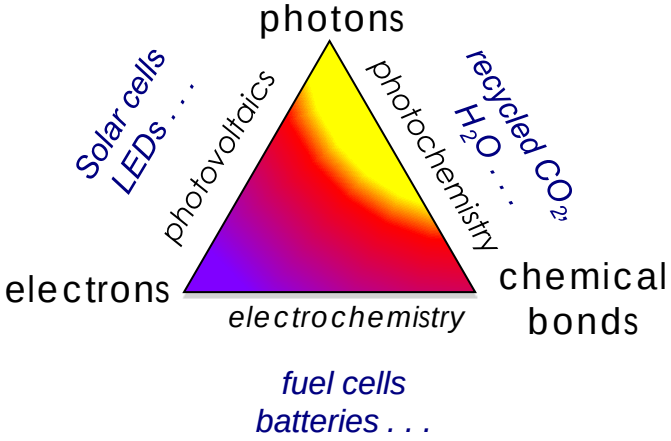
Break the Barriers Among Energy Carriers

Electricity
Clean, efficient, versatile
Low energy density, low capacity storage
Avoids combustion and Carnot efficiency limits

Chemical bonds
Stable, long term, high energy density storage
Conversion to heat by combustion

Photons
Solar energy carrier
Ultimate source of light and heat



Science breakthrough
Seamless connection among three energy carriers
Fungible energy sources and uses
Oil for transportation replaced by electrons from sun . . .

Perspective – Societal Vision for 2050

Societal concerns

- Energy security and predictability
- Climate change
- Economic development and growth

Energy landscape

Versatile, interchangeable energy carriers, sources and uses

Energy as a commodity

widely available in many forms from many sources

International market promotes accessibility and predictability

Perspective – Science Breakthroughs

Mechanics and fluid flow in fractured rock – safe, abundant, cheap shale gas

Mineralization of CO_2 – safe, permanent, benign carbon mitigation

Recycle CO_2 and H_2O to fuel – chemical bonds as a sustainable carrier

Electrical energy storage beyond Li-ion

- multivalent working ions, chemical transformation, non-aqueous flow batteries

High capacity superconducting wind turbines – enable offshore wind

Materials for extreme environments, reprocessing chemistry for spent fuel

- safe, high performance nuclear electricity

Efficient, easy conversion among energy carriers

- Electricity, chemical bonds, photons
- *The carriers*: hydrogen, carbon monoxide, hydrocarbons, alcohols, light, heat . . .
- *The converters: fuel cells, batteries, motors, generators, solar cells, light emitting diodes, internal combustion engines, combined cycle gas turbines, . . .*

International market in commodity energy

- *Science enables the conversion, social and political forces achieve the outcome*

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EU-US Energy Summit
Visions of Sustainable Economic Growth
Sep 11, 2012 Washington DC

Argonne National Laboratory