UCR Department of Physics: 50th Anniversary

"Sensible Options to Ensure our Future: A Need for Good Science"

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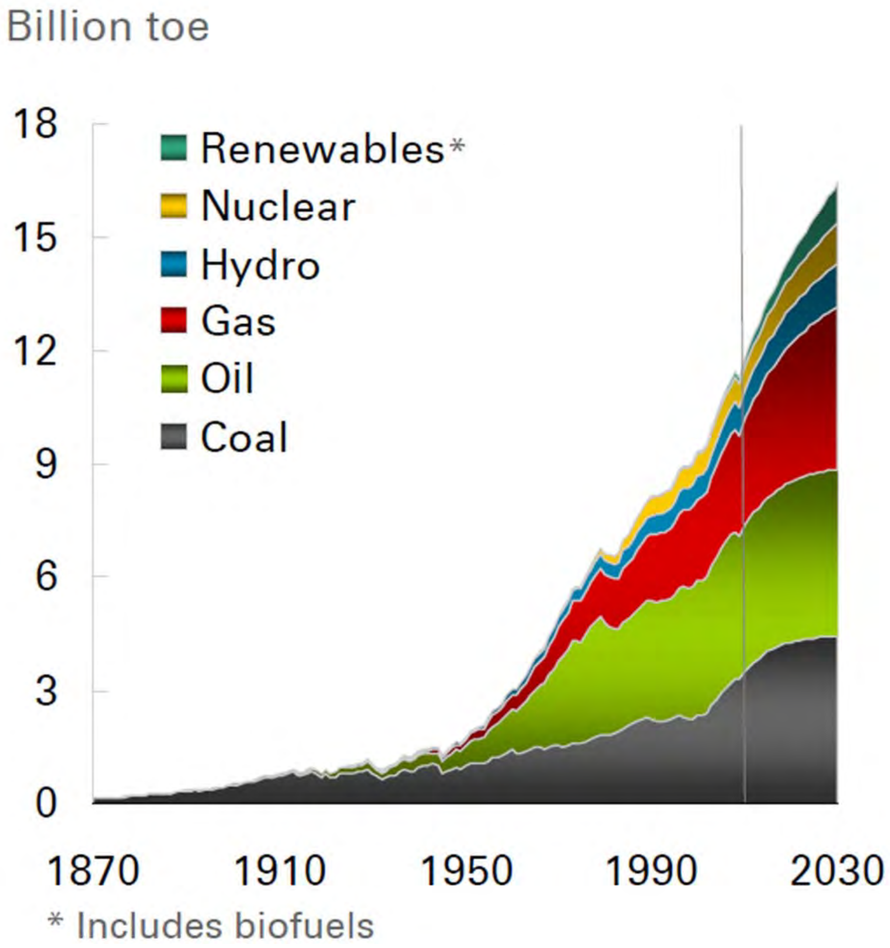
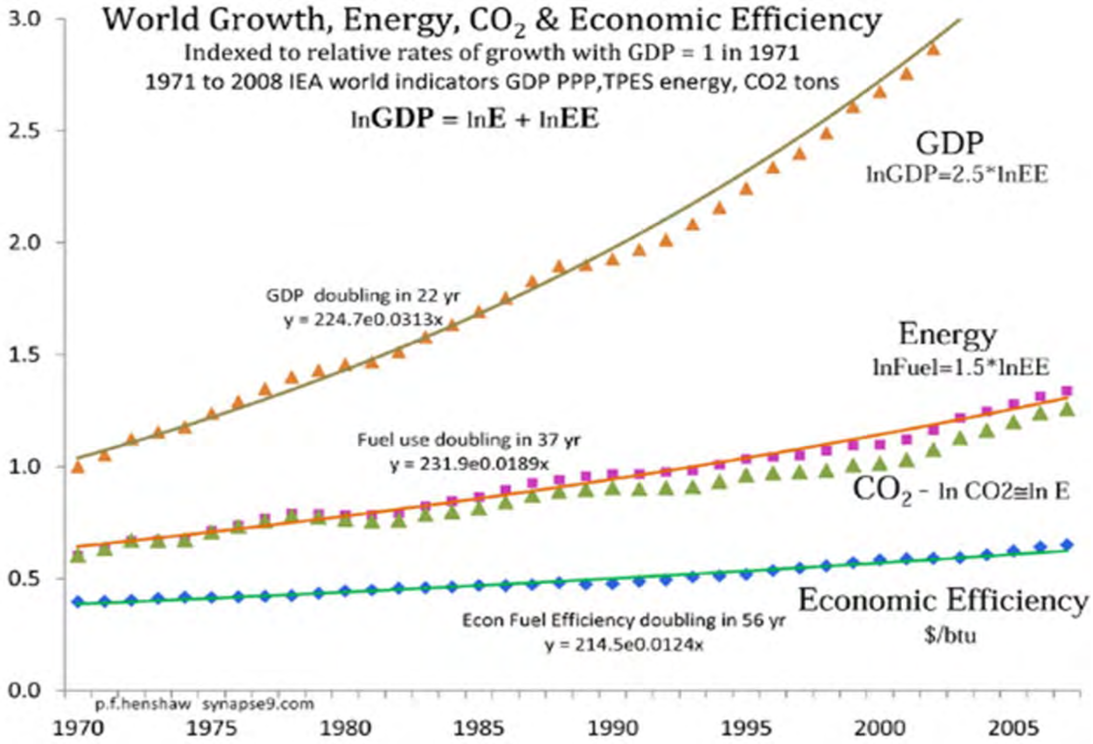
World Commercial Energy Use
(BP Energy Outlook 2030)



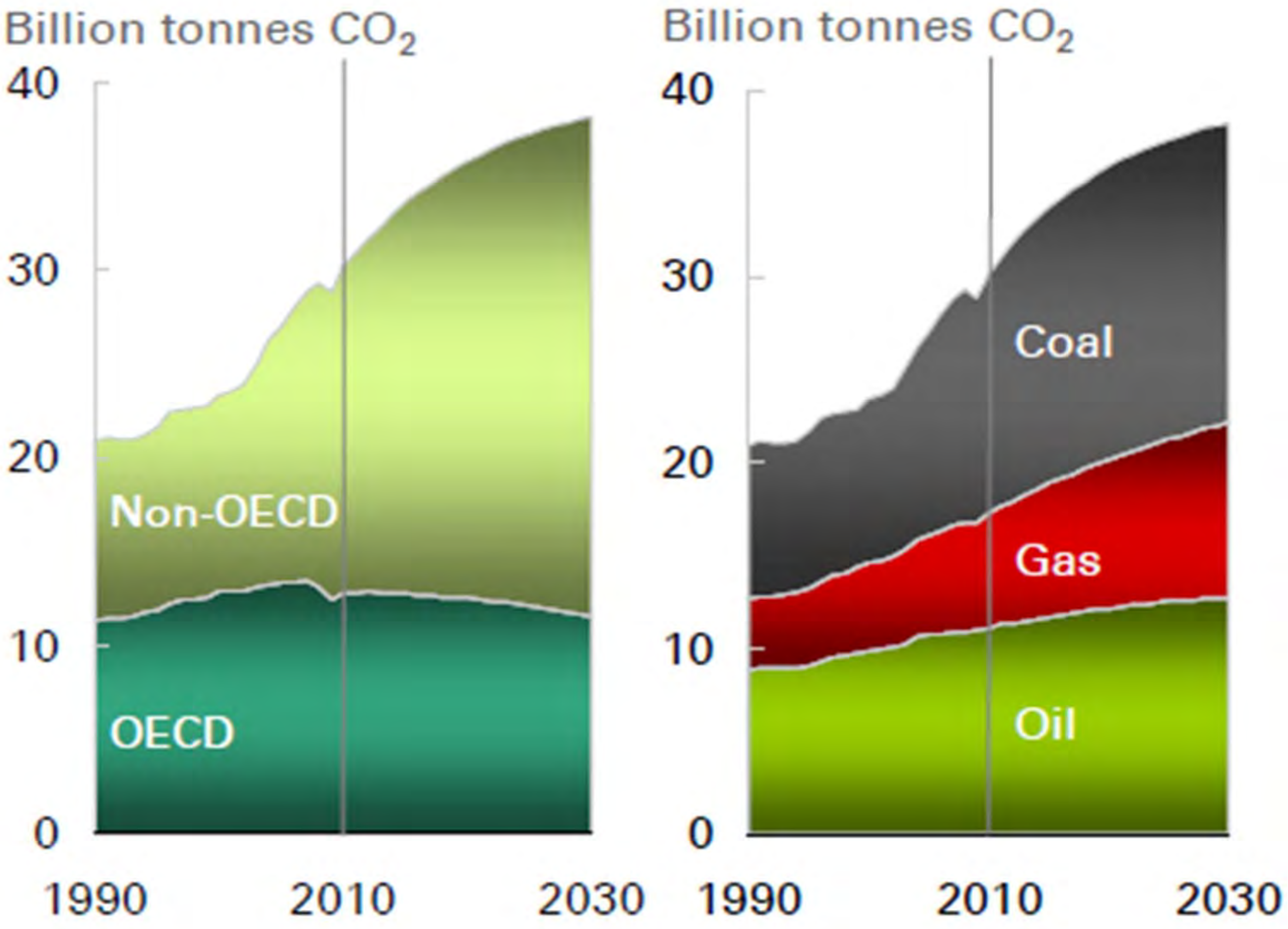
Some inconvenient truths:

Improving economic efficiency enables the creation of more new energy uses than energy savings. The net effect is to increase the rate of resource depletion (Jevons, 1885).

CO_2 is being produced at the same increasing rate as total energy use. New "clean energy" sources are not replacing any fossil fuel use.

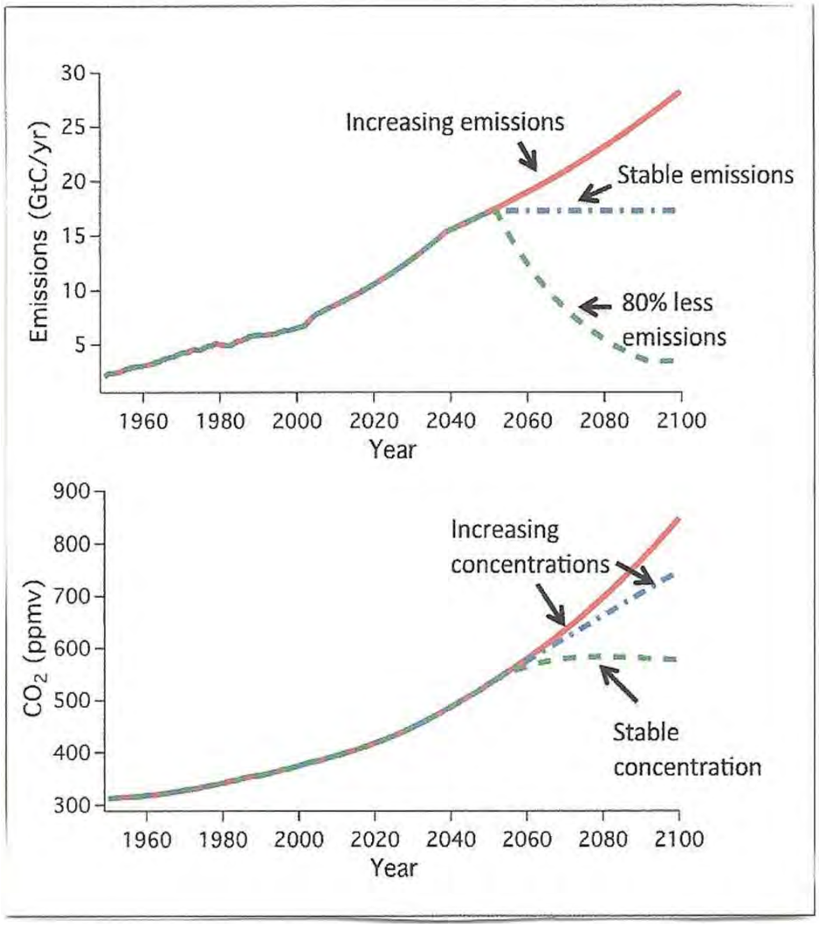


Where does (will) the world CO_2 production come from, and by how much?



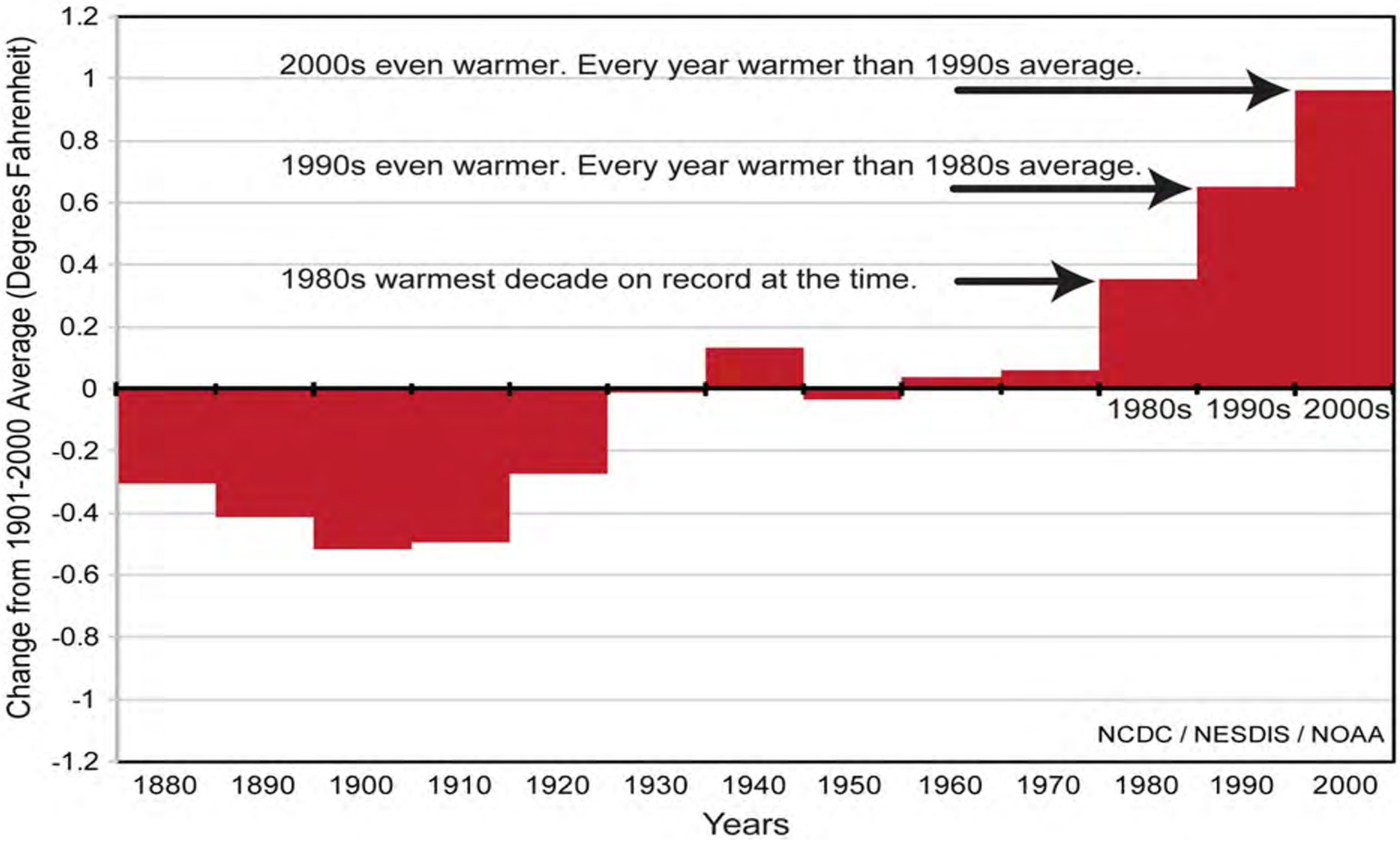
Consequences of CO_2 being produced at the same *increasing* rate as total energy use.

- Even keeping our carbon dioxide emissions *constant will* lead to an *increasing* concentration over time.
- Only by sharply reducing carbon dioxide emissions by 80% can the atmospheric concentration be kept stable.
- The 2050 target of 80% reduction is *required*, as difficult as it is, to stabilize the carbon dioxide concentration in the atmosphere.



Are We Warming? You call it!

[Global Temperature Change, Decade Averages]

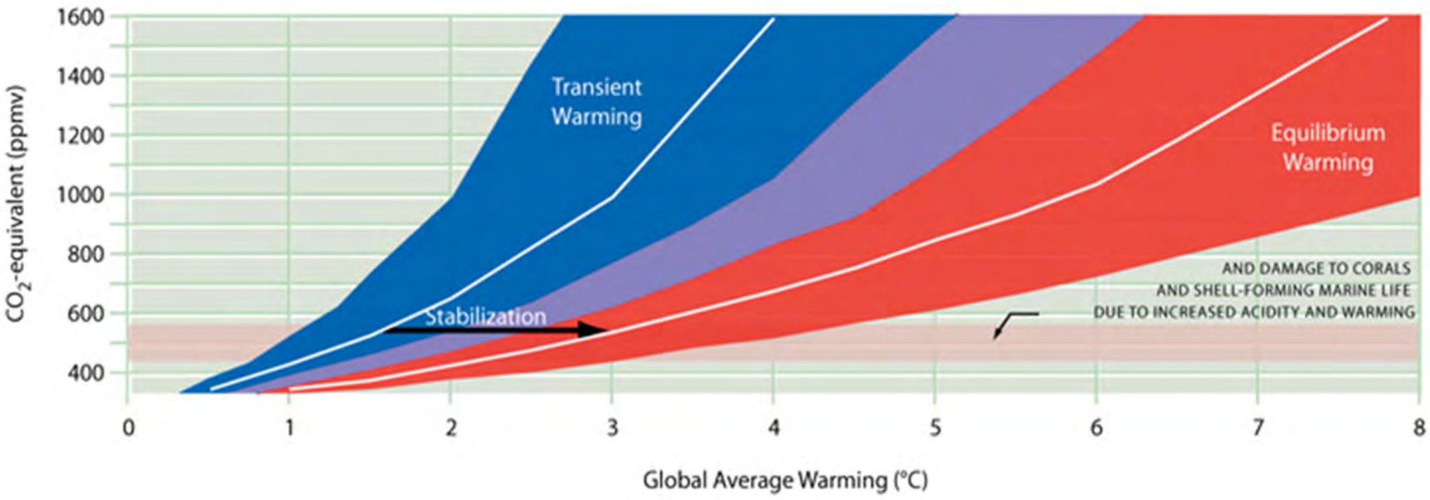


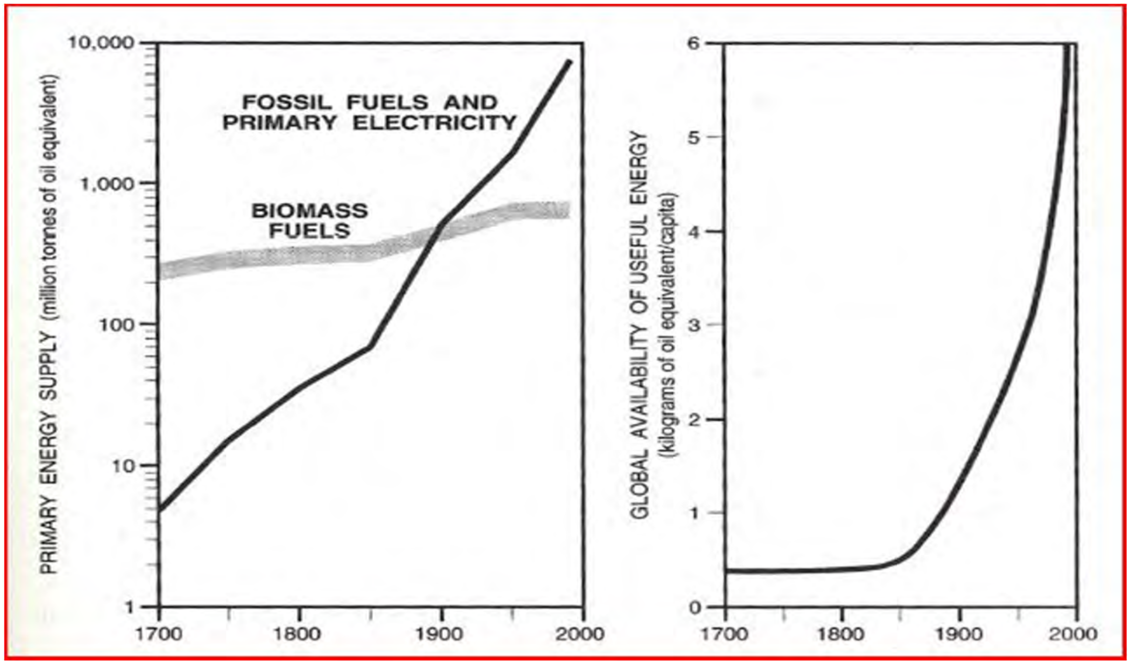
So what happened in 1980?

- *Nothing!*
- From before, equilibrium warming can double transient (immediate) temperature rise.
- It takes about 100 years for the ocean to come into equilibrium with an increase in atmospheric temperatures.
- So what happened in 1880 is the pertinent question.
- That of course was the beginning of the global industrial revolution.
- Are we now experiencing the consequences of that source of CO_2?
- If so, what does that portend for years subsequent to the beginnings of the industrial revolution?

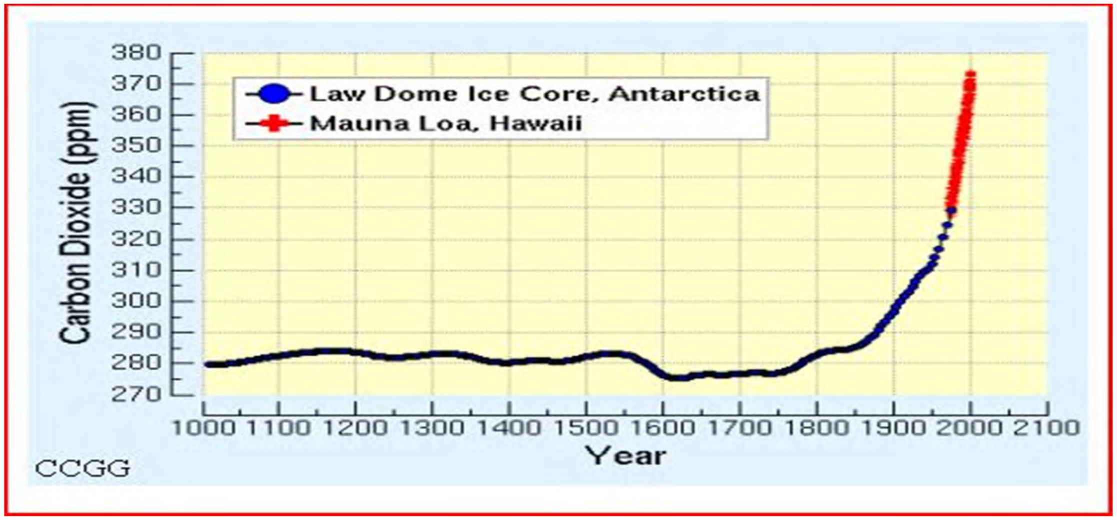
Transient Warming → Equilibrium Warming

Because of time-lags inherent in the Earth’s climate, warming that occurs in response to a given increase in the concentration of carbon dioxide (‘transient climate change’) reflects only about half the eventual total warming (‘equilibrium climate change’) for stabilization at the same concentration.





From “Energy in World History” by Vaclav Smil (Westview Press, Boulder, San Francisco, Oxford, 1994), p. 186.



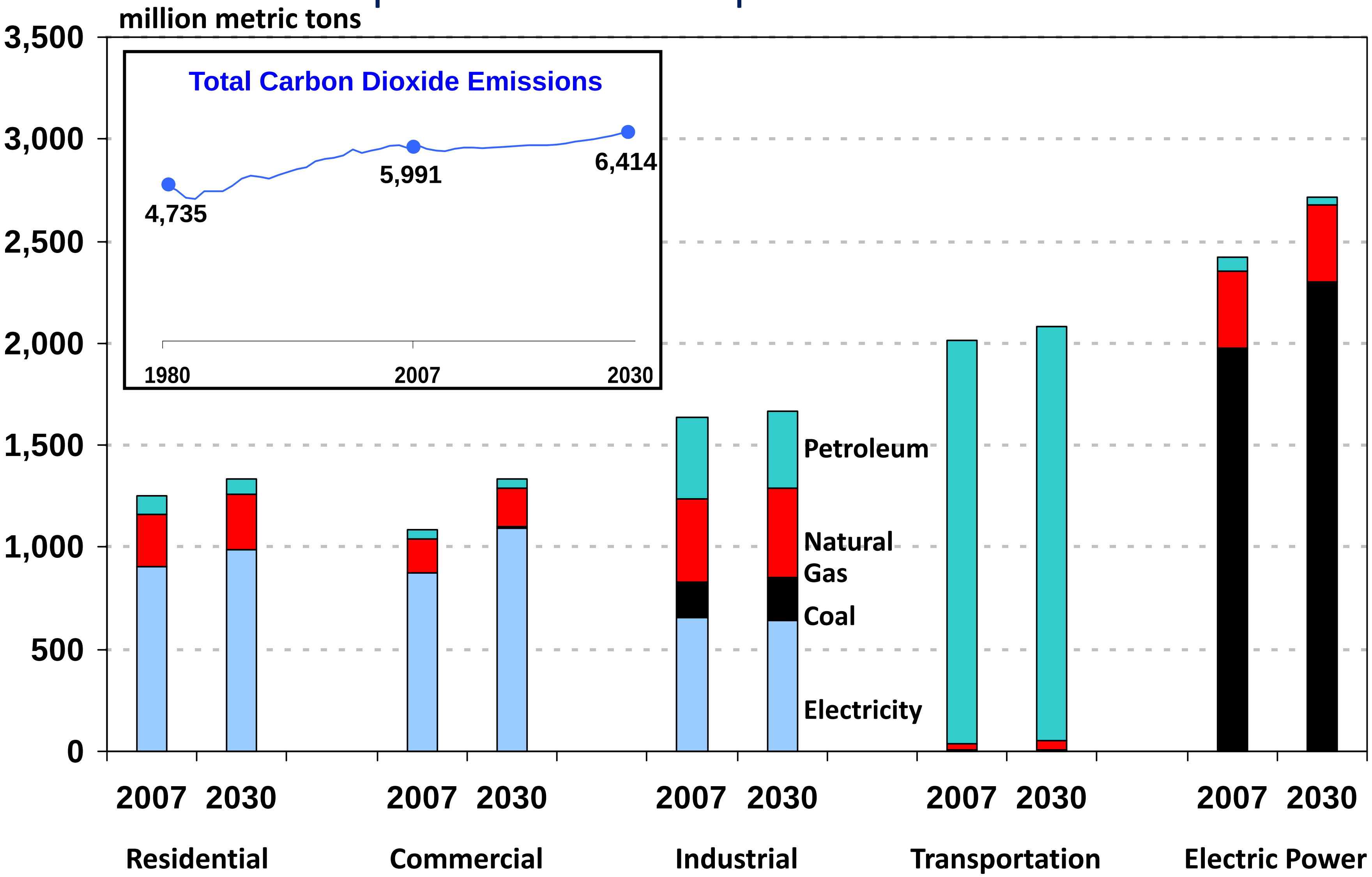
Alternative Future Energy Scenarios

- We can do nothing.
- We can deal with the major CO_2 contributors through new technological developments
  - Cost-Effective Capture and Storage of CO_2 Through Energy Production from Saline Aquifers
  - Fuels from Sunlight
  - Large-Scale Storage for Intermittent (and even steady) Energy Sources

Cost-Effective Capture and Storage of CO_2 Through Energy Production from Saline Aquifers

- The first point of attack is coal-fired power plants. Example: they are the chief United States “culprit” for CO_2 emission growth from 2007 through 2030 (though note transportation):
  - 2,000 million metric tons (2 Gt) in 2007
  - 2,300 million metric tons (2.3 Gt) in 2030
- What’s the problem?
  - The current approach to carbon capture and sequestration (CCS) is not economically viable without either (very) large subsidies or a very high (impossible) price on carbon.
  - Current schemes require roughly 1/3rd of a power plant’s energy for CO_2 capture and pressurization, and neither merchant nor regulated utilities can accommodate this magnitude of added cost.

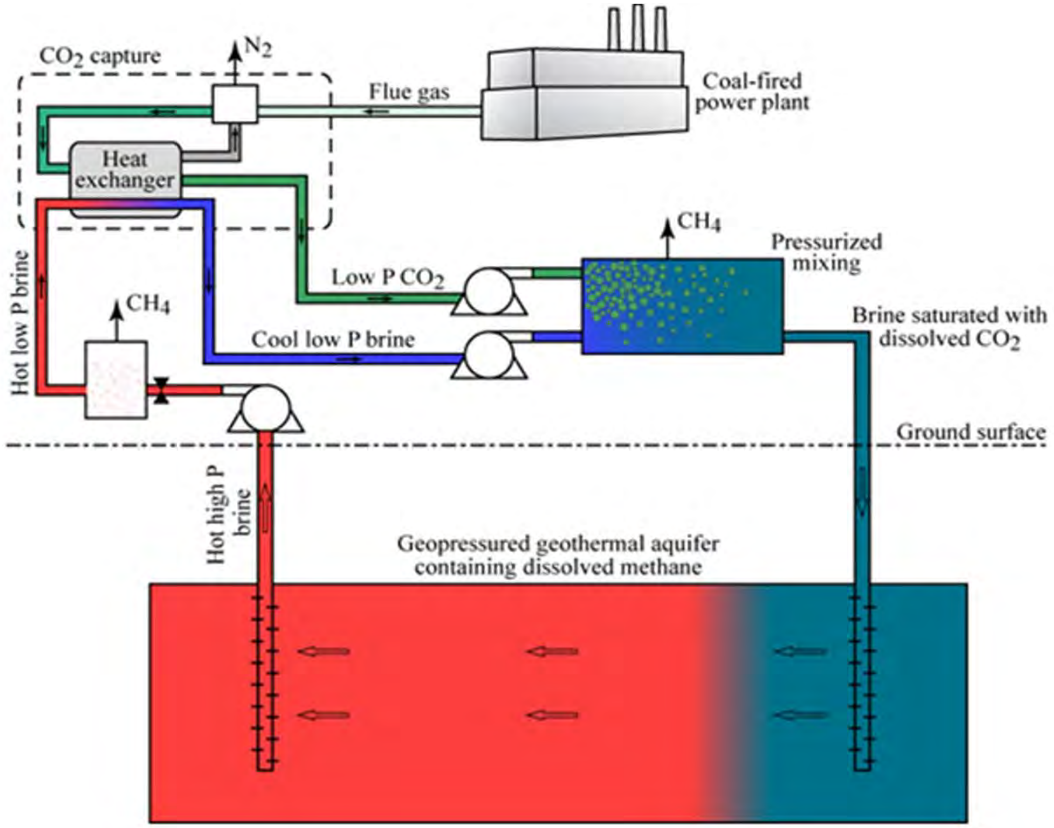
U.S. Carbon Dioxide Emissions by Sector and Fuel, 2007 and 2030. Two bad actors: coal for electricity, and petroleum products for transportation.



Cost-Effective Capture and Storage of CO_2 Through Energy Production from Saline Aquifers

- The production of energy from geothermal aquifers has evolved as a separate, independent technology from the sequestration of carbon dioxide and other greenhouse gases in deep, saline aquifers.
- A game changing new idea combines these two technologies and adds another:
  - Dissolution of carbon dioxide into extracted brine which is then re-injected.
  - Production of methane (natural gas) from the extracted brine.
  - The production of energy from the extracted brine offsets the cost of capture, pressurization, and injection and the subsequent injection of brine containing carbon dioxide back into the aquifer.
  - Methane production + thermal energy offsets the cost of CCS to a point that CCS could survive in a competitive market environment without subsidies or a price on carbon.

How to offset the cost of CCS:



Injection and Production History of Simulations: Σ Value of methane [$186M (at $6/MBtu)] + value of heat [$92M (reduction from 300ºF to 200ºF)] = $278M, or $31/ton of CO_2 captured and stored.

Summary of Aquifer Properties

Length and width, ft	10560
Thickness, ft	330
Depth at top of the formation, ft	15000
Temperature, °F	302
Initial Pressure, psi	11000
Salinity, ppm	150000
Porosity	0.20
Horizontal Permeability, md	200
Vertical Permeability, md	20
Initial CH4 in place, Billions of SCF	40.50
Initial brine in place, Billions of STB	1.18

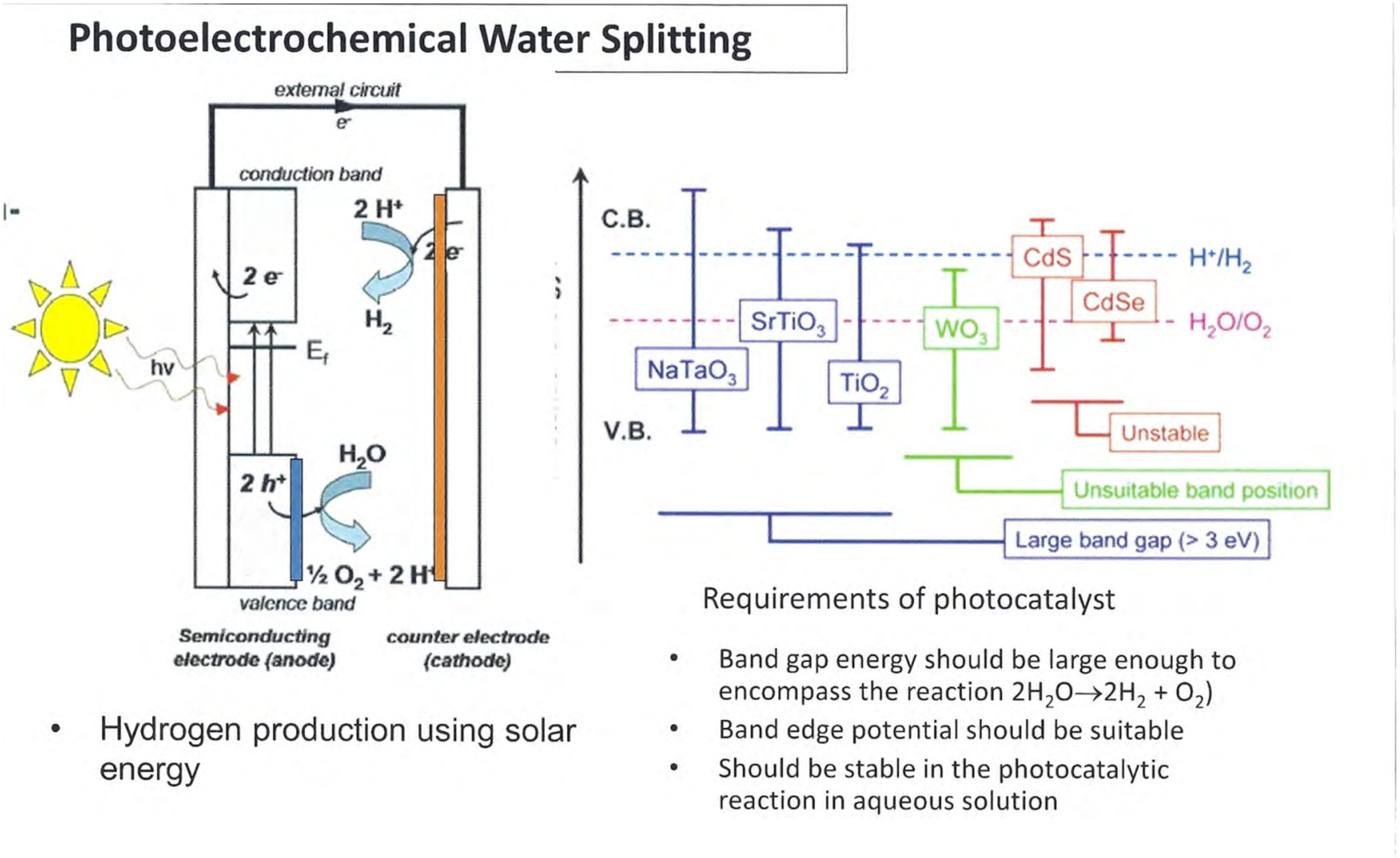
Summary of Injection and Production History

Injection Period, Years	12
Production Period, Years	12
Cumulative Injected CO_2 , Billions of SCF	173
Cumulative Produced CH_4, Billions of SCF	302
Cumulative Injected Brine, Millions of STB	847
Cumulative Produced Brine, Millions of STB	877

Fuels from Sunlight

- Photosynthesis is the process by which plants capture sunlight, and together with CO_2 and water, produce ATP and NADPH, the “fuels” that enable them to grow and reproduce (and produce oxygen, responsible for our atmosphere). Plants are only about 1% efficient capturing sunlight and producing their fuel.
- Can we do what plants do? Can we take sunlight, CO_2 and water and synthetically produce fuel?
- The problem is that CO_2 is very stable, and we have been unable to reduce it synthetically using sunlight and water. As a simplification, we are trying to use sunlight to break apart water into its constituent parts: hydrogen and oxygen.
- Hydrogen has many uses. Typical refineries use a billion cubic feet of hydrogen *each day* produced by reforming natural gas with steam. For every four molecules of hydrogen, a molecule of CO_2 is produced. Production of hydrogen without CO_2 would reduce their carbon “footprint” 30 – 40%. In addition, new coatings for turbine blades are available that allow combustion of hydrogen for production of electricity without CO_2.

Hydrogen from Sunlight



Photoelectrochemical Water Splitting

- Hydrogen production using solar energy

Requirements of photocatalyst

- Band gap energy should be large enough to encompass the reaction $2H_2O \rightarrow 2H_2 + O_2$)
- Band edge potential should be suitable
- Should be stable in the photocatalytic reaction in aqueous solution

Combinatorial Chemistry

Liu et al, J. Phys. Chem. C **2010,** *114*, 1201-1207

Novel semiconducting metal oxides are promising photoelectrocatalysts. New tools allow a combinatorial approach for making a multitude of different complex compositions of metal oxides, all unique, and testing them rapidly for their promise as photoelectrocatalysts.

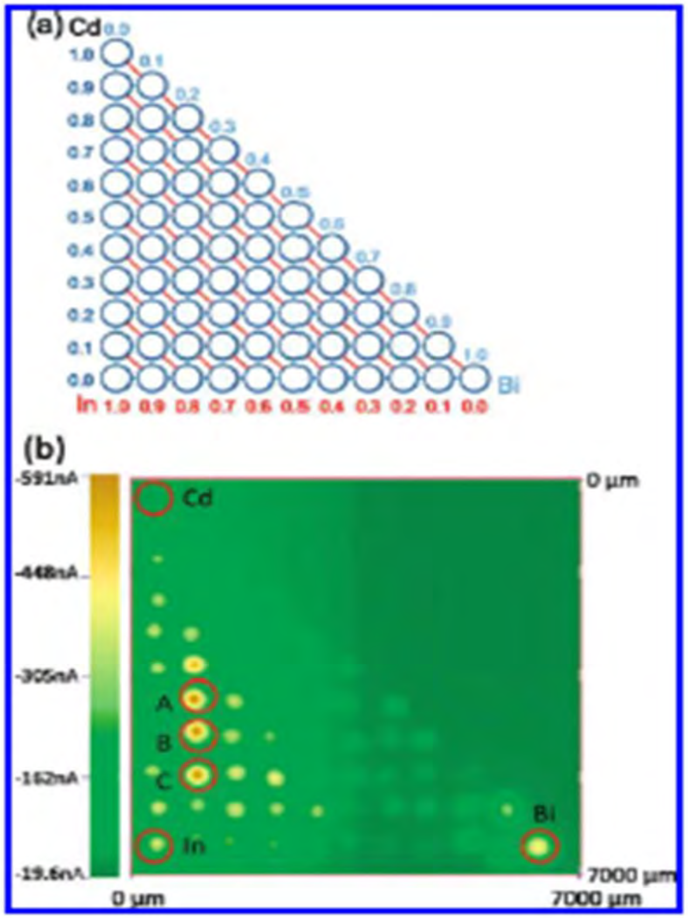
One such method is based on scanning electrochemical microscopy (SECM). Broad arrays of potential active materials and structures may be elucidated using this rapid new technique

Top corner is 100% Cd

Bottom left corner is 100% In

Bottom right corner is 100% Bi

Spots A, B, C represent Cd-In-Bi of 40:50:10, 30:60:10, 20:70:10 (atom %) ratios, respectively



Optimization

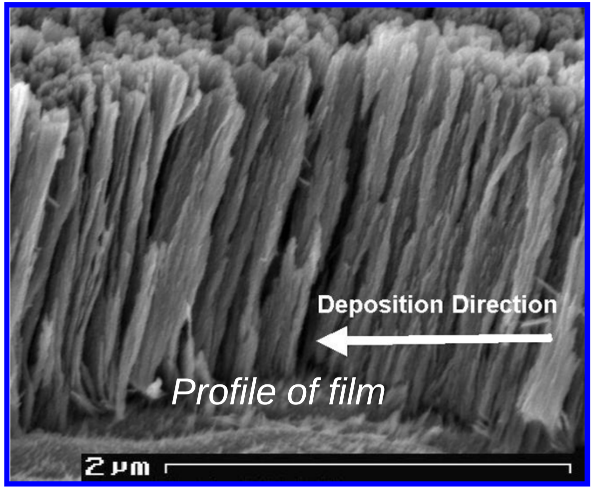
- Addition of yet another metal can increase the photoresponse!
- The Cd-In-Bi oxide with a ratio of 30:60:10 with the addition of Sn increases the photocurrent, with the highest photocurrent found for Sn:Cd:In:Bi = 40:18:36:6.
- This photocurrent is 174% higher under visible light than that of Cd-In oxide alone.
- An example of the sensitivity to electron-hole mobility for given band gap.

Morphology and Structure of Films

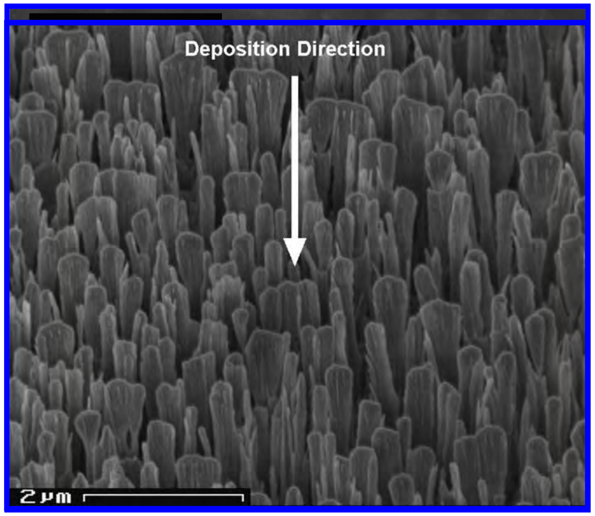
- *Sunlight absorbed vertically, reducing electron transverses nanoscale distances horizontally to do chemistry at the surface before recombination.*

- SEM shows morphology dependent on ϑ
  - Films deposited at 85º
    - Consist of nanocolumns
    - Columns inclined toward source
    - High surface area
  - Film deposited at 70º
    - No apparent nano-columnar structure
    - Film appears dense… *however, surface area measurements show otherwise*
- TEM
  - Surface of columns are rough
  - Individual columns are porous
  - Selected area diffraction shows films are amorphous
    - Confirmed by XRD

SEM of film grown at 85º,100K



SEM of film grown at 70º,100K



Flaherty, Mullins, et al. J. Phys. Chem. C **111** (2007) *4765*

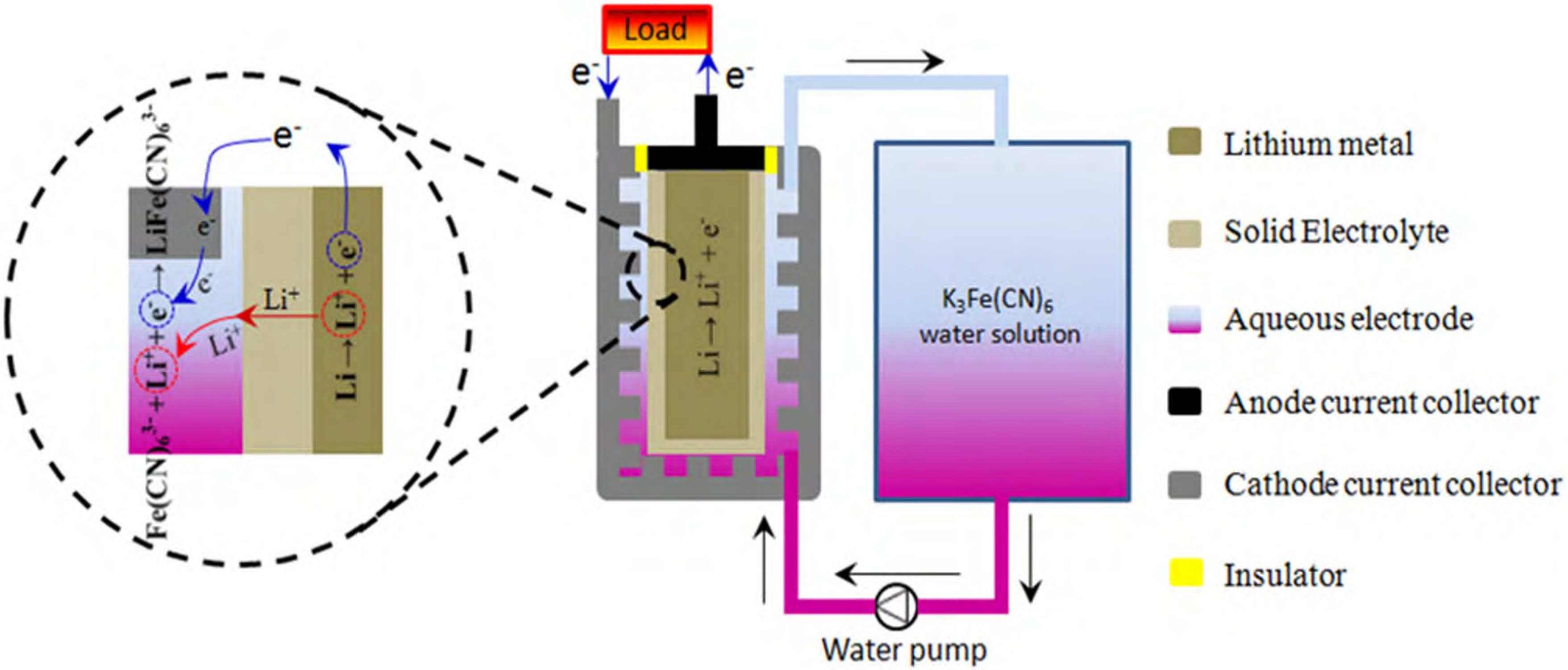
Large-Scale Storage for Intermittent (and even steady) Energy Sources

- Electricity from wind and solar energy sources is intermittent
  - Wind is strongest when load is least (during summer, wind blows at night, electricity needed during day)
  - Solar intensities vary with time (clouds, dust, and other atmospheric disturbances)
- Even “steady” sources need electrical energy storage
  - Nuclear and coal-fired power plants do not take well to cycling
  - Peaking sources are an expensive luxury, operating only at intermittent times
- “Normal” batteries are ill-suited to base-load storage requirements
- “Flow batteries” offer base-load storage capacity. Requirements for aqueous electrodes:
  - High specific energy density
  - Ambient temperature operation
  - Proper redox potentials
  - No side reactions
  - Good stability in water
  - Good reversibility
  - Reliable safety
  - Low cost

Lithium-Water Rechargeable Battery

(Yuhao Lu, John B. Goodenough, Youngsik Kim;

Texas Materials Institute, The University of Texas at Austin)



Feasibility of an alkali-ion battery

- Alkali metal as anode
- Redox couple soluble in aqueous solution as cathode
- Can be extended to
  - Flow-through mode for the cathode
  - Sodium rather than lithium as the anode
  - Lower cost than conventional lithium-ion rechargeable battery
  - Safe operation
  - Coulombic efficiency and voltage greater than Li/air battery with comparable capacity
  - Power output limited by commercially available solid electrolyte. Design of superior solid electrolyte needed
  - Applicable to both the electric-vehicle market and the problem of electrical energy storage for the grid

Summary

- Fossil fuels as an source energy are needed for the foreseeable future.
- New “clean energy” sources are not replacing any fossil fuel use.
- CO_2 production will increase at the same rate as total energy use.
- Need to reduce CO_2 emissions by 80% from 2050 to stabilize the CO_2 concentration in the atmosphere.
- Global warming has a 100 year time lag because of slow vertical communication in the oceans. The warming over the last three decades originated with the industrial revolution.
- New technological develops are required to stabilize CO_2 concentrations:
  - Cost-Effective Capture and Storage of CO_2 Through Energy Production from Saline Aquifers.
  - Fuels from sunlight.
  - Large-Scale Storage for Intermittent (and even steady) Energy Sources.