



Stanford University
Global Climate & Energy Project

50th Anniversary of the Japanese Association
of Groundwater Hydrologists
May 29, 2009

The Future of Energy:
Technology for a Sustainable Energy System

Professor Sally M. Benson
Director, Global Climate and Energy Project
Stanford University

Science and technology for a low GHG emission world.



A Sustainable Energy System

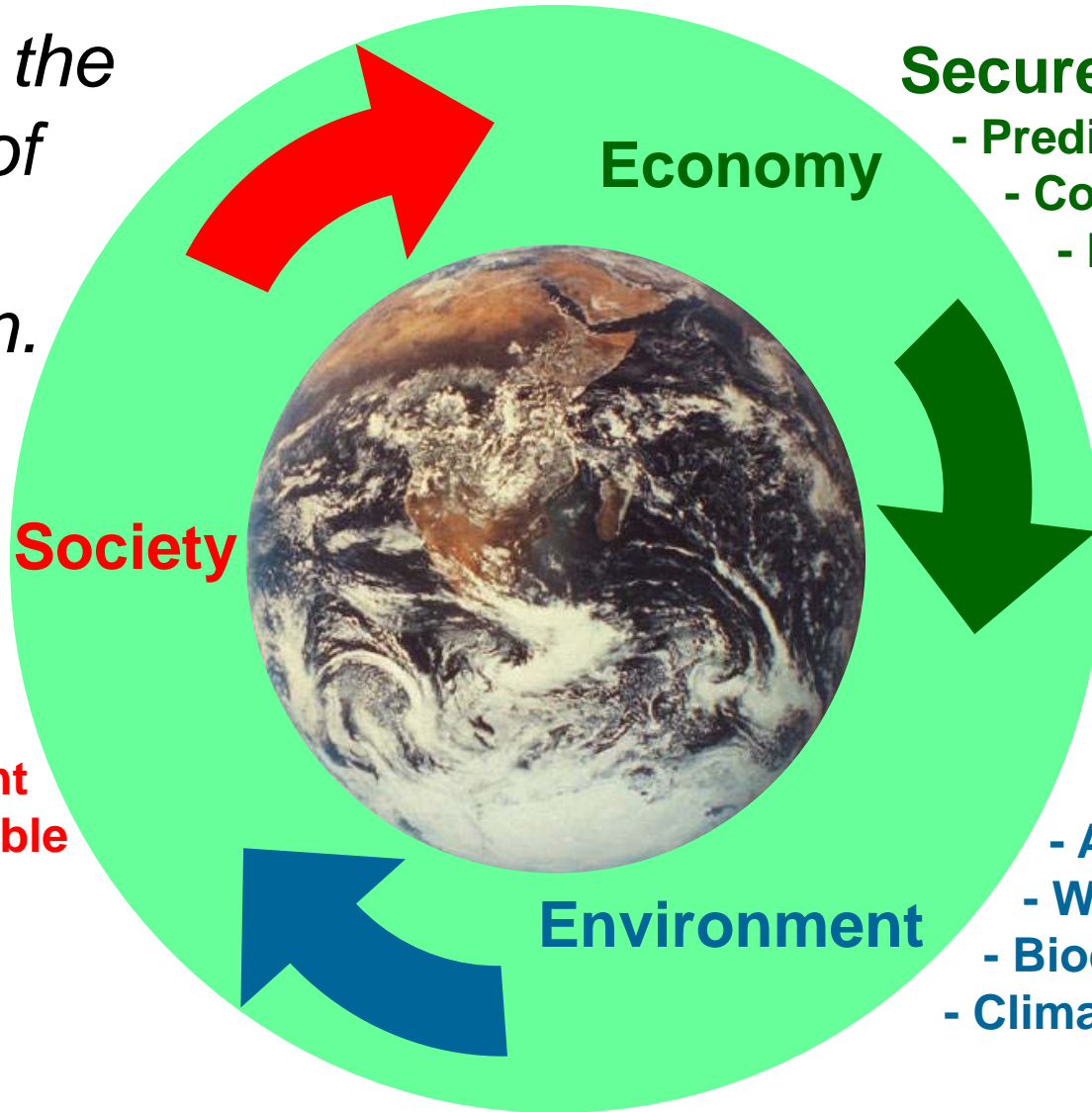


*Energy is the
lifeblood of
modern
civilization.*

Accessible

- Affordable
- Abundant
- Reliable
- Useful
- Efficient
- Equitable

Society



Economy

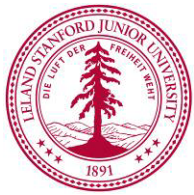
Secure

- Predictable
- Competitive
- Resilient
- Profitable
- Compatible
with National
interests

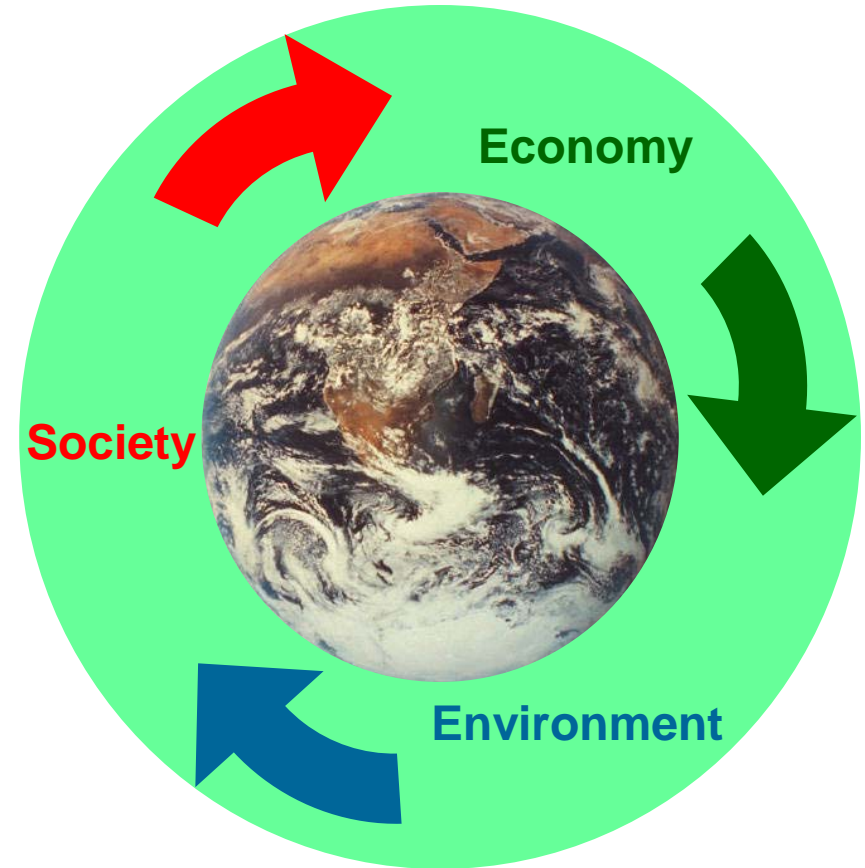
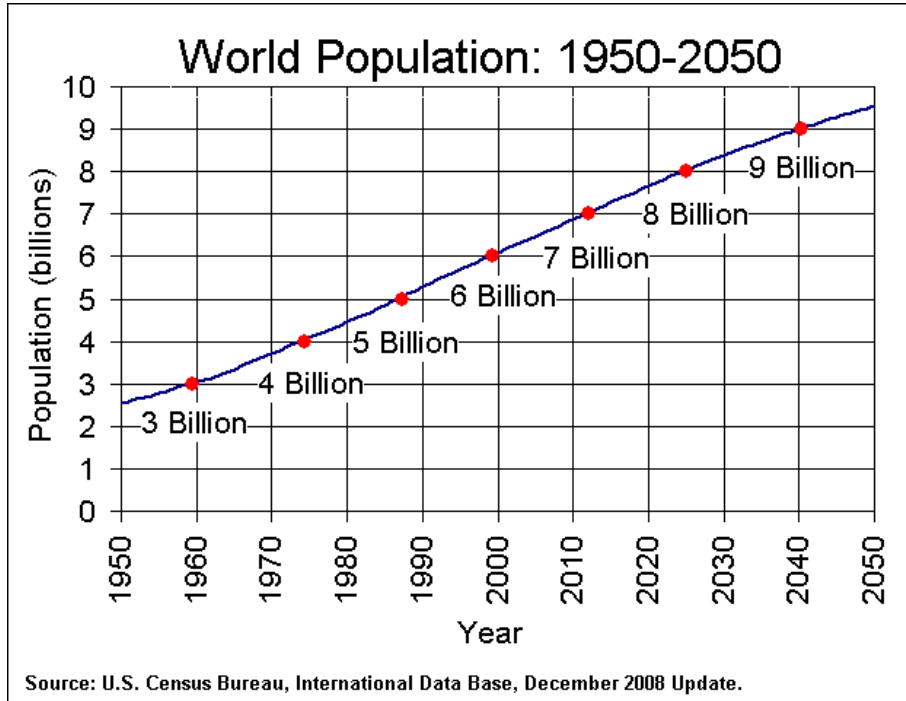
Protective

- Air Quality
- Water Resources
- Biodiversity
- Climate

Environment



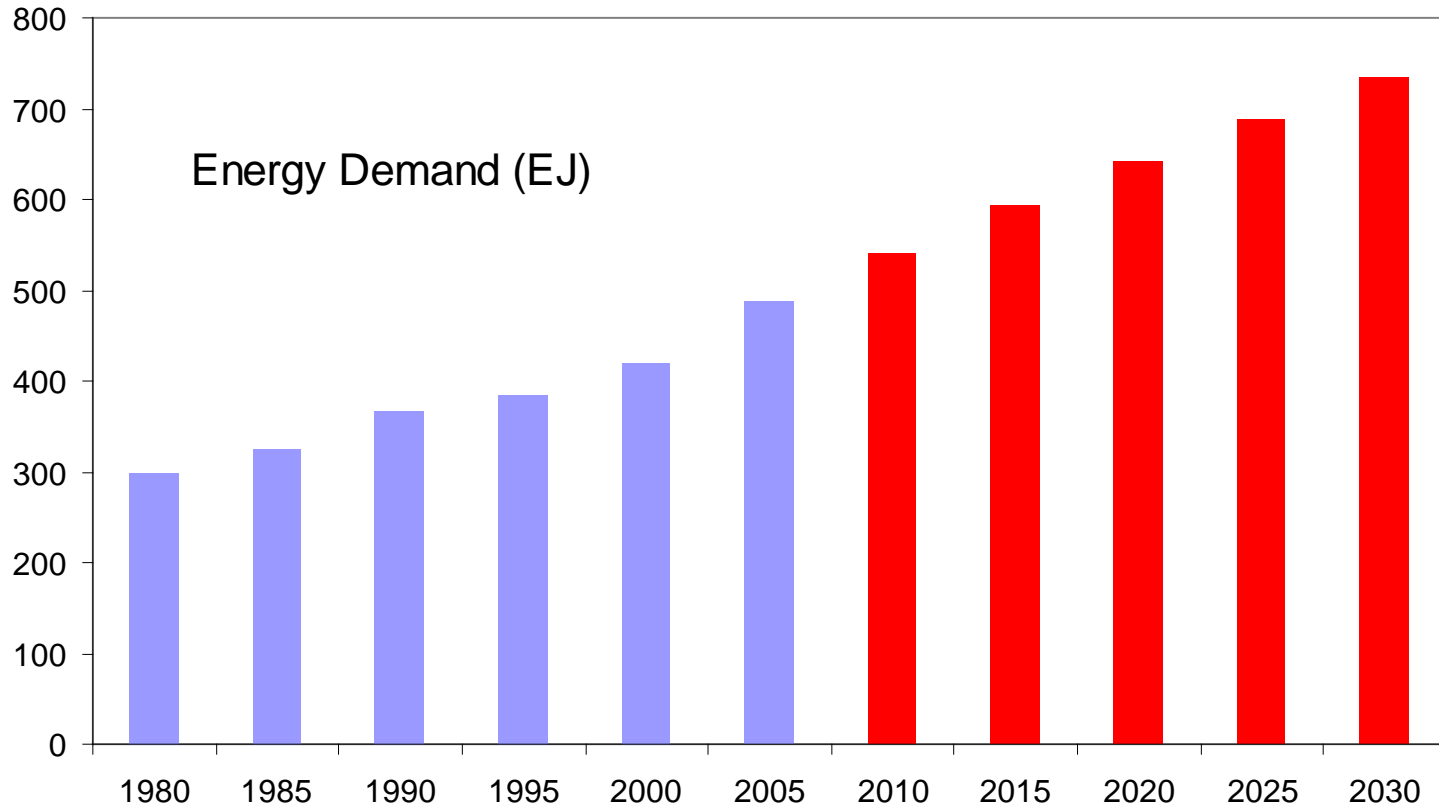
The Challenge



*How Do We Meet Growing Demands for Energy
While Protecting the Planet?*



Projected Energy Demand



50% increase in energy demand by 2030

1 EJ = 10^{18} J

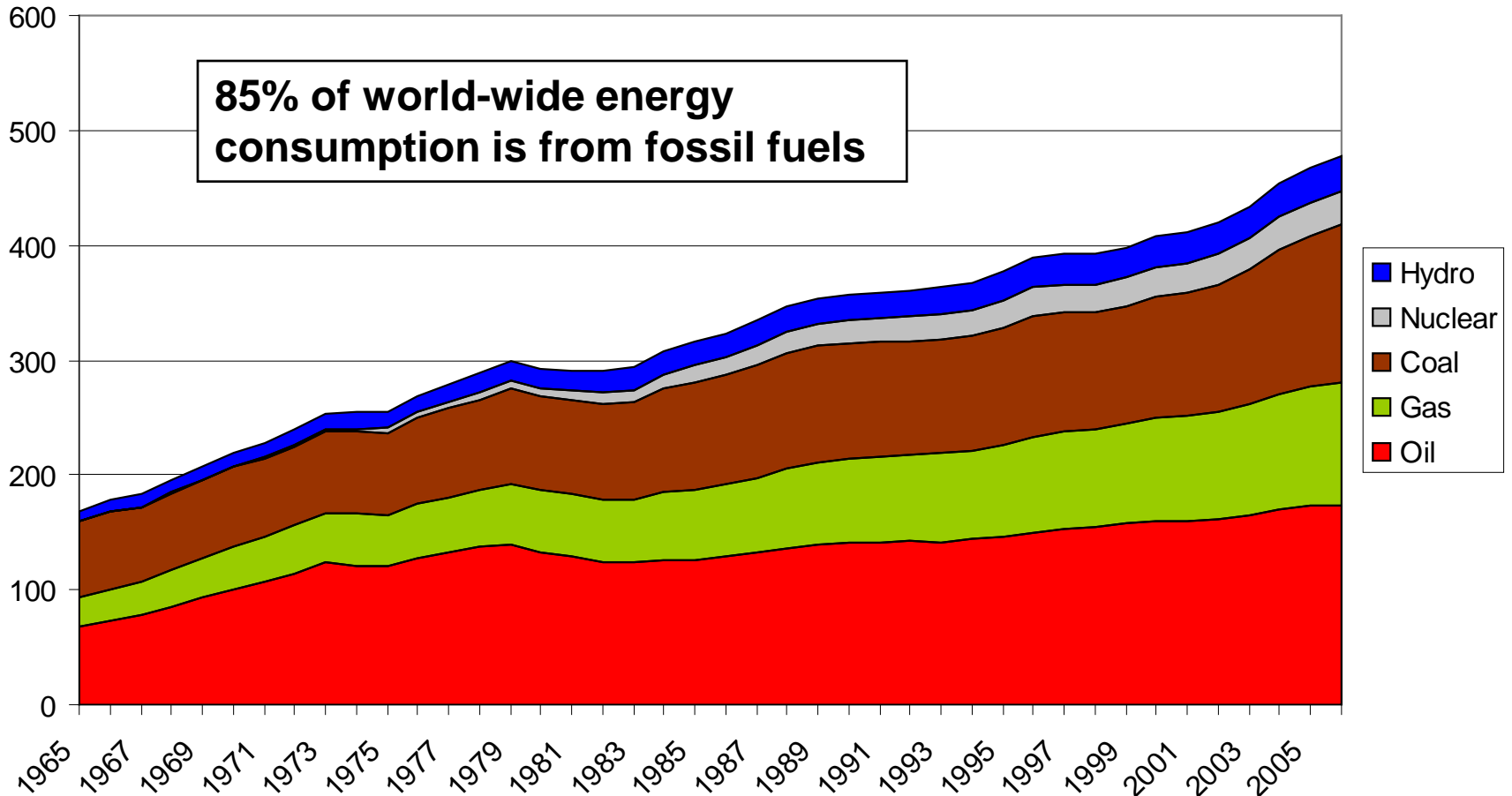
EIA, International Energy Outlook, 2008



Global Energy Consumption



Global Energy Consumption (EJ)



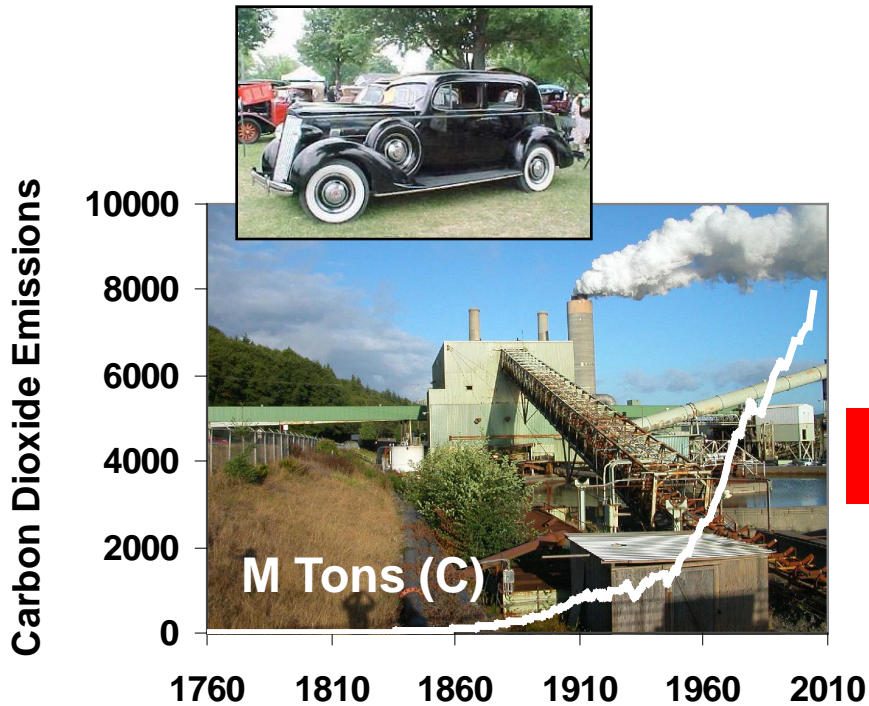
Source: BP World Energy Review, 2007



Carbon Dioxide in the Atmosphere



Carbon dioxide emissions have risen dramatically over the past two hundred years...



*... leading to the buildup of carbon dioxide in the atmosphere,
... global warming, and
... ocean acidification.*



Haven't Carbon Dioxide Concentrations Varied for a Long Time? Yes, but...



GLACIAL-INTERGLACIAL ICE CORE DATA

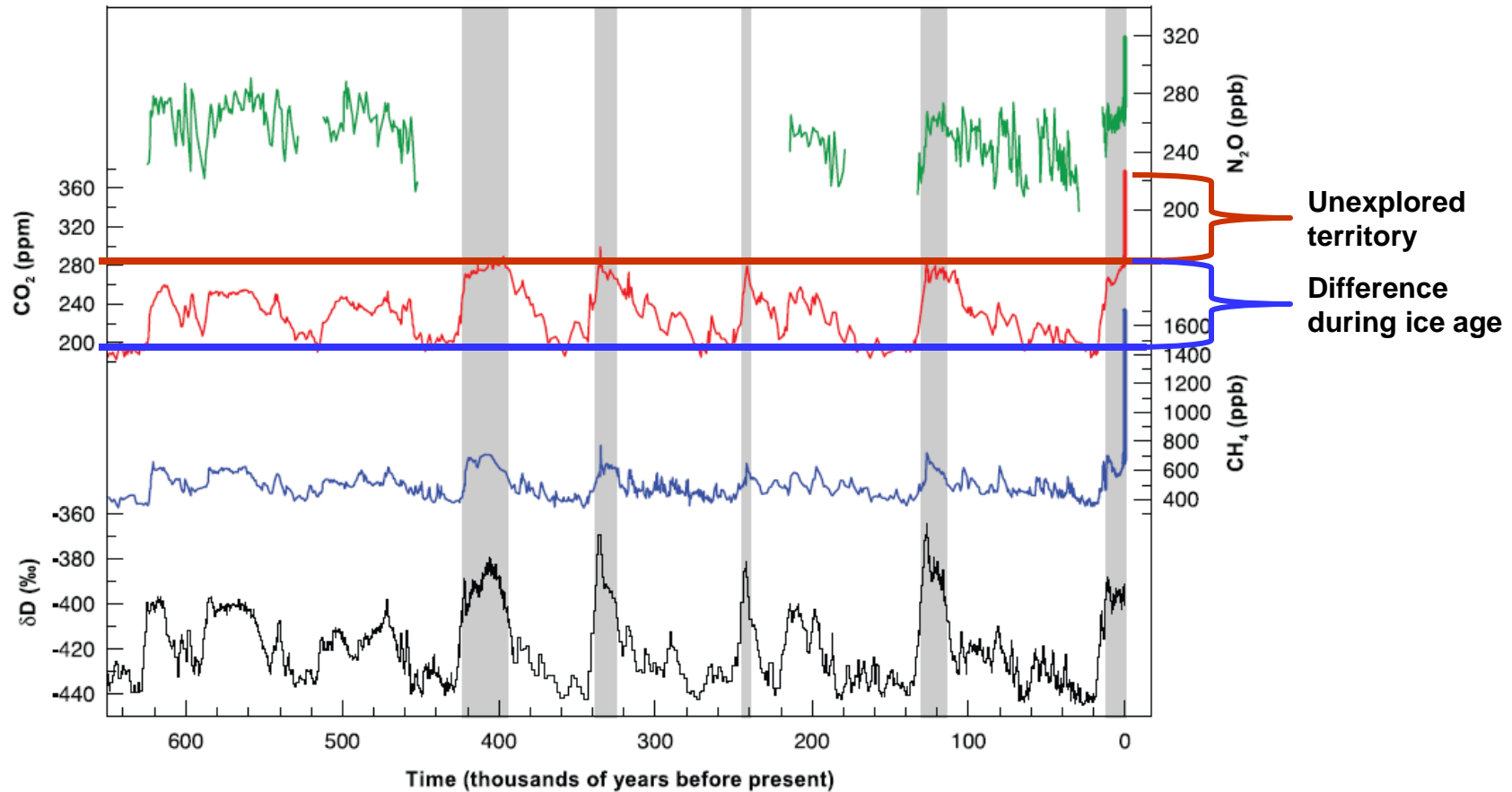
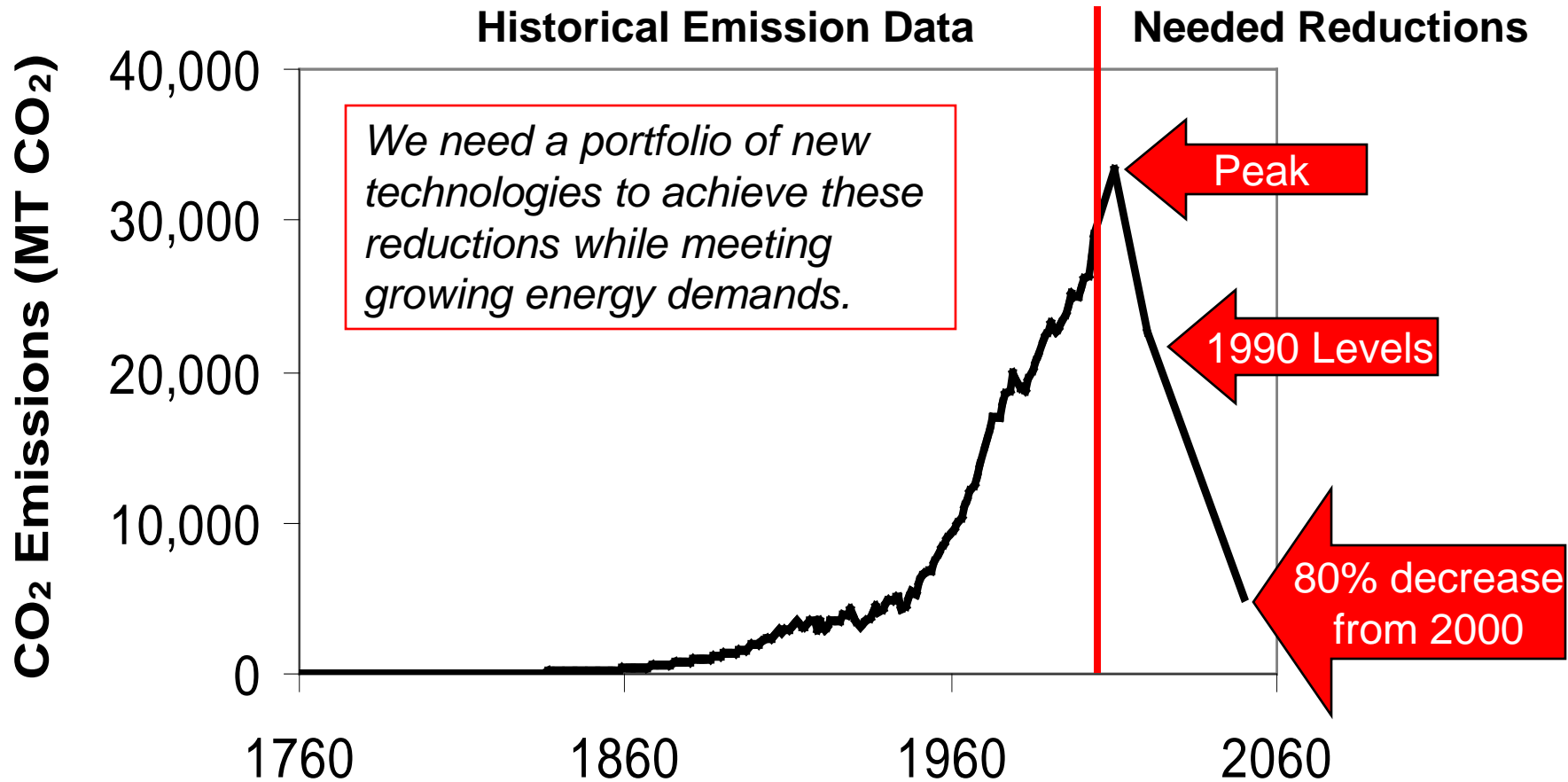


Figure TS.1. Variations of deuterium (δD) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in air trapped within the ice cores and from recent atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm periods. {Adapted from Figure 6.3}



Estimated Emission Trajectory to Stabilize Atmospheric CO₂ Concentrations



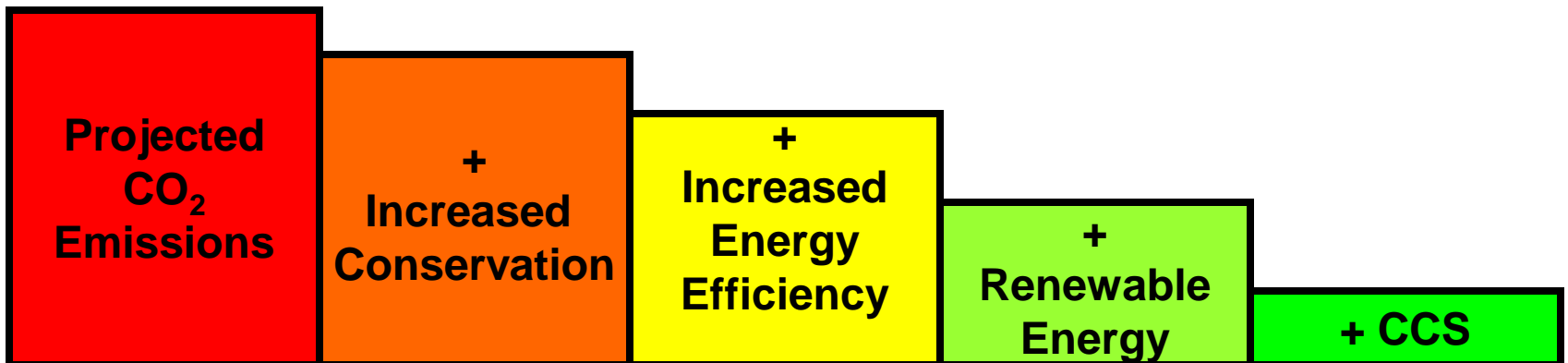
A typical scenario for GHG emission reductions to limit warming to 2°C.



What Can We Do About This?

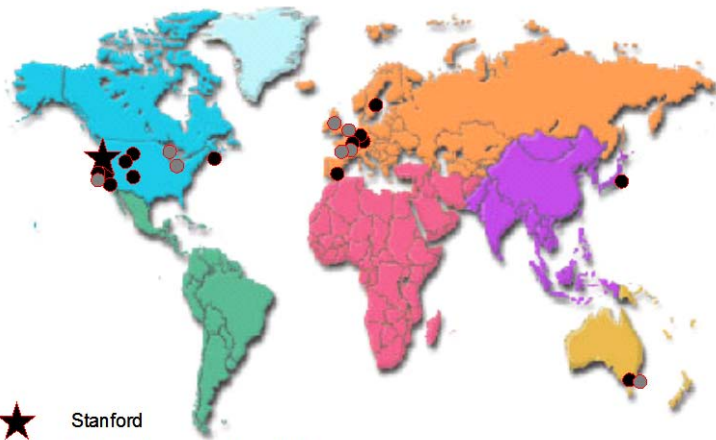


- Energy Conservation
- Energy efficiency improvements
- Low-carbon energy sources
 - Renewable energy (particularly solar and wind energy)
 - Nuclear energy
 - Geothermal energy
- Carbon dioxide capture and sequestration (CCS)





The Global Climate and Energy Project at Stanford University



- ★ Stanford
- Participating outside institutions
- Pending outside institutions

Mission

- Research on low-greenhouse gas emission energy conversions
- Focus on fundamental and pre-commercial research
- Applications in the 10-50 years timeframe

Strategy

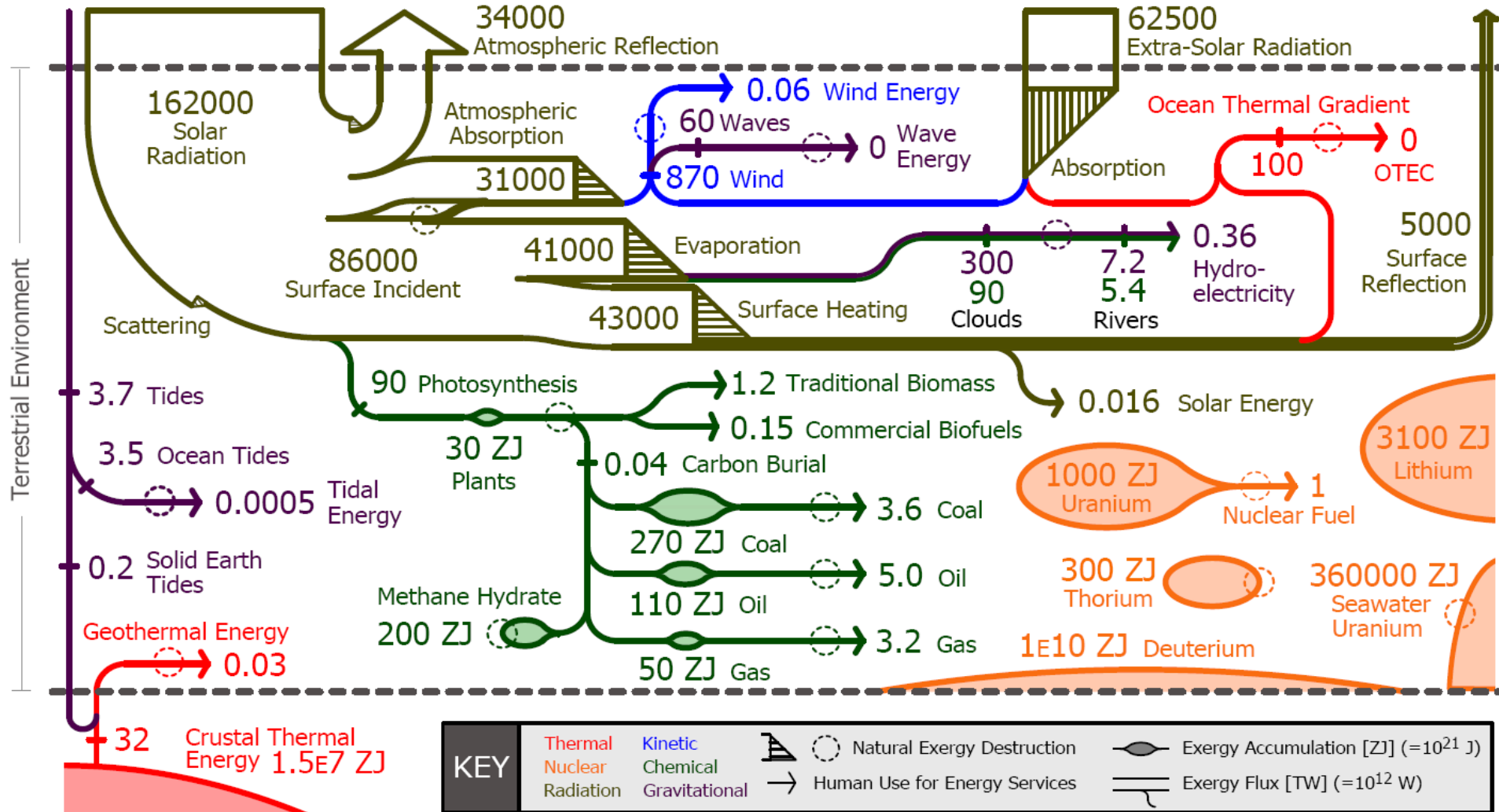
- Research projects with potential for significant impact on reducing emissions
- Look for potential breakthroughs for new conversion options
- High risk / high reward
- Work at Stanford and at other institutions around the world

Schedule and Budget

- 10 years (2003 – 2013+)
- \$225 M



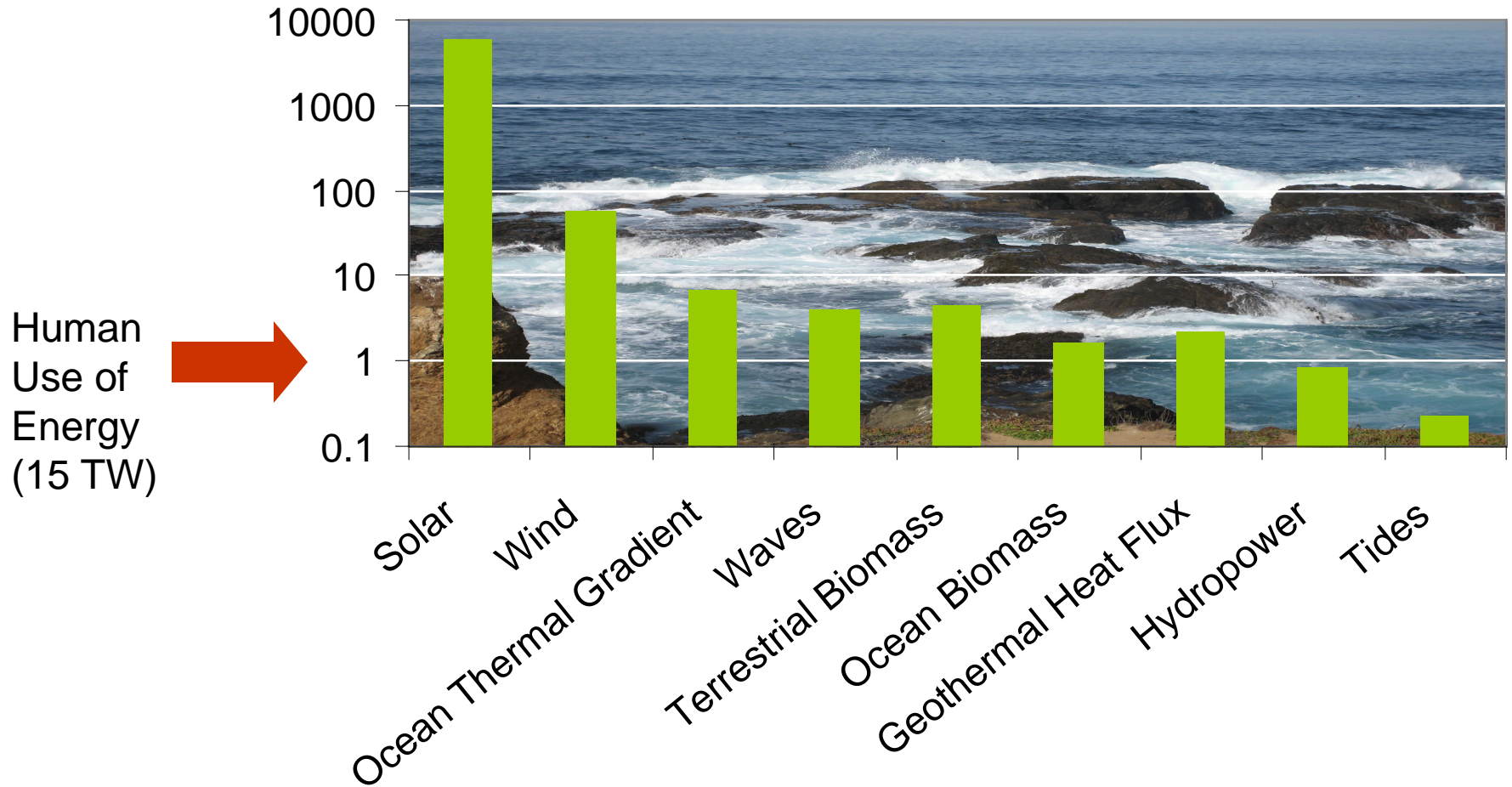
What resources can we use? Exergy flow of planet Earth (TW)



Humans use an average of 15 TW of energy or 450 EJ/year



Renewable Global Exergy Flows

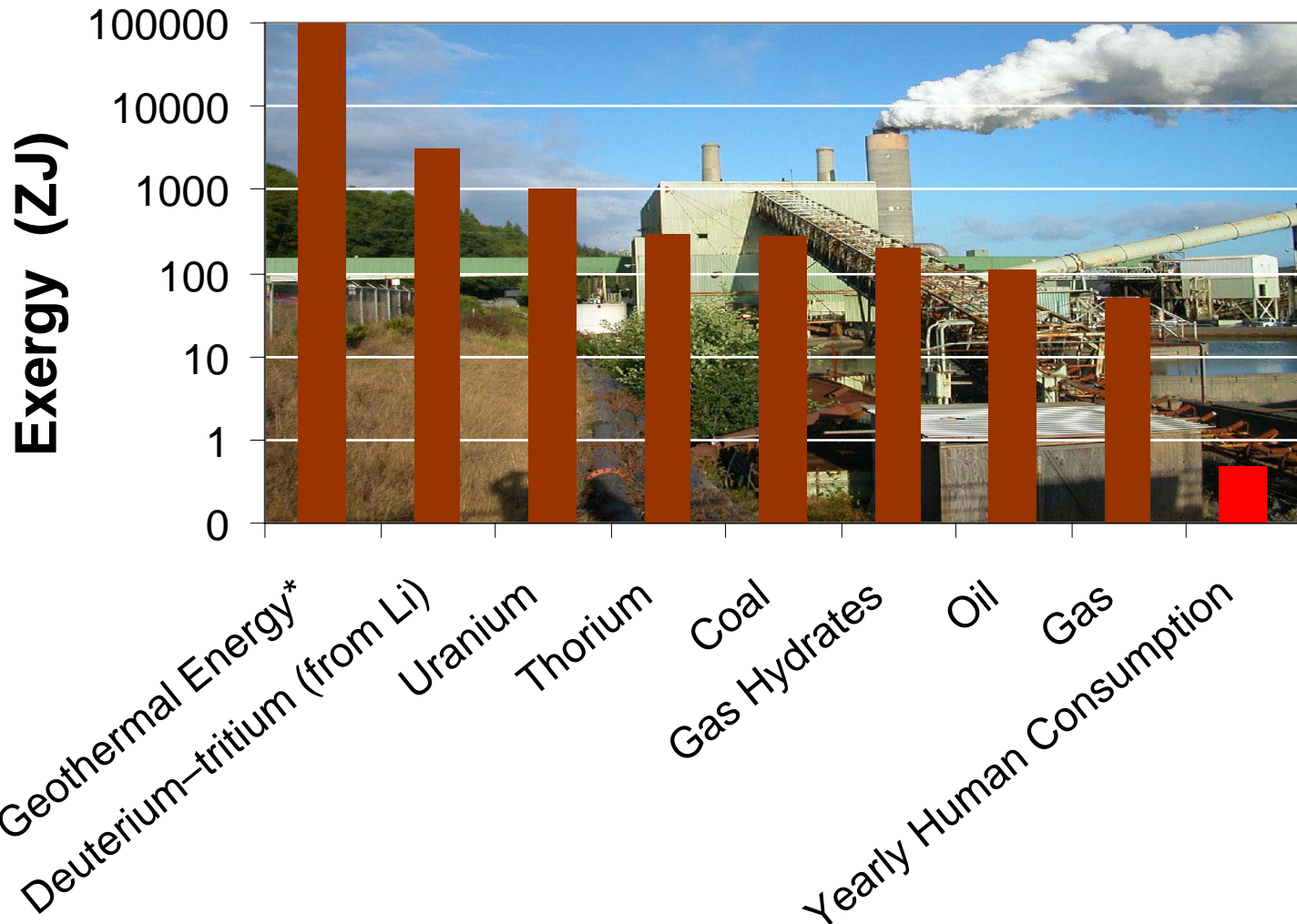


Exergy sources scaled to average consumption in 2004 (15 TW)

From Hermann, 2006: Quantifying Global Exergy Resources, Energy 31 (2006) 1349–1366



Global Exergy Stores

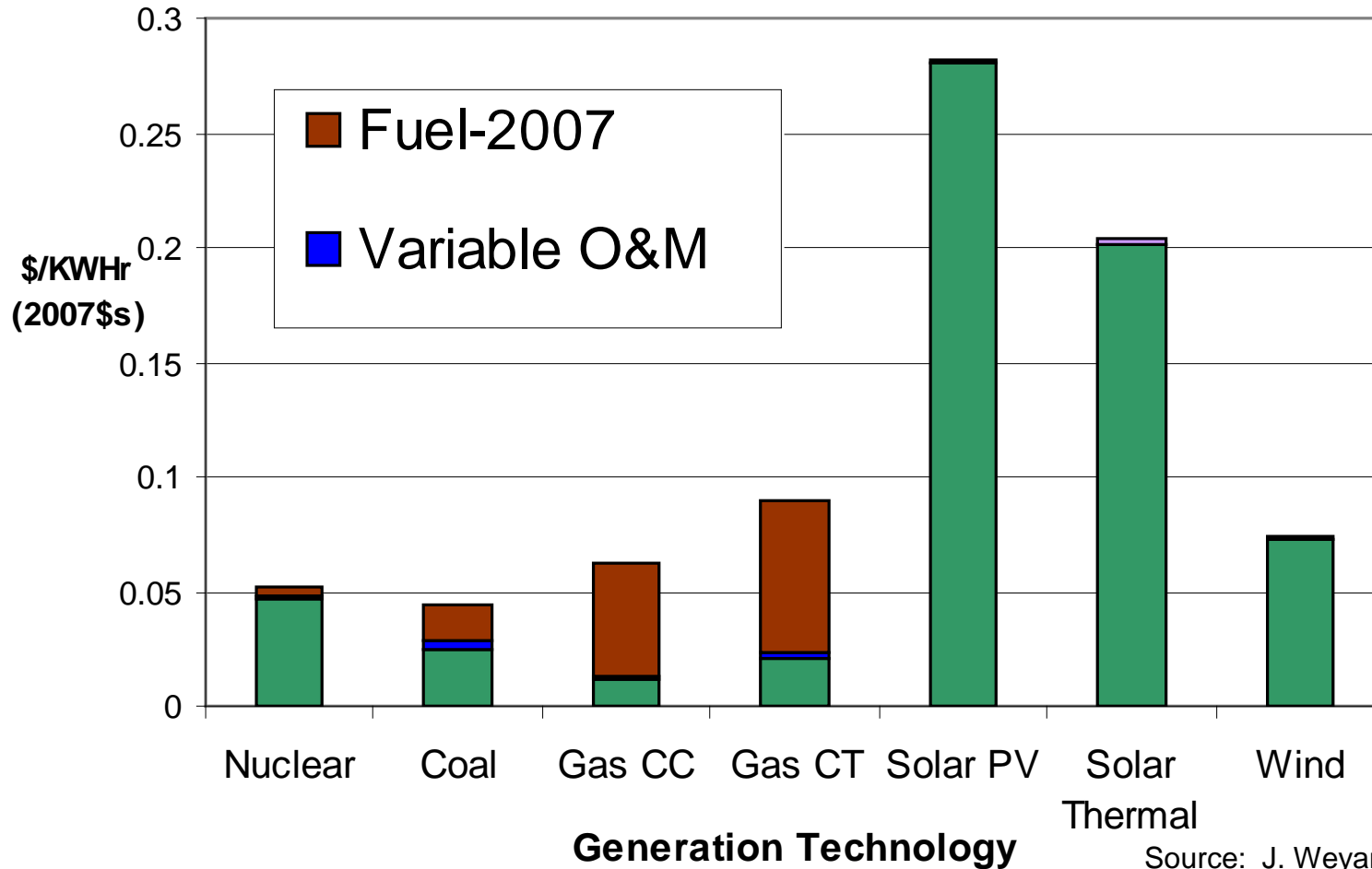




What About Cost?



Electric Generation Cost Comparison (2007 Fuel Prices)



Source: J. Weyant, Energy Modeling Forum, Stanford University



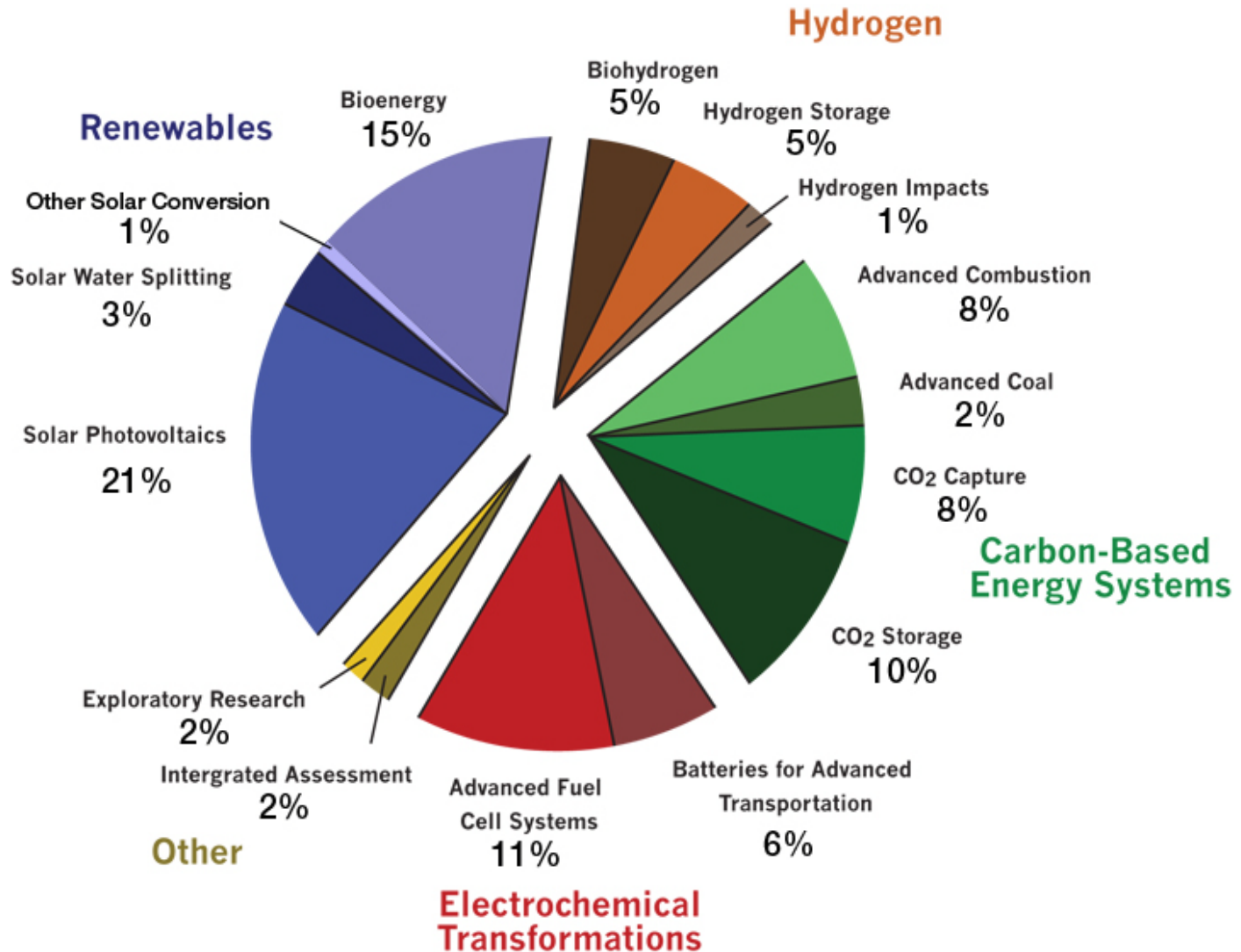
Key Messages: Energy Supply

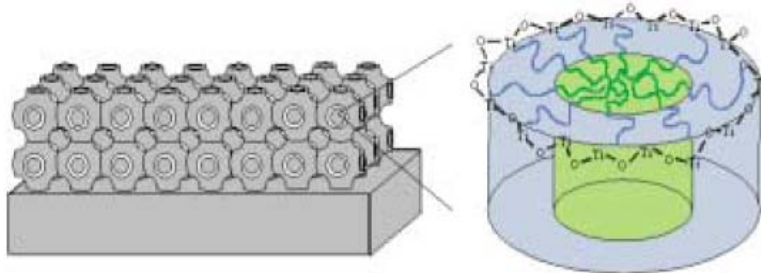


- We are not running out of energy!
 - Renewable energy flows: solar and wind power are largest resources
 - Energy stores: large amount of geothermal, fossil fuels, nuclear fuels
- Using more renewable energy needs
 - Lower the cost of electricity from solar energy
 - Improve integration of wind into the electrical grid
 - Develop methods for using renewable energy for transportation
 - Deal with intermittency, seasonality, and geographic distribution
 - Provide energy storage to support more wind and solar PV
 - Enhance communications, control and transmission for the electric grid to support more renewable energy
- Using energy from fossil fuels needs
 - Reduce or eliminate carbon dioxide emissions from fossil fuels
 - Switch to lower emission fuels (e.g. coal to natural gas)
- Using nuclear energy needs
 - Resolve proliferation and waste disposal issues
 - Gain public support for maintaining and expanding capacity

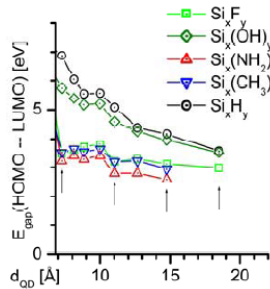
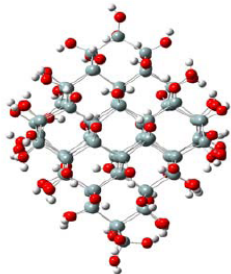


GCEP Research Portfolio





Nano-Structured PV Cells - McGehee



Durable Nanostructured Cells With Si Quantum Dots – *Green et al.*

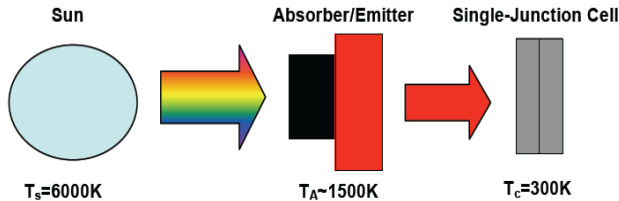
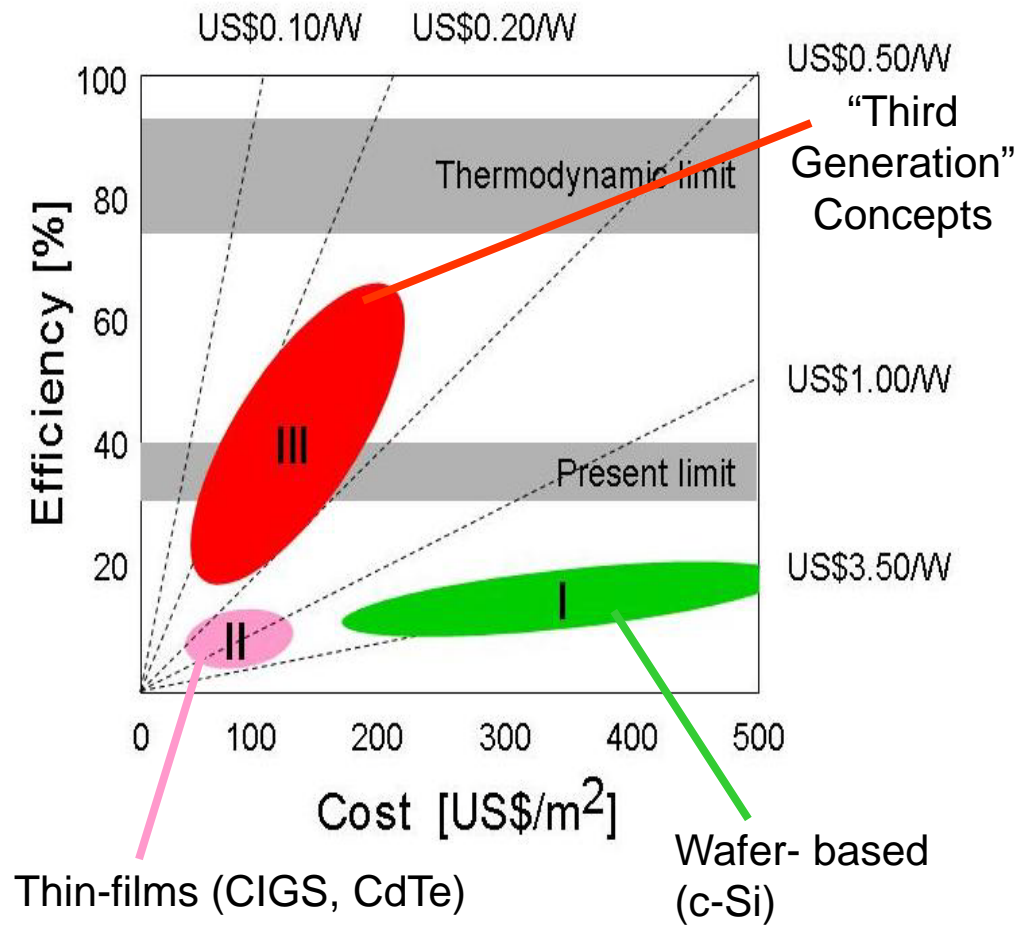


Fig. 1. Schematic of a solar thermo-photovoltaic cell.
Themo-Photovoltaic Cell – *Fan et al.*





Research Projects in Biofuels

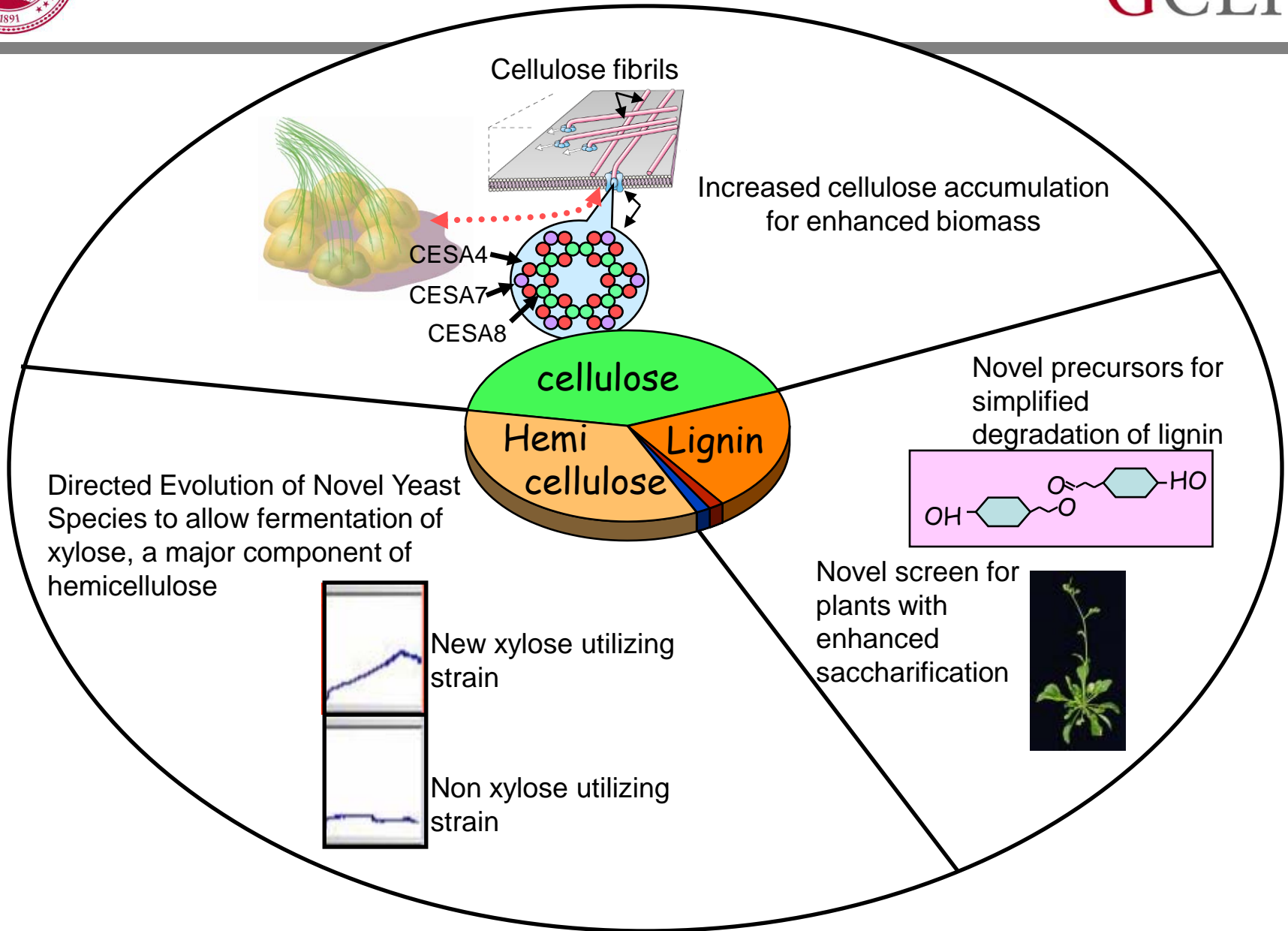
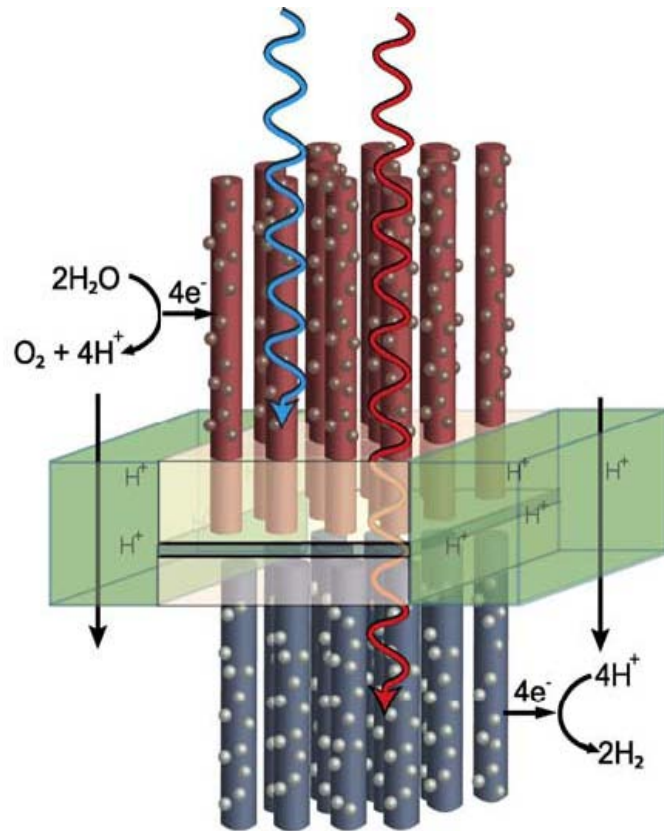
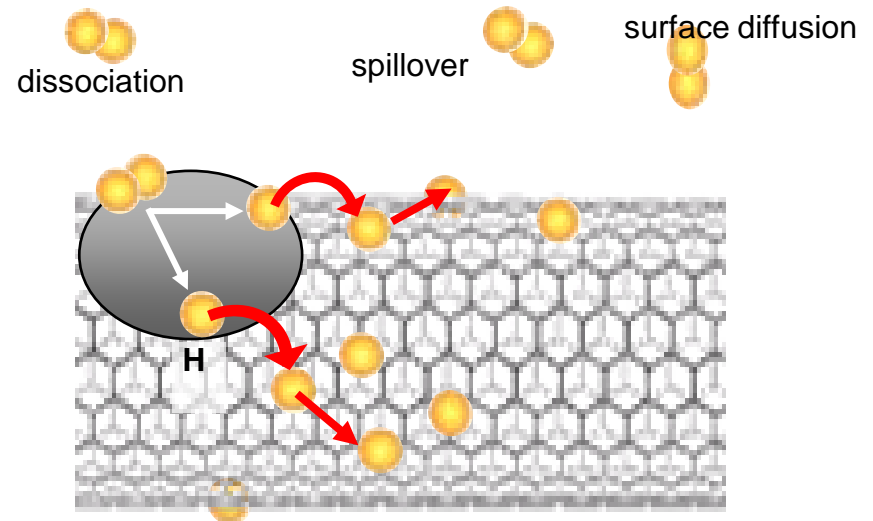
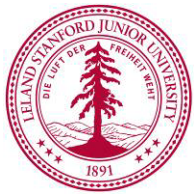


Photo-activated Water Splitting at an Artificial Membrane – *Lewis et al.*



Hydrogen Storage in C-H bonds on Carbon Nanotubes – *Nilsson et al.*

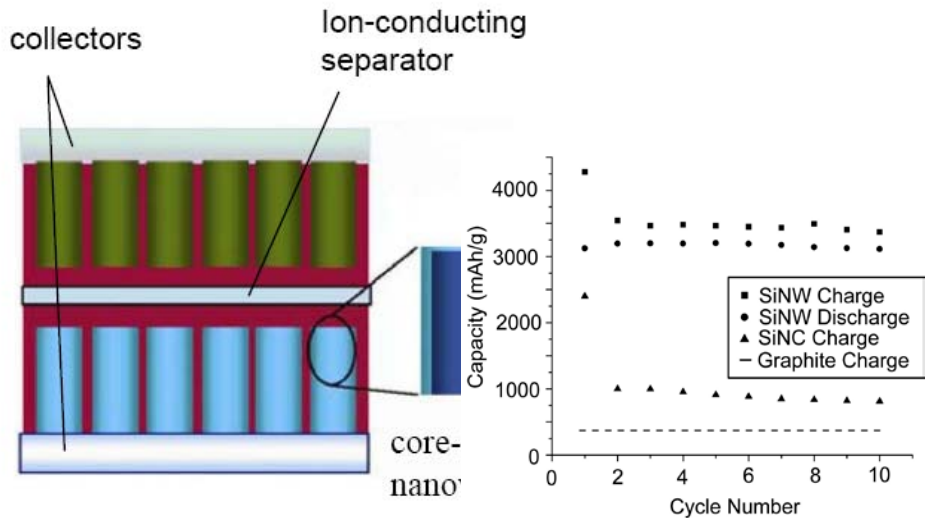




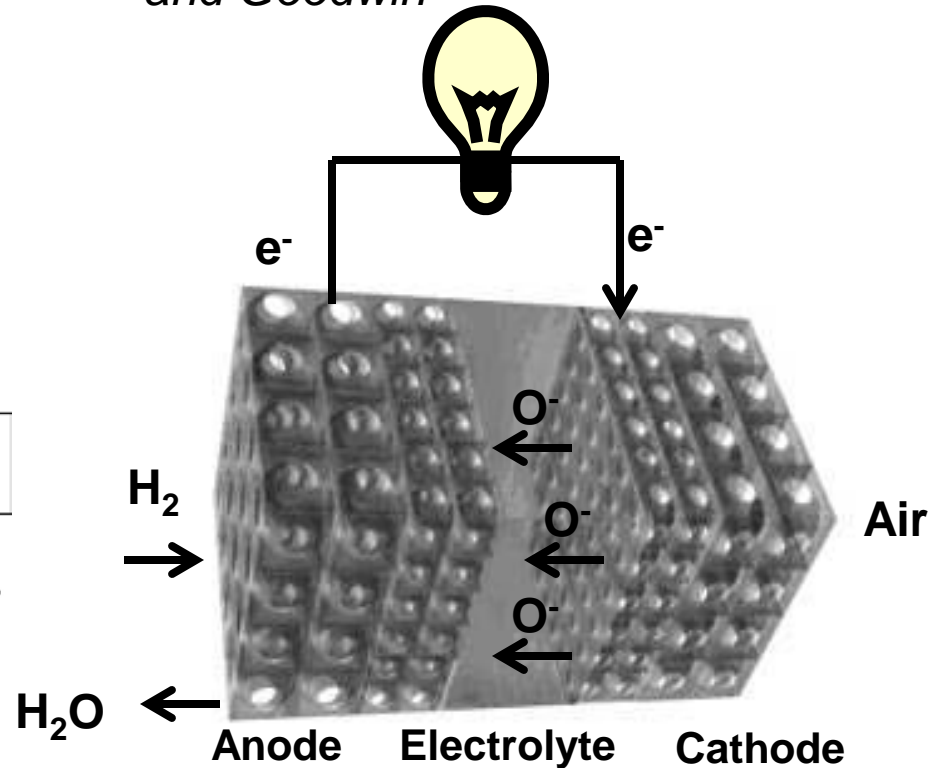
GCEP Research Projects in Electrochemical Transformations



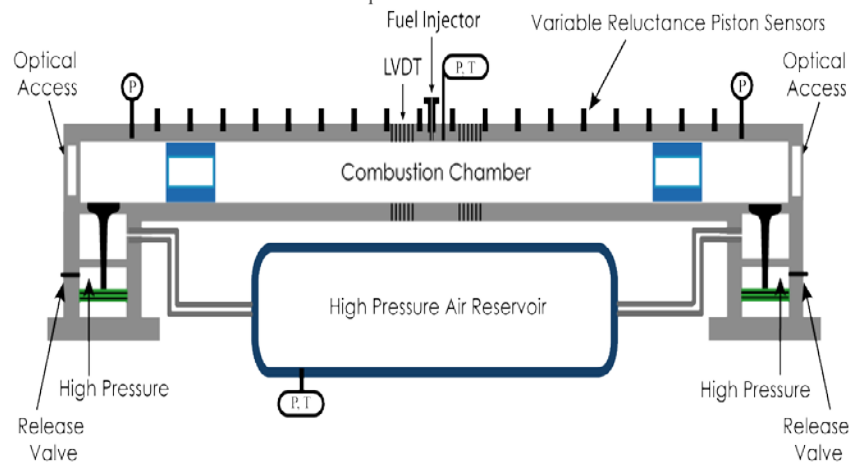
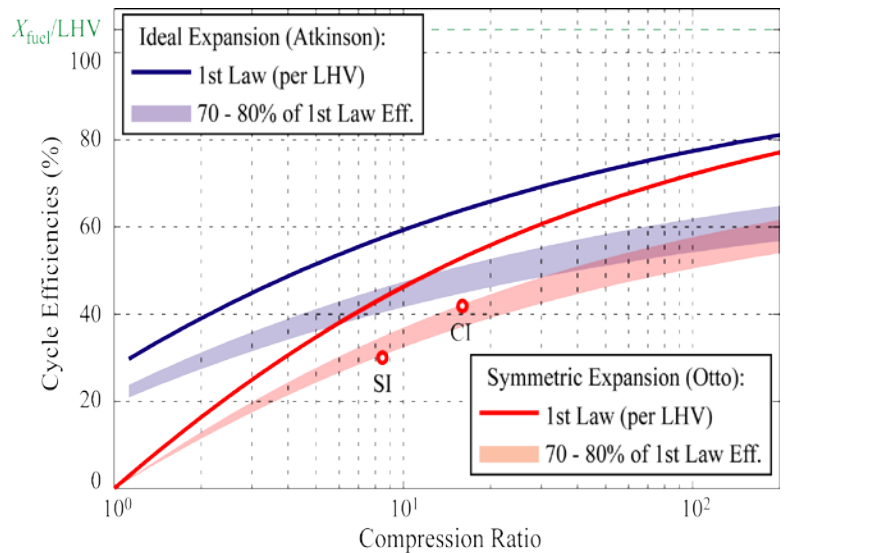
Innovative Battery Technologies for Improved Energy Densities Based on Nanowire Architectures - *Cui*



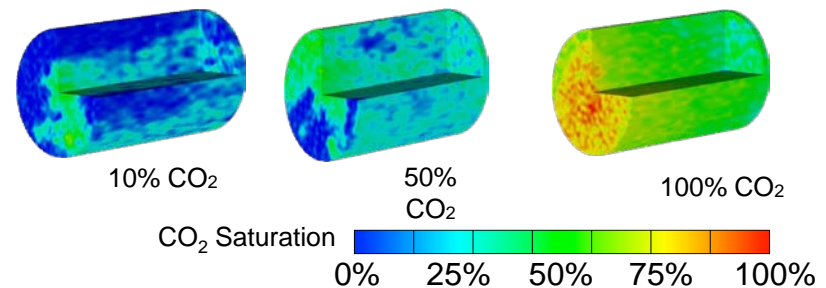
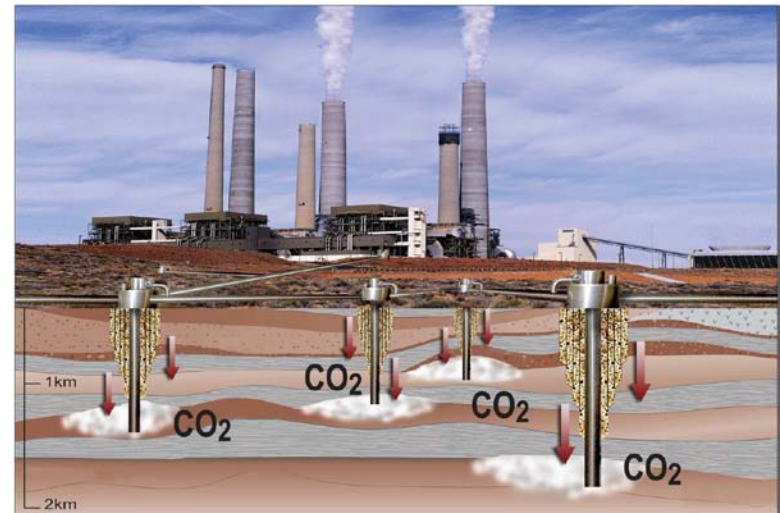
Novel Approaches to Fuel Cell Design and Chemistry Nanoscale Architectural Engineering – *Haile and Goodwin*



Advanced Combustion through Exergy Management – *Edwards*

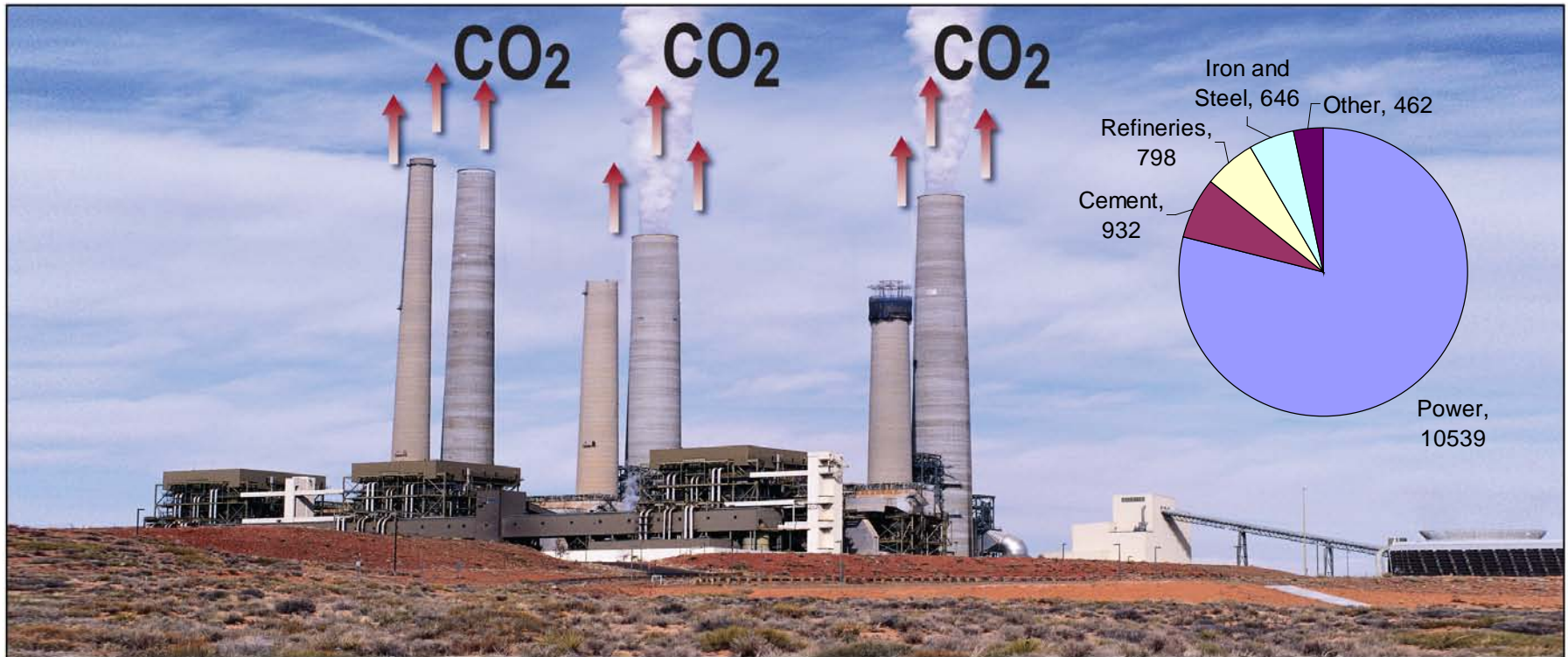


Carbon Dioxide Capture and Sequestration - *Benson*





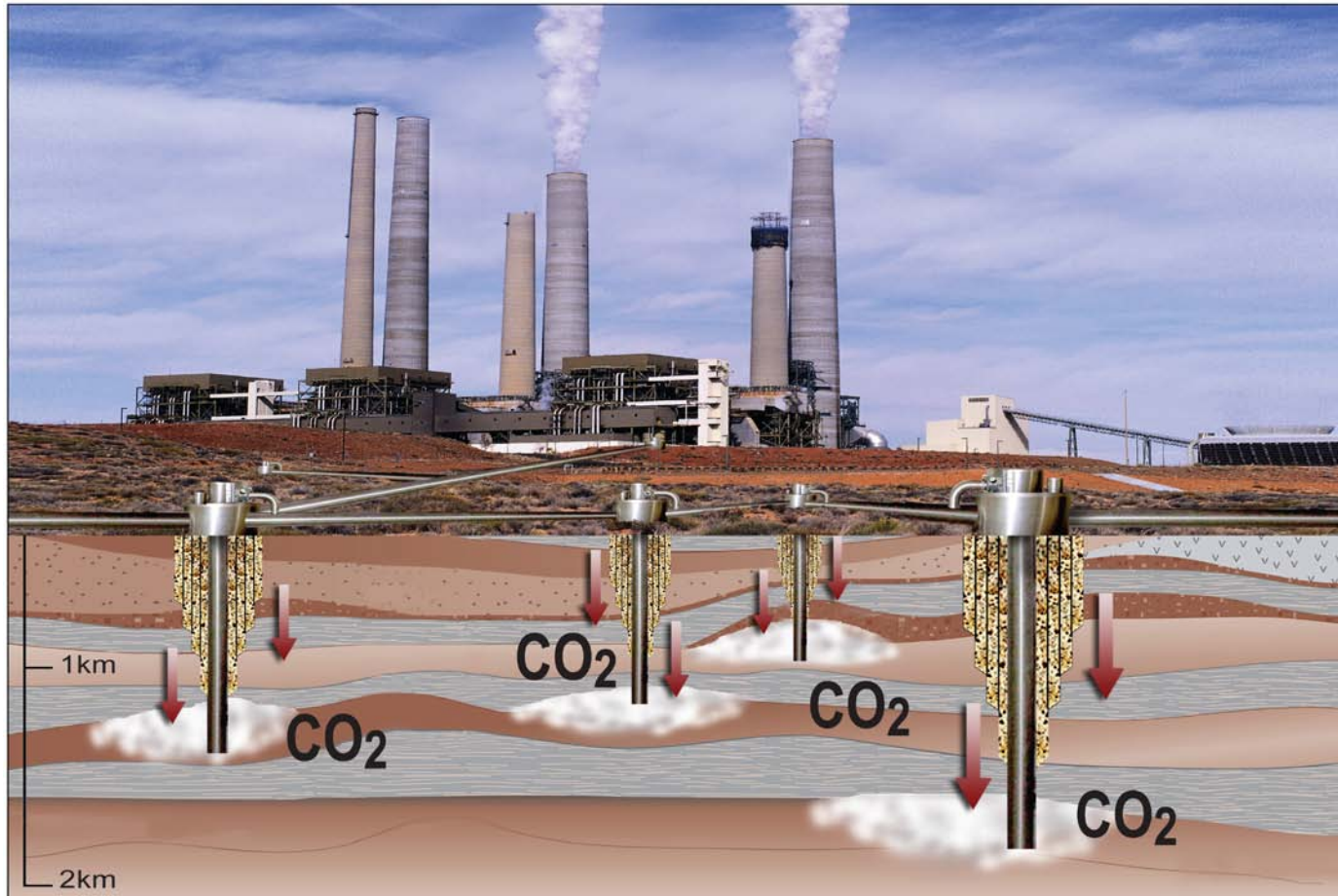
CO₂ Emissions Must be Reduced to Limit Global Warming



- 60% of global fossil fuel emissions come from large stationary sources
- Fraction could be much greater if we adopt electric cars



Capture and Geologic Sequestration



Capture



Compression

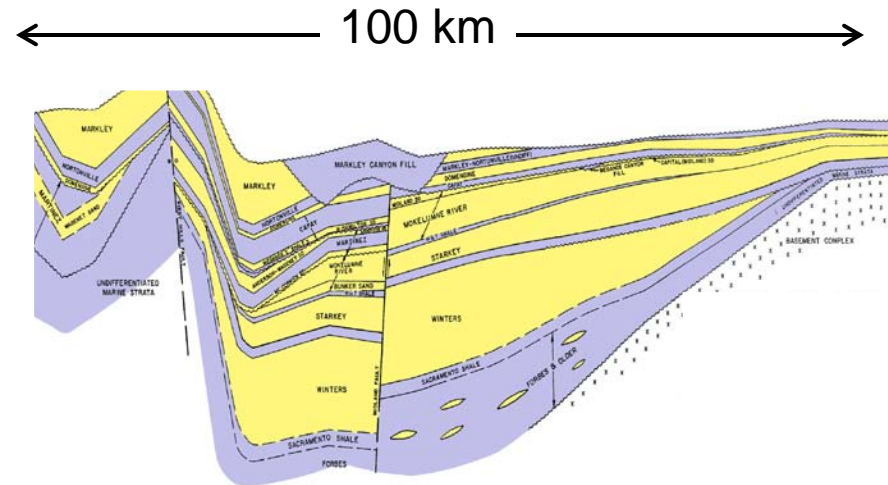
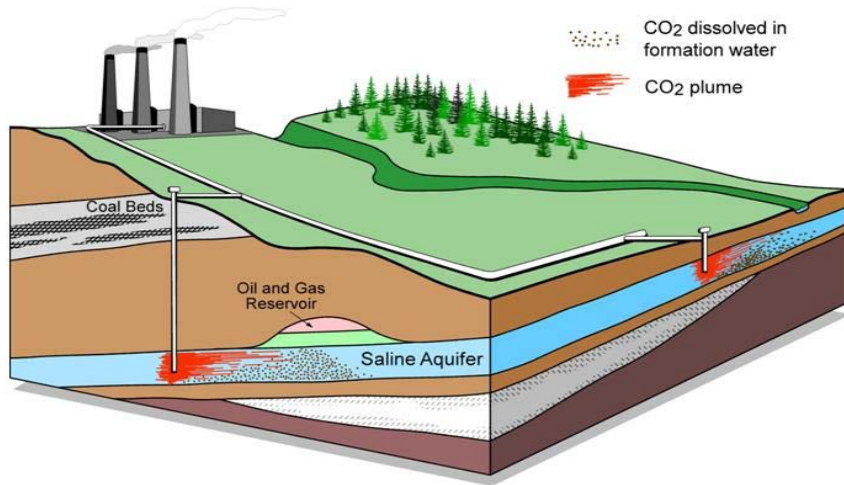


Pipeline
Transport



Deep Underground
Injection

Rocks in deep sedimentary basins are suitable for CO₂ storage.



Specific formation types

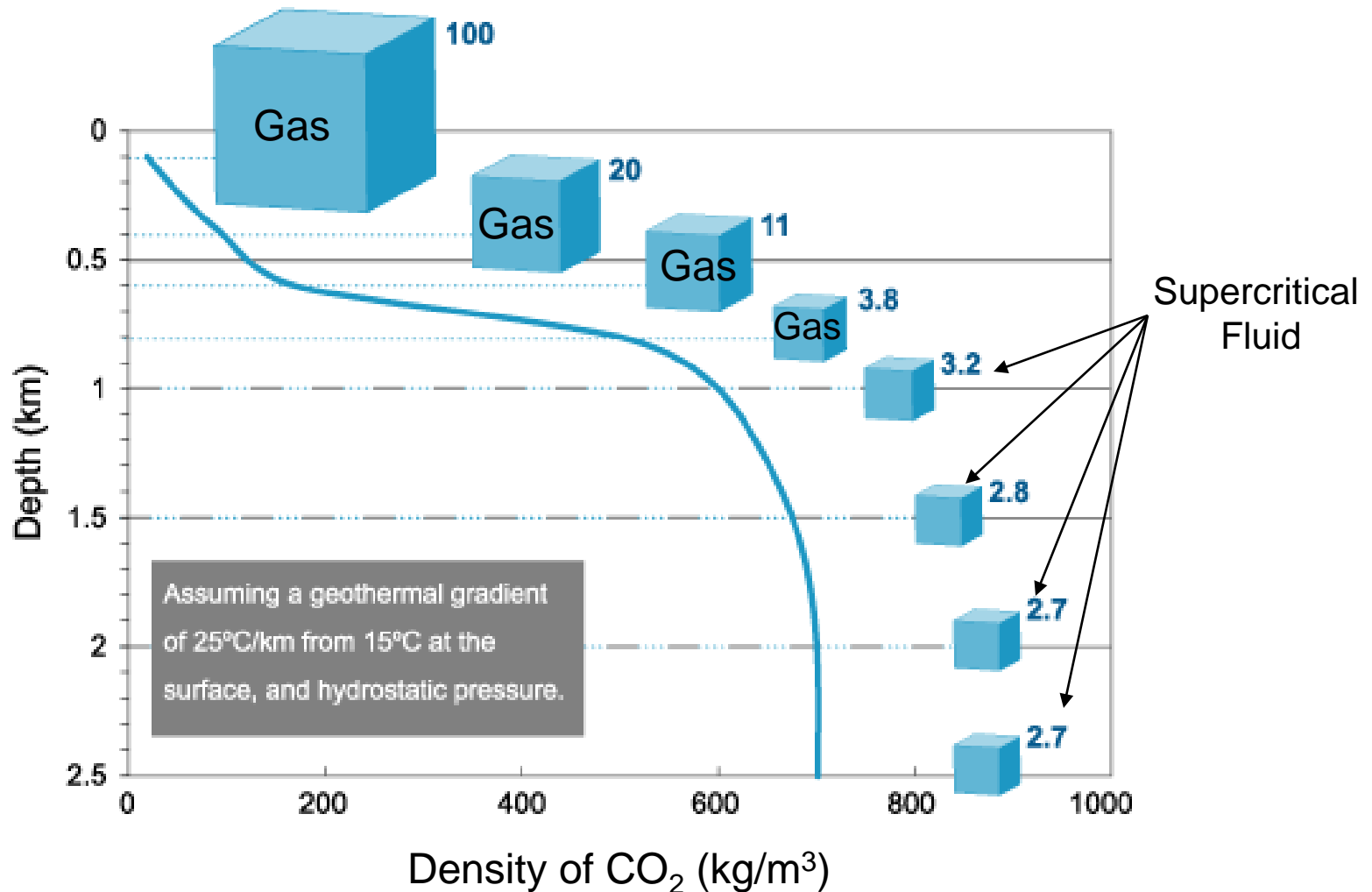
- Oil reservoirs
- Gas reservoirs
- Saline aquifers
- Deep unminable coal beds

Sacramento Valley, California

Example of a sedimentary basin with alternating layers of coarse and fine textured sedimentary rocks.



CO₂ is Sequestered as a Supercritical Fluid





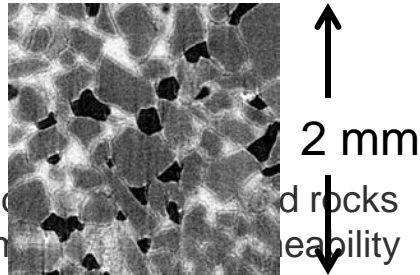
What Keeps the CO₂ Underground?



- Injected at depths of 1 km or deeper into rocks with tiny pore spaces

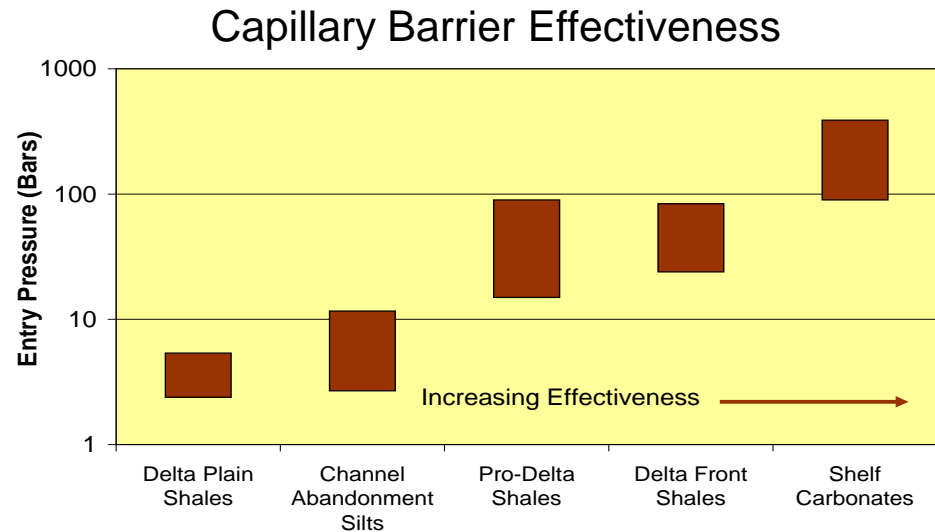
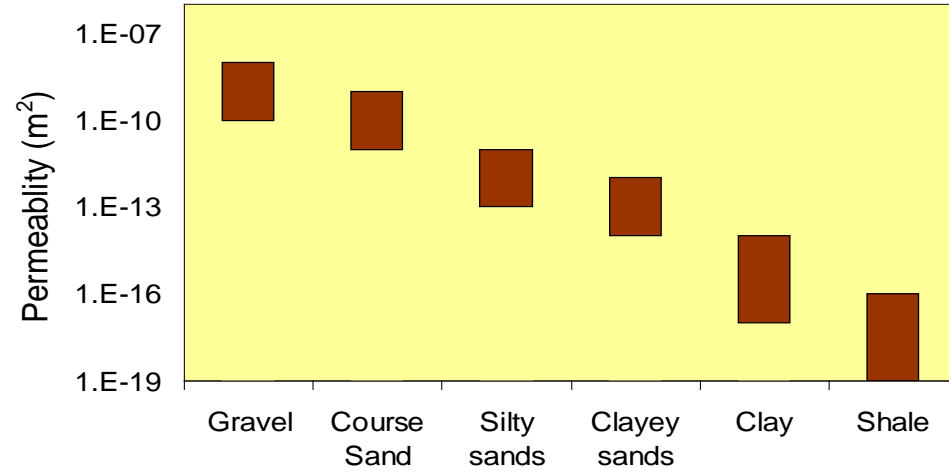
- Primary trapping

- Beneath seals made of clay and rocks that provide a membrane barrier



- Secondary trapping

- CO₂ dissolves in water
- CO₂ is trapped by capillary forces
- CO₂ converts to solid minerals





Some Attributes of Effective Storage Sites



Overburden

**Known condition of active and abandoned wells
Presence of secondary seals**

Seal

**Geographically extensive
Low permeability and high capillary entry pressure
Stable and sealed faults and fractures**

Sequestration Formation

**Greater than 800 m deep
Not a source of drinking water
Satisfactory injectivity
Sufficient storage volume
Hydrologically isolated from drinking water aquifers**

Not to scale



Potential Groundwater Impacts



- CO₂ migration into shallow aquifers
 - Mild acidification, e.g. pH of 4 to 5
 - Potential mobilization of hazardous constituents, e.g. As, Pb
- Displacement and migration of saline brines into shallow aquifers
- Hydrocarbon migration into shallow aquifers
 - e.g. methane, light hydrocarbon liquids
- Migration of gases co-injected with CO₂
 - e.g. H₂S, SO₂, NO₂

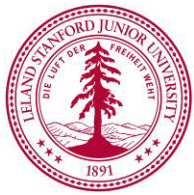
Potential for impacts depends on many site specific factors: seal properties, boundary conditions, size of injection, number and condition of abandoned wells, initial hydraulic heads, and pressure buildup.



Rules of Thumb: Potential for Groundwater Impacts



Attribute	Lower Risk	Higher Risk
Reservoir Size	Larger	Small
Pressure Buildup	Low	High
Seal Properties	Low permeability	Higher permeability
Wells	Few and well sealed	Many and poorly sealed
Injection Fluid	CO ₂ only	CO ₂ + SO ₂ + H ₂ S
Faults	None or inactive	Many and active



Risk Management to Protect Environment, Health and Safety



Financial Responsibility	Financial mechanisms and institutional approaches for long term stewardship (e.g. monitoring and remediation if needed)
Regulatory Oversight	Oversight for site characterization and selection, storage system operation, safety, monitoring and contingency plans
Remediation	Active and abandoned well repair, groundwater cleanup, and ecosystem restoration
Monitoring	Monitoring plume migration, pressure monitoring in the storage reservoir and above the seal, and surface releases
Safe Operations	Well maintenance, conduct of operations, well-field monitoring and controls
Storage Engineering	Number and location of injection wells, strategies to maximize capacity and accelerate trapping, and well completion design
Site Characterization and Selection	Site specific assessment of storage capacity, seal integrity, injectivity and brine migration
Fundamental Storage and Leakage Mechanisms	Multi-phase flow, trapping mechanisms, geochemical interactions, geomechanics, and basin-scale hydrology



Concluding Remarks



- There is no single solution to this challenge. We need to work on a broad portfolio of approaches, with a spectrum of time scales and sources of support.
- Need to get started now:
 - Do now: Conservation, energy efficiency, cost effective wind, solar and geothermal energy
 - Coming soon: Low emission base-load electricity generation
Next generation lower cost solar photovoltaics
Grid integrated energy storage
Updated and more capable electricity grid
 - Ongoing: Research to provide plenty of new options

