# Challenges and Opportunities for Advanced Carbon Capture

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Gaithersburg, Maryland
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# Outline of Talk

- Why the interest in CCS?
- Status of current CCS technology
- Opportunities for advanced carbon capture
- Challenges for advanced carbon capture

# *Why the interest in CCS ?*

*(Carbon Capture and Storage /Sequestration)*



# The Climate Policy Framework

- 1992 U.N. Framework Convention on Climate Change called for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"

# Stabilizing goals to avoid serious impacts are ≤ 450 ppm $CO_{2,\ equiv}$

*Recent assessments indicate potentially serious impacts for more that a 2ºC rise in average global temperature*

| Global avg. temperature increase over pre-industrial | Atmospheric stabilization $CO_{2\text{-equiv}}$ (ppm) *(2005=375 ppm)* | Required change in global $CO_2$ emissions from 2000 to 2050 |
|---|---|---|
| 2.0 – 2.4º C | 445 – 490 | -85% to -50% |

*Source: IPCC, 2007*

*Climate stabilization will require urgent action*

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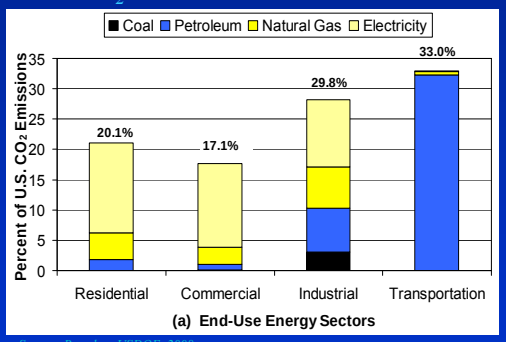
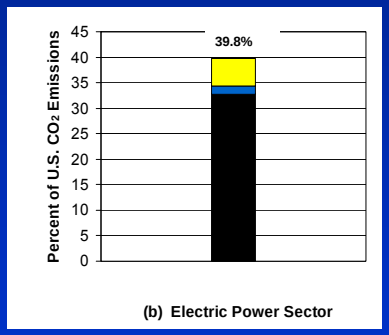
# Sources of U.S. $CO_2$ Emissions

*U.S. $CO_2$ Emissions*




*Source: Based on USDOE, 2008*

Electricity + Vehicles emit ≈ 75% of all $CO_2$

Fossil fuels = 40% of $CO_2$ and 70% of U.S. electricity

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# Motivation for CCS

- Stabilizing atmospheric GHG concentrations will require large reductions in $CO_2$ emissions. But …
- Fossil fuels will continue to be used for many decades —alternatives not able to substitute quickly
- CCS is the ONLY way to get large $CO_2$ reductions from fossil fuel use—a potential bridging strategy
- CCS can also help decarbonize the transportation sector via low-carbon electricity and hydrogen from fossil fuels
- Energy models show that without CCS, the cost of mitigating climate change will be <u>much</u> higher

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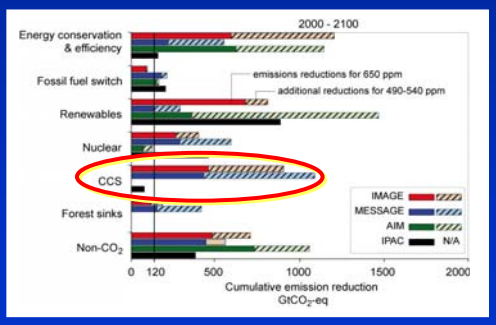
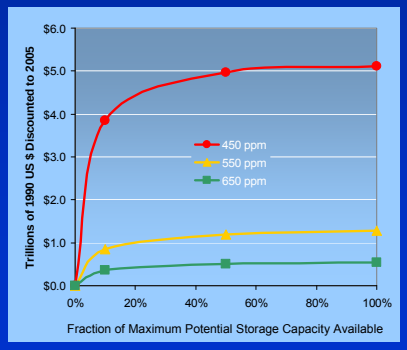
# Cost-Effective Global Strategies Require CCS in the Portfolio

Models show increasing need for CCS as stabilization goal tightens




*Source: IPCC, 2007*

Without CCS the cost of stabilization increases sharply




*Source: J. Edmonds, PNNL, 2008*

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# *Status of CCS technology*

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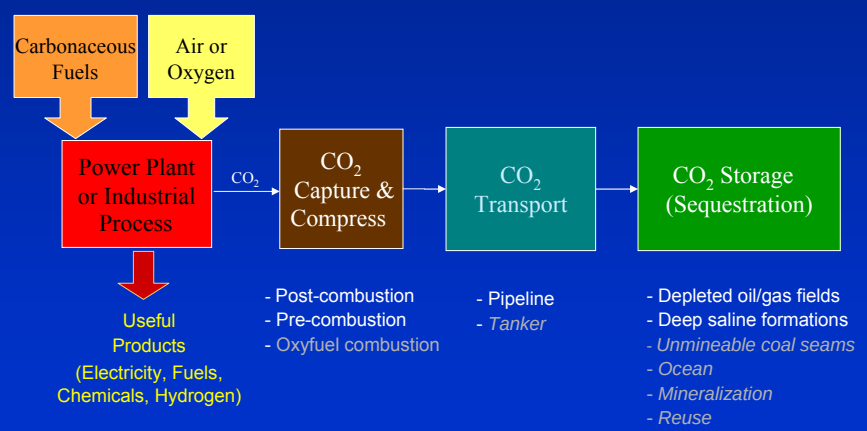
# Schematic of a CCS System

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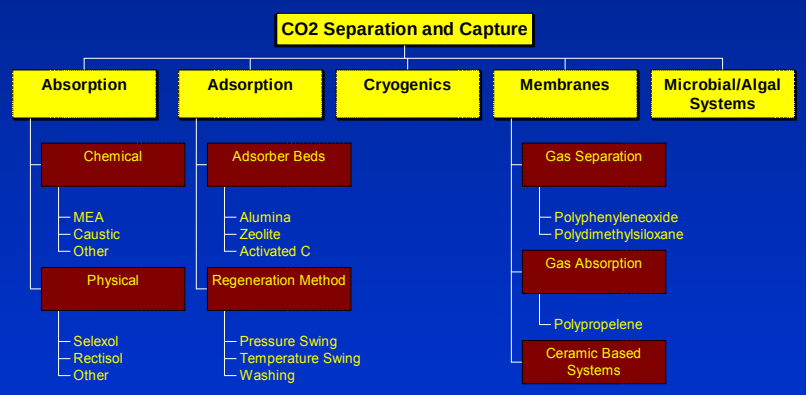
# Many Ways to Capture $CO_2$




*Choice of technology depends strongly on application*

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# Leading Candidates for CCS

- Fossil fuel power plants
  - Pulverized coal combustion (PC)
  - Natural gas combined cycle (NGCC)
  - Integrated coal gasification combined cycle (IGCC)
- Other large industrial sources of $CO_2$ such as:
  - Refineries, fuel processing, and petrochemical plants
  - Hydrogen and ammonia production plants
  - Pulp and paper plants
  - Cement plants

*– Main focus is on power plants, the dominant source of $CO_2$ –*

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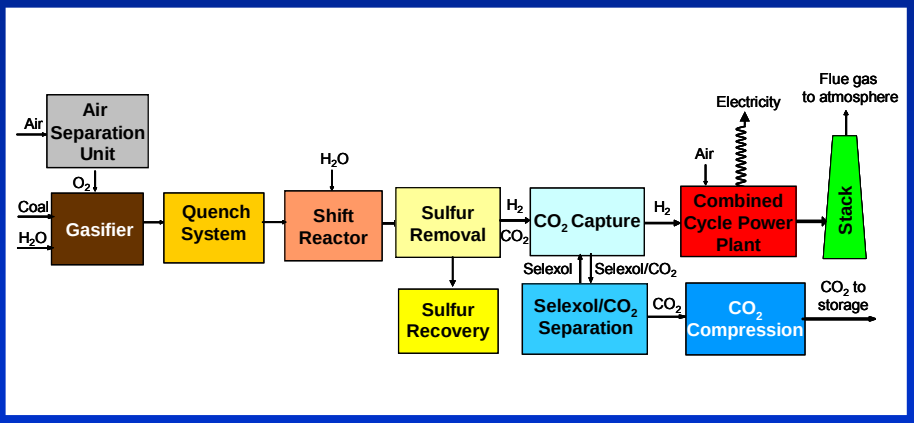
# $CO_2$ Capture Options for Power Plants: Pre-Combustion Capture

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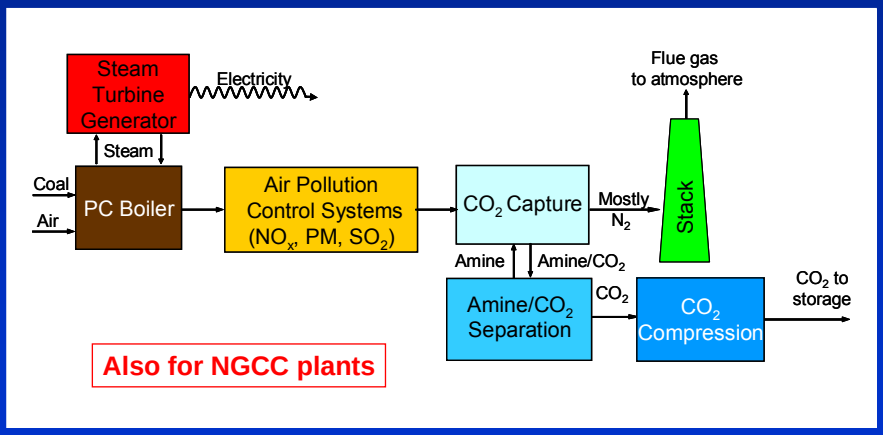
# $CO_2$ Capture Options for Power Plants: Post-Combustion Capture

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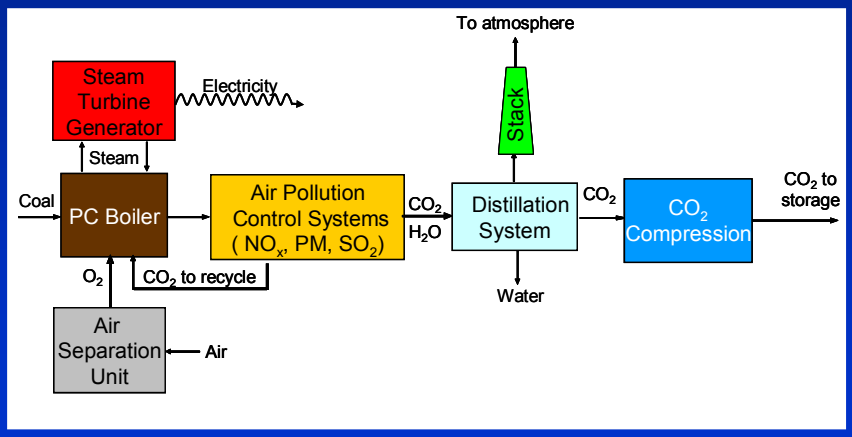
# $CO_2$ Capture Options for Power Plants: Oxy-Combustion Capture

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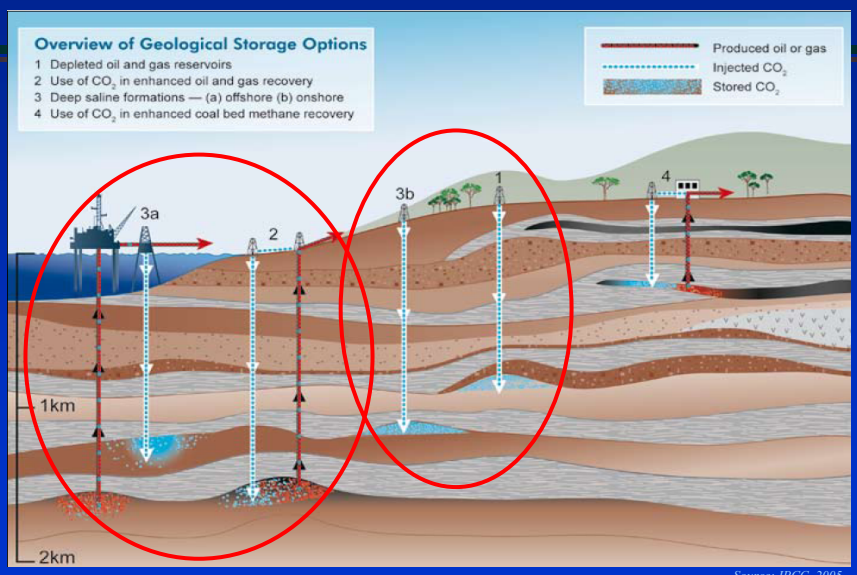
# Geological Storage Options




Source: IPCC, 2005

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# Status of CCS Technology

- Pre- and post-combustion $CO_2$ capture technologies are commercial and widely used in industrial processes; also at several gas-fired and coal-fired power plants, at small scale (~40 MW); $CO_2$ capture efficiencies are typically 85-90%. Oxyfuel capture is still under development.
- $CO_2$ transport via pipelines is a mature technology.
- Geological storage of $CO_2$ is commercial on a limited basis, mainly for EOR; several projects in deep saline formations are operating at scales of ~1 Mt $CO_2$ /yr.
- Large-scale integration of $CO_2$ capture, transport and geological sequestration has been demonstrated at several industrial sites (outside the U.S.) — but not yet at an electric power plant at full-scale.

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# Examples of Pre-Combustion $CO_2$ Capture Systems

(Source: Chevron-Texaco)

Petcoke Gasification to Produce $H_2$
*(Coffeyville, Kansas, USA)*

(Source: Dakota Gasification

Coal Gasification to Produce SNG
*(Beulah, North Dakota, USA)*

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# Pre-Combustion Capture at IGCC Plants

*Pilot plants under construction at two IGCC plants (startup expected in late 2010)*

Buggenhum IGCC Plant
*(The Netherlands)*

Source: Nuon, 2009

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# Post-Combustion Technology for Industrial $CO_2$ Capture

Source: IEA GHG, 2008

BP Natural Gas Processing Plant
*(In Salah, Algeria)*

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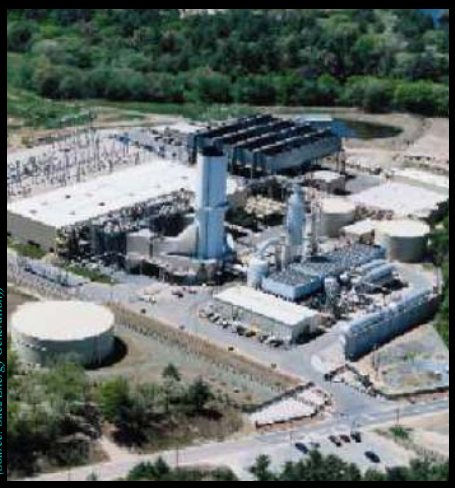
# Post-Combustion $CO_2$ Capture at a Gas-Fired Power Plant



(Source: Suez Energy Generation)

(Source: Flour Daniel)

Bellingham Cogeneration Plant
*(Bellingham, Massachusetts, USA)*

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# Post-Combustion $CO_2$ Capture at Coal-Fired Power Plants

(Source: ABB Lummus)

Shady Point Power Plant
*(Panama, Oklahoma, USA)*

(Source: (IEA GHG)

Warrior Run Power Plant
*(Cumberland, Maryland, USA)*

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# Oxy-Combustion $CO_2$ Capture from a Coal-Fired Boiler

Source: Vattenfall, 2008

30 $MW_t$ Pilot Plant (~10 $MW_e$) at Vattenfall Schwarze Pumpe Station *(Germany)*

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# $CO_2$ Pipelines in the Western U.S.

> 3000 miles of pipeline
~40 $MtCO_2$/yr transported

Source: USDOE/Battelle

Source: NRDC

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# Large-Scale CCS Projects

| Project | Operator | Geological Reservoir | Injection Start Date | Injection Rate ($MtCO_2$/yr ) |
|---|---|---|---|---|
| Sleipner (Norway) | StatoilHydro | Saline Formation | 1996 | 1.0 |
| Weyburn (Canada) | EnCana | Oil Field (EOR) | 2000 | 1.2* |
| In Salah (Algeria) | Sonatrach, BP, StatoilHydro | Depleted Gas Field | 2004 | 1.2 |
| Snohvit (Norway) | StatoilHydro | Saline Formation | 2008 | 0.7 |

* Average rate over 15 year contract. Recent expansion to ~3 Mt/yr for Weyburn + Midale field..

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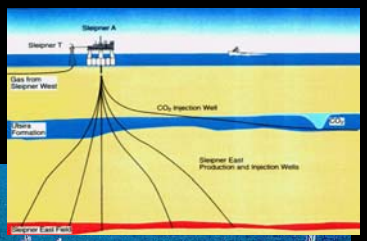
# Geological Storage of Captured $CO_2$ in a Deep Saline Formation

Sleipner Project
*(Norway)*

*Source: Statoil*



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# Geological Storage of Captured $CO_2$ in a Deep Saline Formation

Snohvit LNG Project *(Norway)*

*Source: www.Snohvit, 2009*

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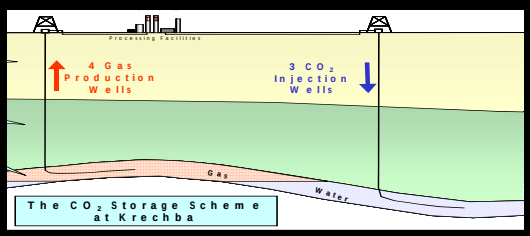
# Geological Storage of Captured $CO_2$ in a Depleted Gas Formation

In Salah /Krechba *(Algeria)*

*Source: BP*

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# Geological Formations in North America

*Oil & Gas Fields*

*Source: NETL, 2009*

*Deep Saline Formations*

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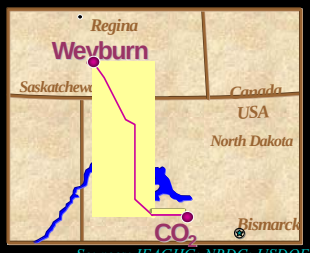
# Geological Storage of Captured $CO_2$ with Enhanced Oil Recovery (EOR)




*Sources: IEAGHG; NRDC; USDOE*

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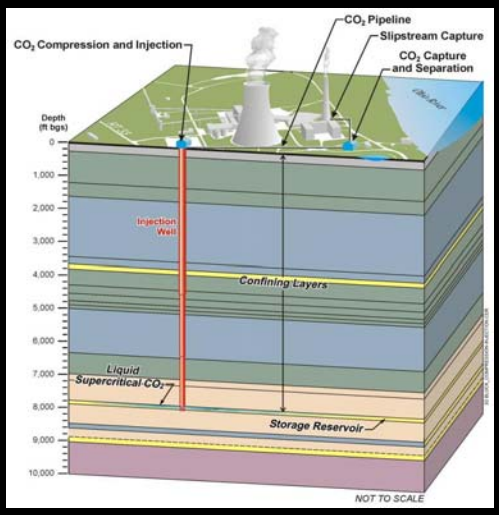
# CCS at a Coal-Fired Power Plant with Storage in a Deep Saline Formation

*(Pilot plant scale)*

20 MW capture unit at AEP's Mountaineer Power Plant
*(West Virginia)*




*Source: AEP, 2009*



# Still Missing

- Full-scale power plant demo #1
- Full-scale power plant demo #2
- Full-scale power plant demo #3
- Full-scale power plant demo #4
- Full-scale power plant demo #5
- Full-scale power plant demo #6
- Full-scale power plant demo #7
- Full-scale power plant demo #8
- Full-scale power plant demo #9
- Full-scale power plant demo #10

## Full-Scale Demonstration Projects Are Urgently Needed to . . .

- Establish the reliability, safety and true cost of CCS in full-scale power plant applications
- Help resolve legal and regulatory issues regarding geological sequestration
- Help address issues of public acceptance
- Begin reducing future costs via learning-by-doing

- Cost per project ≈ $1 billion (install/operate CCS, 400 MW, 5 yrs)

***Financing large-scale projects has been a major hurdle***

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## Clean Coal Power Initiative Awards

(July and December 2009; DOE share = $1.4 billion)

- **Basin Electric Power Cooperative**
  Post-combustion capture (ECO2® ammonia-based process);
  Antelope Valley Station, 120 MW flue gas; Beulah, N.D
- **Hydrogen Energy International LLC**
  New IGCC plant (coal-petcoke w/ full Rectisol capture); Kern County, CA
  > 2 million tons/yr CO2; storage via EOR.
- **American Electric Power Company, Inc.**
  Post-combustion capture (Alstom chilled ammonia process);
  Mountaineer Power Plant, 235 MW flue gas, New Haven, WV
  1.5 million tonnes/yr CO2; storage in two saline formations.
- **Southern Company Services, Inc.**
  Post-combustion capture (MHI amine-based process);
  Alabama Power's Plant Barry, 160 MW flue gas; near Mobile, AL.
  Up to 1 million tonnes/yr CO2; storage in saline formations + possible EOR.
- **Summit Texas Clean Energy, LLC**
  New 400 MW IGCC plant (Siemens w/ 90% capture); near Midland, TX.
  2.7 million tonnes/yr CO2; storage via EOR in Permian Basin

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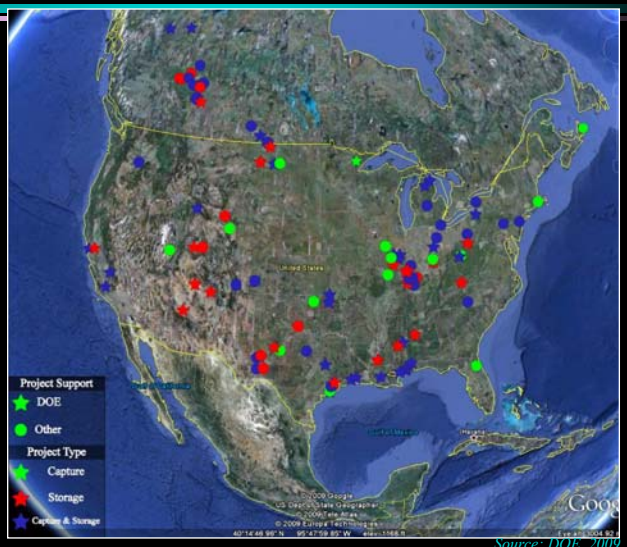
# Many other projects are planned or underway at various scales

- Map shows operating plus proposed or planned projects in the U.S. and Canada. They encompass power plants, industrial sources and research projects spanning a large range of scale.




*Source: DOE, 2009*

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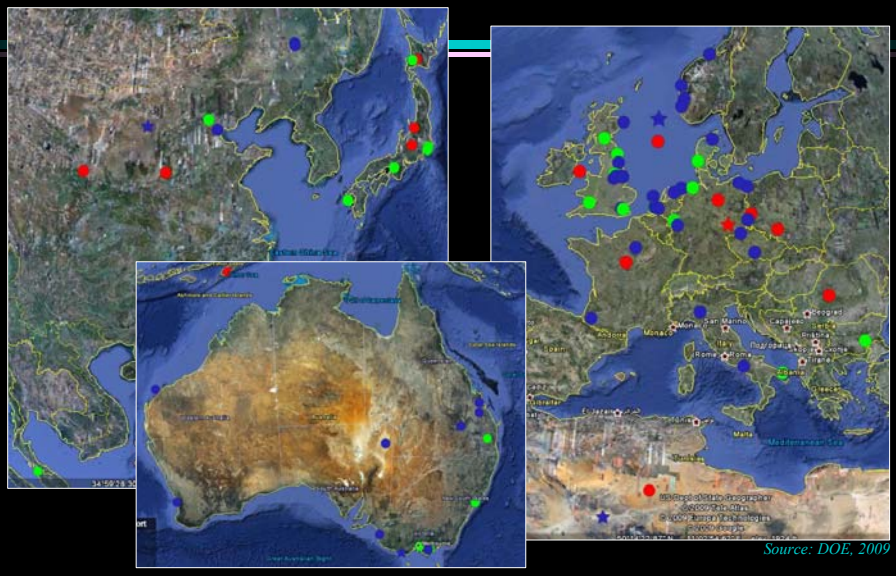
# Substantial CCS Activity Globally



*Source: DOE, 2009*

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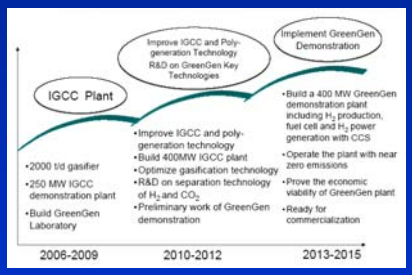
*One Example:*

# IGCC Demonstration in China

The GreenGen Project
*(Tianjin, China)*



Partners include: China Datang Corp., China State Development and Investment Corp., China Guodian Corp., China Huadian Corp., China Power Investment Corp., China National Coal Group and Shenhua Group, Peabody Energy

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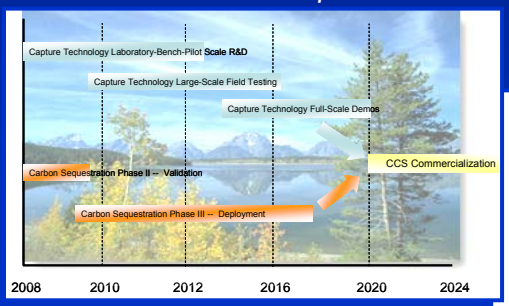
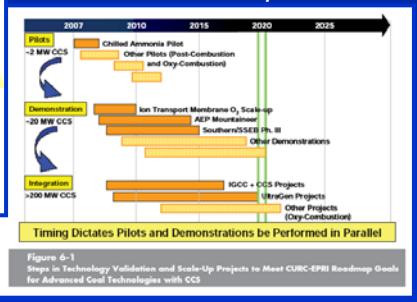
# Roadmaps for CCS Deployment

***DOE Roadmap***




***EPRI Roadmap***




**Commercialization expected by 2020**

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*The cost of CCS*



## Many Factors Affect CCS Costs

- Choice of Power Plant and CCS Technology
- Process Design and Operating Variables
- Economic and Financial Parameters
- Choice of System Boundaries; *e.g.*,
  - One facility vs. multi-plant system (regional, national, global)
  - GHG gases considered ($CO_2$ only vs. all GHGs)
  - Power plant only vs. partial or complete life cycle
- Time Frame of Interest
  - First-of-a-kind plant vs. $n^{th}$ plant
  - Current technology vs. future systems
  - Consideration of technological "learning"

## Common Measures of Cost

- Cost of $CO_2$ Avoided ($/ton $CO_2$ avoided)

$$= \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(CO_2/MWh)_{ref} - (CO_2/MWh)_{ccs}}$$

- Cost of Electricity (COE) ($/MWh)

$$= \frac{(TCC)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC)$$

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## Ten Ways to Reduce Estimated Cost

*(inspired by D. Letterman)*

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume EOR credits for $CO_2$ storage
6. Omit certain capital costs
5. Report $/ton $CO_2$ based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high plant utilization (capacity factor)
1. Assume **all of the above !**

*. . . and we have not yet considered the CCS technology!*

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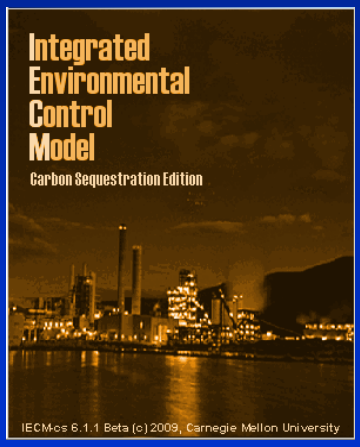
# Analyzing Options for Power Plants
## (IECM: The Integrated Environmental Control Model)

- A desktop/laptop computer model developed for DOE/NETL; free and publicly available at: www.iecm-online.com
- Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  - PC, IGCC and NGCC plants
  - All flue/fuel gas treatment systems
  - $CO_2$ capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
  - Major update in late 2009

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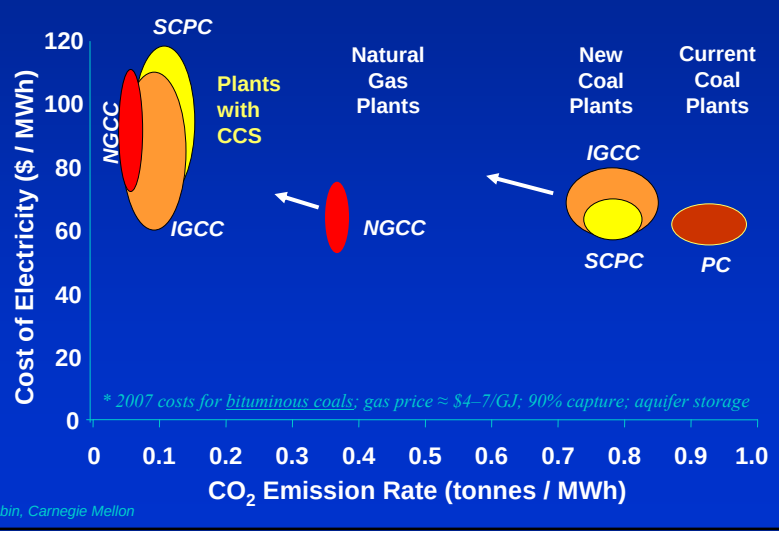
# Estimated Cost of New Power Plants with and without CCS

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# Incremental Cost of CCS for New Power Plants Using Current Technology

Increase in levelized cost for 90% capture

| Incremental Cost of CCS *relative to same plant type* without CCS based on bituminous coals | Supercritical Pulverized Coal Plant | Integrated Gasification Combined Cycle Plant |
|---|---|---|
| **Increases in capital cost ($/kW) and generation cost ($/kWh)** | **~ 60–80%** | **~ 30–50%** |

*The added cost to consumers due to CCS will be much smaller, reflecting the number and type of CCS plants in the generation mix at any given time.*

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# Typical Cost of $CO_2$ Avoided

(Relative to a SCPC reference plant w/o CCS)

Levelized cost in US$ per tonne $CO_2$ avoided

| Power Plant System *(relative to a SCPC plant without CCS)* | New Supercritical Pulverized Coal Plant | New Integrated Gasification Combined Cycle Plant |
|---|---|---|
| **Deep aquifer storage** | **~ $70 /t$CO_2$** | **~ $50 /t$CO_2$** |
| Enhanced oil recovery (EOR) storage | Cost reduced by ~ $20–30 /t$CO_2$ | |

*Source: Based on IPCC, 2005; Rubin et al, 2007; DOE, 2007*

- ***Capture accounts for most (~80%) of the total cost***

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# High capture energy requirements is a major factor in high CCS costs

| Power Plant Type | Added fuel input (%) per net kWh output |
|---|---|
| Existing subcritical PC | ~40% |
| New supercritical PC | 25-30% |
| New coal gasification (IGCC) | 15-20% |
| New natural gas (NGCC) | ~15% |

*Changes in plant efficiency due to CCS energy requirements also affect plant-level pollutant emission rates (per MWh). A site-specific context is needed to evaluate the net impacts.*



# Breakdown of "Energy Penalty" for $CO_2$ Capture (SCPC and IGCC)

| Component | Approx. % of Total Reqm't |
|---|---|
| Thermal Energy | ~60% |
| $CO_2$ Compression | ~30% |
| Pumps, Fans, etc. | ~10% |

*What is the potential for advanced capture technology?*

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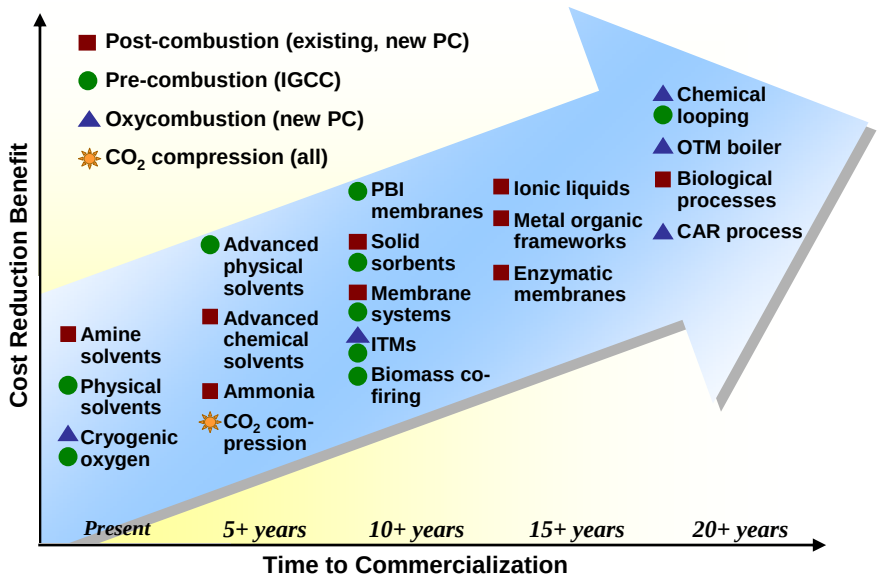
## Better Capture Technologies Are Emerging



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# Two Approaches to Estimating Potential Cost Savings

- *Method 1*: Engineering-Economic Analysis
  - A "bottom up" approach based on engineering process models, informed by judgments regarding potential improvement in key parameters

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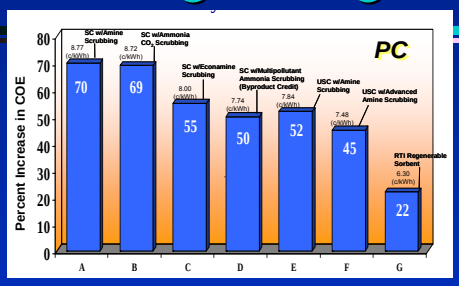
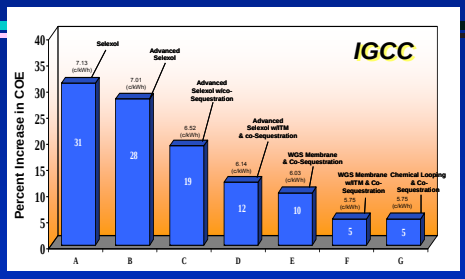
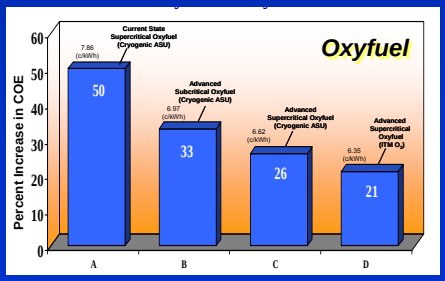
# Potential Cost Reductions Based on Engineering-Economic Analysis




*19% -28% reductions in COE w/ CCS*

*Source: DOE/NETL, 2006*

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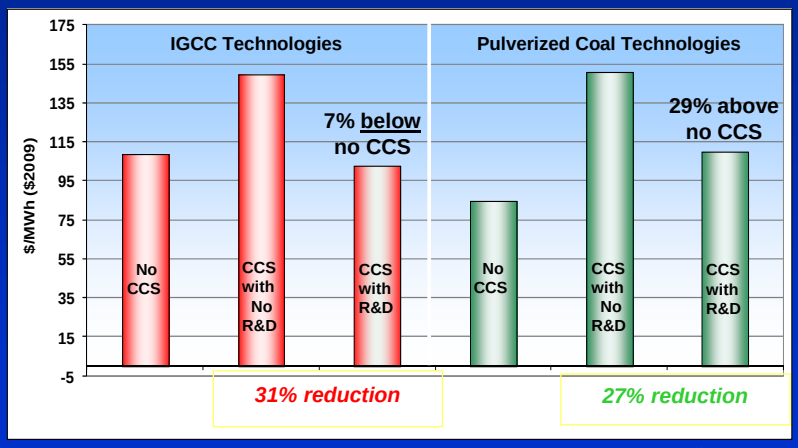
# Potential Cost Reductions Based on Engineering-Economic Analysis




Source: DOE/ NETL, 2010

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# Two Approaches to Estimating Future Technology Costs

- *Method 1:* Engineering-Economic Analysis
  - A "bottom up" approach based on engineering process models, informed by judgments regarding potential improvements in key process parameters
- *Method 2:* Use of Historical Experience Curves
  - A "top down" approach based on applications of mathematical "learning curves" or "experience curves" that reflect historical trends for analogous technologies or systems

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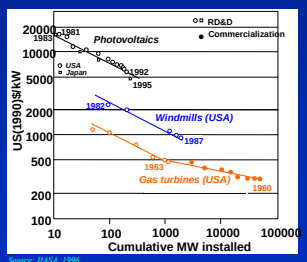
# Empirical "Learning Curves"

- Cost trends modeled as a log-linear relationship between unit cost and cumulative production or capacity: $y = ax^{-b}$




Source: IIASA, 1996

- Case studies used for power plant components:
  - Flue gas desulfurization systems (FGD)
  - Selective catalytic reduction systems (SCR)
  - Gas turbine combined cycle system (GTCC)
  - Pulverized coal-fired boilers (PC)
  - Liquefied natural gas plants (LNG)
  - Oxygen production plants (ASU)
  - Hydrogen production plants (SMR)

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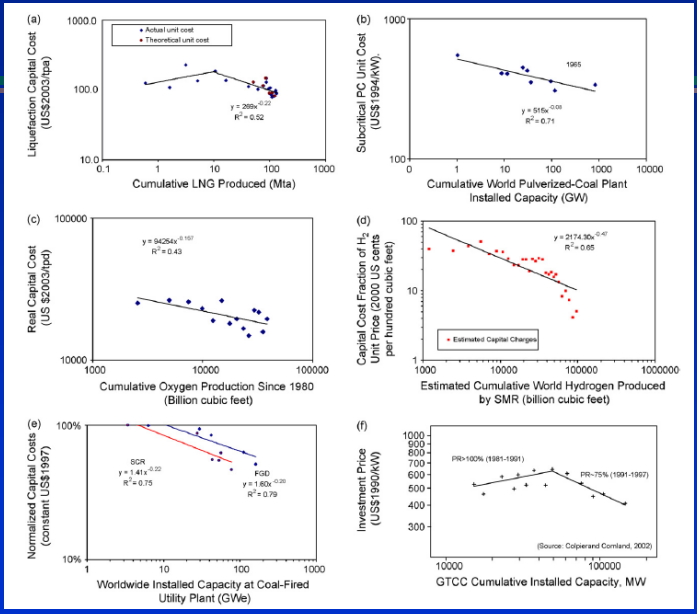
# Experience Curves for Case Study Technologies

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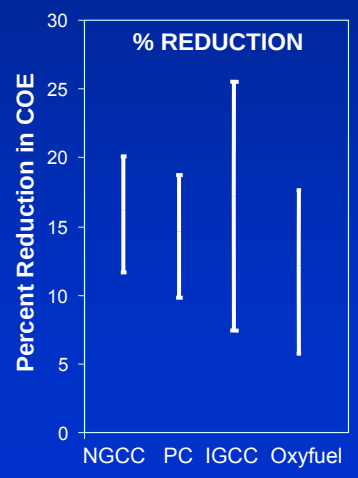
# Projected Cost Reductions for Power Plants with $CO_2$ Capture

(after 100 GW of cumulative CCS capacity worldwide)




- Plant-level learning curves developed from component-level analyses
- **Upper bound of ranges are similar to estimates from "bottom-up" analyses**

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# Conclusions

- Significant potential beyond 2020 to reduce the cost of carbon capture via:
  - New or improved $CO_2$ capture technologies
  - Improved plant efficiency and utilization

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*What are the challenges for carbon capture beyond 2020?*

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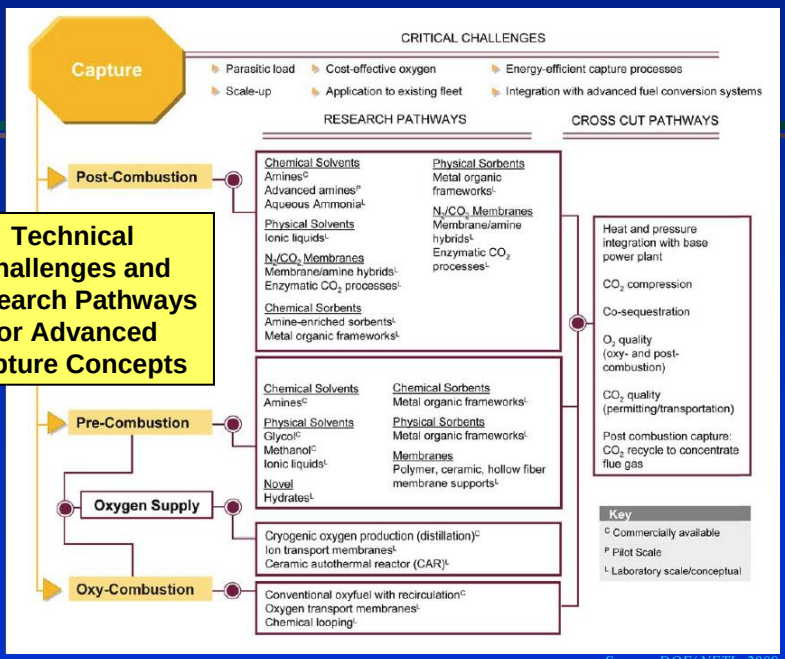


**Technical Challenges and Research Pathways for Advanced Capture Concepts**

Source: DOE/ NETL, 2009

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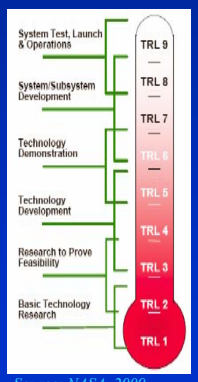
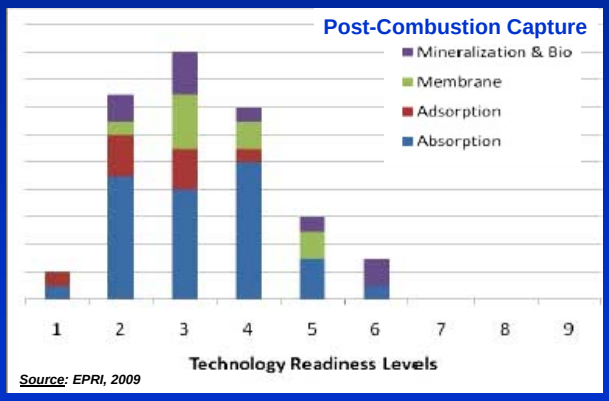
# Most New Capture Concepts Are Far from Commercial Availability

**Technology Readiness Levels**




*Source: NASA, 2009*




***Source*: EPRI, 2009**

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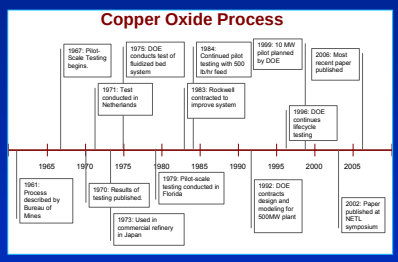
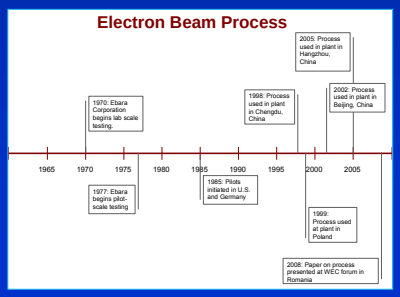
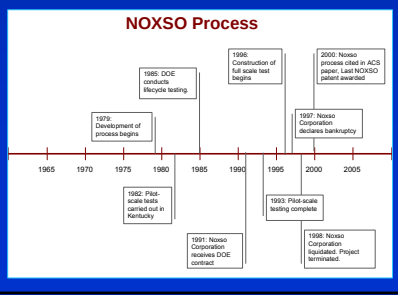
# Most new concepts take decades to commercialize…many never make it

Development timelines for three novel processes for combined $SO_2$–$NO_x$ capture

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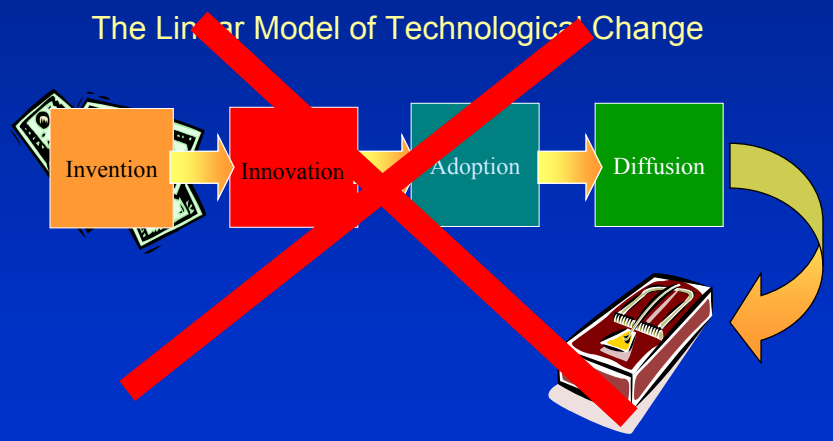
*Challenge 1:*

# Accelerate the Pace of Innovation

The Linear Model of Technological Change

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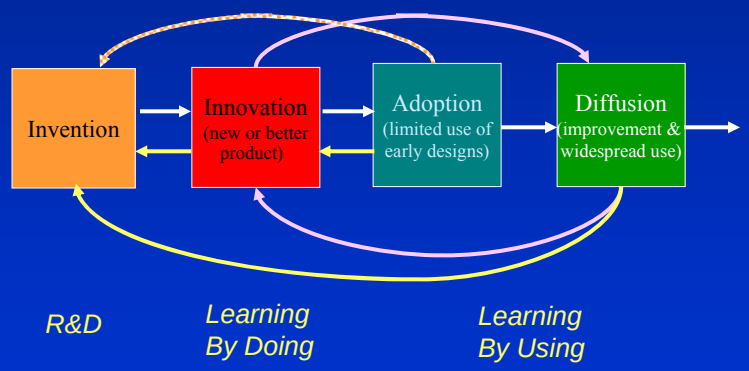
# A More Realistic Model

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## Accelerating Innovation Requires

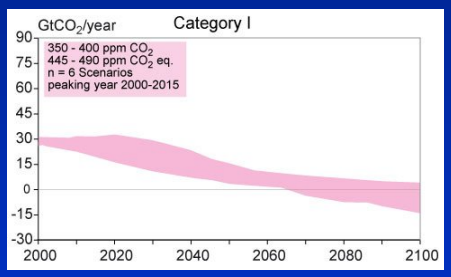
- Closer coupling and interaction between R&D performers and technology developers /users
- Better methods to identify promising options, evaluate new processes /concepts, and reduce number and size of pilot and demonstration projects (e.g., via improved simulation methods)
- New models for organizing the research enterprise
- Substantial and sustained support for R&D



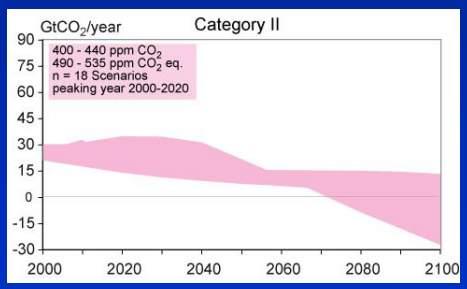
## The Critical Role of Policy

- *Reminder:* The pace and direction of innovations in carbon capture beyond 2020 will be strongly influenced by climate policy—which is critical for establishing markets for CCS technologies

# What it Takes to Stabilize Atmospheric GHG Concentration




*Source: IPCC, 2007*




**Stabilizing atmospheric concentrations beyond 2020 may require "negative $CO_2$ emissions" by end of the century**

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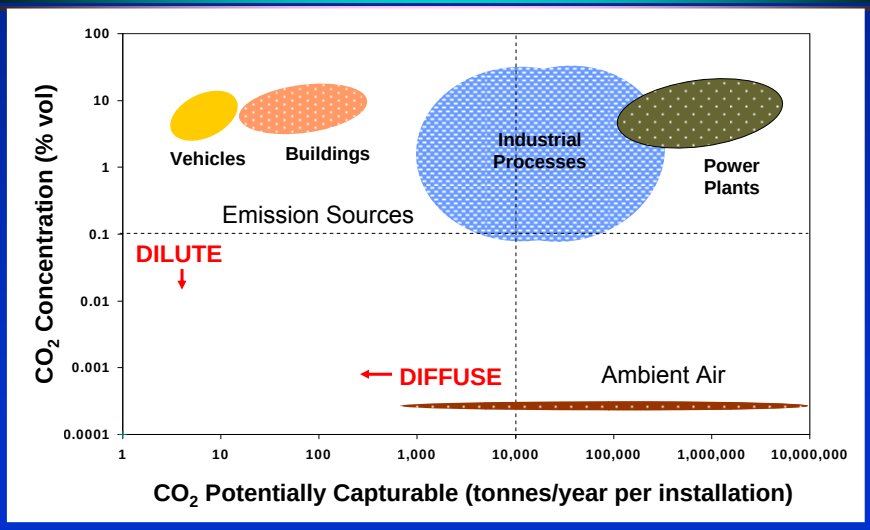
# *Challenge 2:* Capture of Dilute and Diffuse $CO_2$

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## Final Thoughts

- This is an exciting time to be working on carbon capture—now and beyond 2020
- While the challenges are significant, so too are the opportunities to greatly lower the costs (and thus increase the prospects) of avoiding serious consequences of global climate change

*Yes we can!*



## *Thanks*

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