# The Outlook for Advanced Carbon Capture Technology

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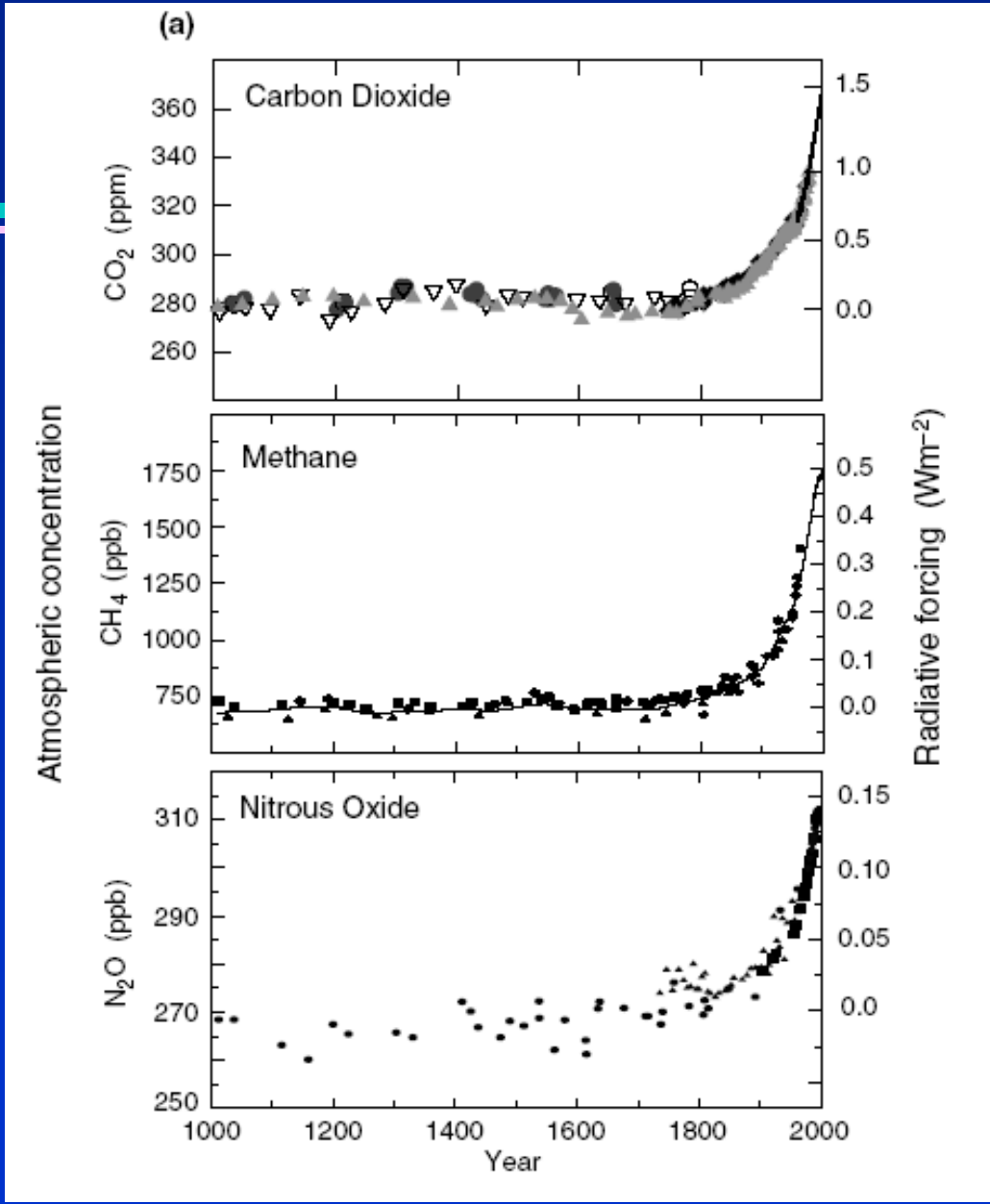
# Outline of Talk

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

# *Why the interest in carbon capture ?*

# Drivers of Global Climate Change

- Concentrations of greenhouse gases in the atmosphere are rising sharply due to GHG emissions from human activities
- The resulting heat-trapping effect leads to climate change on a global scale




*Source: IPCC, 2001*

# The Climate Change Policy Driver

- 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"

# Stabilization Requires Large Emission Reductions, Soon

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

| Required change in global $CO_{2,\ equiv}$ emissions from 2000 to 2050 |
| --- |
| **–85% to –50%** |

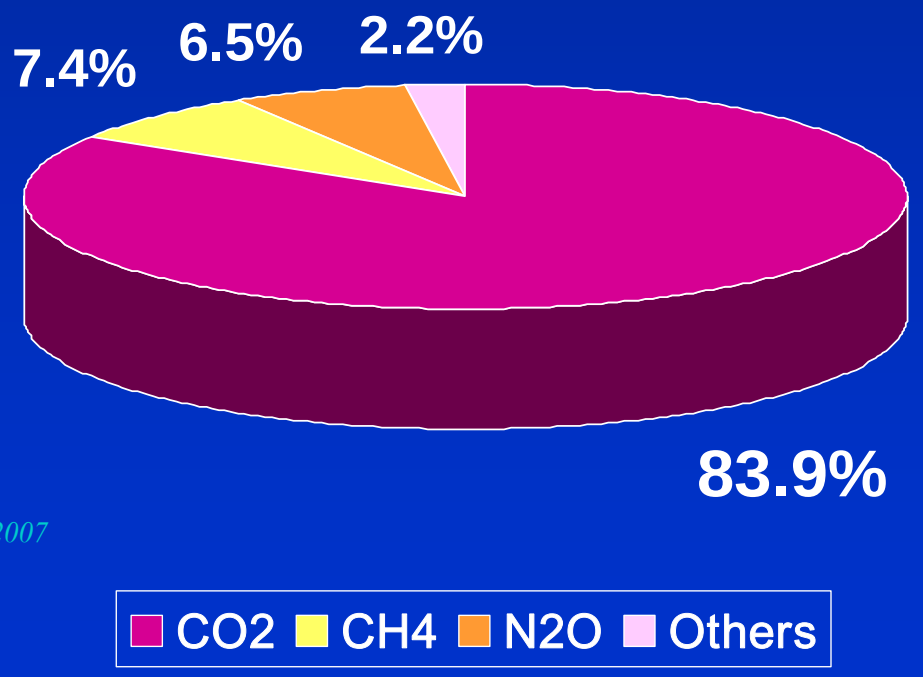
*Source: IPCC, 2007*

*Stabilizing climate change will require urgent action*

# $CO_2$ from Energy Use is the Dominant Greenhouse Gas

*U.S. Greenhouse Gas Emissions*

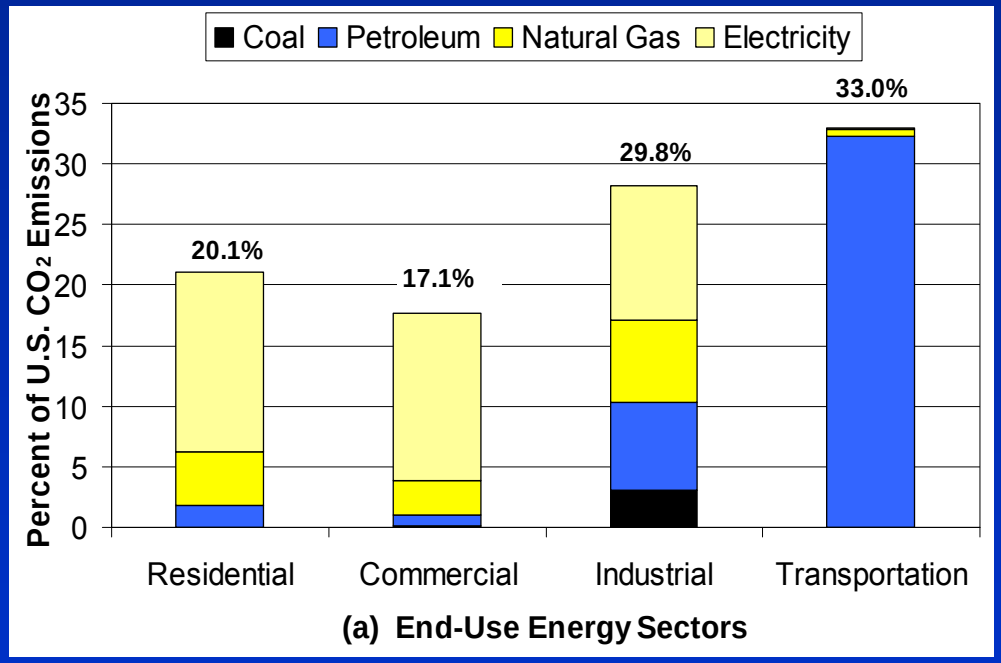
*weighted by 100-yr Global Warming Potential (GWP)*

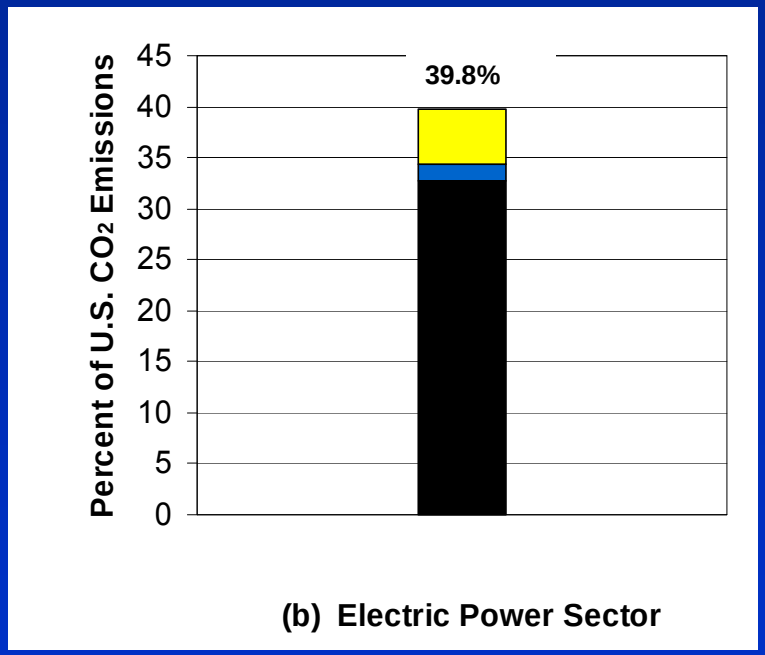



*Source: USEPA, 2007*

# Sources of $CO_2$ Emissions

*U.S. $CO_2$ Emissions*




*Source: Based on USDOE, 2008*

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

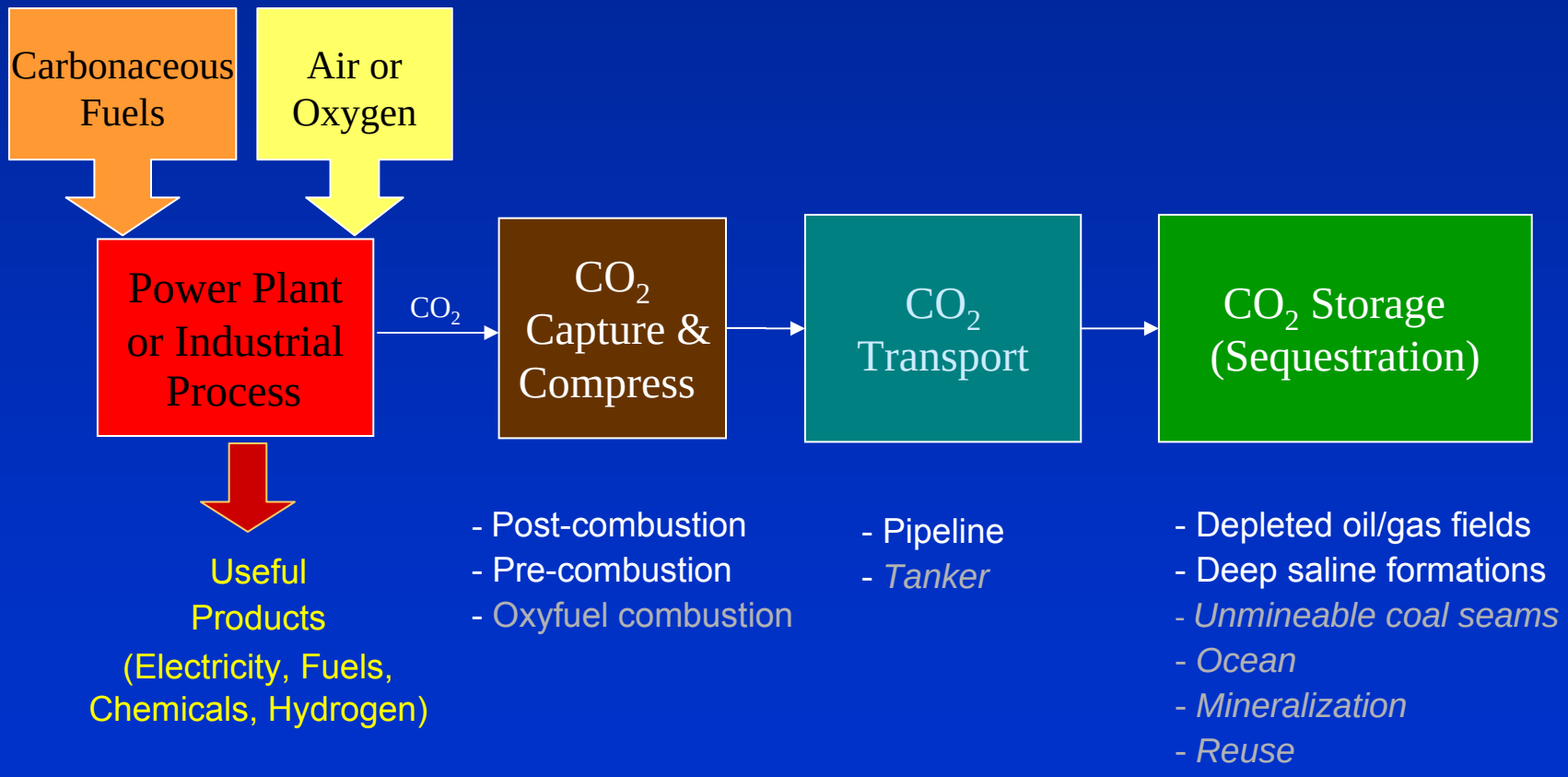
Fossil fuels = 40% of $CO_2$ and 70% of U.S. electricity

# Motivation for Carbon Capture and Storage (CCS)

- 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-economic models show that without CCS, the cost of mitigating climate change will be <u>much</u> higher

# *Status of CCS technology*

# Schematic of a CCS System

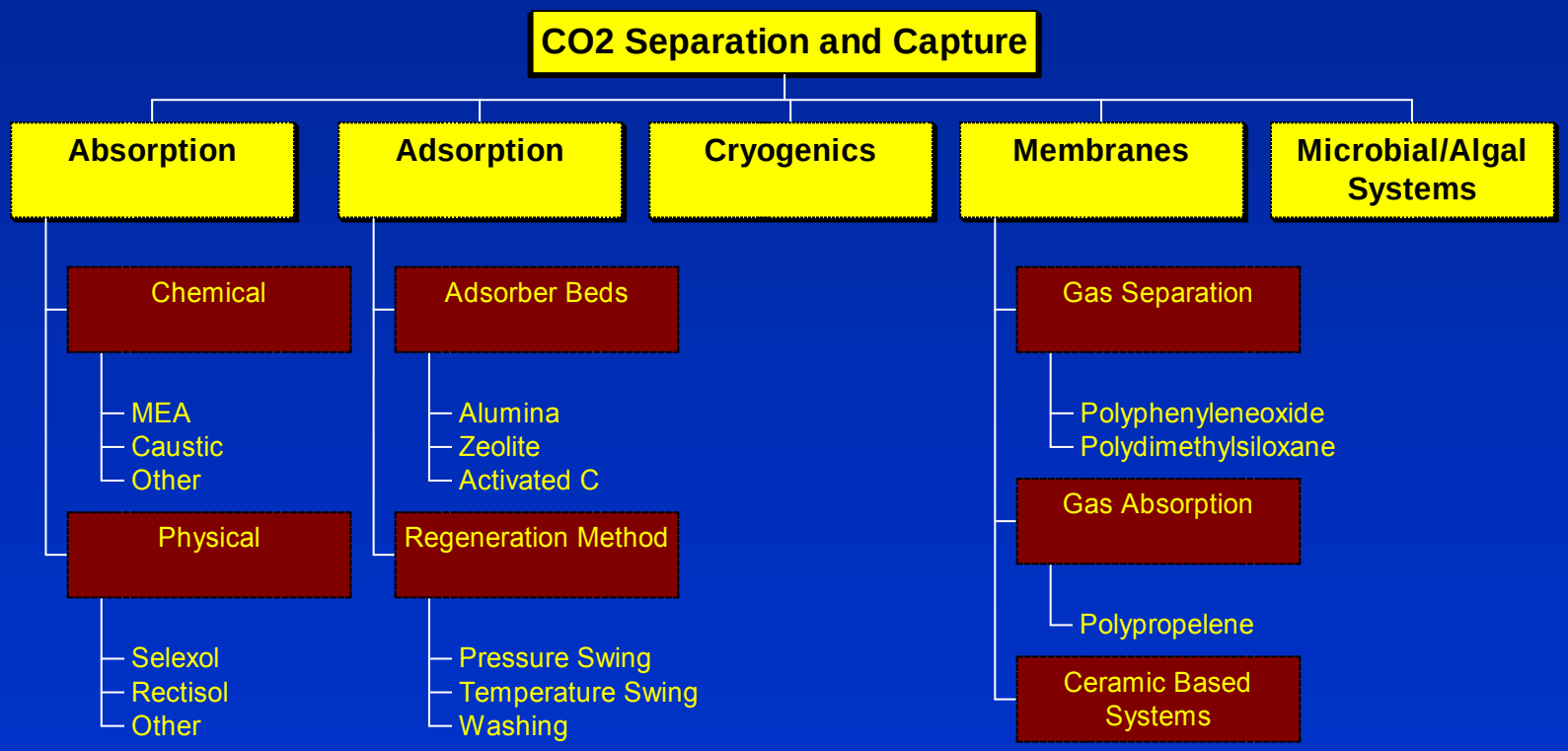


# Leading Candidates for CCS

- 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

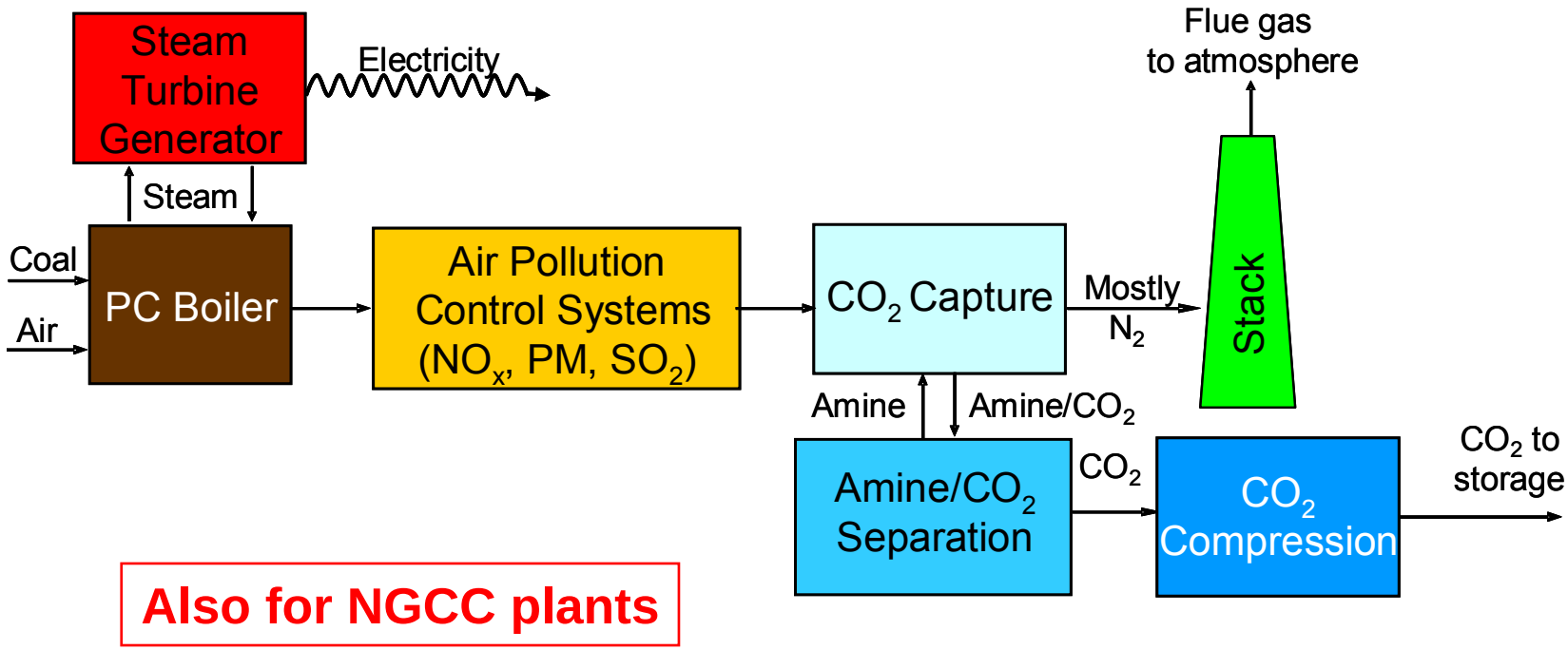
*– Main focus is on power plants, the dominant source of $CO_2$ –*

# Many Ways to Capture $CO_2$



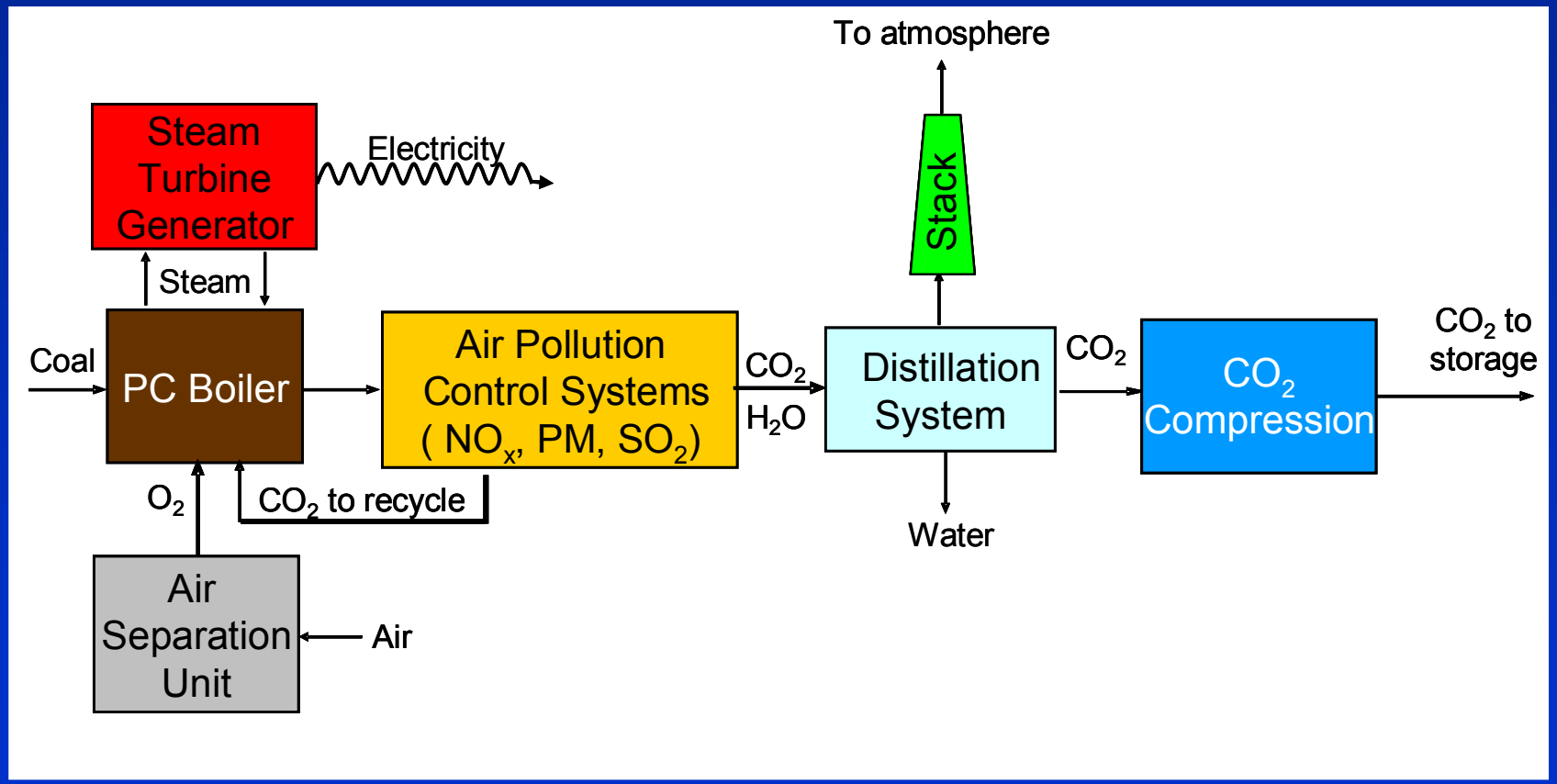

*Choice of technology depends strongly on application*

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

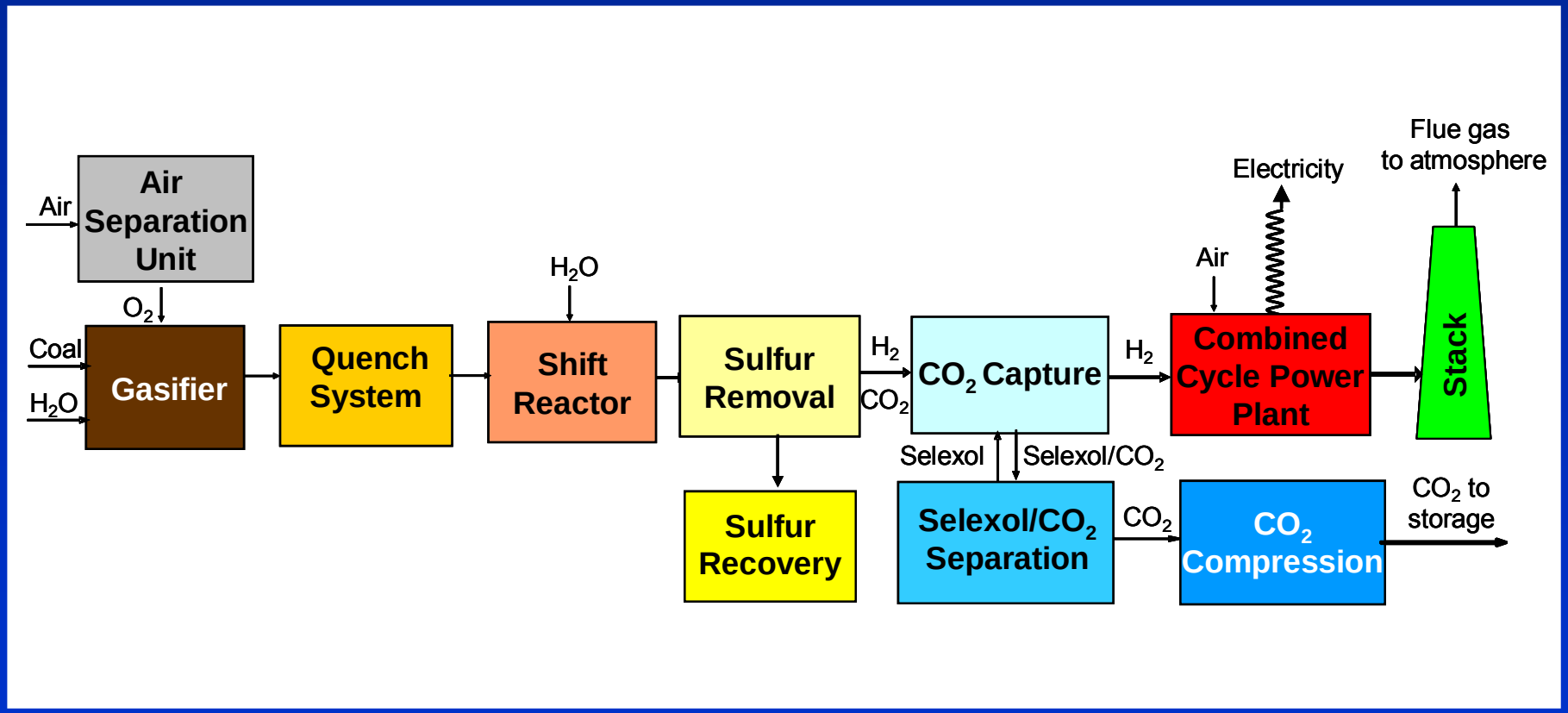



**Also for NGCC plants**

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



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



# 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; $CO_2$ 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 <u>at full-scale.</u>

# 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)*

# 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*

# Post-Combustion Technology for Industrial $CO_2$ Capture

*Source: IEA GHG, 2008*

BP Natural Gas Processing Plant

*(In Salah, Algeria)*

*E.S. Rubin, Carnegie Mellon*

# Examples of Post-Combustion $CO_2$ Capture at U.S. Power Plants


(Source: Flour Daniel)

Bellingham Cogeneration Plant

*(Bellingham, Massachusetts, USA)*


(Source: (IEA GHG)

Warrior Run Power Plant

*(Cumberland, Maryland, USA)*

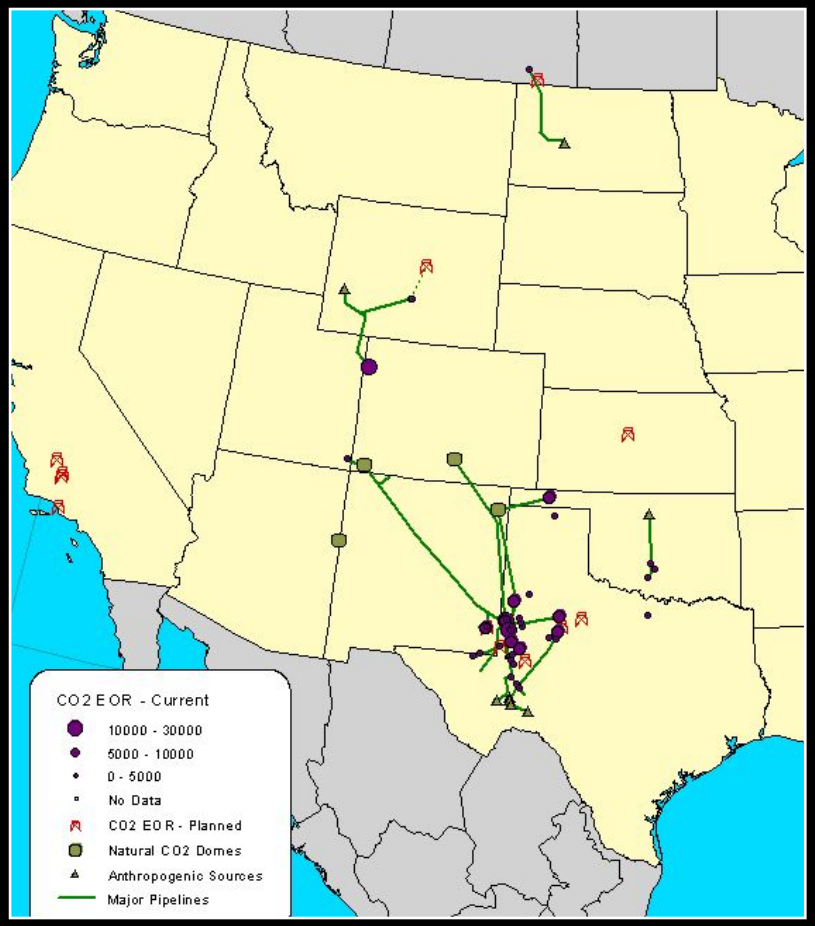
# Oxy-Combustion $CO_2$ Capture from a Coal-Fired Boiler

*Source: Vattenfall, 2008*

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

# $CO_2$ Pipelines in the United States

~ 3600 miles of pipeline
~50 $MtCO_2$/yr transported




*Source: USDOE/Battelle*


*Source: NRDC*

# Large-Scale CCS Projects Now Operating

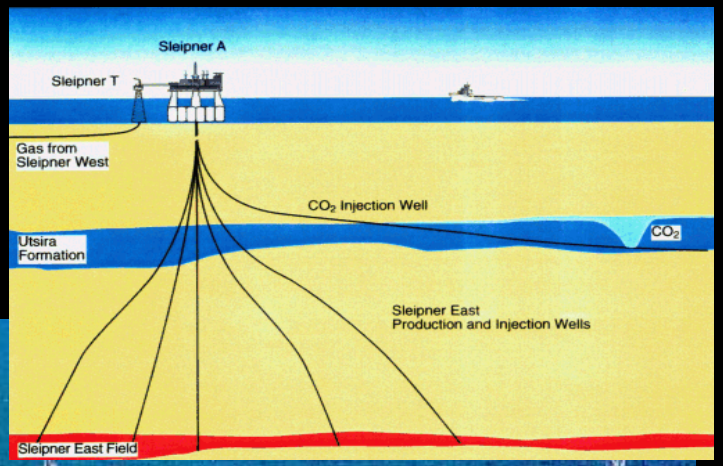
| Project | Operator | Geological Reservoir | Injection Start Date | Injection Rate ($MtCO_2$/yr ) |
|---|---|---|---|---|
| Sleipner (Norway) | StatoilHydro | Saline Formation | 1996 | 1.0 |
| Weyburn (Canada) | EnCana | Oil Field (EOR) | 2000 | 1.2* |
| In Salah (Algeria) | Sonatrach, BP, StatoilHydro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

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


## Sleipner Project
*(Norway)*

*Source: Statoil*




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

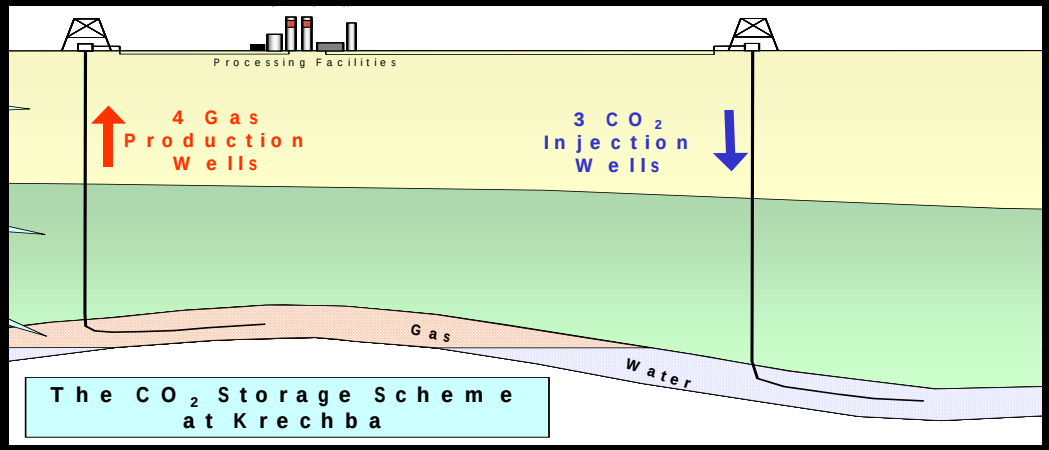

## Snohvit LNG Project *(Norway)*

*Source: www.Snohvit, 2009*


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

## In Salah /Krechba *(Algeria)*


*Source: BP*




*E.S. Rubin, Carnegie Mellon*

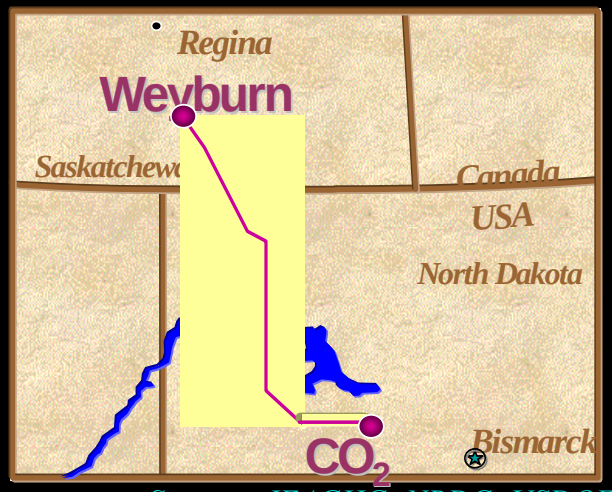
# Geological Formations in North America

*Oil & Gas Fields*

*Deep Saline Formations*

*Source: NETL, 2009*

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

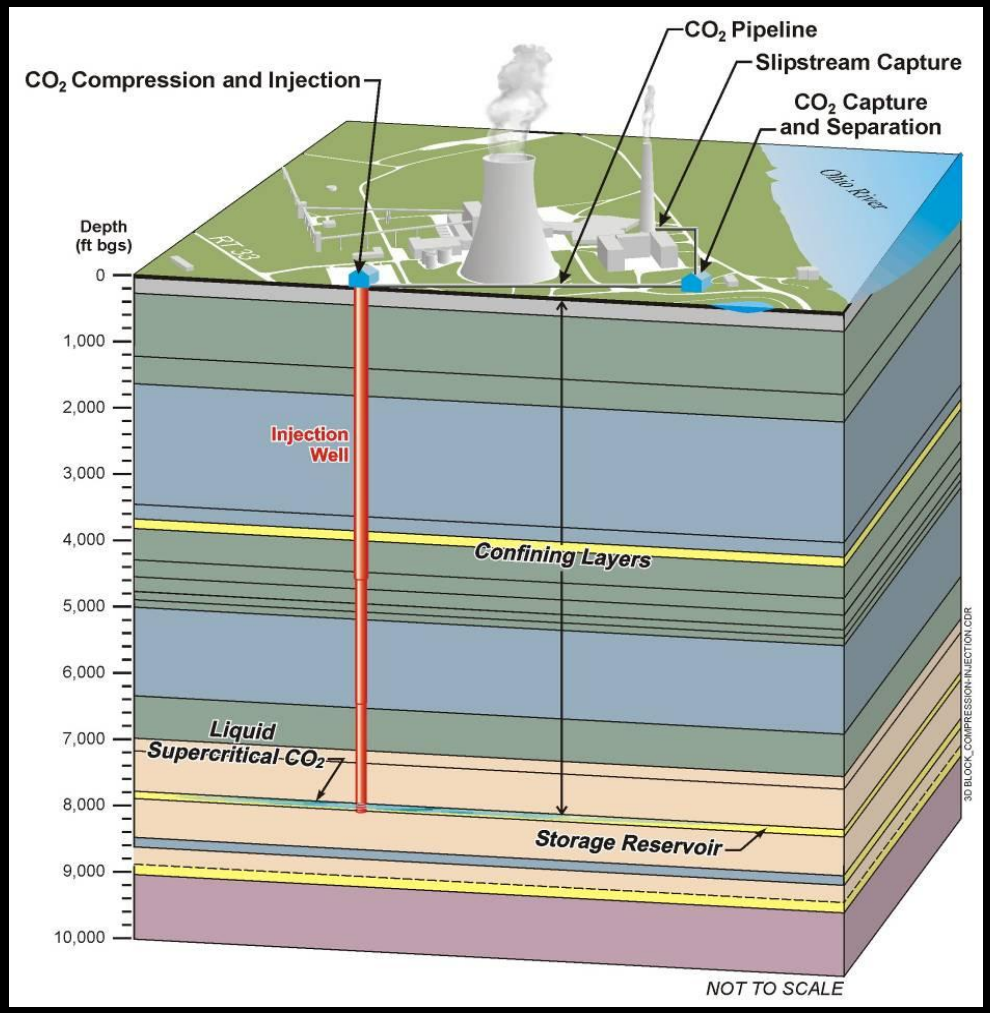




Sources: IEAGHG; NRDC; USDOE

# 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 . . .

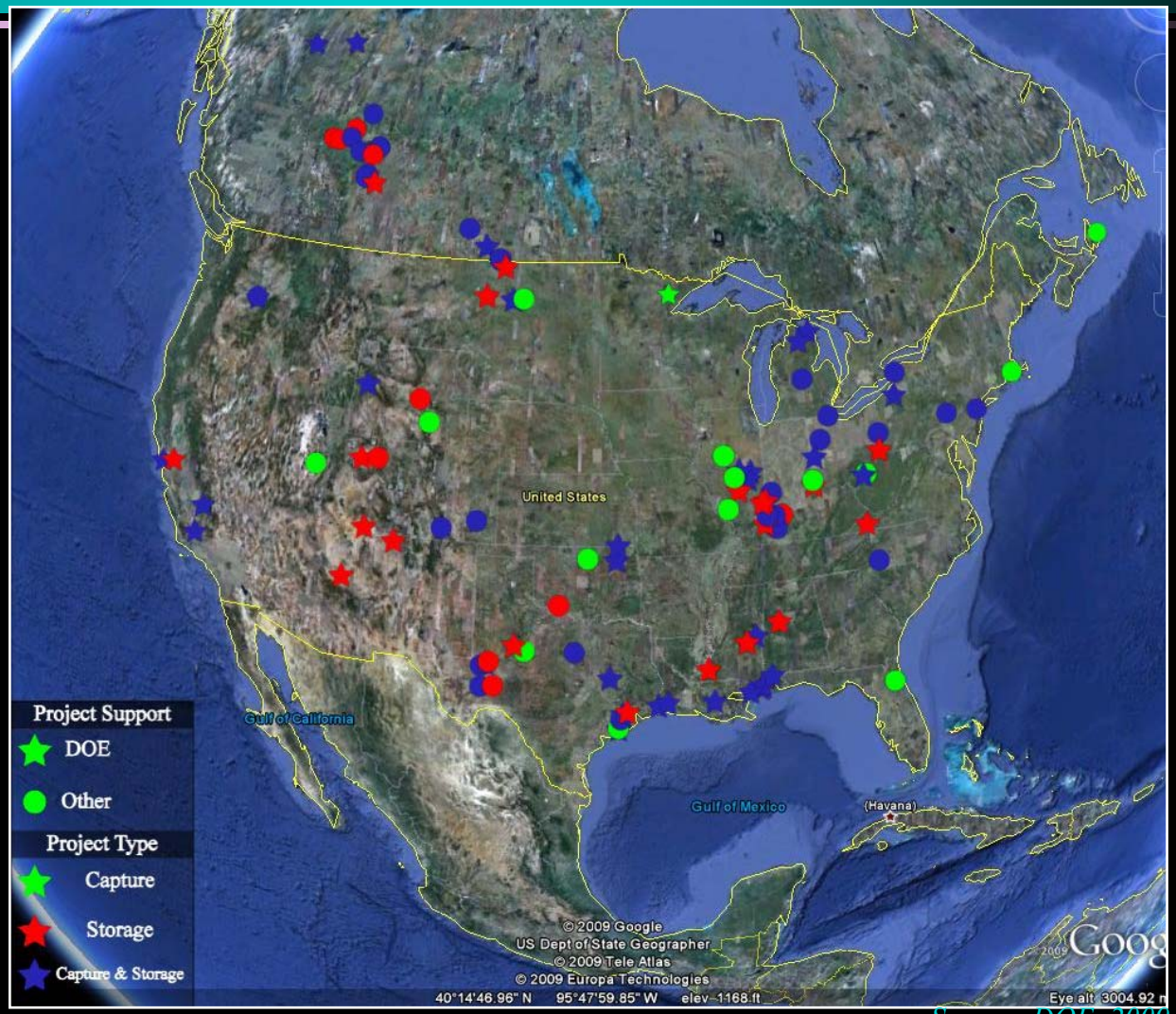
- Establish the reliability, safety and true cost of CCS in full-scale power plant applications
- Help resolve legal and regulatory issues regarding geological sequestration
- Help address issues of public acceptance
- Begin reducing future costs via learning-by-doing

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

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

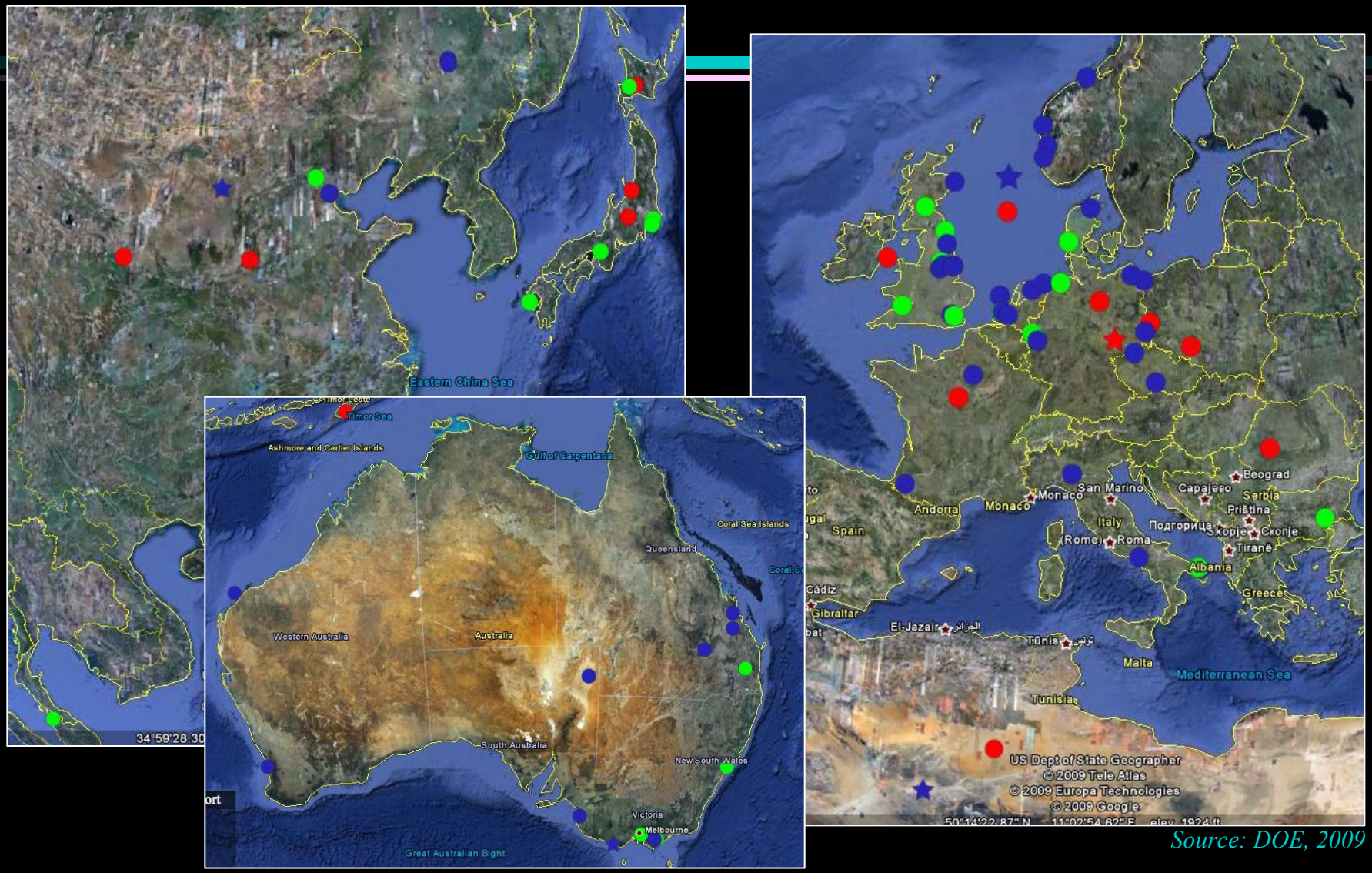
# Many projects are planned or underway at various scales

- 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*

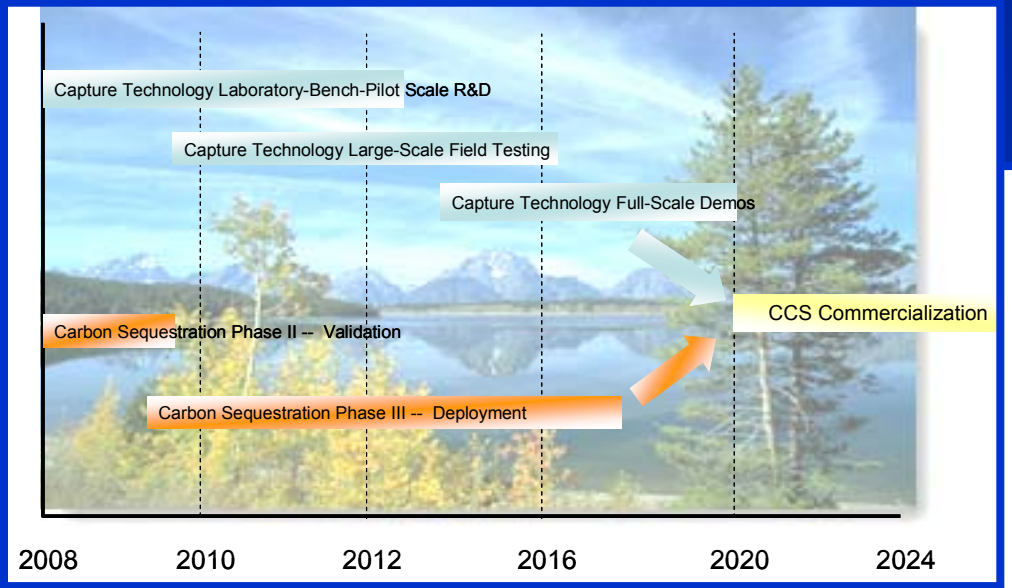
# Substantial CCS Activity Globally




*Source: DOE, 2009*

# Roadmaps for CCS Deployment

***DOE Roadmap***




***EPRI Roadmap***

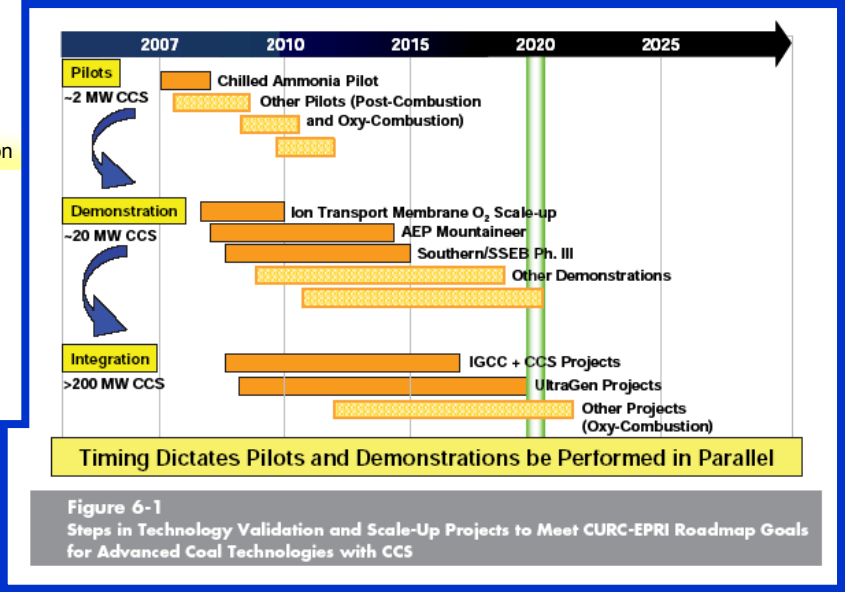



Figure 6-1
Steps in Technology Validation and Scale-Up Projects to Meet CURC-EPRI Roadmap Goals for Advanced Coal Technologies with CCS

**Commercialization expected by 2020**

*E.S. Rubin, Carnegie Mellon*

# *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 Electricity (COE) ($/MWh)

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

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

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

***Also:*** - Cost of $CO_2$ Captured ($/ton $CO_2$ captured)

- Cost of $CO_2$ Reduced/Abated ($/ton $CO_2$ abated)

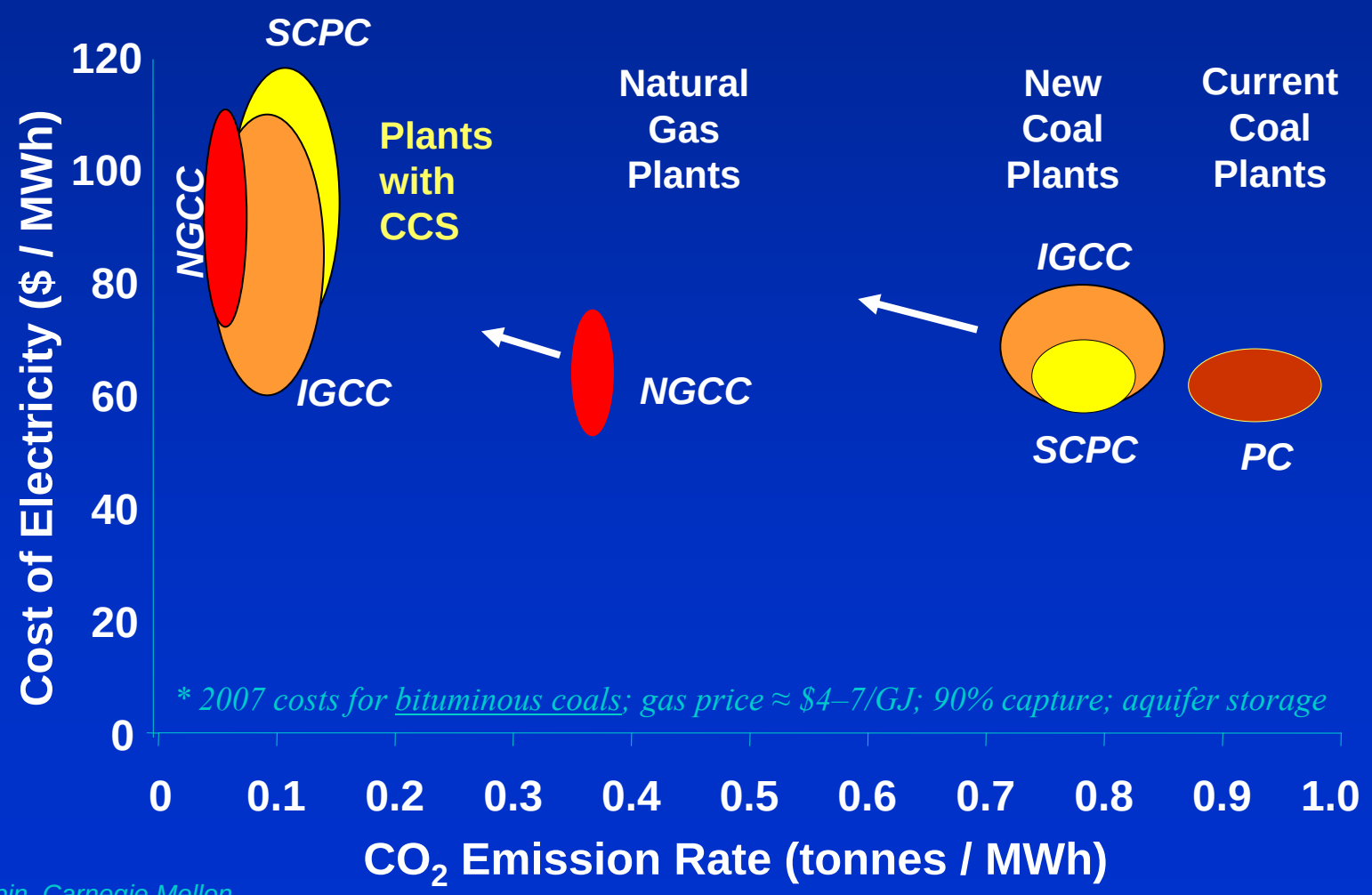
# Ten Ways to Reduce Estimated Cost

*(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!*

# Estimated Cost of New Power Plants with and without CCS



# 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.*

# Typical Cost of $CO_2$ Avoided

## (Relative to a new SCPC reference plant; bituminous coals)

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$CO_2$** **±\$15/t** | **~ \$50 /t$CO_2$** **±\$10/t** |
| Enhanced oil recovery (EOR) storage | Cost reduced by ~ \$20–30 /t$CO_2$ | |

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

- ***Costs to retrofit existing plants could be much higher***
- ***Capture accounts for most (~80%) of the total cost***

# 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% |

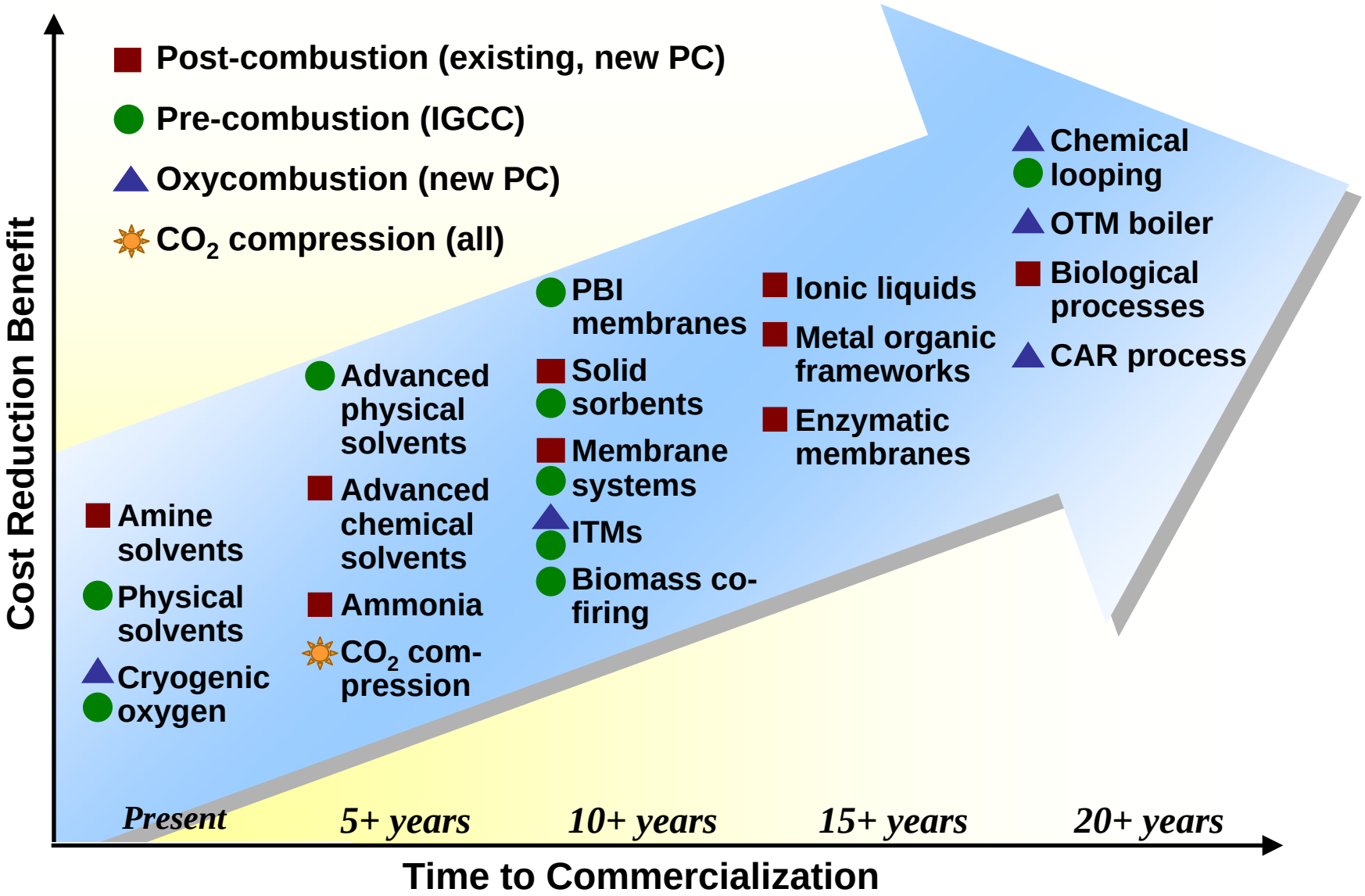
*Changes in plant efficiency due to CCS energy requirements also affect plant-level pollutant emission rates (per MWh). A site-specific context is needed to evaluate the net impacts.*

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

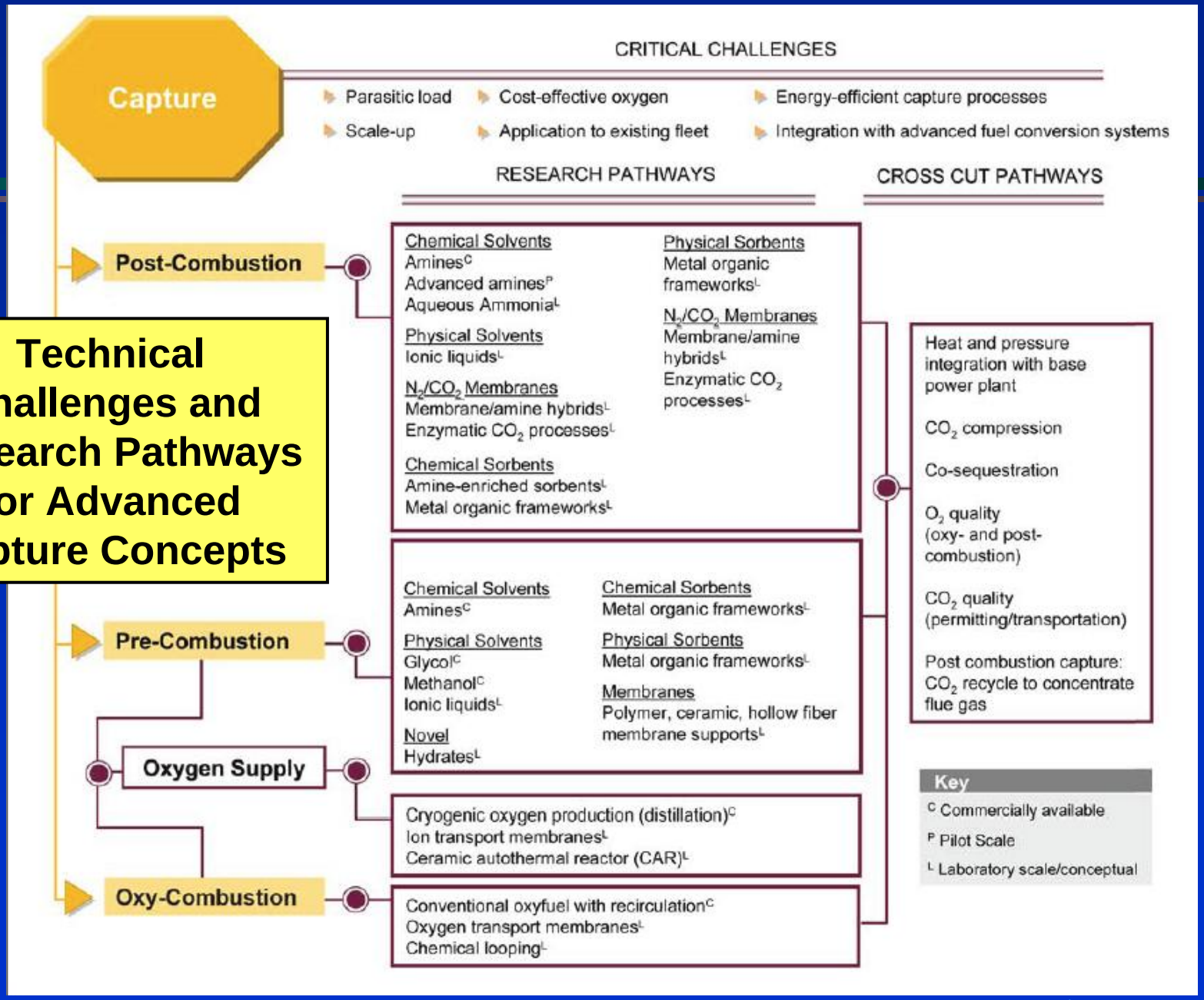
| Component | Approx. % of Total Reqm't |
|---|---|
| Thermal Energy | ~60% |
| $CO_2$ Compression | ~30% |
| Pumps, Fans, etc. | ~10% |

*What is the potential for lower-cost capture technology?*

# Better Capture Technologies Are Emerging



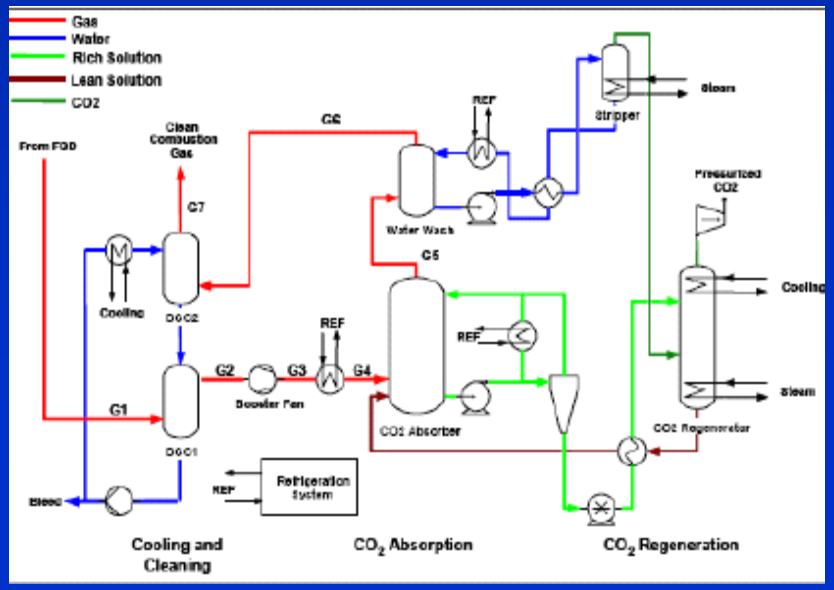
# Technical Challenges and Research Pathways for Advanced Capture Concepts



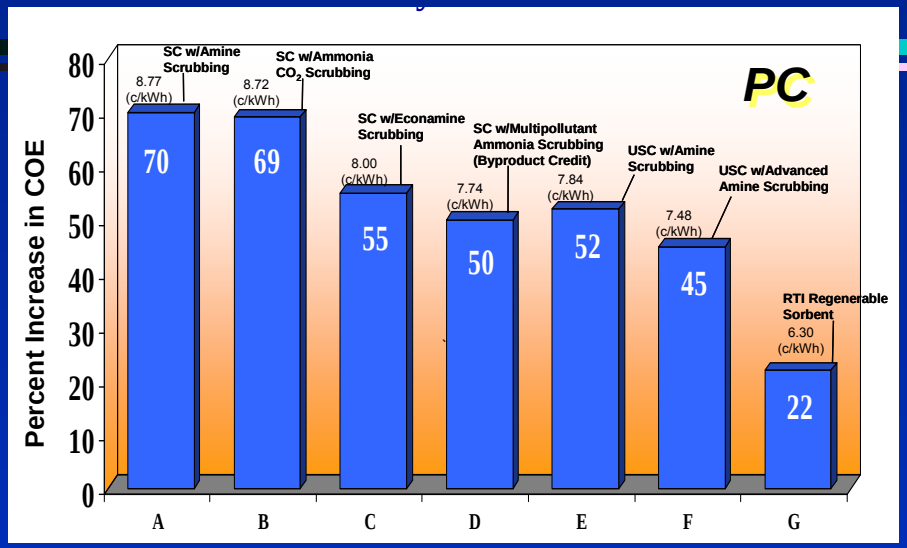

*Source: DOE/ NETL, 2009*

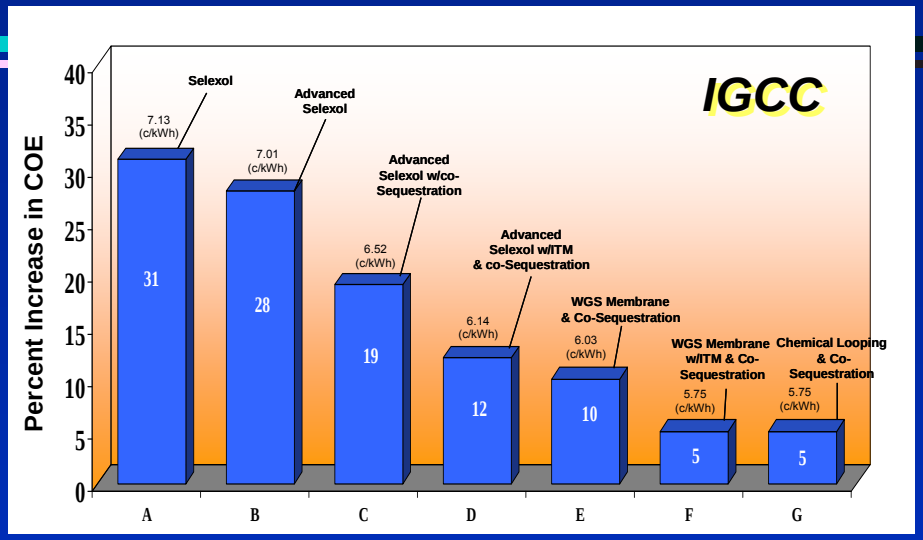
# Two Approaches to Estimating Potential Cost Savings

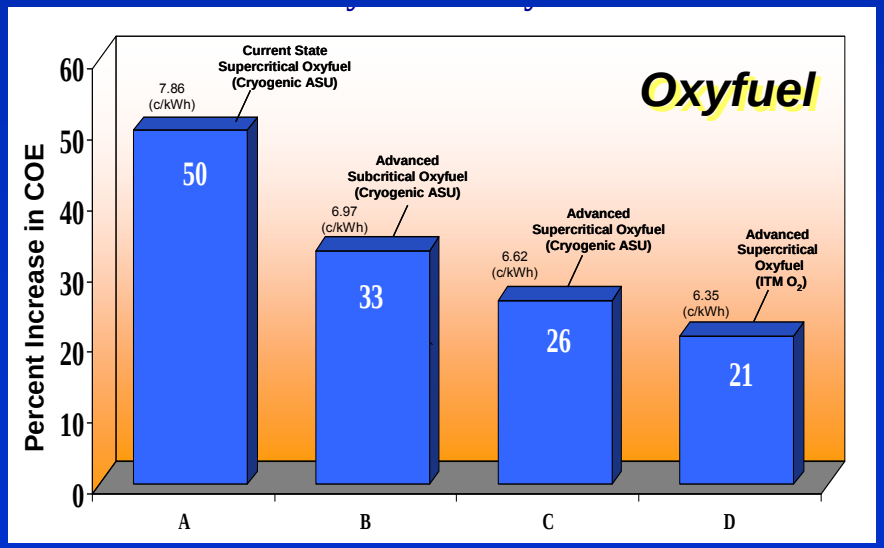
- *Method 1*: Engineering-Economic Analysis
  - A "bottom up" approach based on engineering process models (informed by judgments regarding potential improvement in key parameters)



# Potential Cost Reductions Based on Engineering-Economic Analysis



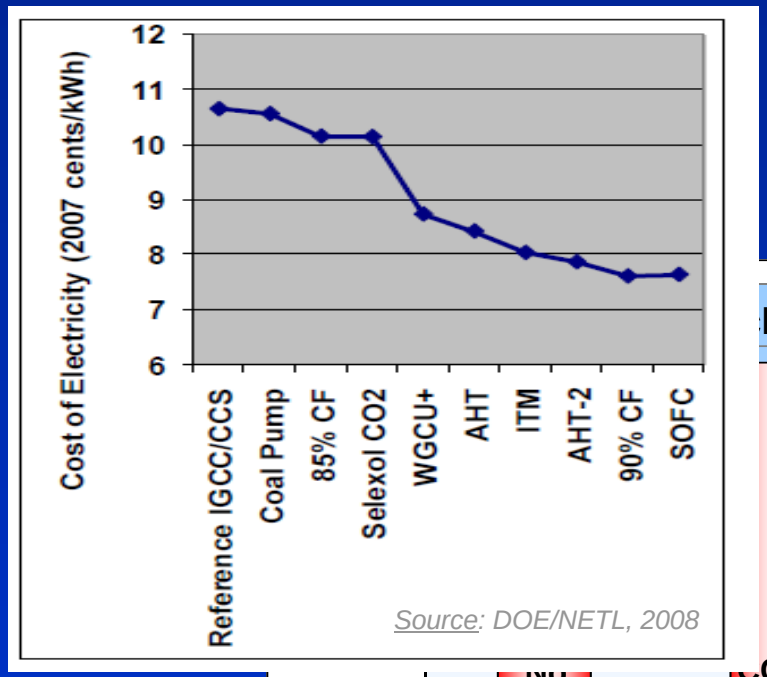



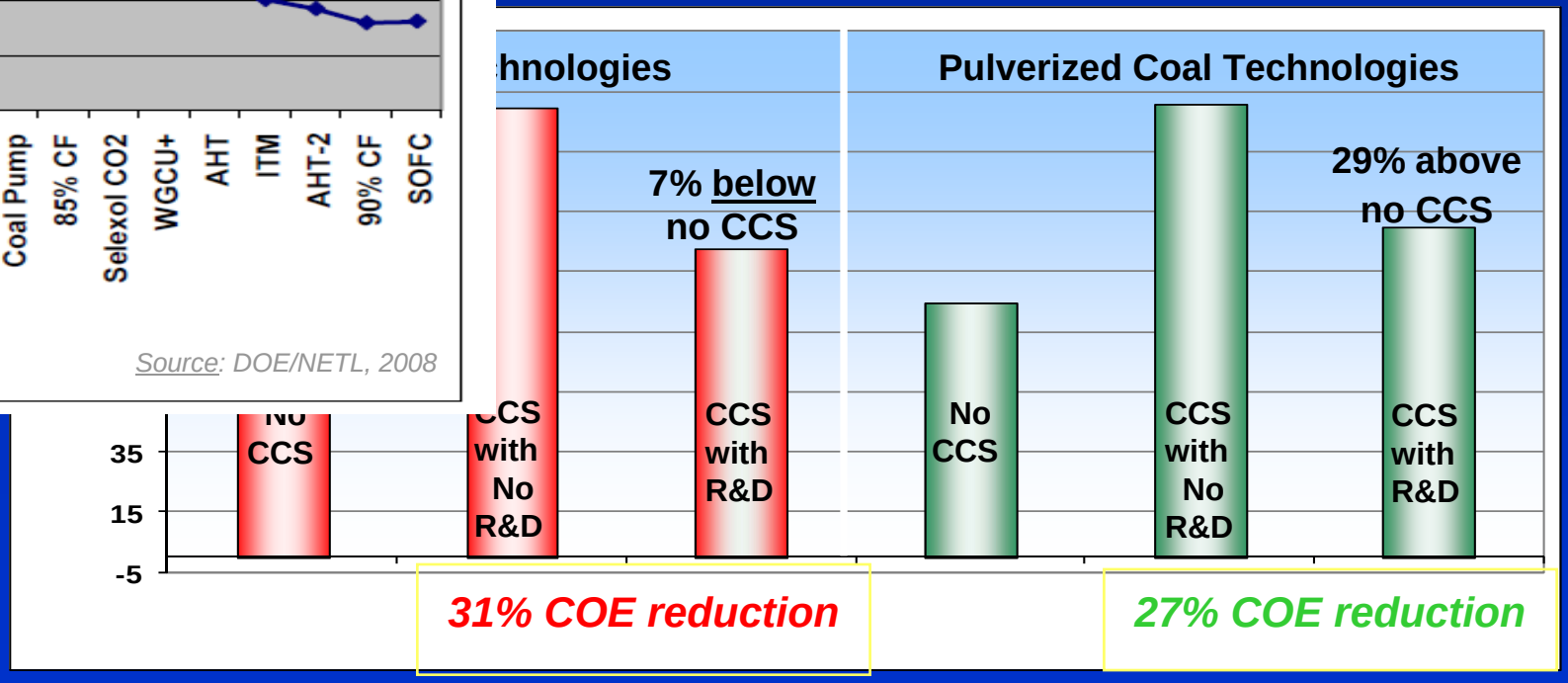




*19% -28% reductions in COE w/ CCS*

*Source: DOE/NETL, 2006*

# Potential Cost Reductions Based on Engineering-Economic Analysis

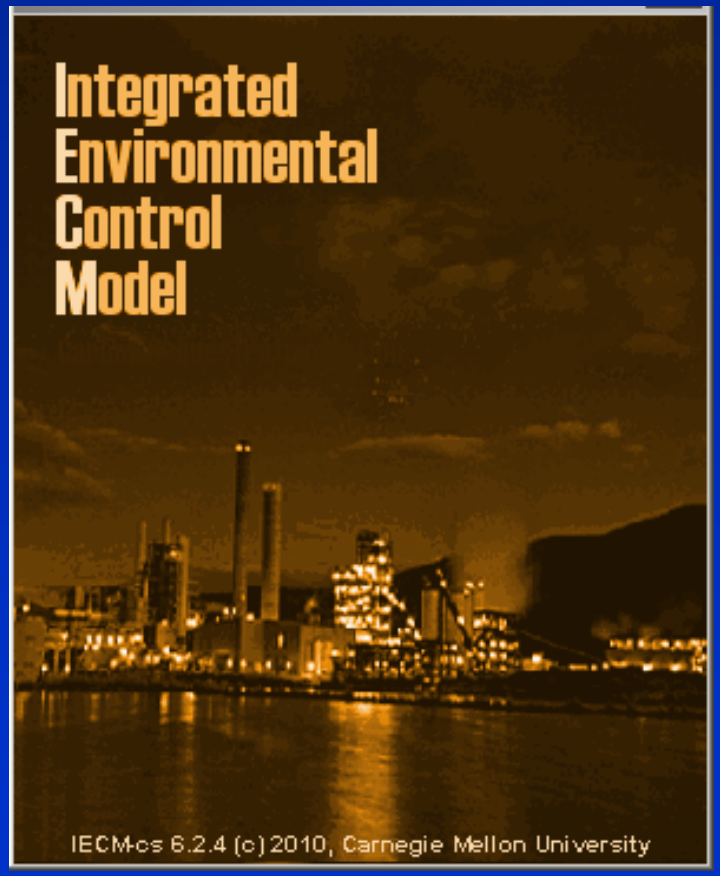



Source: DOE/ NETL, 2010

# 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 updates in late 2009 & 2010

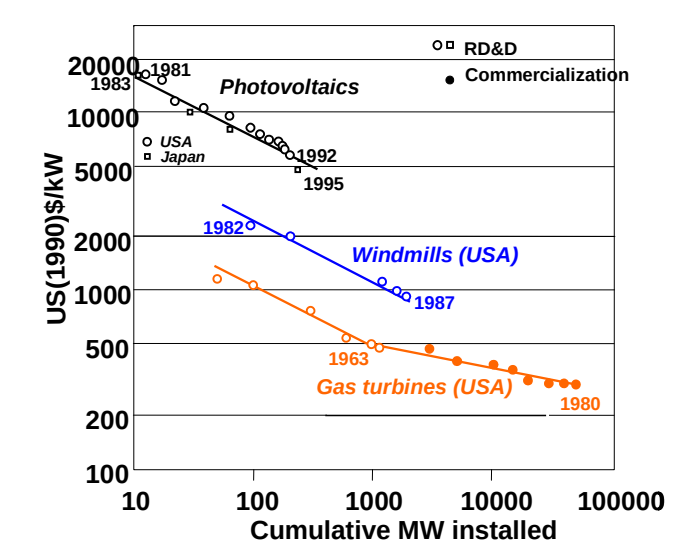


# Current IECM Developments

- Performance and Cost Models of Advanced $CO_2$ Capture Systems:
  - Advanced liquid solvents (Peter Versteeg)
  - Solid sorbent systems (Justin Glier)
  - Membrane capture systems (Haibo Zhai)
  - Advanced oxy-combustion (Kyle Borgert)
  - Chemical looping combustion (Hari Mantripragada)
- International cost adjustment module (Hana Gerbelova)
- Other model enhancements (Karen Kietzke)

# Two Approaches to Estimating Future Technology Costs

- *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



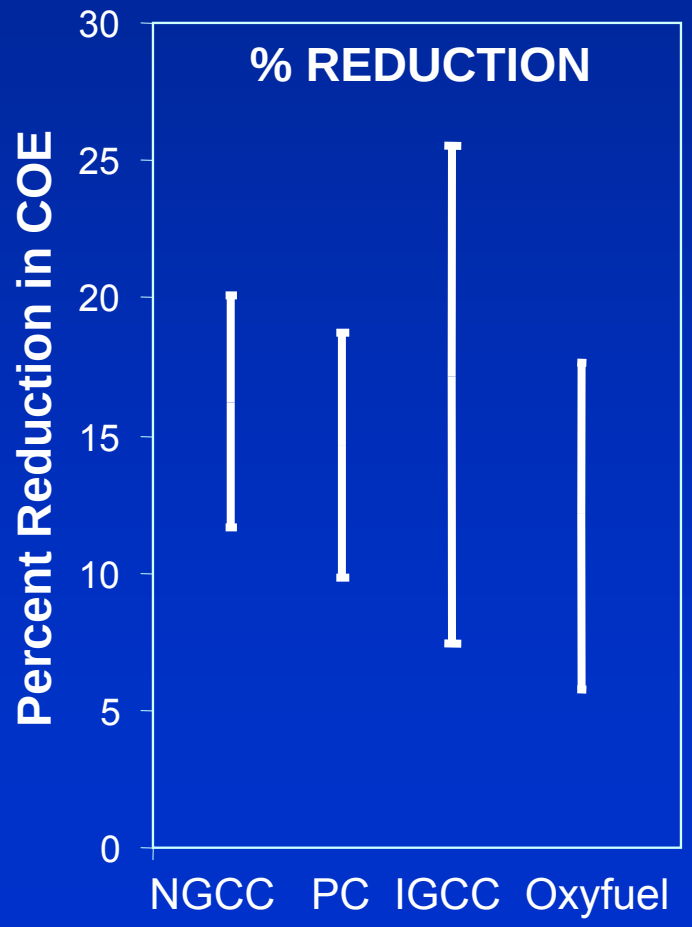

Source: IIASA, 1996

# Empirical "Learning Curves"

- Cost trends modeled as a log-linear relationship between unit cost and cumulative production or capacity: $y = ax^{-b}$
- Case studies used to estimate learning rates 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)

# Potential Cost Reductions Based on Learning Curve Analysis*

(after 100 GW of cumulative CCS capacity worldwide)




- **Upper bound of projected cost reduction are similar to estimates from DOE's "bottom-up" analyses**

* Plant-level learning curves developed from component-level analyses for each system

# Projected Cost Reductions, 2001–2050

## (Based on Learning Curves + Global Energy Model)

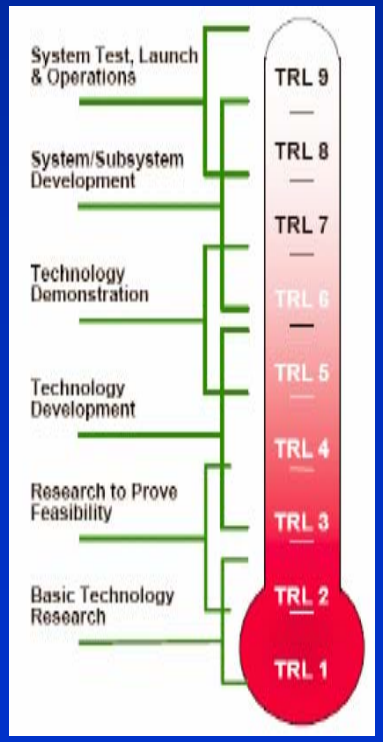
### Results for two policy scenarios, 2001–2050

| Power Plant System | Reduction in Cost of Electricity ($/MWh) | Reduction in Mitigation Cost ($/t$CO_2$ avoided) |
|---|---|---|
| NGCC – CC | 12% – 40% | 13% – 60% |
| IGCC – CC | 22% – 52% | 19% – 58% |
| PC – CC | 14% – 44% | 19% – 62% |

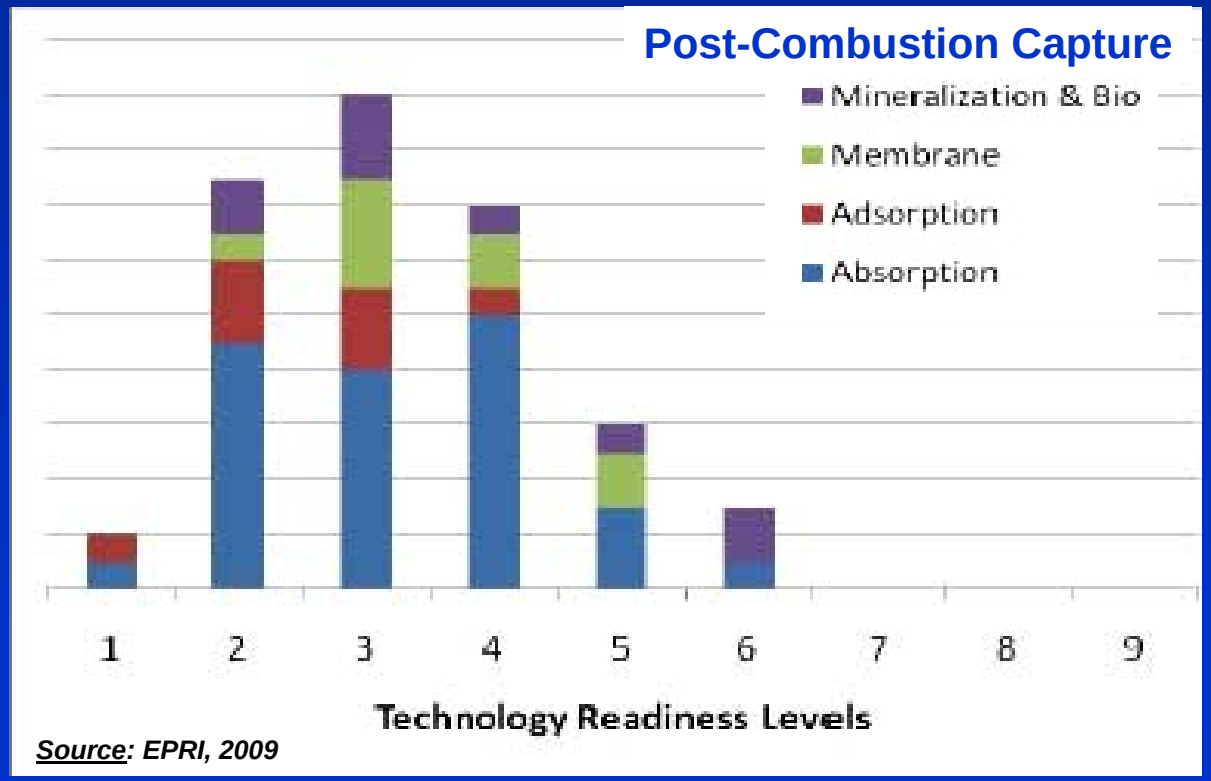
*Source: van den Broek,et al., 2009*

# Most New Capture Concepts Are Far from Commercial Availability

**Technology Readiness Levels**



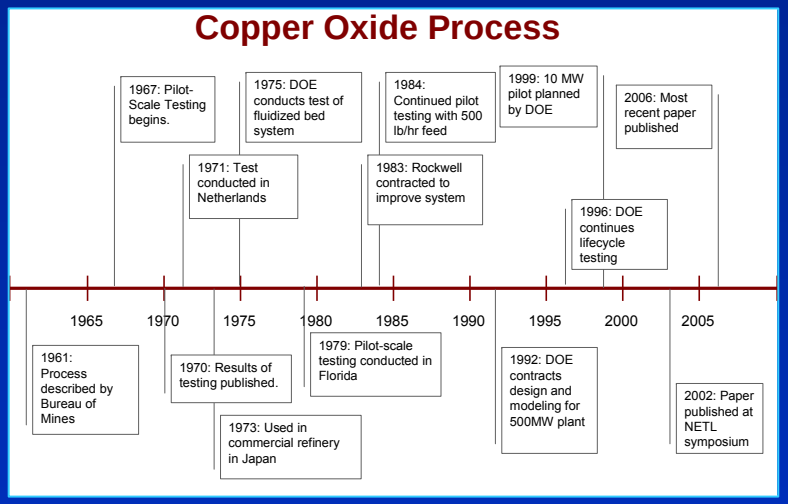

*Source: NASA, 2009*

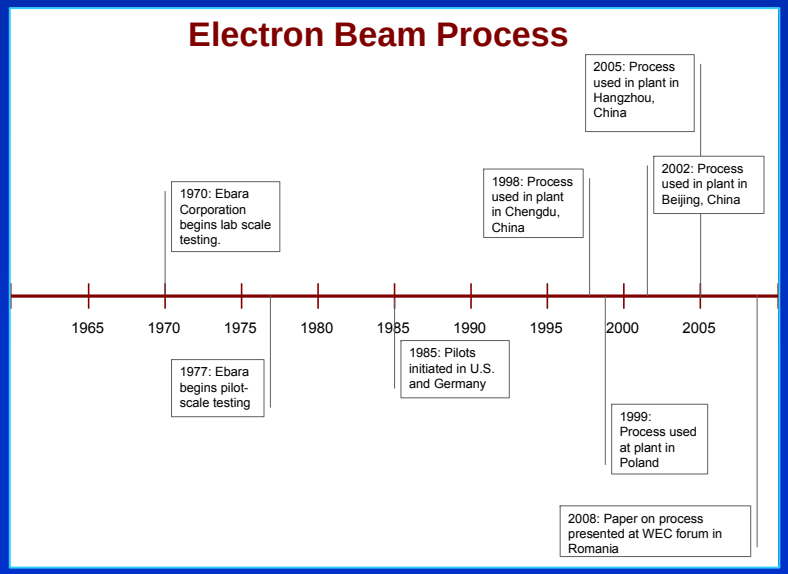


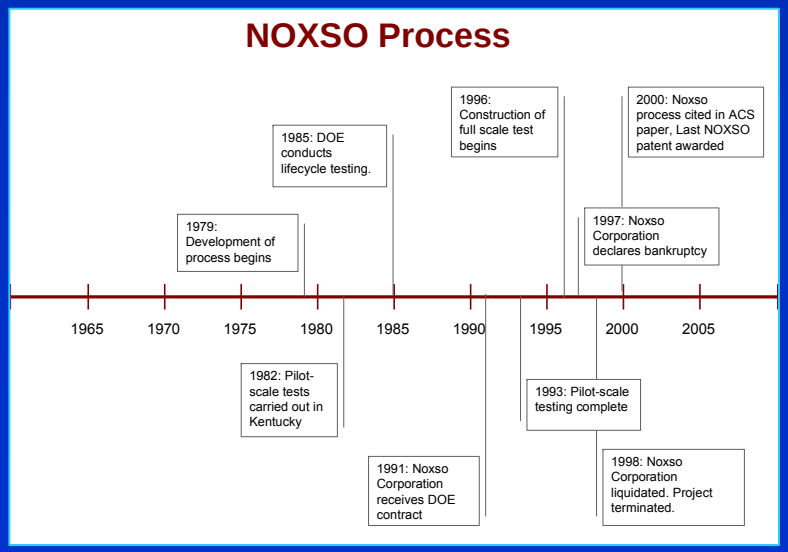

***Source*: EPRI, 2009**

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

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

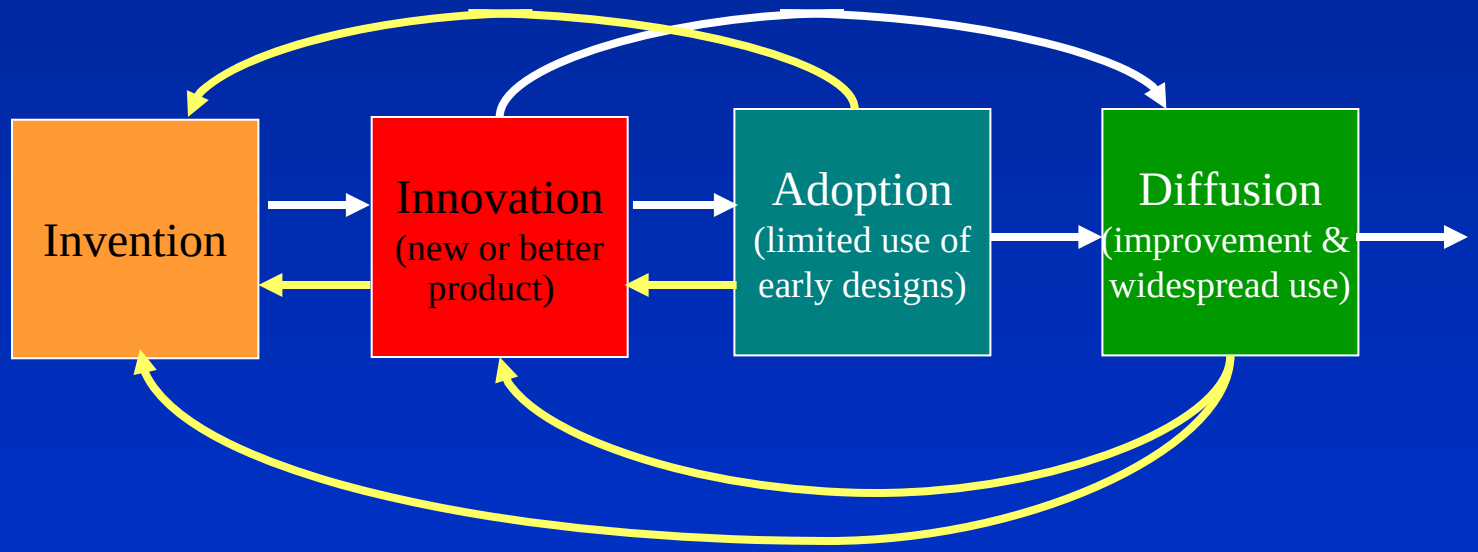


# *Challenge:*
# Accelerate the Pace of Innovation

## The Process of Technological Change




*R&D*

*Learning By Doing*

*Learning By Using*

# 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
- Government policies that create and foster markets for CCS technologies

# Conclusions

- While the challenges are significant, so too are the <u>opportunities</u> to reduce the cost of carbon capture via:
  - New or improved $CO_2$ capture technologies
  - Improved plant efficiency and utilization
- In turn, this can greatly reduce the costs (and thus increase the likelihood) of avoiding the most serious impacts of climate change
- So— an exciting time to be working on this problem!

# *Thank You*

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