What Energy Modelers Need to Know About Carbon Capture and Storage

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Outline of Talk

- Current status of CCS technology
- Costs and impacts on plant performance
- Factors affecting deployment of CCS
- Incorporating uncertainty in models

Status of CCS technology

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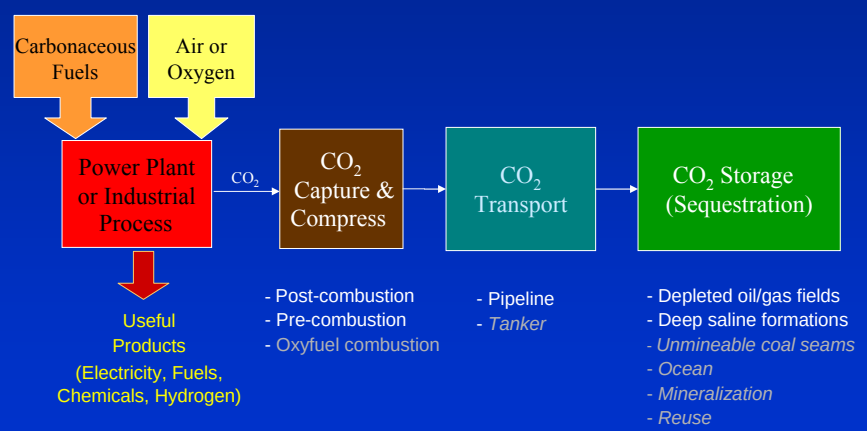
Schematic of a CCS System



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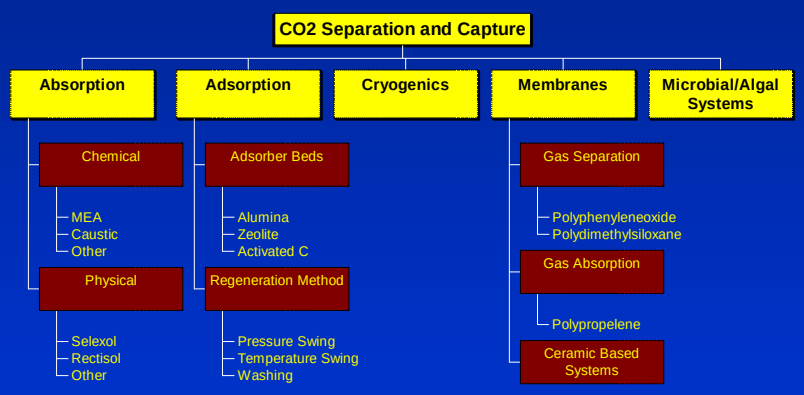
Many Ways to Capture CO_2



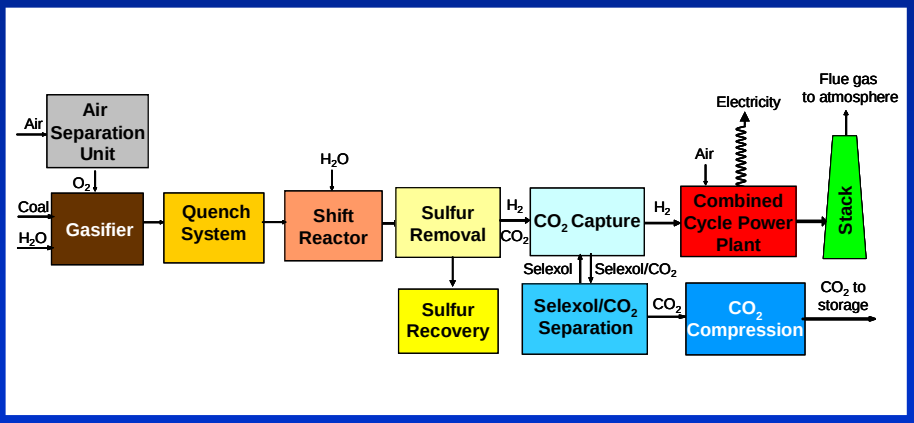
Choice of technology depends strongly on application

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 –

CO_2 Capture Options for Power Plants: Pre-Combustion Capture



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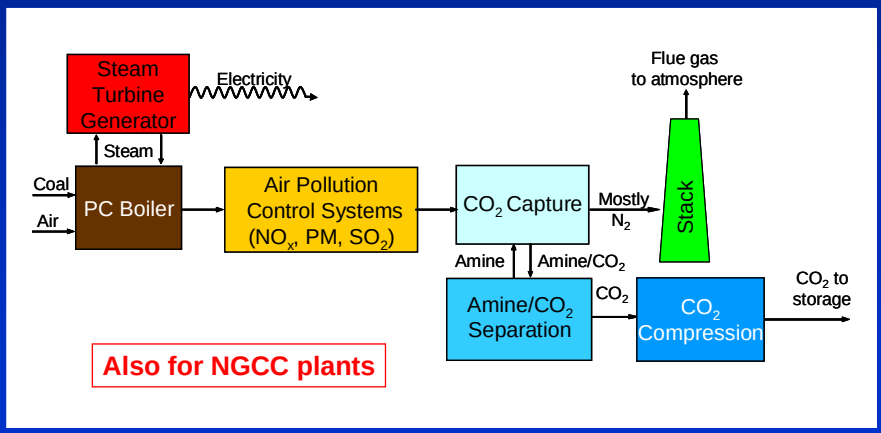
CO_2 Capture Options for Power Plants: Post-Combustion Capture



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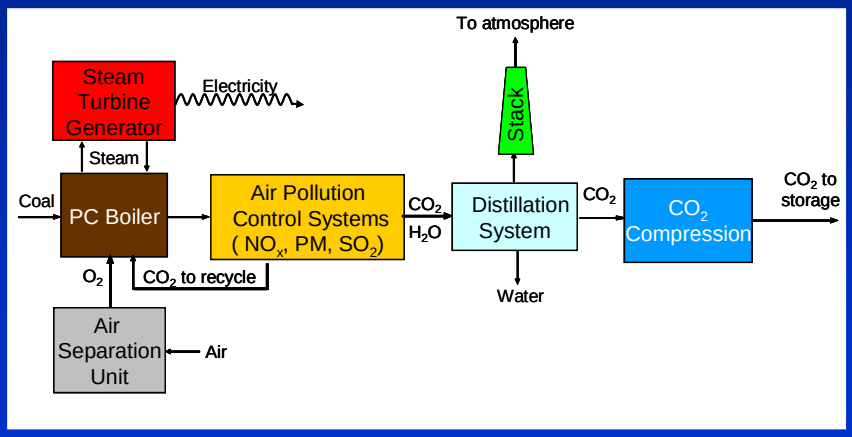
CO_2 Capture Options for Power Plants: Oxy-Combustion Capture



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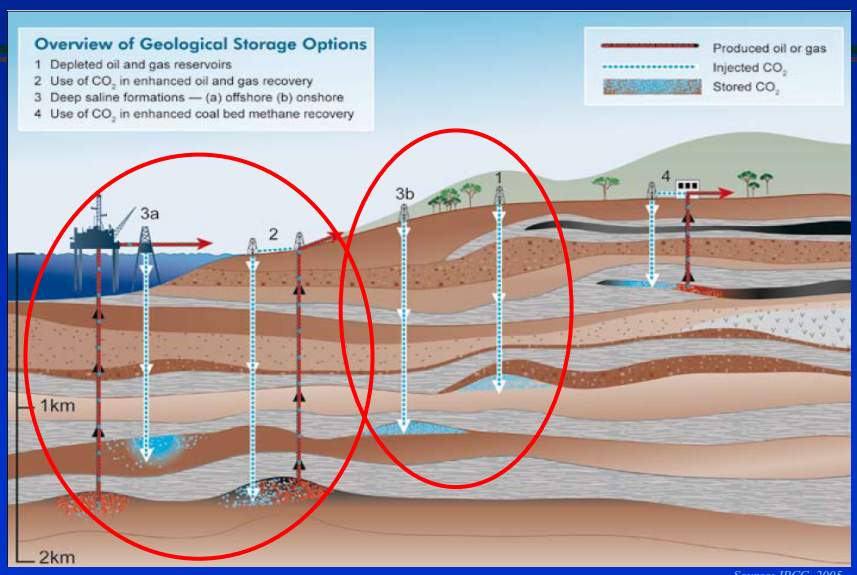
Geological Storage Options



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 U.S. Power Plants

(Source: Flour Daniel)

Bellingham Cogeneration Plant
(Bellingham, Massachusetts, 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..

A 500 MW coal plant would inject about 3 $MtCO_2$/yr

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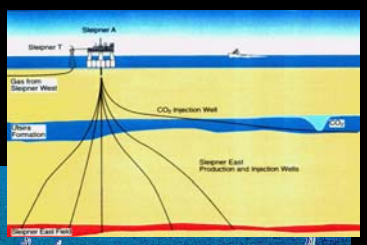
Geological Storage of Captured CO_2 in a Deep Saline Formation

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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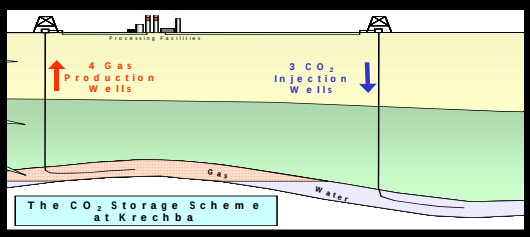
Geological Storage of Captured CO_2 in a Depleted Gas Formation

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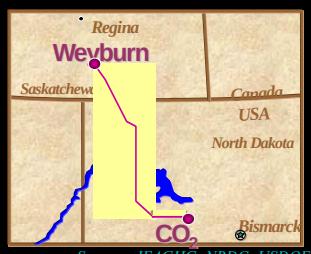
Geological Storage of Captured CO_2 with Enhanced Oil Recovery (EOR)



Sources: IEAGHG; NRDC; USDOE

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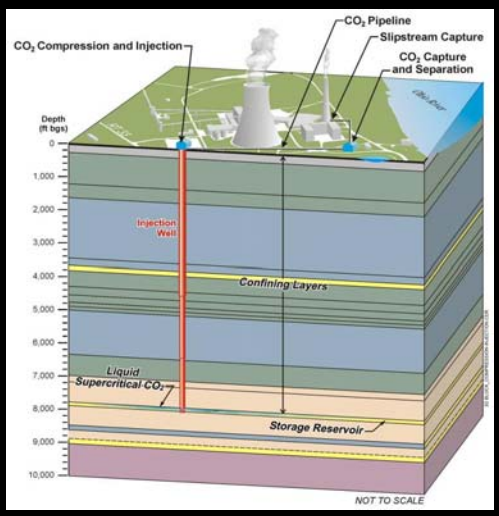
CCS at a Coal-Fired Power Plant with Storage in a Deep Saline Formation

(Pilot plant scale)

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



Source: AEP, 2009

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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

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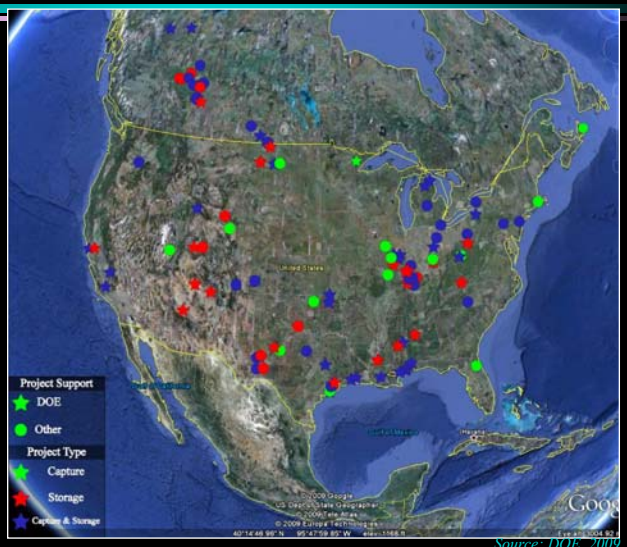
Many projects are planned or underway at various scales

- 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

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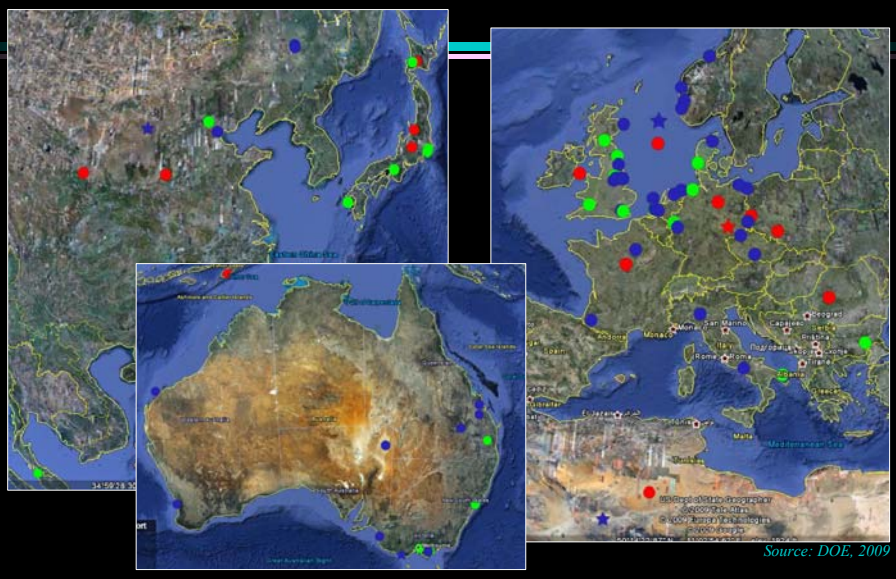
Substantial CCS Activity Globally



Source: DOE, 2009

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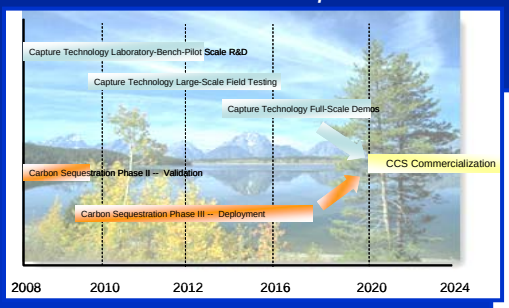
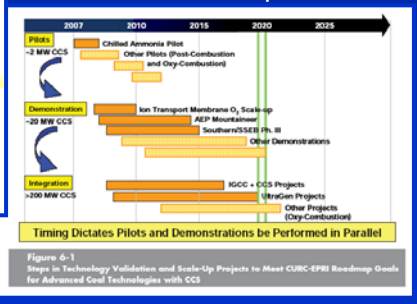
Roadmaps for CCS Deployment

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 Electricity (COE) ($/MWh)

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

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

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

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Ten Ways to Reduce CCS Cost

(inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel price
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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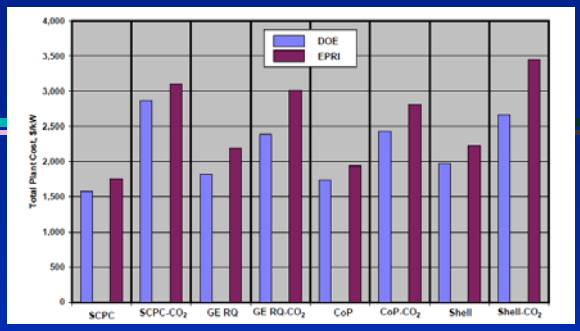
Sources of Recent Cost Estimates

- IPCC, 2005: Special Report on CCS
- Rubin, et.al, 2007: *Energy Policy, 35*
- EPRI, 2007: Report No. 1014223
- DOE, 2007: Report DOE/NETL-2007/1281
- EPRI, 2008: Report No. 1018329
- DOE, 2009: Pgh Coal Conference Presentation
- DOE, 2010: Low-Rank Coal Study (forthcoming)

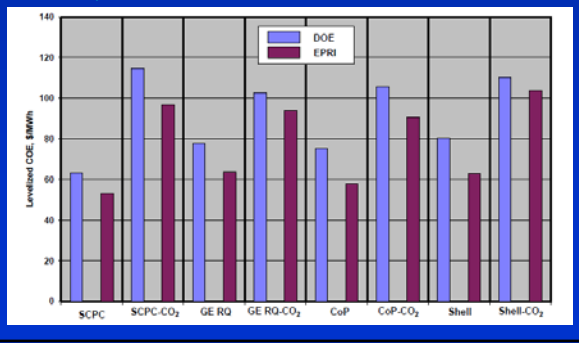
DOE vs. EPRI

- EPRI's capital costs ($/kW) are higher that DOE's

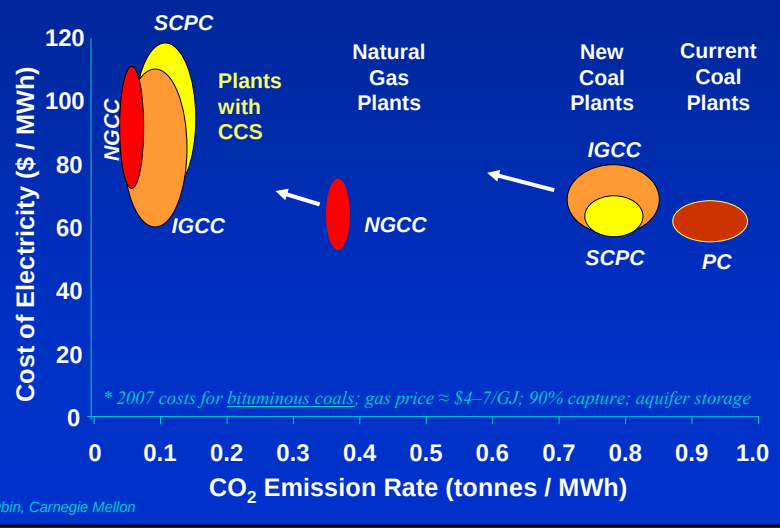


Source: EPRI, 2007

- EPRI's levelized costs of electricity ($/MWh) are lower than DOE's



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; 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

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

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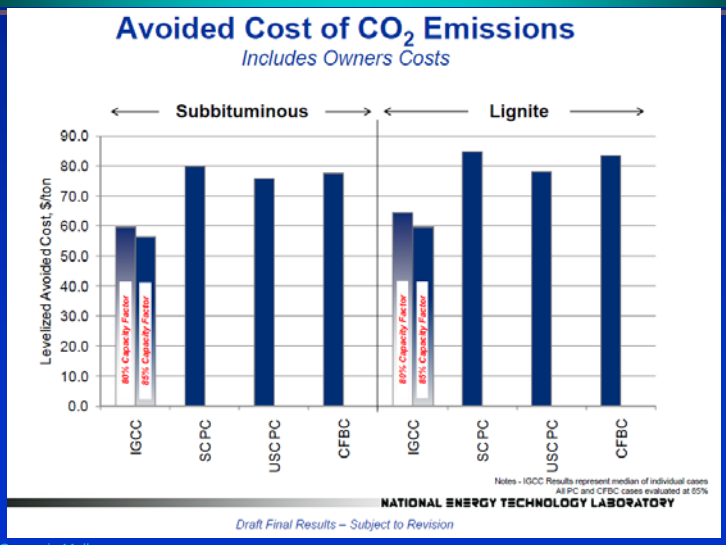
DOE Cost Results for Low-Rank Coals at Western Power Plants



Source: NETL, 2009

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CCS energy requirements affect plant efficiency, emissions, and cost

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.

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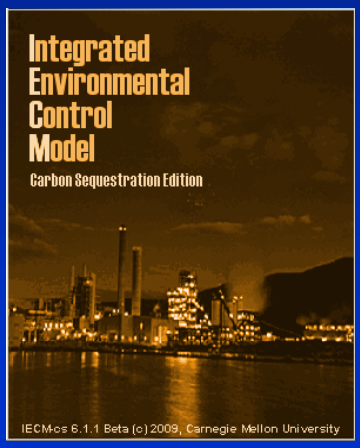
A Power Plant Cost & Performance Model

(IECM: The Integrated Environmental Control Model)

- A desktop/laptop computer model developed for DOE/NETL; free and available at: **www.iecm-online.com**
- Provides systematic estimates of performance, emissions, costs and uncertainties using user-specified designs and parameter values for:
  - 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 2010 update now available



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What is the potential for future cost reductions?

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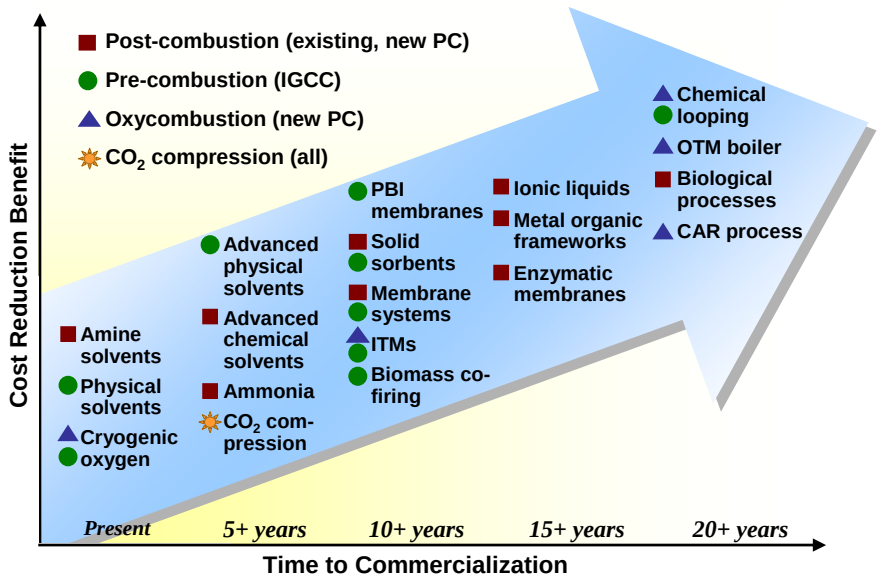
Better Capture Technologies Are Emerging



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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

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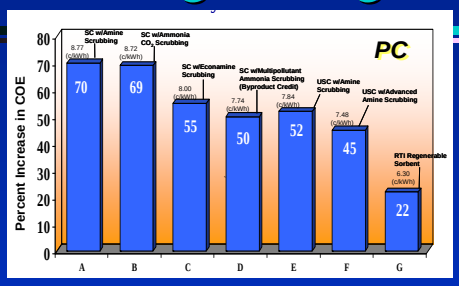
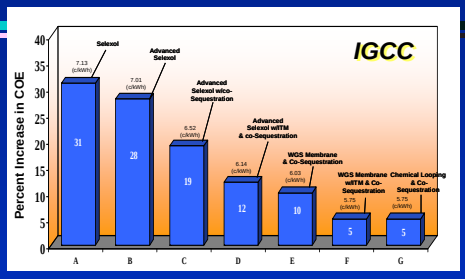
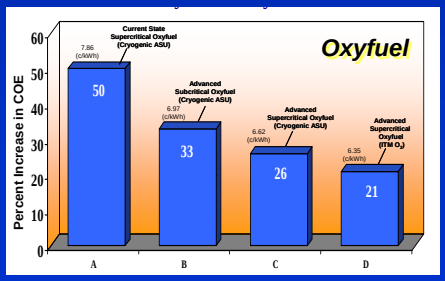
Potential Cost Reductions Based on Engineering-Economic Analysis







19% -28% reductions in COE w/ CCS

Source: DOE/NETL, 2006

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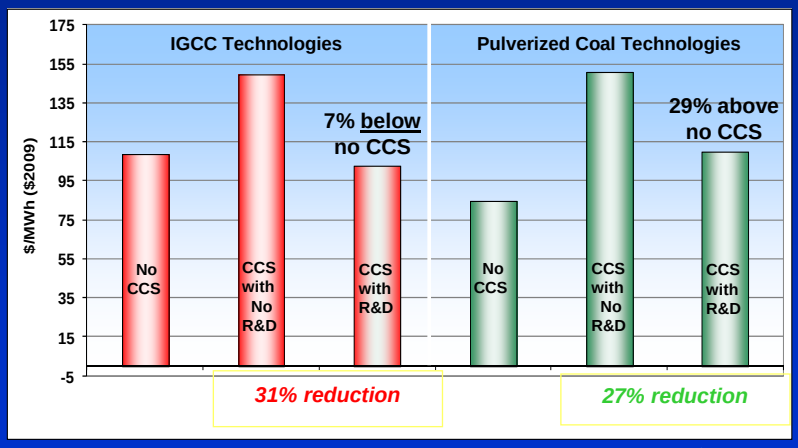
Potential Cost Reductions Based on Engineering-Economic Analysis



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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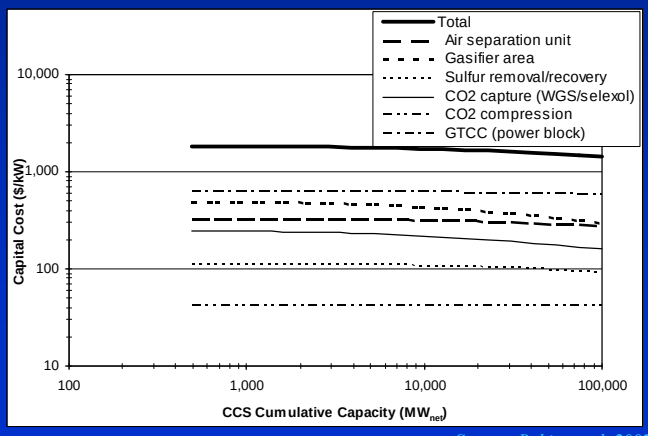
Projected Learning Curve for an IGCC Plant with CCS

Assumes learning begins with first CCS plant



Source: Rubin, et.al, 2007

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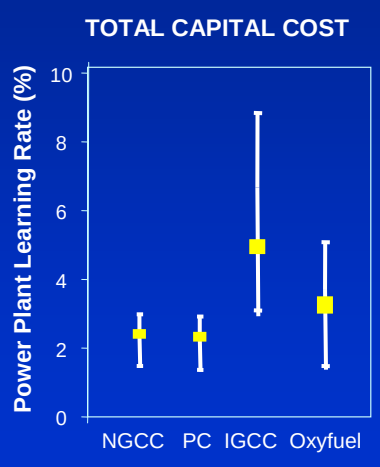
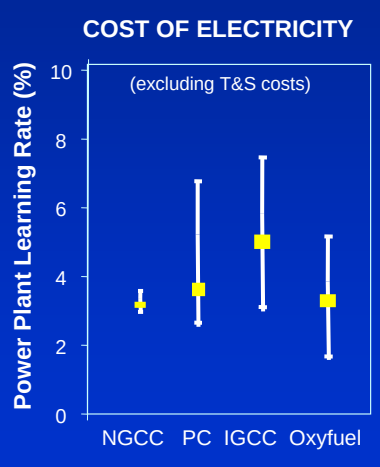
Range of Learning Rate Results for Four Plant Types w/ CO_2 Capture





Source: Rubin, et.al, 2007

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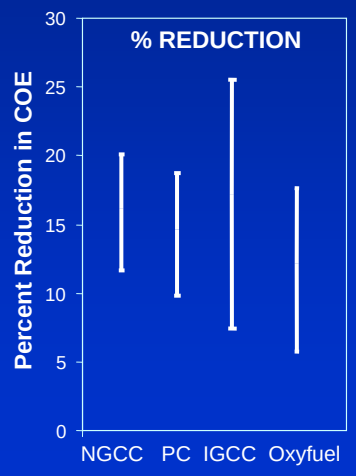
Potential Cost Reductions for 4 Plant Types Based on Learning Curves *

(*After 100 GW of cumulative CCS capacity worldwide)



- **Upper bounds are similar to estimates from DOE's "bottom-up" analyses**
- **Lower bounds are smaller by factors of 2 to 3**

Source: Rubin, et.al, 2007

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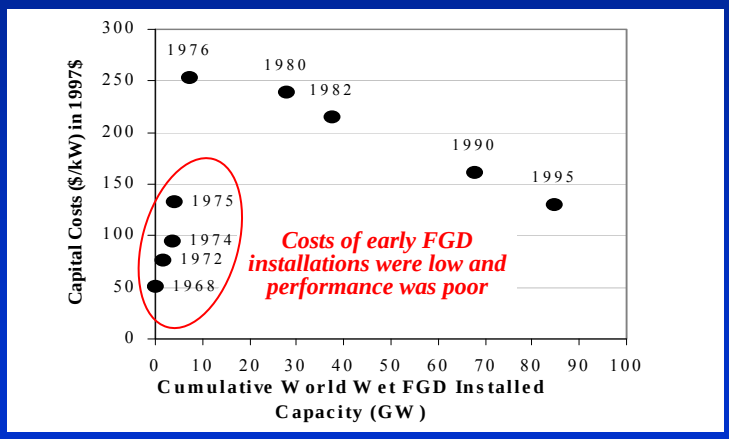
Many Sources of Uncertainty

Early Trend of FGD Capital Cost



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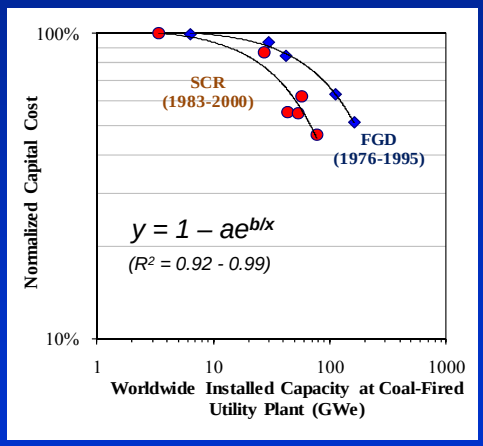
Best-fit models for initial deployment of FGD/SCR differ from classic model



Hypothesis:

The regulatory-driven deployment of these environmental technologies results in large initial capacity increments without the subsequent benefits of LBD, R&D, etc, which reduces the cost of future generations of these technologies

Who would use it and why?

Why Would CCS be Adopted?

Carrots

- Financial subsidies or other government incentives
- Profit from sale of captured CO_2 (for EOR, etc.)

Sticks

- A carbon price or tax greater than the cost of CCS
- A performance standard or other type of regulation that requires the use of CCS for compliance

Most energy models focus on carbon prices, but other policy drivers also can be important

Constraints on CCS Use

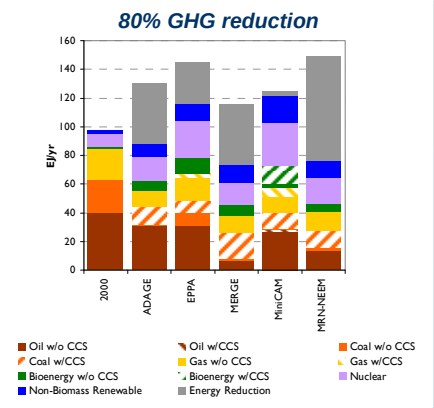
- Retrofits on existing plants could be precluded by:
  - Limitations on available physical space
  - Limited or no access to geological storage capacity
  - Unacceptable costs related to plant characteristics (e.g., size, age, efficiency, energy penalty, etc.)
  - Public opposition to CCS
- Applications to new plants could be precluded by:
  - Limited or no access to geological storage capacity
  - Public opposition to CCS
  - Industry aversion to CCS (or to some forms of it)

CCS Needs Are Feasible But Urgency Is Required

Least-cost U.S. energy mix in 2050 for a GHG policy scenario (80% below 1990 levels):

Results from five models

(Source: EMF22, 2009)



***CCS Needed in 2035** (EMF22): 230 – 1600 TWh (~30–230 GW)*
***Technical Potential** (AEF, 2009): 3000 TWh (~ 430 GW)*

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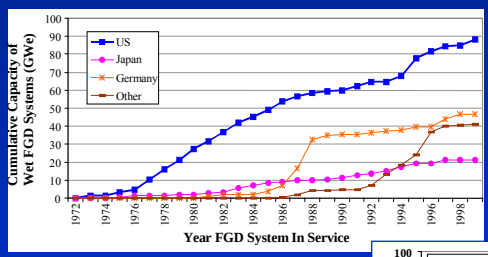
Deployment of Post-Combustion SO_2 and NO_x Capture at Coal-Fired Plants

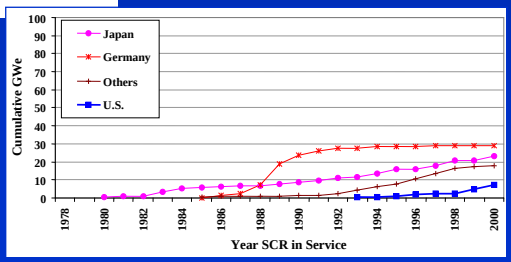


Flue Gas Desulfurization (FGD) systems:

Average ≈ 10 GW/yr

Selective Catalytic Reduction (SCR) systems:

Average ≈ 5 GW/yr



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How can we better represent uncertainties in model results?

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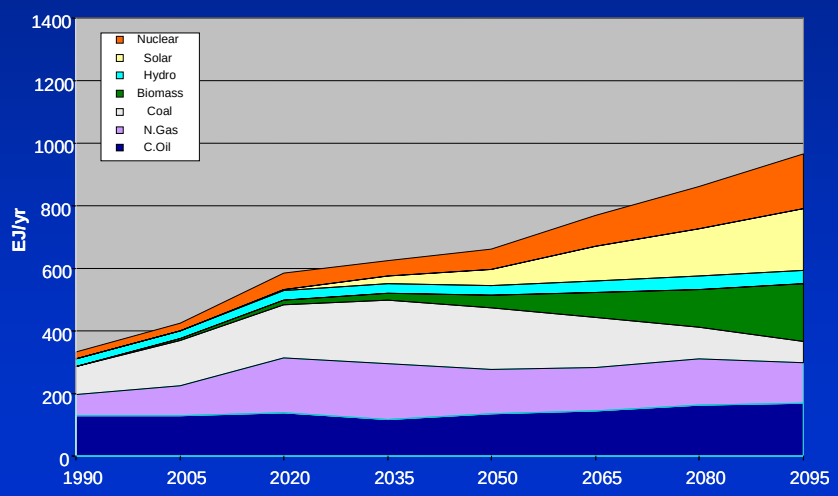
Typical Display of a Model Run



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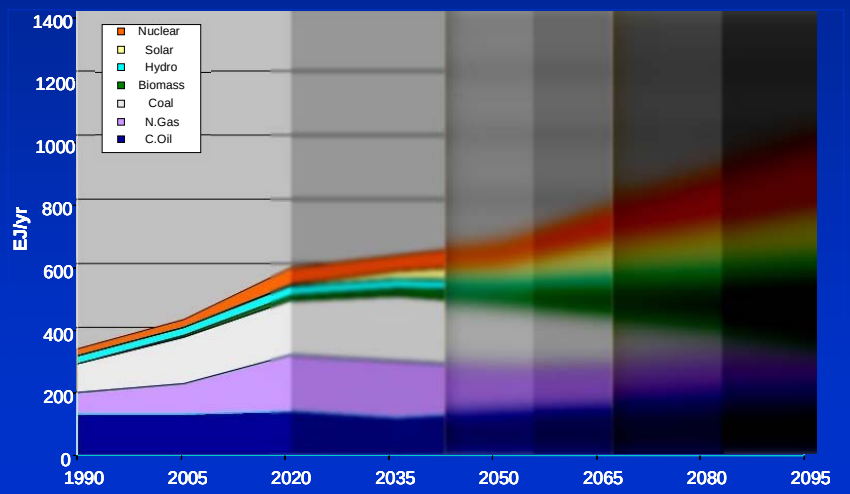
What I'd Like to See



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Thank You

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