

The Status of CO₂ Capture and Storage Technology

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Outline of Talk

- Why the interest in CCS?
- Status of current CCS technology
- Current cost estimates
- Potential for cost reductions

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Why the interest in CCS ?

(Carbon Capture and Storage /Sequestration)

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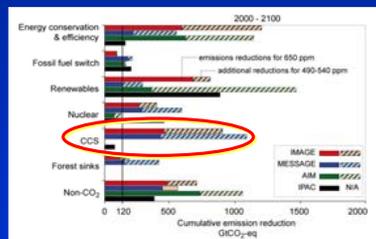
Motivation for CCS

- Stabilizing atmospheric GHG concentrations will require large reductions in CO₂ 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 CO₂ 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 much higher

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Cost-Effective Global Strategies Require CCS in the Portfolio

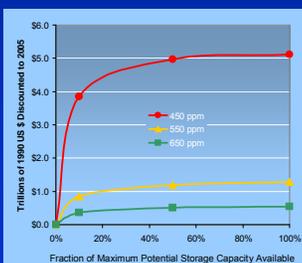
Models show increasing need for CCS as stabilization goal tightens



Source: IPCC, 2007

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Without CCS the cost of stabilization increases sharply

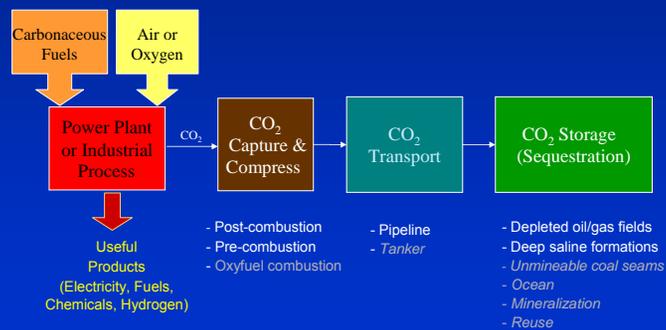


Source: J. Edmonds, PNNL, 2008

Status of CCS technology

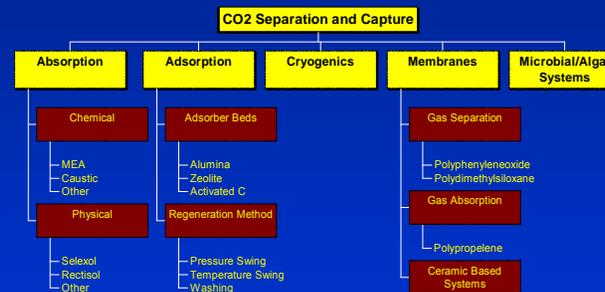
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Schematic of a CCS System



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Many Ways to Capture CO₂



Choice of technology depends strongly on application

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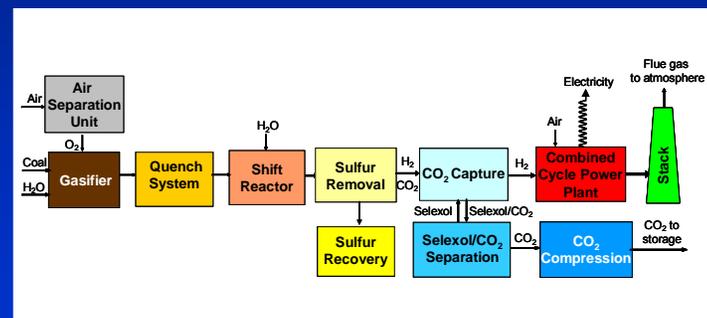
Leading Candidates for CCS

- Fossil fuel power plants
 - Pulverized coal combustion (PC)
 - Natural gas combined cycle (NGCC)
 - Integrated coal gasification combined cycle (IGCC)
- Other large industrial sources of CO₂ 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 CO₂ —

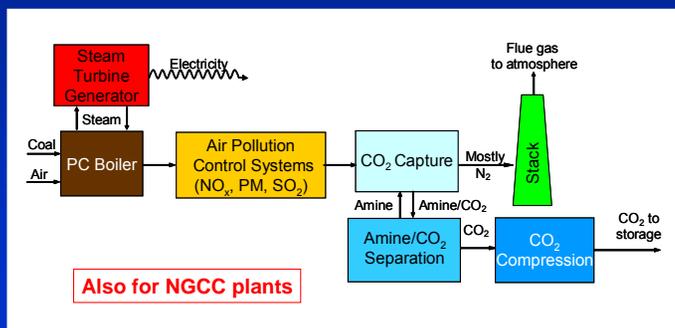
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CO₂ Capture Options for Power Plants: Pre-Combustion Capture



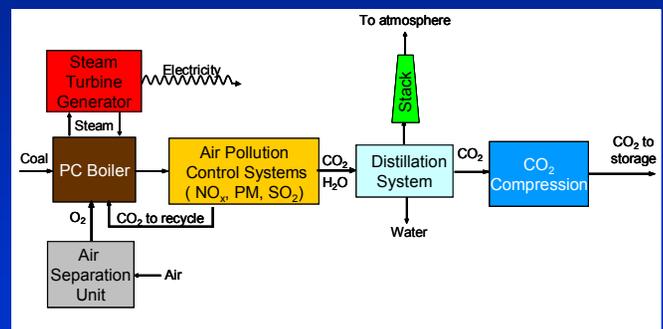
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CO₂ Capture Options for Power Plants: Post-Combustion Capture



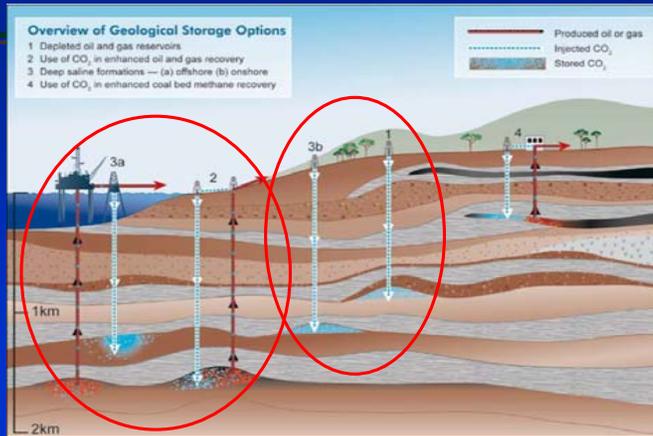
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CO₂ Capture Options for Power Plants: Oxy-Combustion Capture



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Geological Storage Options



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Status of CCS Technology

- Pre- and post-combustion CO₂ 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); CO₂ capture efficiencies are typically 85-90%. Oxyfuel capture is still under development.
- CO₂ transport via pipelines is a mature technology.
- Geological storage of CO₂ is commercial on a limited basis, mainly for EOR; several projects in deep saline formations are operating at scales of ~1 Mt CO₂/yr.
- Large-scale integration of CO₂ 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 CO₂ Capture Systems



Petoche Gasification to Produce H₂
(Coffeyville, Kansas, USA)

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

(Source: Dakota Gasification)

Pre-Combustion Capture at IGCC Plants



Puertollano IGCC Plant
(Spain)

Source: Eucema, 2007

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



Buggenum IGCC Plant
(The Netherlands)

Source: Nuon, 2009

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Post-Combustion Technology for Industrial CO₂ Capture

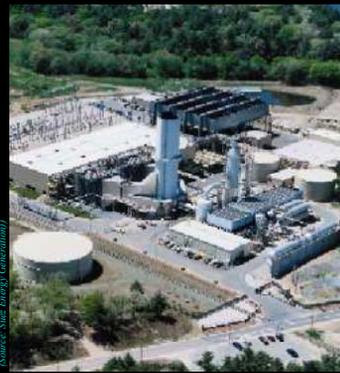


BP Natural Gas Processing Plant
(In Salah, Algeria)

Source: IEA GHG, 2008

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Post-Combustion CO₂ Capture at a Gas-Fired Power Plant



Source: Suez Energy (Germany)



Source: Plant Design

Bellingham Cogeneration Plant
(Bellingham, Massachusetts, USA)

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Post-Combustion CO₂ Capture at Coal-Fired Power Plants



Source: IBB (Germany)

Shady Point Power Plant
(Panama, Oklahoma, USA)

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Source: IEA GHG

Warrior Run Power Plant
(Cumberland, Maryland, USA)

Oxy-Combustion CO₂ Capture from a Coal-Fired Boiler



Source: Vattenfall, 2008



30 MW_e Pilot Plant (~10 MW_c)
at Vattenfall Schwarze Pumpe Station
(Germany)

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CO₂ Pipelines in the Western U.S.

> 3000 miles of pipeline
~40 MtCO₂/yr transported



Source: USDOE/Battelle

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Source: NRDC

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.

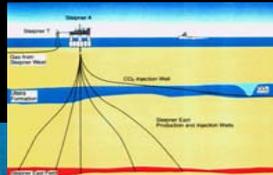
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Geological Storage of Captured CO₂ in a Deep Saline Formation



Sleipner Project (Norway)

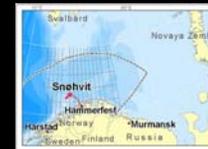
Source: Statoil



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Geological Storage of Captured CO₂ in a Deep Saline Formation

Snohvit LNG Project (Norway)



Source: www.Snohvit, 2009



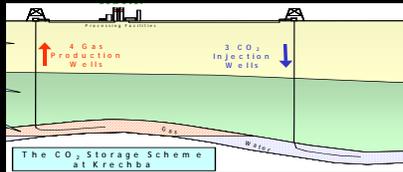
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Geological Storage of Captured CO₂ in a Depleted Gas Formation

In Salah /Krechba (Algeria)



Source: BP



The CO₂ Storage Scheme at Krechba

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Geological Formations in North America

Oil & Gas Fields

Deep Saline Formations



Source: NETL, 2009



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Geological Storage of Captured CO₂ with Enhanced Oil Recovery (EOR)



Weyburn Field, Canada



Sources: IEAGHG, NRDC, USDOE

Dakota Coal Gasification Plant, ND



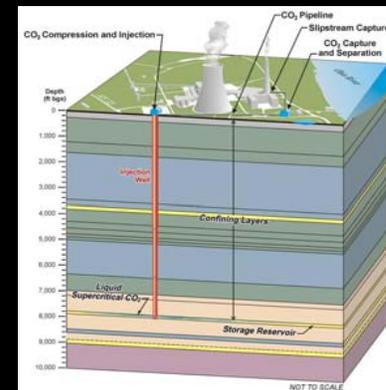
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CCS at a Coal-Fired Power Plant with Storage in a Deep Saline Formation

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

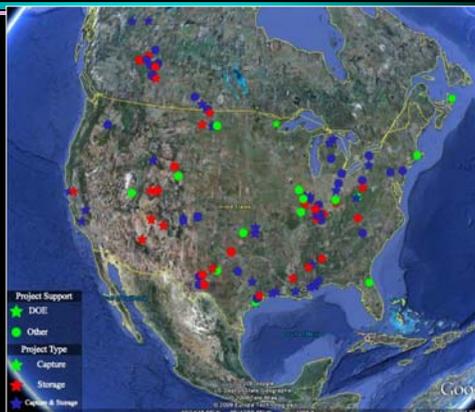
- Establish the **reliability, safety** and true **cost** of CCS in full-scale power plant applications
 - Help resolve legal and regulatory issues regarding geological sequestration
 - Help address issues of public acceptance
 - Begin reducing future costs via learning-by-doing
- Cost per project \approx \$1 billion (install/operate CCS, 400 MW, 5 yrs)

Financing large-scale projects has been a major hurdle

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Many projects are planned or underway at various scales

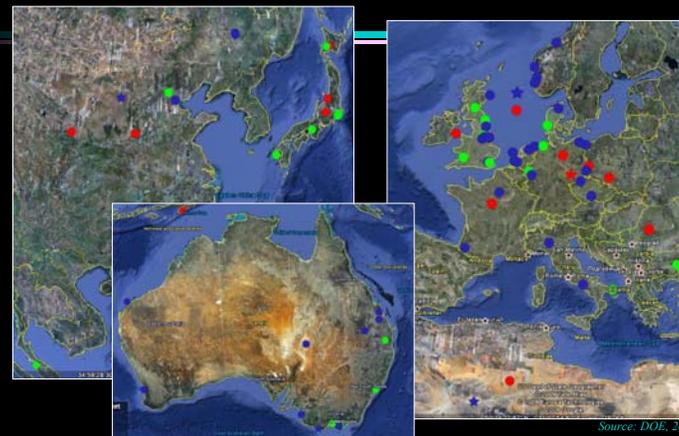
- Map shows **operating plus proposed or planned** projects in the U.S. and Canada. They encompass power plants, industrial sources and research projects spanning a large range of scale.



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Source: DOE, 2009

Substantial CCS Activity Globally



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Common Measures of Cost

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

$$= \frac{(TCC)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC)$$
- Cost of CO₂ Avoided (\$/ton CO₂ avoided)

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

Also: - Cost of CO₂ Captured (\$/ton CO₂ captured)
 - Cost of CO₂ Reduced/Abated (\$/ton CO₂ abated)

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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 CO₂ storage
6. Omit certain capital costs
5. Report \$/ton CO₂ 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!

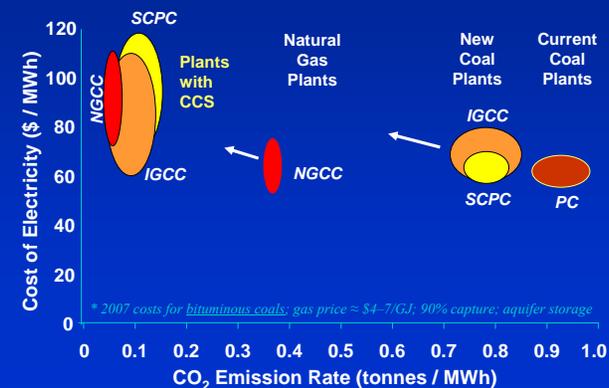
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Sources of Recent Cost Estimates

- IPCC, 2005: Special Report on CCS
- Rubin, et.al, 2007: *Energy Policy* paper
- 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)

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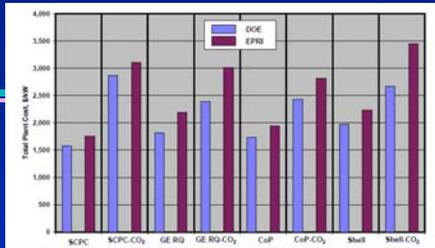
Estimated Cost of New Power Plants with and without CCS



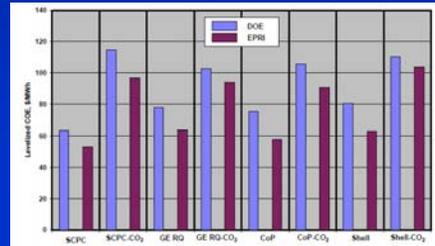
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DOE vs. EPRI

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



Source: EPRI, 2007



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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 <i>relative to same plant type without CCS based on bituminous coals</i>	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 CO₂ Avoided

(Relative to a SCPC reference plant; bituminous coals)

Levelized cost in US\$ per tonne CO₂ 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 /tCO ₂ ±\$15/t	~ \$50 /tCO ₂ ±\$10/t
Enhanced oil recovery (EOR) storage	Cost reduced by ~ \$20–30 /tCO ₂	

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

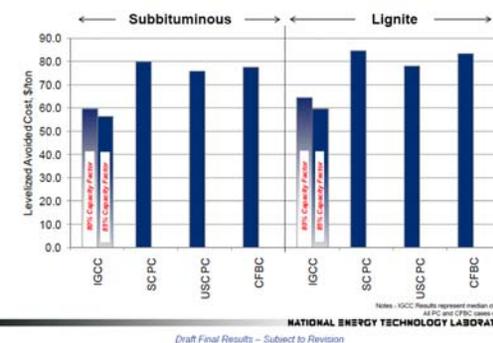
- Capture accounts for most (~80%) of the total cost

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

Avoided Cost of CO₂ Emissions

Includes Owners Costs



Draft Final Results - Subject to Revision

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Source: NREL, 2009

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.

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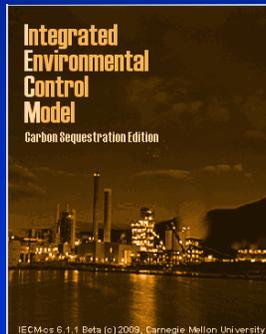
Breakdown of “Energy Penalty” for CO₂ Capture (SCPC and IGCC)

Component	Approx. % of Total Reqmt
Thermal Energy	~60%
CO ₂ Compression	~30%
Pumps, Fans, etc.	~10%

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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
 - CO₂ capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
 - Major updates in late 2009 & 2010



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The cost of CO₂ transport and storage

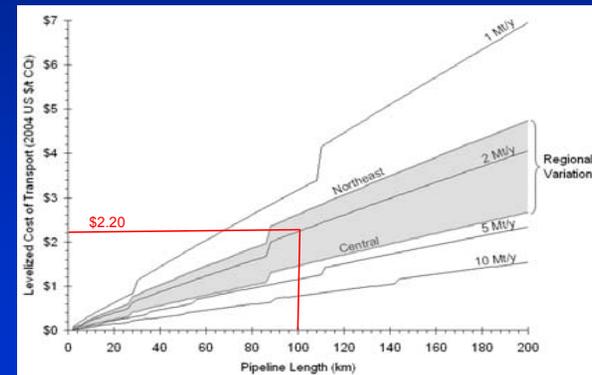
Pipeline Cost Model

- Multi-variate regression models based on data from 236 on-shore natural gas pipelines constructed in the U.S. from 1994 to 2003
 - Capital cost model is linear in pipe diameter, logarithmic in pipe length; reported in \$2004.
- Separate models for 6 regions
- Cost breakdowns for:
 - Materials
 - Labor
 - Eng'g, Overheads, AFUDC
 - Right-of-way



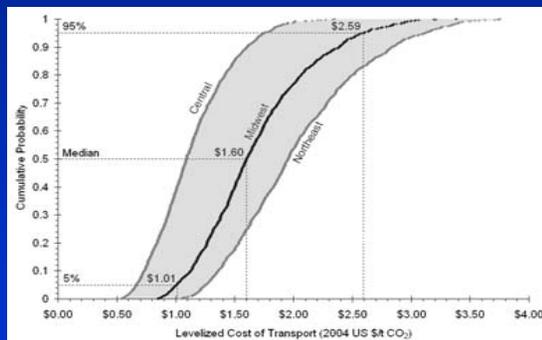
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Levelized Cost of Transport: Deterministic Results



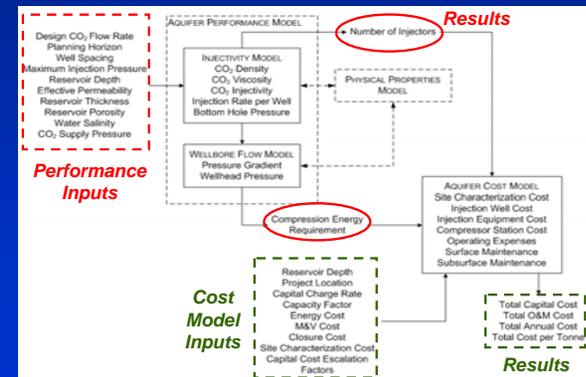
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Levelized Cost of Transport: Probabilistic Results



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Saline Formation Storage Model



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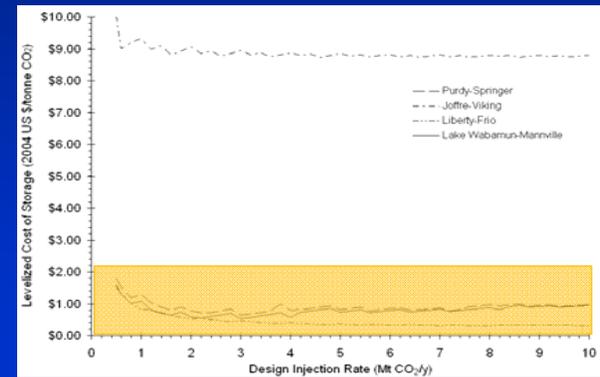
Illustrative Case Studies

- Data from 4 sites, with kh values from 4,500 to 940,000 md·ft
- Capital recovery factor =15% for all cases

Parameter	Northeast Purdy Unit	Joffre-Viking Pool	South Liberty	Lake Wabamun Area
Location	Oklahoma	Alberta	Texas	Alberta
Reservoir	Purdy Springer A	Viking Aquifer	Frio Formation	Mannville Aquifer
Lithology	Sandstone	Sandstone	Sandstone	Sandstone
Depth (m)	2,499	1,500	1,850	1,514
Permeability, k (md)	44	507	944	23
Net Sand, h (m)	91	30	300	59

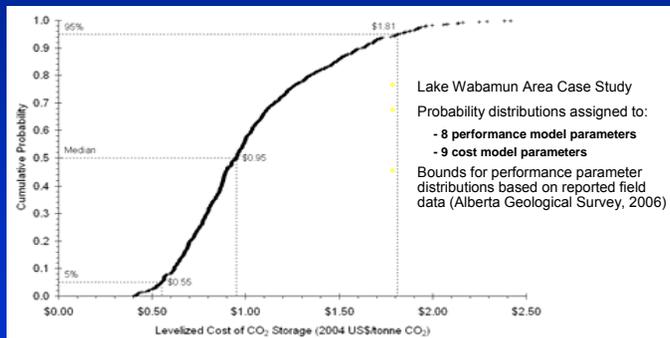
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Levelized Cost of CO₂ Storage



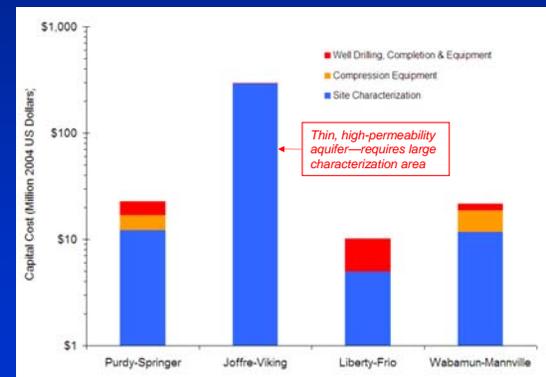
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Levelized Cost of CO₂ Storage: Probabilistic Results



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Capital Cost Breakdown



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Full details in technical reports & papers (available from IECM website)

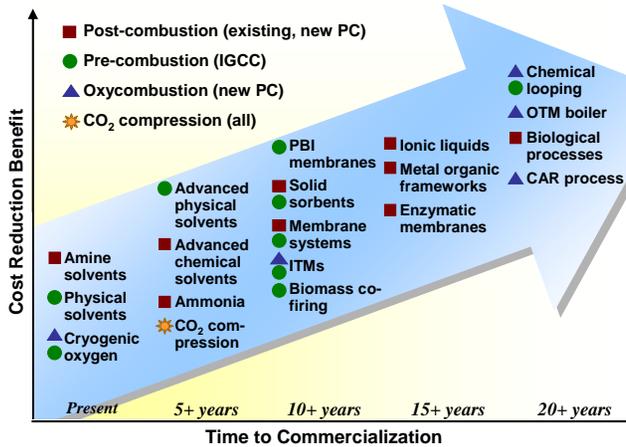


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What is the potential for lower-cost capture technology?

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Better Capture Technologies Are Emerging



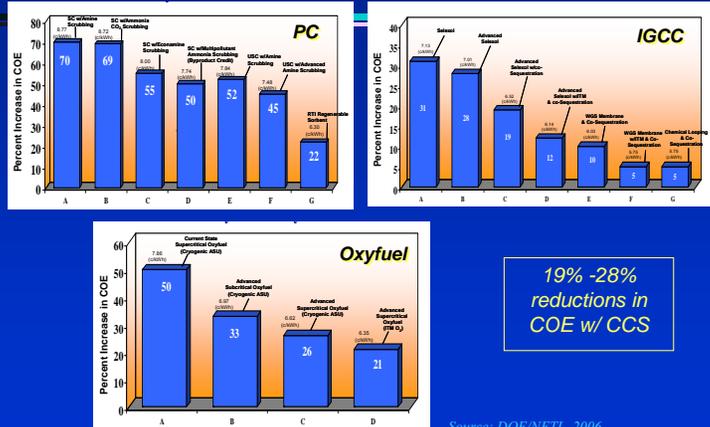
OFFICE OF FOSSIL ENERGY

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

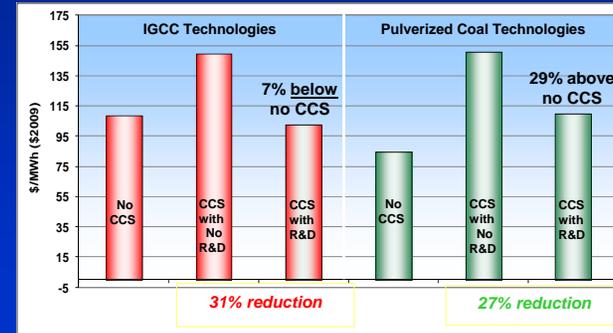
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Potential Cost Reductions Based on Engineering-Economic Analysis



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Potential Cost Reductions Based on Engineering-Economic Analysis



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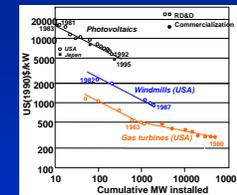
Two Approaches to Estimating Future Technology Costs

- 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”

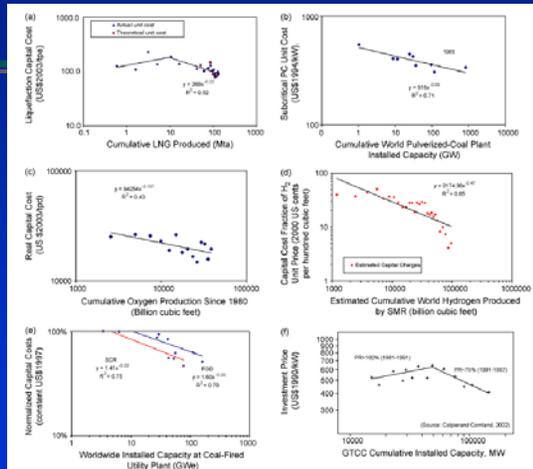
- Cost trends modeled as a log-linear relationship between unit cost and cumulative production or capacity: $y = ax^{-b}$



- 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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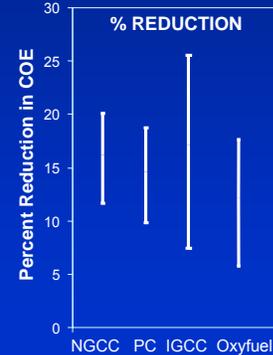
Experience Curves for Case Study Technologies



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Potential Cost Reductions Based on Learning Curve Analysis *

(after 100 GW of cumulative CCS capacity worldwide)



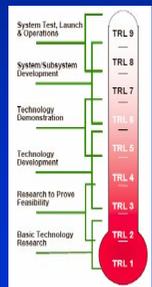
- Upper bound of projected cost reduction are similar to estimates from DOE's "bottom-up" analyses

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

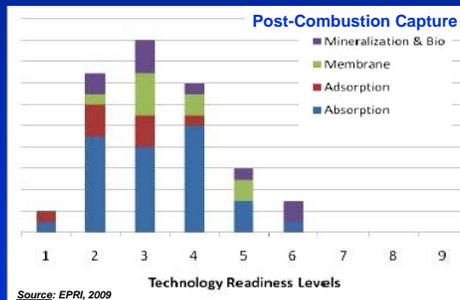
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Most New Capture Concepts Are Far from Commercial Availability

Technology Readiness Levels



Source: NASA, 2009

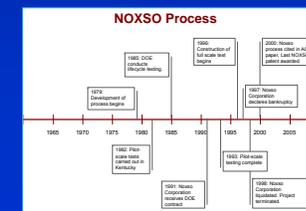
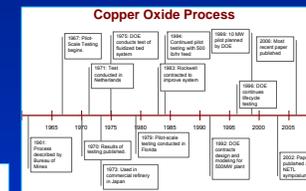
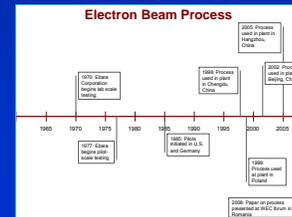


Source: EPRI, 2009

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Most new concepts take decades to commercialize...many never make it

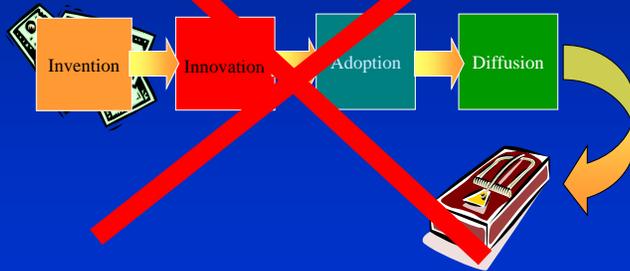
Development timelines for three novel processes for combined SO₂-NO_x capture



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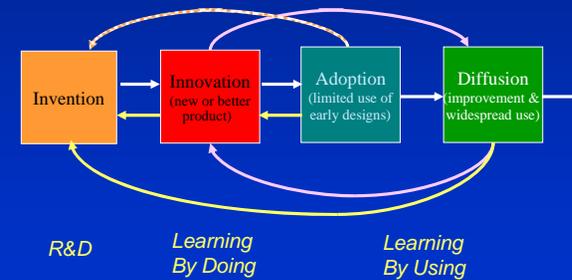
Challenge 1: Accelerate the Pace of Innovation

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

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The Critical Role of Policy

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

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Conclusions

- Significant potential to reduce the cost of carbon capture via:
 - New or improved CO₂ capture technologies
 - Improved plant efficiency and utilization
- But must also build and operate some full-size plants with current technology....
- And enact policies that create and foster markets for CCS technologies

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Thank You

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