The Status of CO_2 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

Why the interest in CCS ?

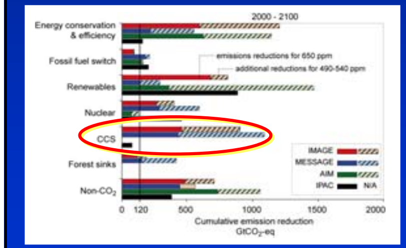
(Carbon Capture and Storage /Sequestration)

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

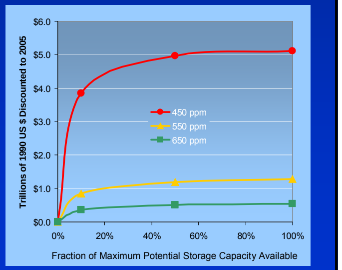
Cost-Effective Global Strategies Require CCS in the Portfolio

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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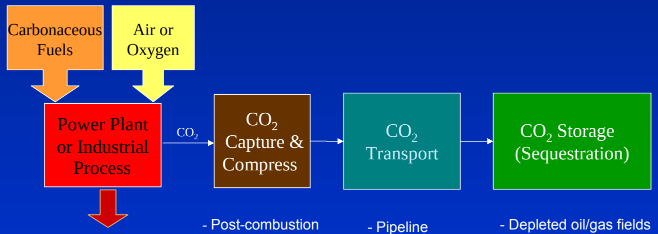
Schematic of a CCS System



Useful Products
(Electricity, Fuels, Chemicals, Hydrogen)

- Post-combustion
- Pre-combustion
- *Oxyfuel combustion*

- Pipeline
- *Tanker*

- Depleted oil/gas fields
- Deep saline formations
- *Unmineable coal seams*
- *Ocean*
- *Mineralization*
- *Reuse*

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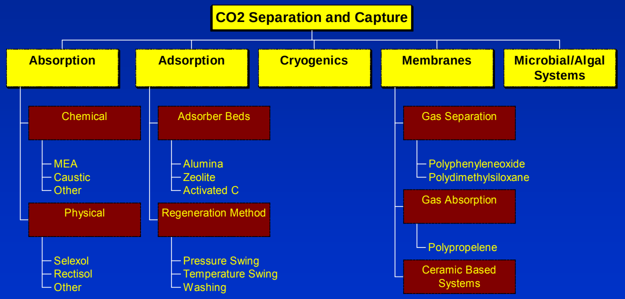
Many Ways to Capture CO$_2$



CO2 Separation and Capture

- **Absorption**
  - Chemical
    - MEA
    - Caustic
    - Other
  - Physical
    - Selexol
    - Rectisol
    - Other
- **Adsorption**
  - Adsorber Beds
    - Alumina
    - Zeolite
    - Activated C
  - Regeneration Method
    - Pressure Swing
    - Temperature Swing
    - Washing
- **Cryogenics**
- **Membranes**
  - Gas Separation
    - Polyphenyleneoxide
    - Polydimethylsiloxane
  - Gas Absorption
    - Polypropelene
  - Ceramic Based Systems
- **Microbial/Algal Systems**

Choice of technology depends strongly on application

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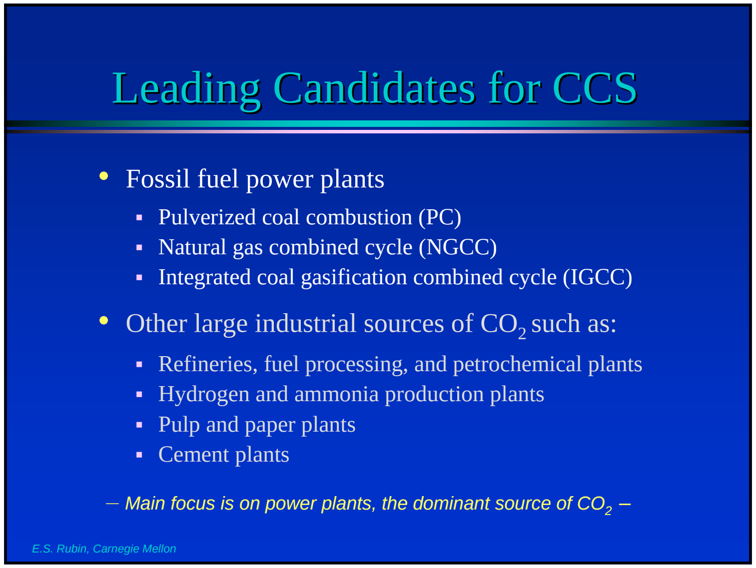

Leading Candidates for CCS

- 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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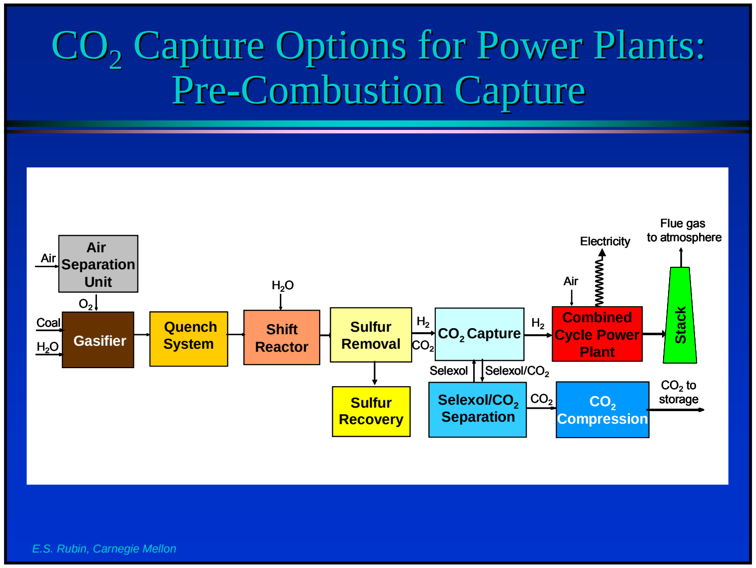

CO_2 Capture Options for Power Plants: Pre-Combustion Capture

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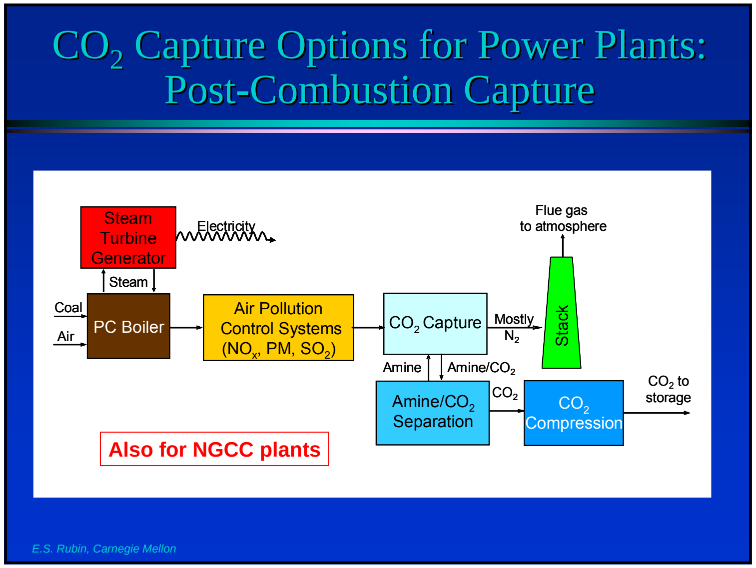

CO_2 Capture Options for Power Plants: Post-Combustion Capture

Also for NGCC plants

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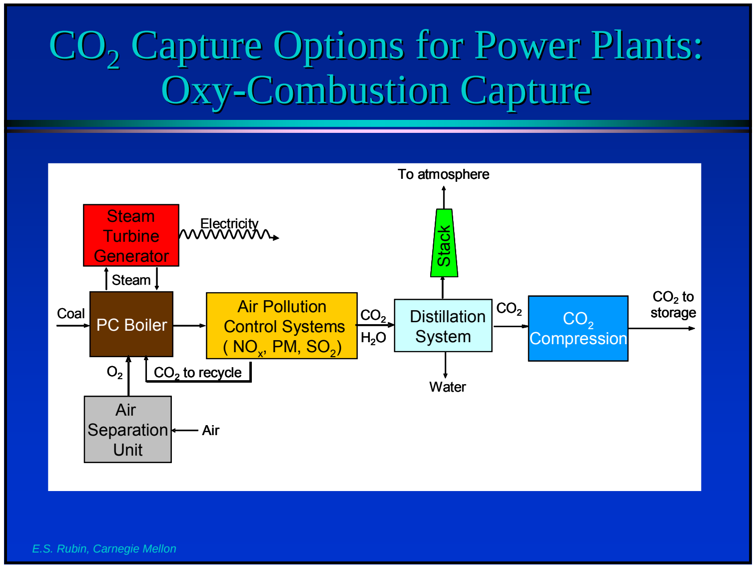

CO_2 Capture Options for Power Plants: Oxy-Combustion Capture

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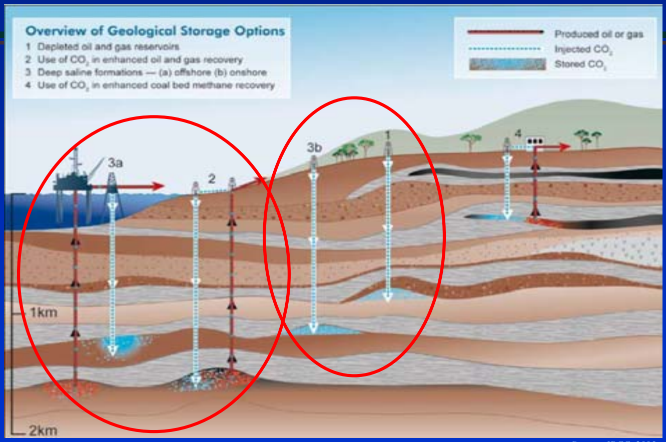
Geological Storage Options



Source: IPCC, 2005

Status of CCS Technology

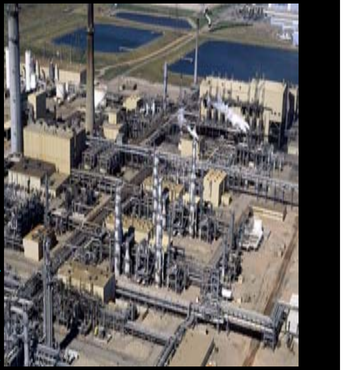
- Pre- and post-combustion CO_2 capture technologies are commercial and widely used in industrial processes; also at several gas-fired and coal-fired power plants, at small scale (~40 MW); CO_2 capture efficiencies are typically 85-90%. Oxyfuel capture is still under development.
- CO_2 transport via 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.

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

Puertollano IGCC Plant

(Spain)

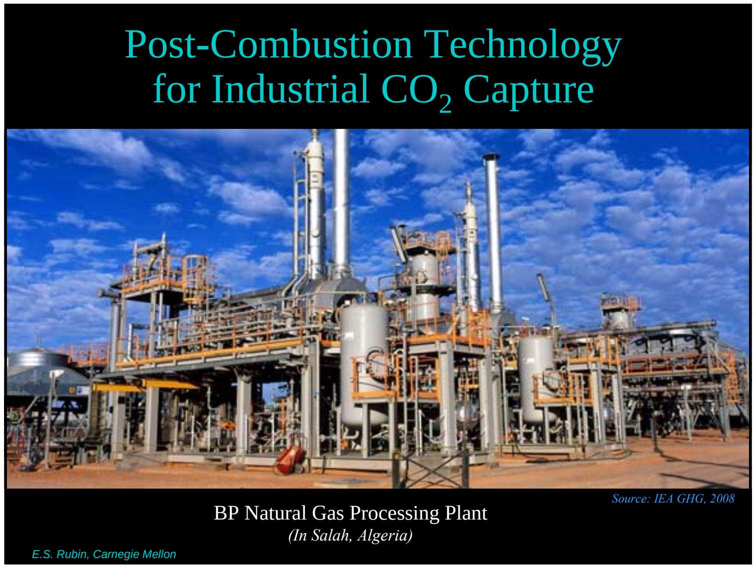
Source: Elcano, 2007

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)

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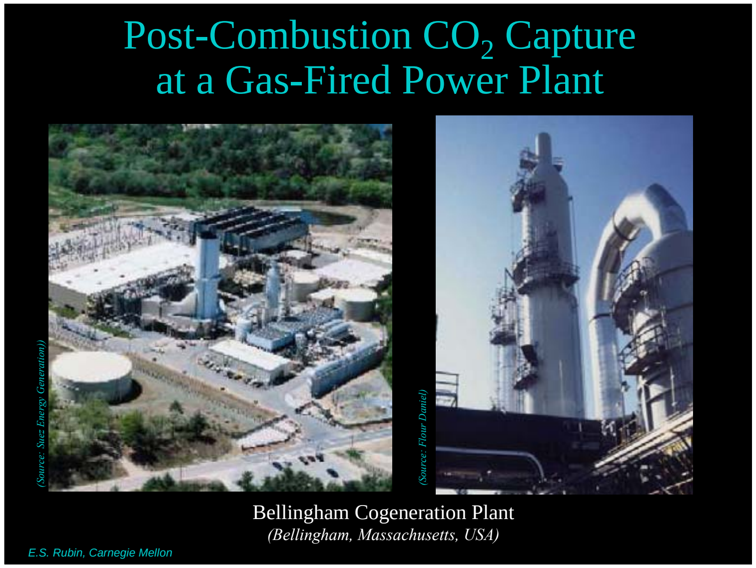

Post-Combustion CO_2 Capture at a Gas-Fired Power Plant

(Source: Suez Energy Generation)

(Source: Flour Daniel)

Bellingham Cogeneration Plant
(Bellingham, Massachusetts, USA)

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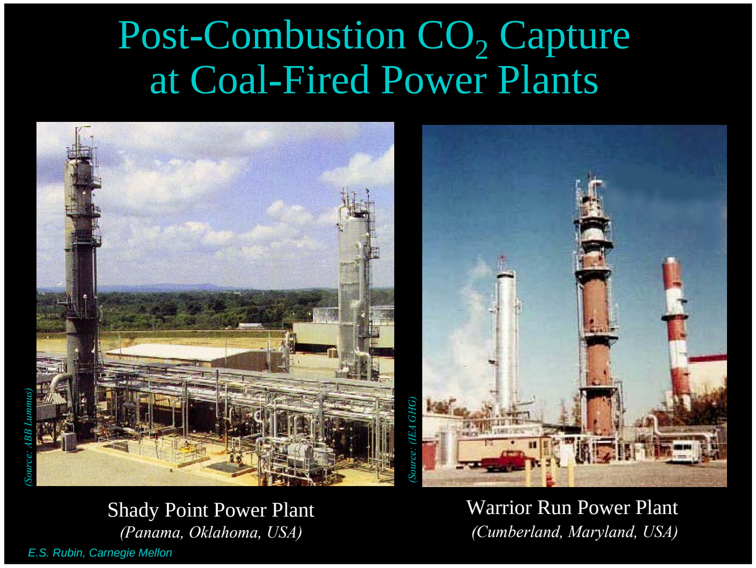

Post-Combustion CO_2 Capture at Coal-Fired Power Plants

(Source: ABB Lummus)

Shady Point Power Plant
(Panama, Oklahoma, USA)

(Source: IEA GHG)

Warrior Run Power Plant
(Cumberland, Maryland, USA)

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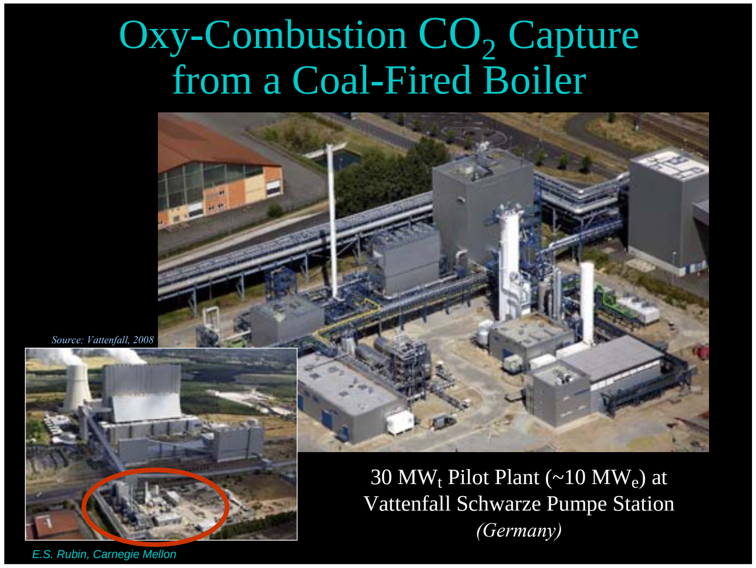

Oxy-Combustion CO_2 Capture from a Coal-Fired Boiler

Source: Vattenfall, 2008

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

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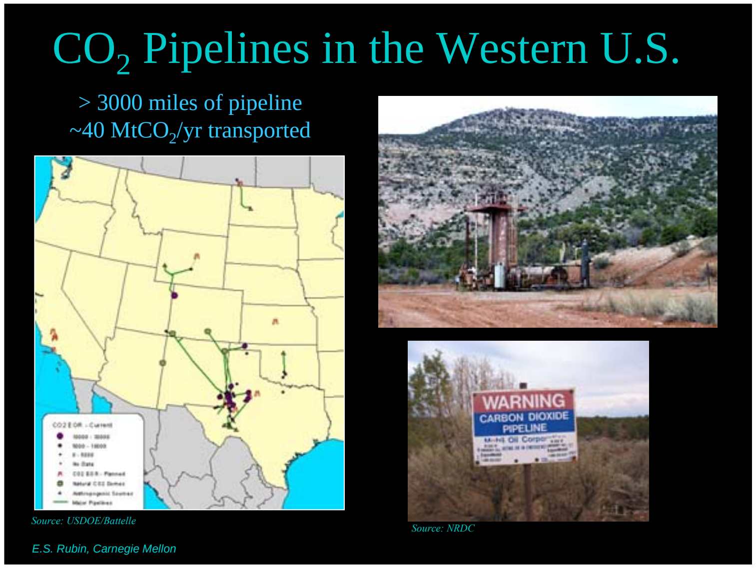

CO$_2$ Pipelines in the Western U.S.

> 3000 miles of pipeline
~40 MtCO$_2$/yr transported

Source: USDOE/Battelle

Source: NRDC

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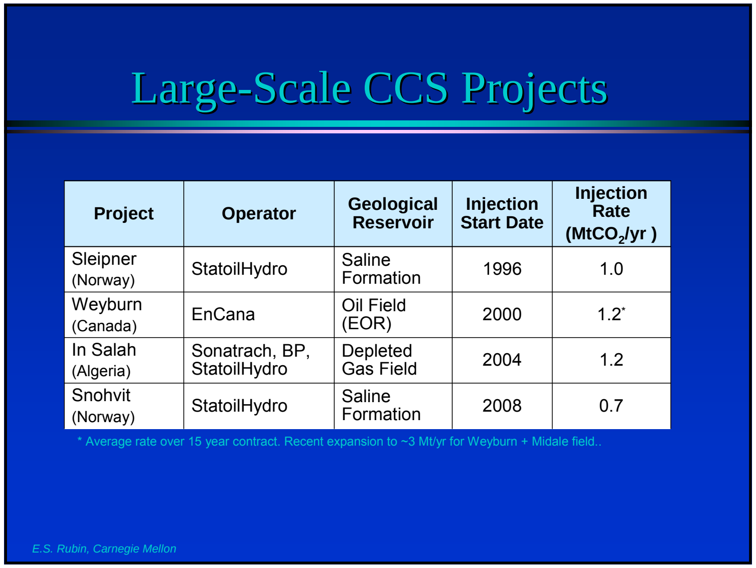

Large-Scale CCS Projects

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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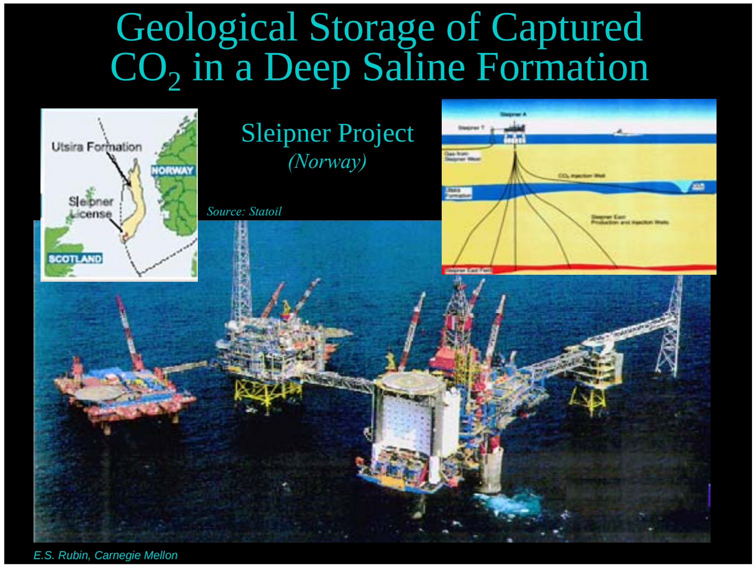

Geological Storage of Captured CO$_2$ in a Deep Saline Formation

Sleipner Project
(Norway)

Source: Statoil

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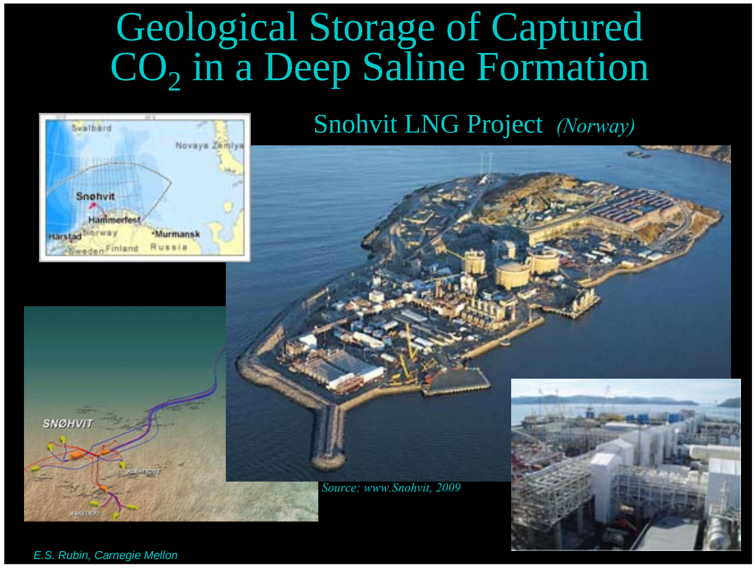

Geological Storage of Captured CO$_2$ in a Deep Saline Formation

Snohvit LNG Project *(Norway)*

Source: www.Snohvit, 2009

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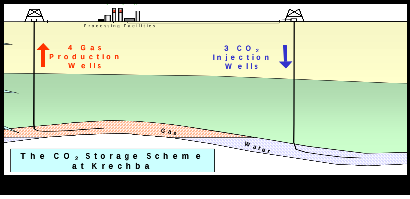
Geological Storage of Captured CO_2 in a Depleted Gas Formation

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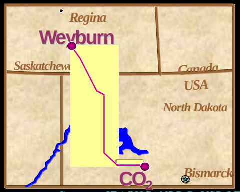
Geological Storage of Captured CO_2 with Enhanced Oil Recovery (EOR)

Weyburn Field, Canada



Sources: IEAGHG; NRDC; USDOE

Dakota Coal Gasification Plant, ND

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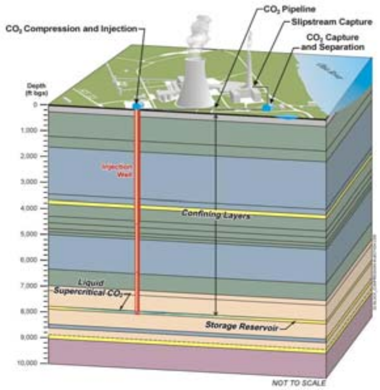
CCS at a Coal-Fired Power Plant with Storage in a Deep Saline Formation

(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

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

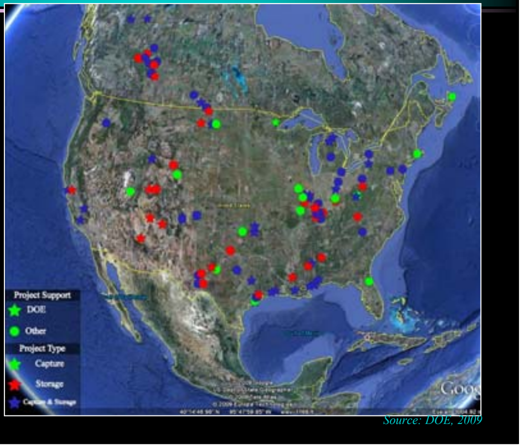
- Establish the reliability, safety and true cost of CCS in full-scale power plant applications
- Help resolve legal and regulatory issues regarding geological sequestration
- Help address issues of public acceptance
- Begin reducing future costs via learning-by-doing

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

Financing large-scale projects has been a major hurdle

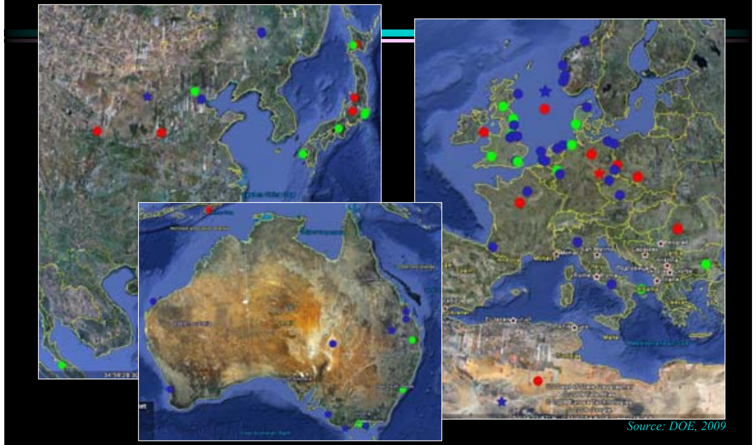
Many projects are planned or underway at various scales

- 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



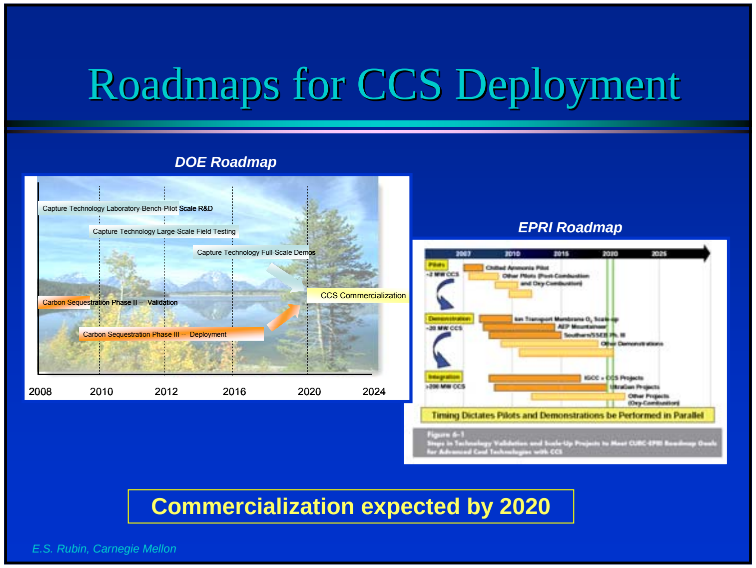
Source: DOE, 2009

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



Roadmaps for CCS Deployment

DOE Roadmap

EPRI Roadmap

Commercialization expected by 2020

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)

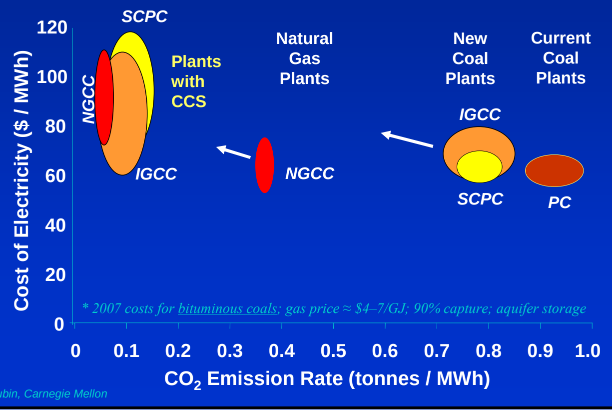
10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume EOR credits for CO_2 storage
6. Omit certain capital costs
5. Report $/ton CO_2 based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high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

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

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)

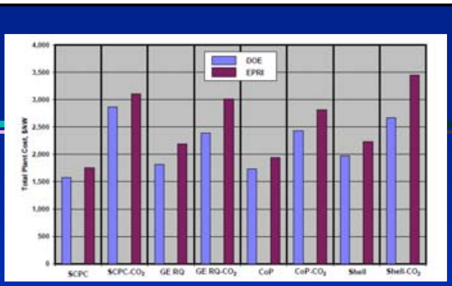
Estimated Cost of New Power Plants with and without CCS



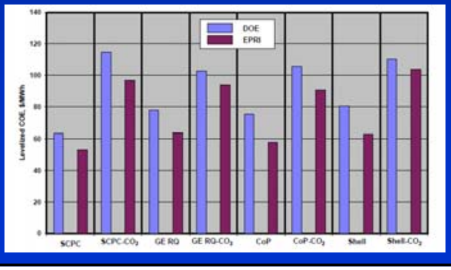
** 2007 costs for <u>bituminous coals</u>; gas price ≈ $4–7/GJ; 90% capture; aquifer storage*

DOE vs. EPRI

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



Source: EPRI, 2007



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 SCPC reference plant; bituminous coals)

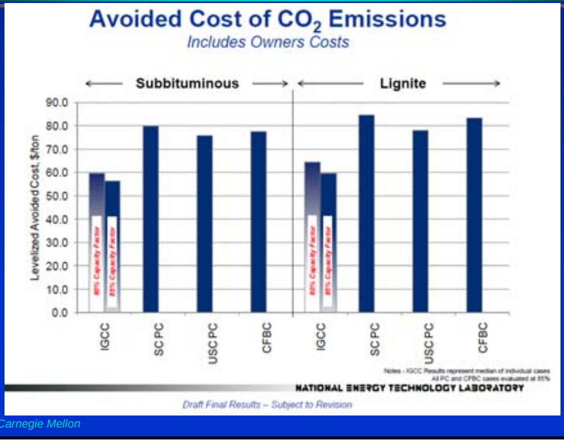
Levelized cost in US$ per tonne CO_2 avoided

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***

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



Source: NETL, 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%

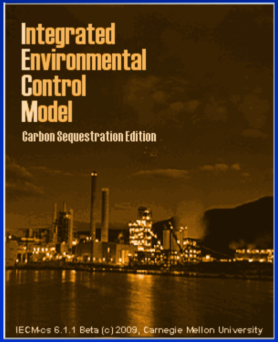
Changes in plant efficiency due to CCS energy requirements also affect plant-level pollutant emission rates (per MWh). A site-specific context is needed to evaluate the net impacts.

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%

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

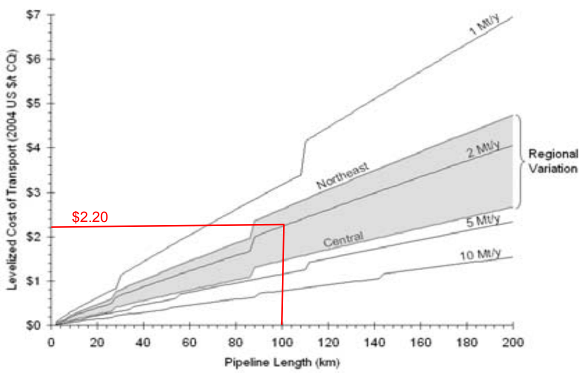


The cost of CO_2 transport and storage

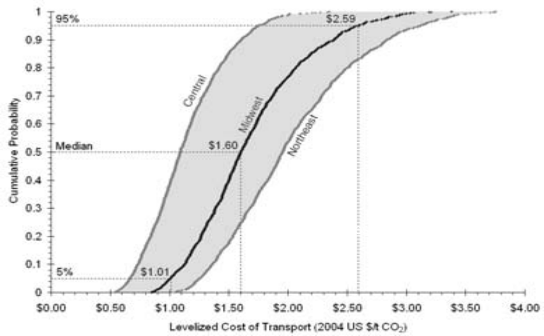
Pipeline Cost Model

- 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

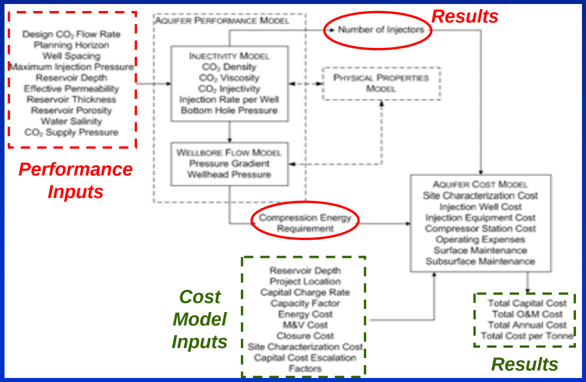
Levelized Cost of Transport:
Deterministic Results



Levelized Cost of Transport:
Probabilistic Results



Saline Formation Storage Model

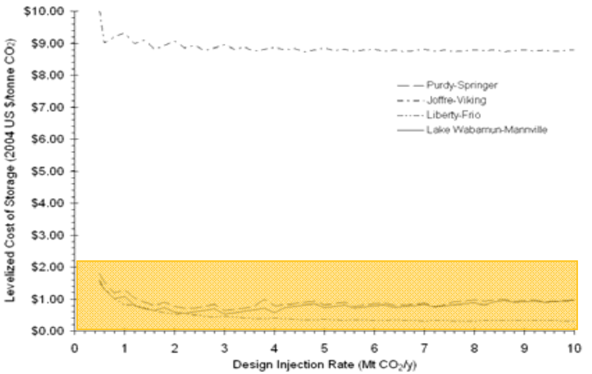


Illustrative Case Studies

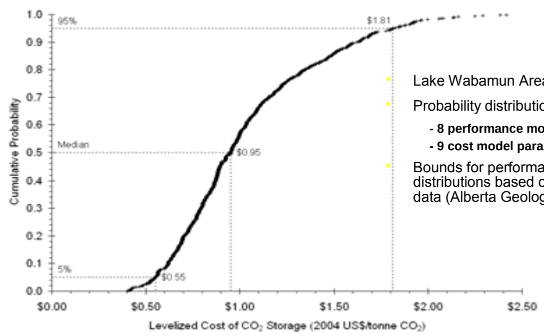
- Data from 4 sites, with *kh* values from 4,500 to 940,000 md·ft
- Capital recovery factor =15% for all cases

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

Levelized Cost of CO_2 Storage

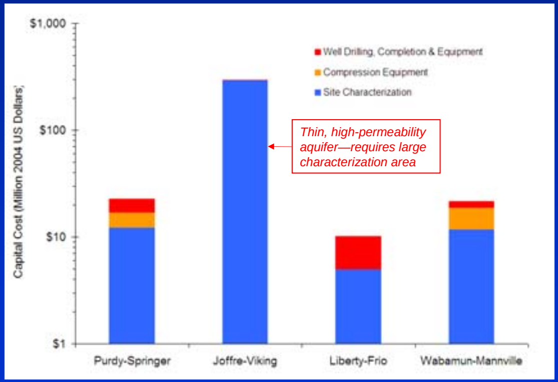


Levelized Cost of CO_2 Storage: *Probabilistic Results*



- Lake Wabamun Area Case Study
- Probability distributions assigned to:
  - **- 8 performance model parameters**
  - **- 9 cost model parameters**
- Bounds for performance parameter distributions based on reported field data (Alberta Geological Survey, 2006)

Capital Cost Breakdown



Thin, high-permeability aquifer—requires large characterization area

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

Technical Documentation:
The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs

Final Report of

Work Performed Under Contract No.: DE-AC26-04NT41817
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Reporting Period End, May 2008

Report Submitted, April 2008

to

U.S. Department of Energy
National Energy Technology Laboratory

An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage

Sean T. McCoy, Edward S. Rubin

Energy Procedia

GHGT-9

Variability and Uncertainty in the Cost of Saline Formation Storage

Sean T. McCoy, Edward S. Rubin

ScienceDirect

Energy Procedia

GHGT-9

The effect of high oil prices on EOR project economics

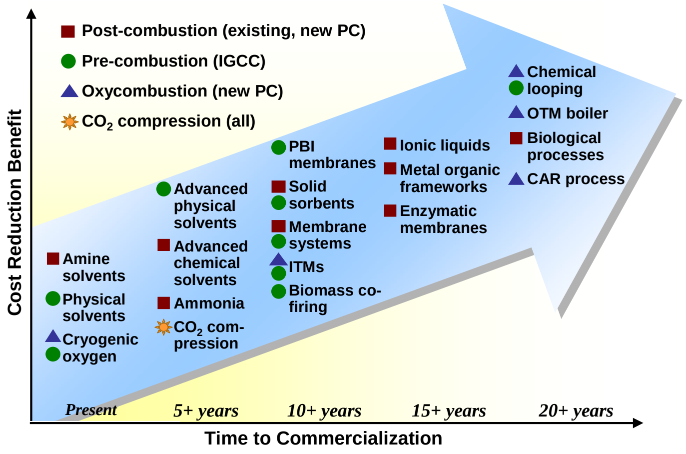
Sean T. McCoy, Edward S. Rubin

E.S. Rubin, Carnegie Mellon

What is the potential for lower-cost capture technology?

E.S. Rubin, Carnegie Mellon

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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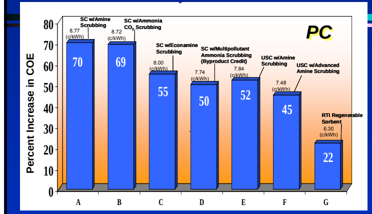
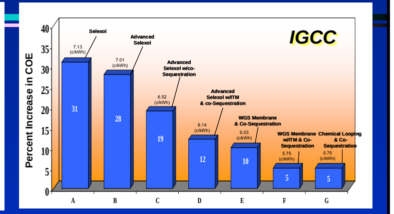
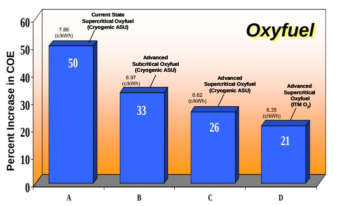
Potential Cost Reductions Based on Engineering-Economic Analysis



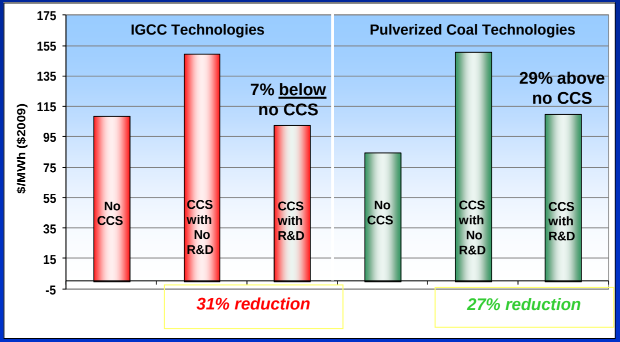




19% -28% reductions in COE w/ CCS

Source: DOE/NETL, 2006

Potential Cost Reductions Based on Engineering-Economic Analysis



Source: DOE/ NETL, 2010

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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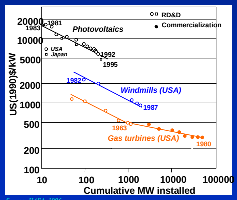
Empirical "Learning Curves"

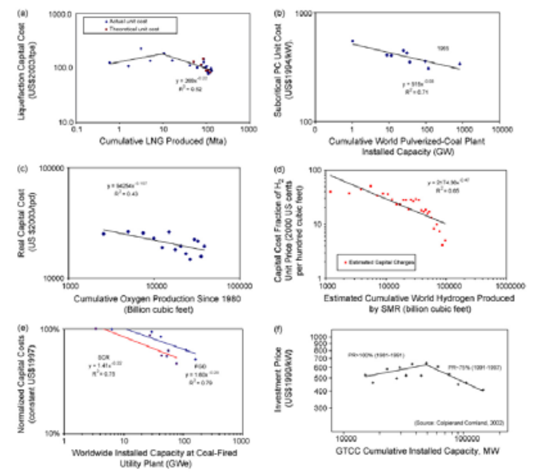
- Cost trends modeled as a log-linear relationship between unit cost and cumulative production or capacity: $y = ax^{-b}$



Source: IIASA, 1996

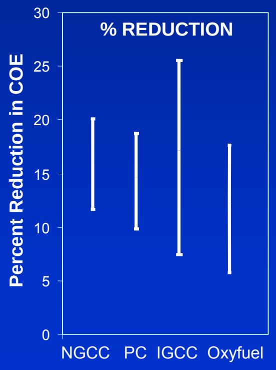
- Case studies used for power plant components:
  - Flue gas desulfurization systems (FGD)
  - Selective catalytic reduction systems (SCR)
  - Gas turbine combined cycle system (GTCC)
  - Pulverized coal-fired boilers (PC)
  - Liquefied natural gas plants (LNG)
  - Oxygen production plants (ASU)
  -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

Experience Curves for Case Study Technologies



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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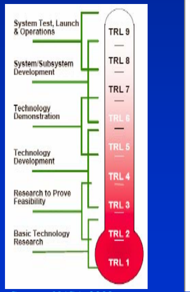
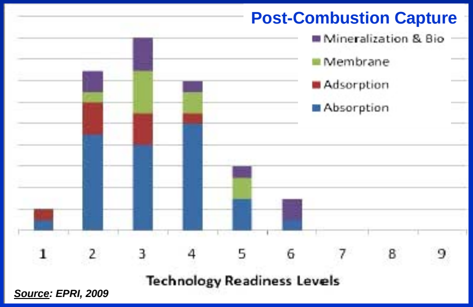
Most New Capture Concepts Are Far from Commercial Availability

Technology Readiness Levels



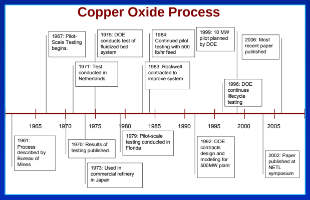
Source: NASA, 2009



***Source*: EPRI, 2009**

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

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



1961: Process described by Bureau of Mines

1967: Pilot-Scale Testing begins.

1970: Results of testing published.

1971: Test conducted in Netherlands

1973: Used in commercial refinery in Japan

1975: DOE conducts test of fluidized bed system

1979: Pilot-scale testing conducted in Florida

1983: Rockwell contracted to improve system

1984: Continued pilot testing with 500 lb/hr feed

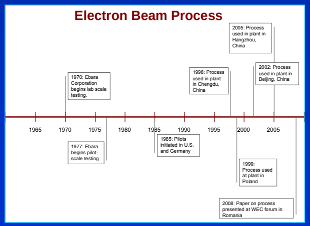
1992: DOE contracts design and modeling for 500MW plant

1996: DOE continues lifecycle testing

1999: 10 MW pilot planned by DOE

2002: Paper published at NETL symposium

2006: Most recent paper published



1970: Ebara Corporation begins lab scale testing.

1977: Ebara begins pilot-scale testing

1985: Pilots initiated in U.S. and Germany

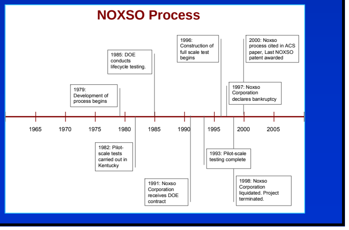
1998: Process used in plant in Chengdu, China

1999: Process used at plant in Poland

2002: Process used in plant in Beijing, China

2005: Process used in plant in Hangzhou, China

2008: Paper on process presented at WEC forum in Romania



1979: Development of process begins

1982: Pilot-scale tests carried out in Kentucky

1985: DOE conducts lifecycle testing.

1991: Noxso Corporation receives DOE contract

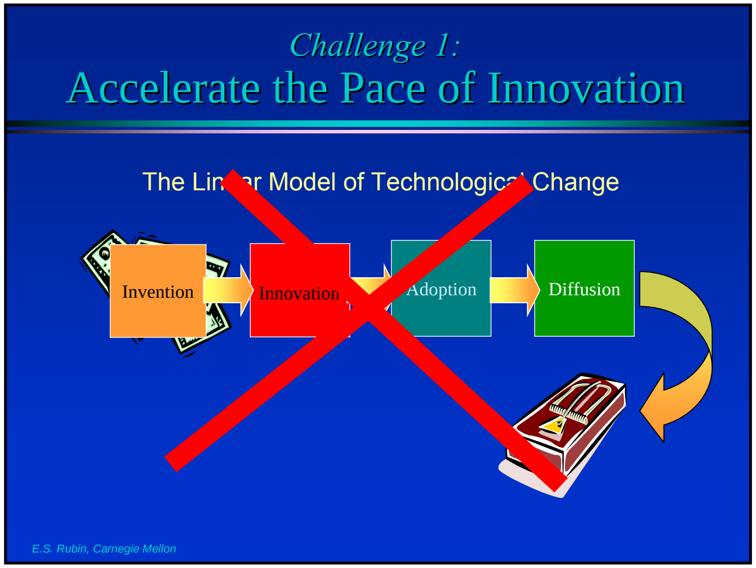
1993: Pilot-scale testing complete

1996: Construction of full scale test begins

1997: Noxso Corporation declares bankruptcy

1998: Noxso Corporation liquidated. Project terminated.

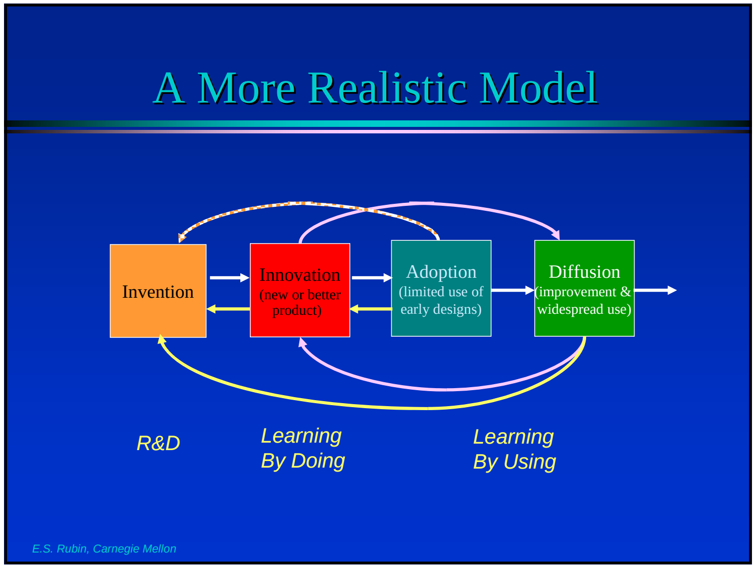
2000: Noxso process cited in ACS paper, Last NOXSO patent awarded



Challenge 1:
Accelerate the Pace of Innovation

The Linear Model of Technological Change

E.S. Rubin, Carnegie Mellon



A More Realistic Model

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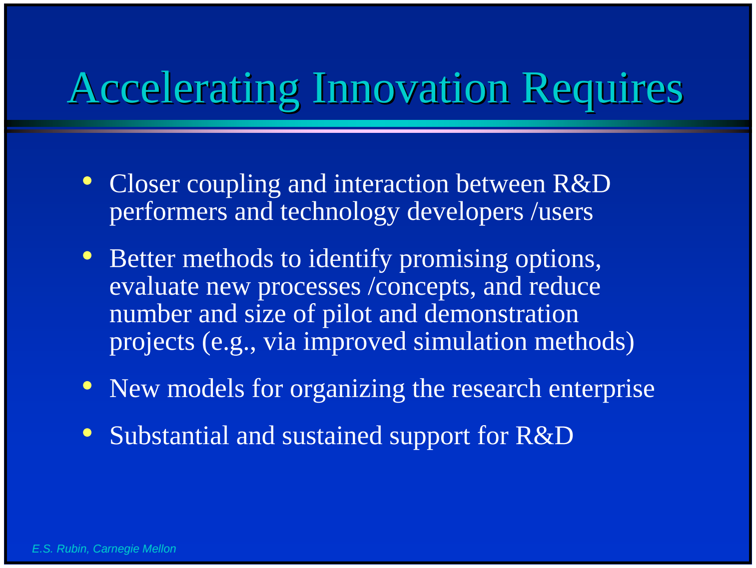

Accelerating Innovation Requires

- 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

E.S. Rubin, Carnegie Mellon

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

E.S. Rubin, Carnegie Mellon

Conclusions

- Significant potential to reduce the cost of carbon capture via:
  - New or improved CO_2 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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