# Carbon Capture and Storage Technology

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## Outline of Talk

- Why the interest in $CO_2$ capture and storage (CCS)?
- Current status and cost of CCS technology
- Potential for improved technology
- Barriers to CCS deployment
- Future outlook

## *Why the interest in CCS ?*



## The Policy Framework

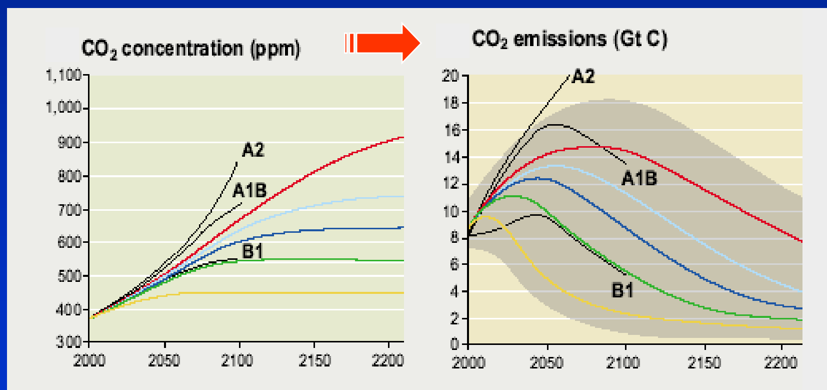
- 1992 U.N. Framework Convention on Climate Change calls for:

  "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"

- *192 countries are parties to the Convention*

# What it Takes to Stabilize Atmospheric $CO_2$ Concentration

(a) Atmospheric Stabilization Scenarios (b) Required $CO_2$ Emissions




*Source: IPCC, 2001*

Must drastically reduce future $CO_2$ emissions

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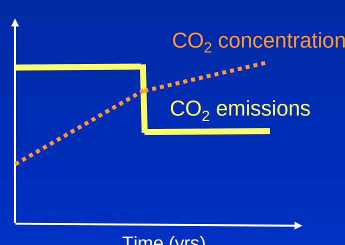
# Unlike conventional air pollutants, most GHGs stay in the atmosphere for centuries

Atmospheric $CO_2$ Concentration vs. $CO_2$ Emissions




*$\tau_{atm, CO2} \approx$ 100 years*

*Current and projected $CO_2$ emissions are "filling the bathtub" faster than it is being "drained"—so the atmospheric level keeps rising… even when emissions are reduced by a modest amount*

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# Avoiding Serious Climate Change Impacts Requires Action Now

*The most recent IPCC assessment indicates potentially serious impacts for more that a 2ºC rise in average global temperature*

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

*Source: IPCC, 2007*

Fossil fuels provide over 80% of our energy and are the dominant source of $CO_2$ (a third of U.S. emissions is from burning coal for electricity generation)

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# The Motivation for CCS

- Fossil fuels, especially coal, will continue to be used extensively for many decades to come—alternatives not easily able to achieve large $CO_2$ reductions needed to stabilize atmospheric level of GHGs
- CCS could allow continued coal use as a bridge to a more sustainable future — also a potential link to carbon-free energy for transportation
- Energy-economic models show that including CCS in a portfolio of options significantly reduces the cost of mitigating climate change

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# *CCS Overview*

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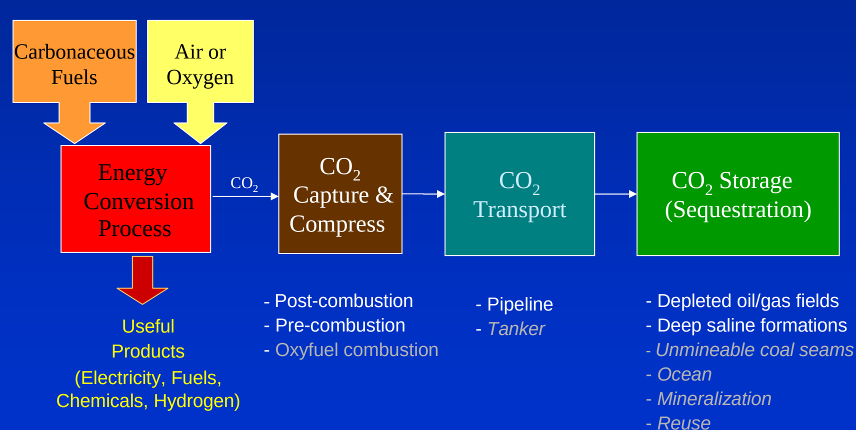
# Schematic of a CCS System

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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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# 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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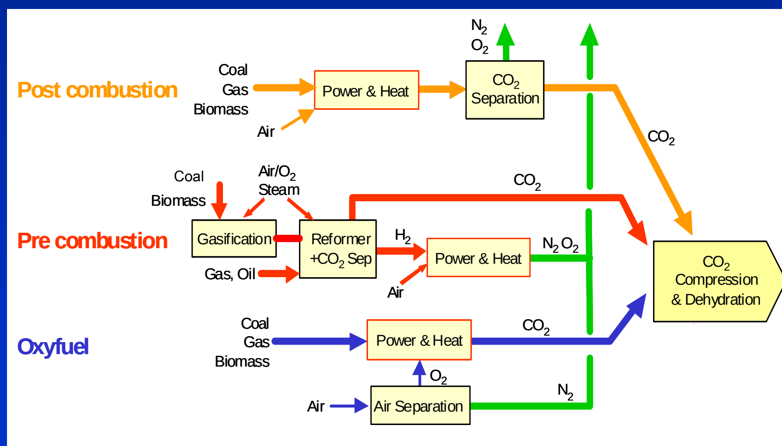
# $CO_2$ Capture Options for Power Plants




*Source: IPCC SRCCS, 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 (~50 MW); $CO_2$ capture efficiencies are typically 85-90%. Oxyfuel capture still under development.
- $CO_2$ pipelines are a mature technology
- Geological storage is commercial on a limited basis, mainly for EOR; several sequestration projects are now operating at scale of ~1 Mt $CO_2$ /yr
- Integration of $CO_2$ capture, transport and geological sequestration has been demonstrated in several industrial applications—but not yet at an electric power plant, and not yet in the U.S.

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# $CO_2$ Capture Projects


*Source: IEA GHG, 2007*

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# Examples of Post-Combustion $CO_2$ Capture at Coal-Fired 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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# Examples of Post-Combustion $CO_2$ Capture at Gas-Fired Plants

(Source: Suez Energy Generation))

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

(Source: Mitsubishi Heavy Industries)

Petronas Urea Plant Flue Gas
*(Keda, Malaysia)*

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## Integrated Coal Gasification Combined Cycle (IGCC) Plant

Polk Power Station, Tampa, Florida
(250 MW, no $CO_2$ capture)

*Source: TECO, 2004*

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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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# Example of Oxyfuel Combustion Capture System

*Source: Vattenfall, 2008*

Vattenfall Schwarze Pumpe Station

*(Germany)*

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# Example of Industrial $CO_2$ Capture

(using post-combustion capture technology)

*Source: IEA GHG, 2008*

BP Natural Gas Processing Plant

*(In Salah, Algeria)*

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

~40 $MtCO_2$/yr transported


*Source: USDOE/Battelle*


*Source: NRDC*

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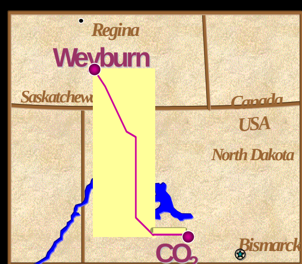
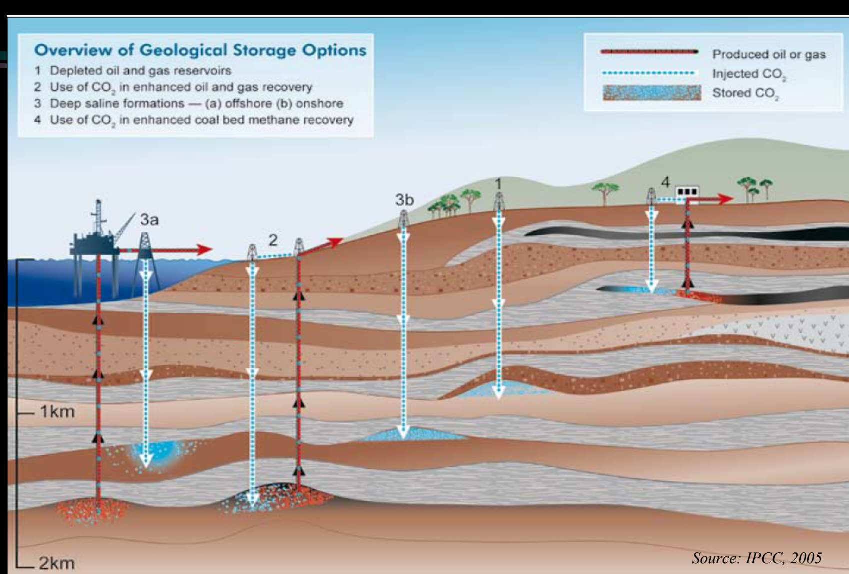
## A 200-mile pipeline delivers captured $CO_2$ from North Dakota to Saskatchewan




Sources: IEAGHG; NRDC; USDOE




## Geological Storage Options



# Global Storage Capacity Estimates

| Reservoir Type | Lower Estimate ($GtCO_2$) | Upper Estimate ($GtCO_2$) |
|---|---|---|
| Deep saline formations | 1000 | Uncertain, but possibly ~$10^4$ |
| Oil and gas fields | 675* | 900* |
| Unminable coal seams | 3–15 | 200 |

* Estimates are 25% larger if "undiscovered reserves" are included. (Source: IPCC, 2005)

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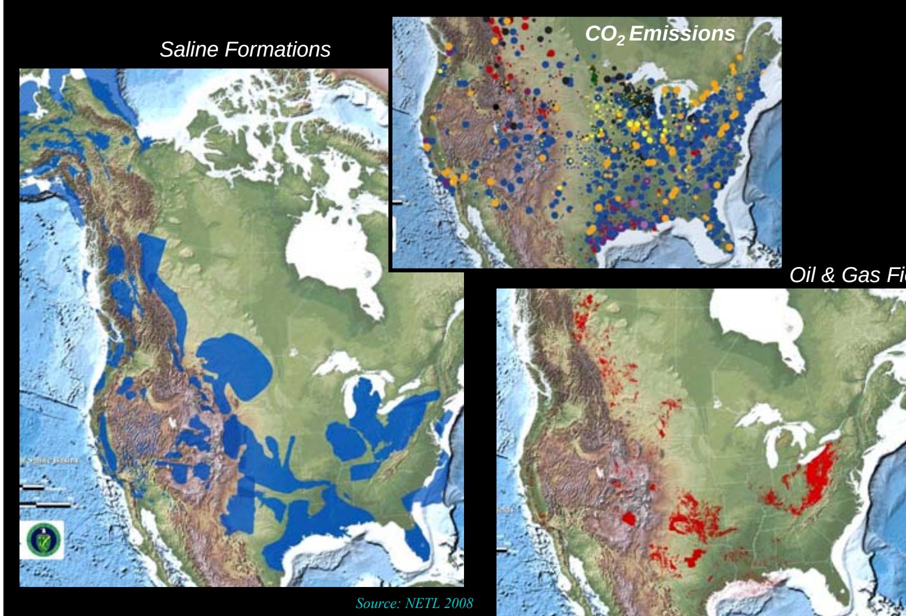
# $CO_2$ Sources and Geological Formations




*Source: NETL 2008*

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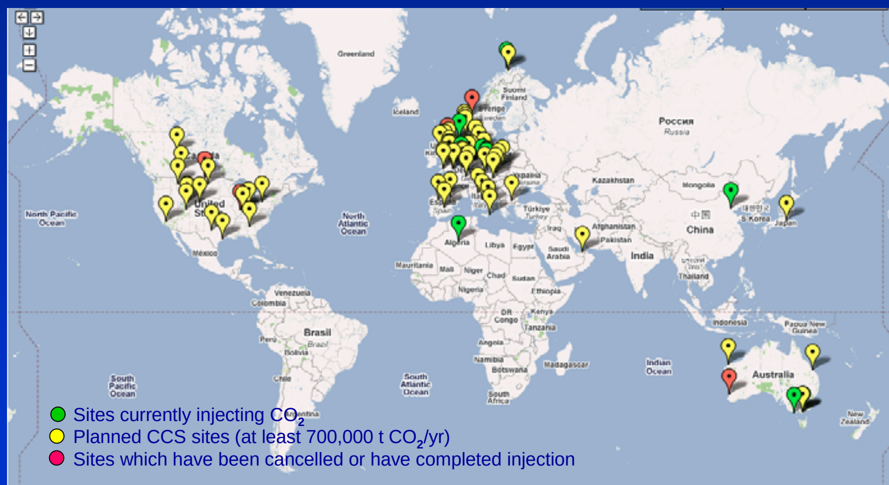
# Existing/Proposed $CO_2$ Storage Sites




Source: SCCS, 2009

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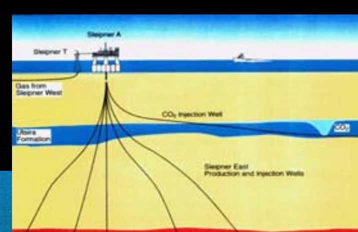
# Geological Storage of Captured $CO_2$ in a Deep Saline Formation


Sleipner Project

*(Norway)*




*Source: Statoil*

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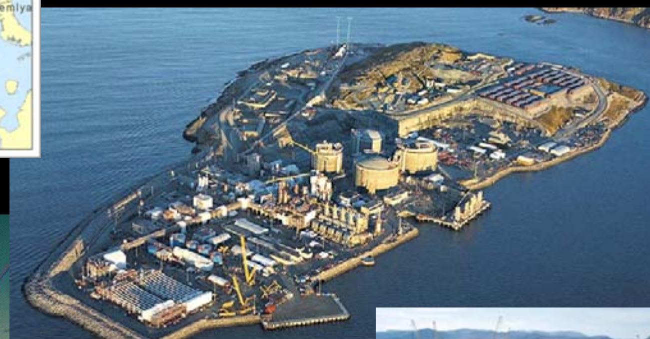
## Geological Storage of Captured $CO_2$ in a Deep Saline Formation

### Snohvit LNG Project *(Norway)*





*Source: www.Snohvit, 2009*

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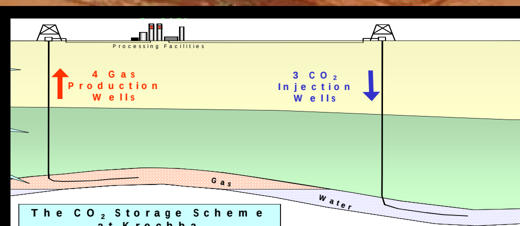
## Geological Storage of Captured $CO_2$ in a Depleted Gas Reservoir

### In Salah /Krechba *(Algeria)*


*Source: BP*

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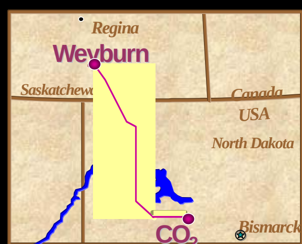
# Geological Storage of Captured $CO_2$ with Enhanced Oil Recovery (EOR)

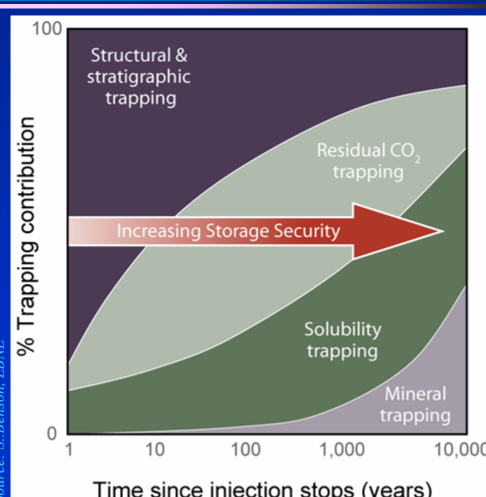




Sources: IEAGHG; NRDC; USDOE




# Trapping Mechanisms Provide Increasing Storage Security with Time

- Storage security depends on a combination of physical and geochemical trapping mechanisms
- Over time, $CO_2$ trapping mechanisms increase the security of storage
- ***Appropriate site selection and management are the key to secure storage***




*Source: S. Benson, LBNL*

## *The cost of CCS*

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## 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
  - Current technology vs. future (improved) systems
  - Consideration of technological "learning"

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# Ten Ways to Reduce the Estimated Cost of $CO_2$ Abatement

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel costs
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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# Representative CCS Costs for New Power Plants Using Current Technology

Levelized costs in constant 2007 US\$
(based on current technology w/ bituminous coals)

| 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%** |

***VERY IMPORTANT TO NOTE :***
*The added cost to consumers will be much smaller, reflecting the number and type of CCS plants in the power generation mix at any given time*

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# Typical Cost of $CO_2$ Avoided

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

Levelized cost in 2007 US$ per tonne $CO_2$ avoided
(based on current technology w/ bituminous coals)

| 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$** | **~ $50 /tCO$_2$** |
| 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*
- *Different choices of reference plant without CCS will yield different avoidance costs*

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# Important Reminders

- No one has yet built and operated a CCS system at a large (e.g., 500 MW) power plant. Hence, "true" costs are unknown.
- Construction costs have escalated rapidly in recent years but are now leveling off; future trends are uncertain.

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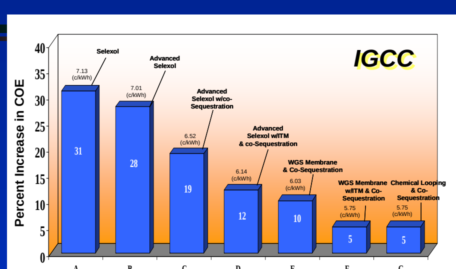
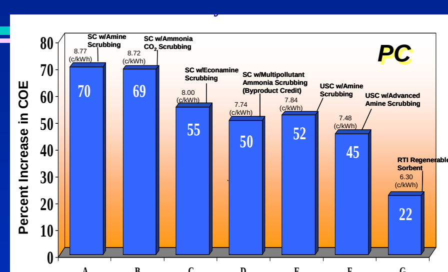
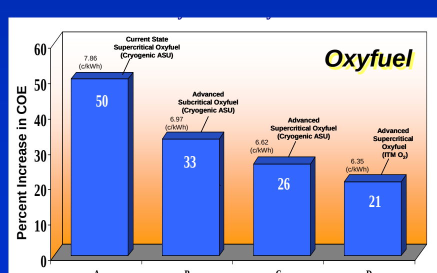
## *What is the potential for improved technology?*



# Potential Cost Reductions for CCS




19% -28% reductions in total cost of electricity

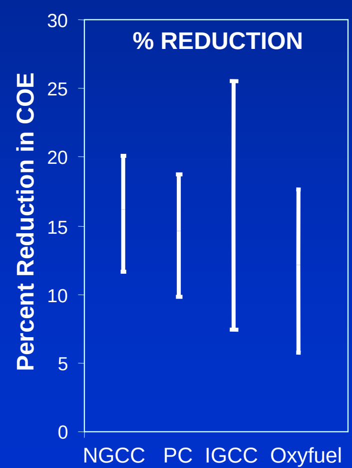
*Source: DOE Office of Fossil Energy, 2006*

# Estimated CCS Cost Reductions Based on Learning Curves

(after 100 GW of cumulative CCS capacity worldwide)

Technology innovation tends to lower costs as experience is gained from manufacture and use of a technology, and R&D is sustained.

Cost reduction estimates are similar to those from "bottom-up analyses.

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# Current Activity

- A variety of CCS projects are proposed or planned in different parts of the world
  (here is a sample)

| Project Name | Location | Feedstock | Size MW | Capture Process | CO2 Fate | Start-up |
|---|---|---|---|---|---|---|
| Total Lacq | France | Oil | 35 | Oxy | Seq | 2008 |
| Vattenfall Oxyfuel | Germany | Coal | 30/300/1000 | Oxy | Undecided | 2008 |
| AEP Alstom Mountaineer | USA | Coal | 30 | Post | Seq | 2008 |
| Callide-A Oxy Fuel | Australia | Coal | 30 | Oxy | Seq | 2009 |
| GreenGen | China | Coal | 250/800 | Pre | Seq | 2009 |
| Williston | USA | Coal | 450 | Post | EOR | 2009-15 |
| NZEC | China | Coal | Undecided | Undecided | Seq | 2010 |
| E.ON Killingholme | UK | Coal | 450 | Pre | Seq | 2011 |
| AEP Alstom Northeastern | USA | Coal | 200 | Post | EOR | 2011 |
| Sargas Husnes | Norway | Coal | 400 | Post | EOR | 2011 |
| Scottish& So Ferrybridge | UK | Coal | 500 | Post | Seq | 2011-2012 |
| Naturkraft Kårstø | Norway | Gas | 420 | Post | Undecided | 2011-2012 |
| ZeroGen | Australia | Coal | 100 | Pre | Seq | 2012 |
| WA Parish | USA | Coal | 125 | Post | EOR | 2012 |
| Coastal Energy | UK | Coal/Petcoke | 800 | Pre | EOR | 2012 |
| UAE Project | UAE | Gas | 420 | Pre | EOR | 2012 |
| Appalachian Power | USA | Coal | 629 | Pre | Undecided | 2012 |
| Wallula Energy | USA | Coal | 600-700 | Pre | Seq | 2013 |
| RWE npower Tilbury | UK | Coal | 1600 | Post | Seq | 2013 |
| Tenaska | USA | Coal | 600 | Post | EOR | 2014 |
| BP Rio Tinto Kwinana | Australia | Coal | 500 | Pre | Seq | 2014 |
| UK CCS project | UK | Coal | 300-400 | Post | Seq | 2014 |
| Statoil Mongstad | Norway | Gas | 630 CHP | Post | Seq | 2014 |
| RWE Zero CO2 | Germany | Coal | 450 | Pre | Seq | 2015 |
| Monash Energy | Australia | Coal | 60 k bpd | Pre | Seq | 2016 |
| Powerfuel Hatfield | UK | Coal | 900 | Pre | EOR | Undecided |
| ZENG Worsham-Steed | USA | Gas | 70 | Oxy | EOR | Undecided |
| Polygen Project | Canada | Coal/Petcoke | 300 | Pre | Undecided | Undecided |
| ZENG Risavika | Norway | Gas | 50-70 | Oxy | Undecided | Undecided |
| E.ON Karlshamn | Sweden | Oil | 5 | Post | Undecided | Undecided |

Source: MIT, 2008

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## Many Government Programs and Public-Private Partnerships Are Already In Place

*Some of the government programs supporting CCS:*

- Australia
- Canada
- China
- European Union
- United Kingdom
- United States

*Funding levels and scale of projects vary widely*

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

- Establish the reliability and true cost of CCS in commercial power plant applications
  - For different technologies, coal types, and geological settings
- Help establish legal and regulatory requirements for geological sequestration at large scales
- Reduce future cost of CCS via learning-by-doing plus sustained R&D

*Financing large-scale CCS projects has been a major hurdle; not clear where/when we'll see the first large power plant demo*

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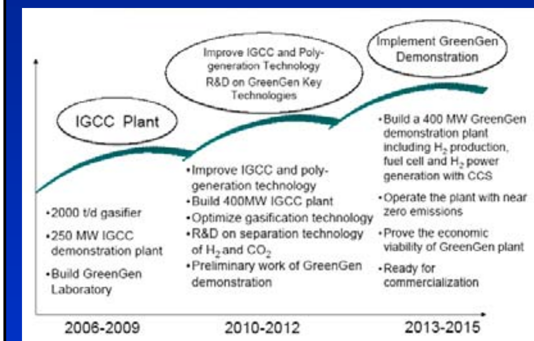
# It might be the GreenGen Project
## (Tianjin, China)




Partners include: China Datang Corp., China State Development and Investment Corp., China Guodian Corp., China Huadian Corp., China Power Investment Corp., China National Coal Group and Shenhua Group, Peabody Energy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# *Barriers to CCS Deployment*

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# Barriers to CCS Deployment

- No current policy mandate or strong incentives for large reductions in $CO_2$ emissions
- High cost of current technology
- Lack of experience in utility applications
- No established regulatory framework for licensing large-scale geological sequestration projects in U.S.
- Uncertainties about public acceptance
- Unresolved legal issues related to $CO_2$ pipelines, sub-surface property rights and long-term liabilities

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# The CCSReg Project is examining these issues in detail


*Project web site: www.CCSReg.org*

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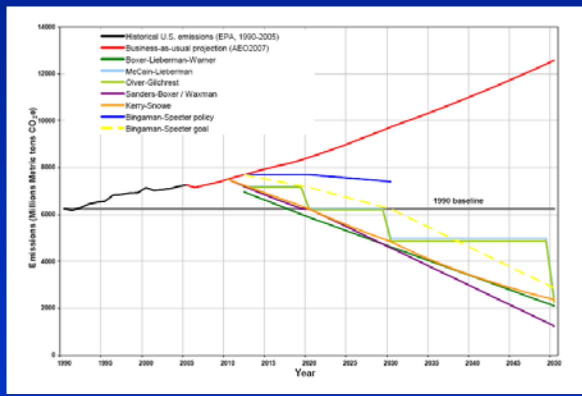
## *Future outlook*



## Recent Cap & Trade Bills Included Incentives for CCS




*Source: Pew Center on Global Climate Change, 2008*

*<u>No agreement on policy</u> in 110th Congress;  new efforts by 111th Congress and USEPA are works in progress*

# Will CCS be Used to Mitigate Global Climate Change ?

- Will very likely see successful demo of CCS technology in next ~5 years;  but …
- Widespread CCS deployment will not occur without a strong policy driver
- **WATCH THIS SPACE FOR UPDATES**




# *Thank You*

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