The Outlook for CO_2 Capture and Storage

And Its Role in a Low-Carbon Energy Future

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Guest Lecture
19-656: CO_2 Capture and Sequestration
Carnegie Mellon University

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Outline of Talk

- The problem of climate change
- Why the interest in CCS?
- The good news
- The not-so-good news
- Future outlook

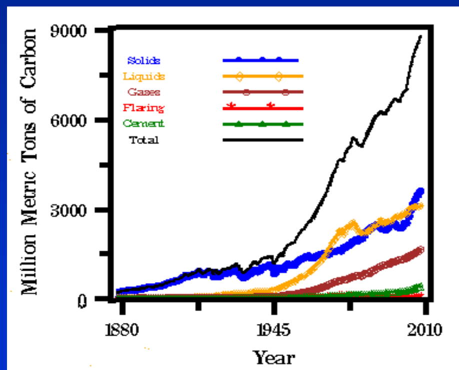
The problem of global climate change

Major Greenhouse Gases (GHGs) Emitted from Human Activities

Symbol	Name	Common Sources
CO_2	Carbon Dioxide	Fossil fuel combustion, forest clearing, cement production, etc.
CH_4	Methane	Landfills, production and distribution of natural gas & petroleum, fermentation from the digestive system of livestock, rice cultivation, fossil fuel combustion, etc.
N_2O	Nitrous Oxide	Fossil fuel combustion, fertilizers, nylon production, manure, etc.
HFC's	Hydrofluorocarbons	Refrigeration gases, aluminum smelting, semiconductor manufacturing, etc.
PFC's	Perflourocarbons	Aluminum production, semiconductor industry, etc.
SF_6	Sulfur Hexafluoride	Electrical transmissions and distribution systems, circuit breakers, magnesium production, etc.

Unlike "conventional" air pollutants, GHGs—once emitted—are not easily removed. Most remain in the atmosphere for centuries.

Global GHG Emissions Have Been Increasing Rapidly



Source: ORNL, 2011

Continued increases are projected under "business as usual"

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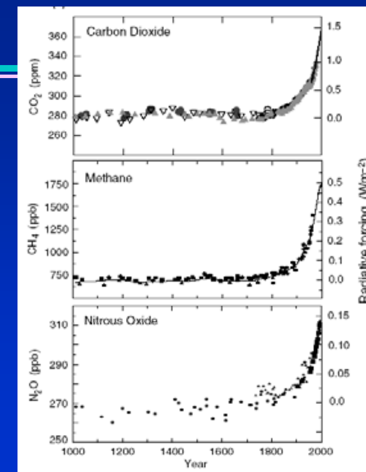
Atmospheric GHG Levels

- Greenhouse gas (GHG) concentrations in the atmosphere have been increasing rapidly as a result of human activities



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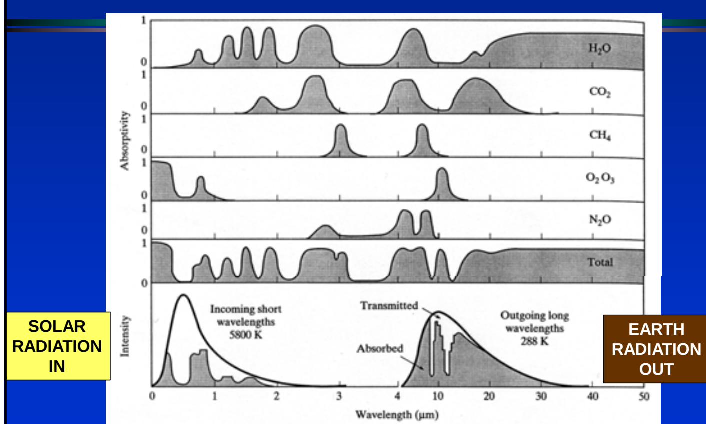
Source: IPCC, 2001

Greenhouse Gases Trap Heat



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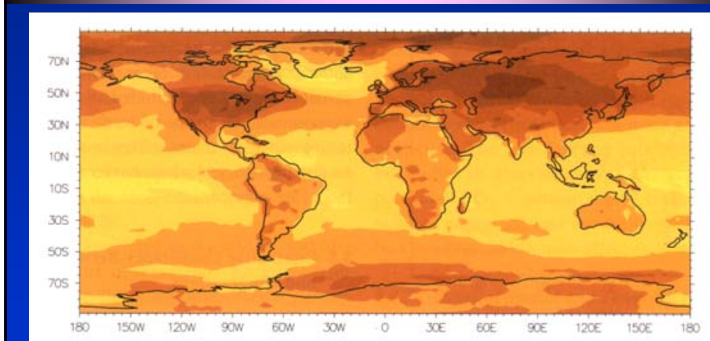
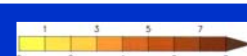
Predicted Temperature Changes for a Doubling of Atmospheric CO_2 Concentration



Source: IPCC



Temperature Increase (C)

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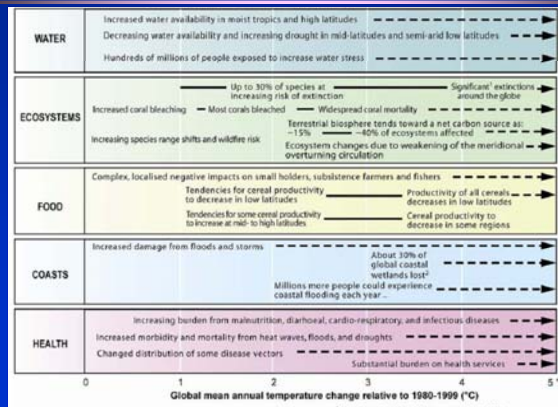
Impacts of climate change increase at higher global temperatures



Source: IPCC, 2007

More extreme events are expected as atmospheric concentration rises

The Climate Policy Driver

- 1992 U.N. Framework Convention on Climate Change called for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"

**192 countries are parties to the convention*

Implication of Stabilization

- Because of their long atmospheric lifetimes (typically measured in centuries), stabilizing current GHG *emissions* is not sufficient to stabilize atmospheric *<u>concentrations</u>*
- Global emissions must be reduced significantly, *no matter what stabilization target is selected!*

<u>Analogy</u>: To stabilize the water level in a slow-draining tub, the open faucets must be tightened to a trickle

Mitigating Climate Change Requires Large Emission Reductions

The most recent IPCC assessment indicates a need for large reductions by 2050 to avoid serious impacts (*>2ºC rise)*

Required change in global GHG emissions from 2000 to 2050
–50% to –85%

Source: IPCC, 2007

This conclusion was affirmed in the recent (2010) report of the U.S. National Academies: "America's Climate Choices"

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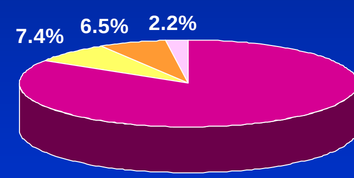
Focus on CO_2 from Energy Use — the Dominant Greenhouse Gas

U.S. Greenhouse Gas Emissions

weighted by 100-yr Global Warming Potential (GWP)



Total in 2005 = 7.26 Gt CO_2 equiv.

Source: USEPA, 2007

CO2 CH4 N2O Others

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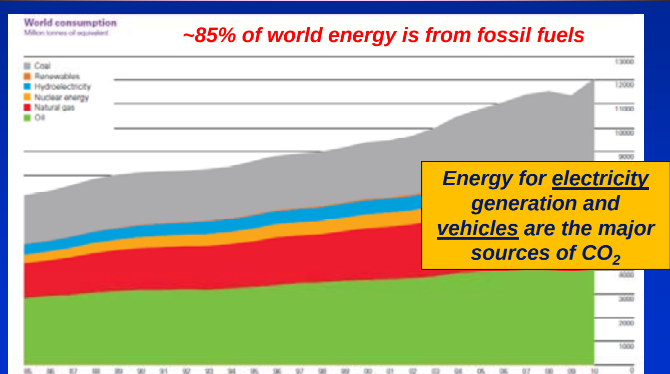
Trend in World Energy Use



Source: BP, 2011

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Why the interest in CCS ?

(carbon capture and storage, or sequestration)

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Options to Mitigate CO_2 Emissions

- Reduce the demand for energy used in buildings, transportation, and industrial activities
- Improve the efficiency of energy conversion and utilization, so less fuel is needed to meet demands
- Produce and use alternative energy sources with low or no GHG emissions
- Capture and sequestration CO_2 at large industrial sources to prevent its release to the atmosphere

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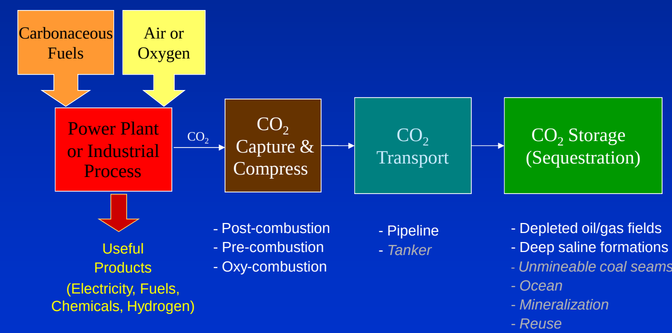
Schematic of a CCS System



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Motivation for CCS

- CCS is the <u>ONLY</u> way to get large CO_2 reductions from continued use of fossil fuels—a potential bridging strategy to a <u>sustainable</u> energy future
- CCS can also help decarbonize the transportation sector (via low-carbon electricity and hydrogen from fossil fuels)

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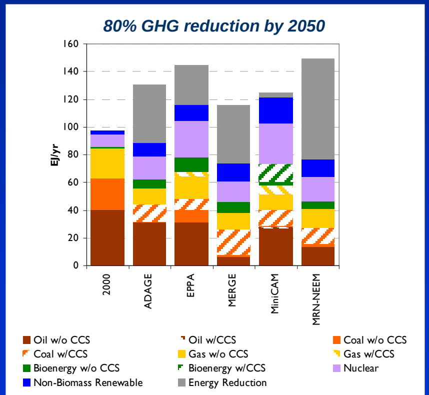
What It Takes to Reach GHG Goals

Least-cost U.S. energy mix in 2050 for a GHG policy scenario according to five energy models

All indicate that <u>major changes</u> in the energy system are needed

CCS PLAYS A MAJOR ROLE (for coal, gas, and biomass)



Source: EMF22, 2009

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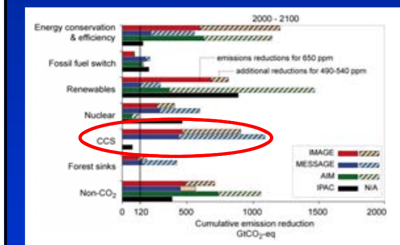
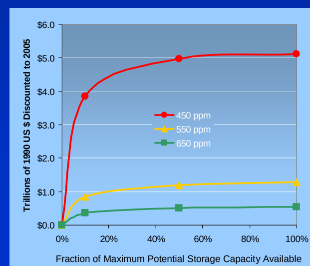
Cost-Effective Global Strategies Also Require CCS in the Portfolio

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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The Good News

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CCS Technology

- Is real
- It works
- It is effective
- It is commercially available

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Applications of CO_2 Capture

Gas-fired power plant

(Source: Flour Daniel)

Coal-fired power plant

(Source: (IEA GHG)

H_2 production plant

(Source: Chevron-Texaco)

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CO_2 Pipelines in the Western U.S.

> 3000 miles of pipeline
~50 $MtCO_2$/yr transported

Source: USDOE/Battelle

Source: NRDC

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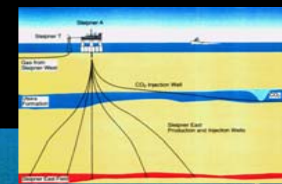
Captured CO_2 Stored in a Deep Saline Formation

Sleipner Project
(Norway)

Source: Statoil



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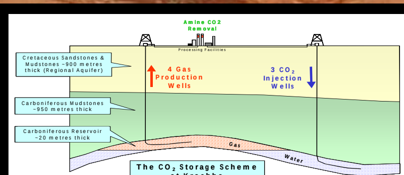
Captured CO_2 Stored in a Depleted Gas Formation

In Salah /Krechba *(Algeria)*

Source: BP



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Geological Formations in North America

Oil & Gas Fields

Deep Saline Formations

Source: NETL, 2009

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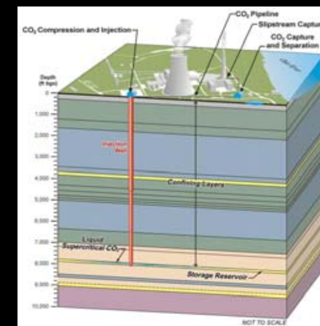
Captured CO_2 Stored with Enhanced Oil Recovery (EOR)

Sources: IEAGHG; NRDC; USDOE

CCS at a Coal-Fired Power Plant

(Pilot plant with storage in a deep saline formation)



Source: AEP, 2009

20 MW pilot plant at AEP's Mountaineer Power Plant *(West Virginia)*

The Not-So-Good News

Current CCS Technology

- Is relatively expensive at present
- Not yet proven at full-scale power plants
- Some remaining legal and regulatory issues
- Uncertain public acceptance in some areas
- Few if any incentives to deploy CCS

Key Barriers to CCS Deployment

- Policy
- Policy
- Policy

Without a policy requirement or incentive there is little or no reason to deploy CCS

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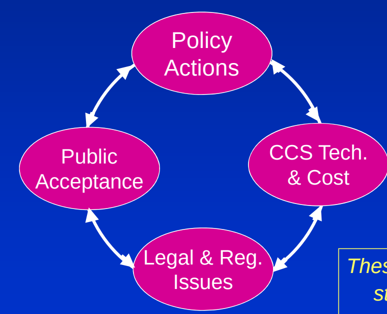
Strong Interactions Between Policy and Other Key Factors



These interactions depend strongly on local and national settings

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What If We Could Make it Cheaper?

Measures of CCS Cost:

- Increased cost of electricity
- Cost of CO_2 avoided
- Cost of CO_2 captured
- Capital cost
- Dispatch (variable) cost

Cost of CCS for New Coal-Based 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%**

- ***Capture accounts for most (~80%) of the total cost***
- *Retrofit of existing plants typically has a higher cost*
- *Added cost to consumers will be much smaller*
  (reflecting the CCS capacity in the generation mix at any given time)

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CCS Cost for New NGCC Plants (Current Technology)

Increase in levelized cost for 90% capture

Cost Measure	New NGCC Cost Increase with CCS
% Increase in generation cost ($/kWh) (relative to NGCC w/o CCS)	**~ 30–45%**
Cost of CO_2 Avoided:	
Relative to NGCC:	**~$100 /t$CO_2$**
Relative to SCPC:	**~$40 /t$CO_2$**

Definition of Key Costs

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

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

- Cost of Electricity Generation ($/MWh)

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

Many factors influence the cost of CCS

Ten Ways to Reduce CCS Cost

(inspired by D. Letterman)

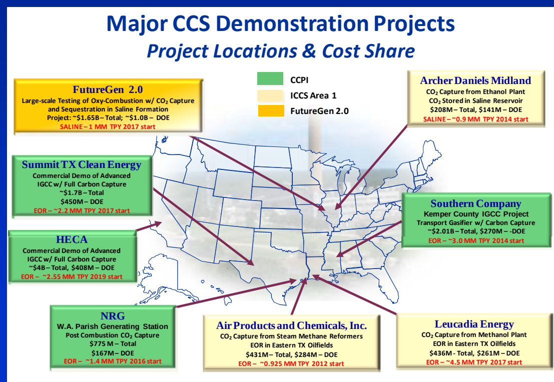
10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel price
7. Assume EOR credits for CO_2 storage
6. Omit certain capital costs
5. Report $/ton CO_2 based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high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

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

Future Outlook

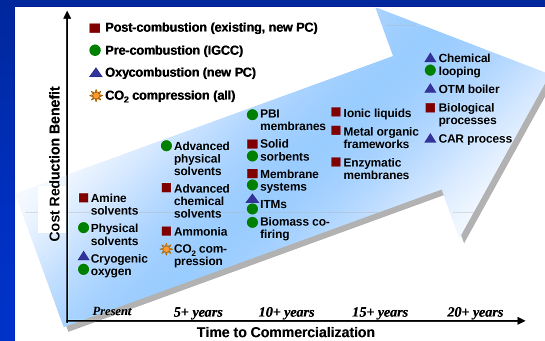
Large-Scale Demonstrations

(Planned projects in the U.S. as of December 2013)



Source: USDOE, 2013

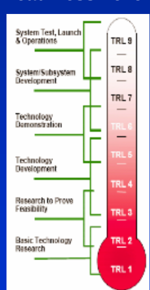
R&D Programs Seek to Develop Lower-Cost Technologies



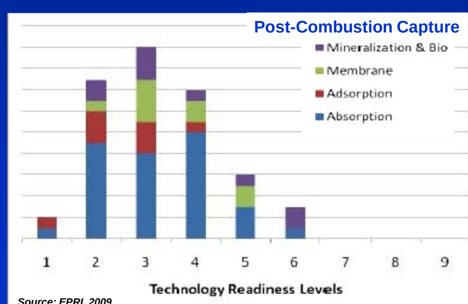
Source: USDOE, 2010

Most New Capture Concepts Are Far from Commercial Availability

Technology Readiness Levels

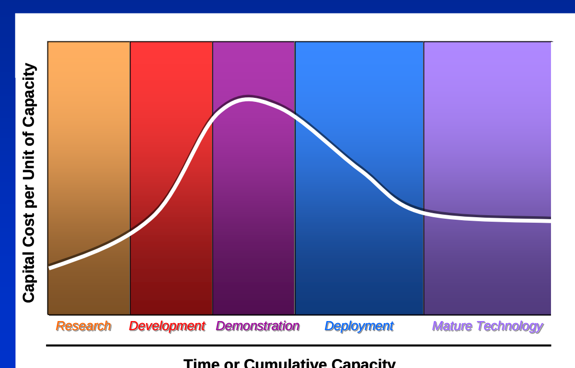


Source: NASA, 2009



Source: EPRI, 2009

Typical Cost Trend for a New Technology



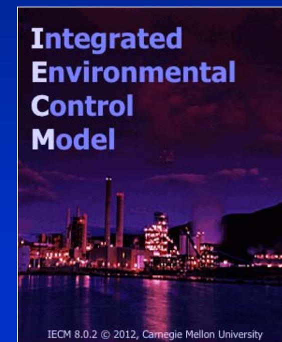
Source: Based on EPRI, 2008

Two Approaches to Estimating Future Technology Costs

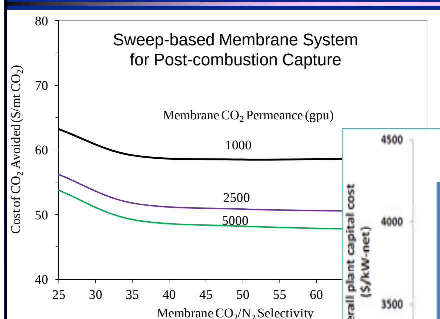
- *Method 1:* Engineering-Economic Analysis
  - A "bottom up" approach based on engineering process models, informed by judgments regarding potential improvements in key process parameters
- *Method 2:* Use of Historical Experience Curves
  - A "top down" approach based on applications of mathematical "learning curves" or "experience curves" that reflect historical trends for analogous technologies or systems

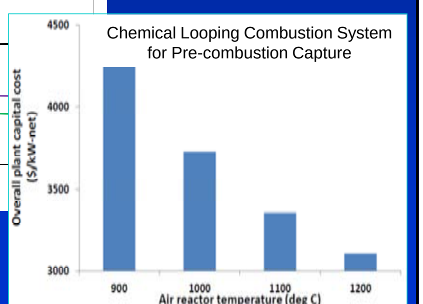
IECM: A Tool for Analyzing Power Plant Design Options

- A desktop/laptop computer simulation model developed for DOE/NETL
- 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)
- Free and publicly available at: www.iecm-online.com



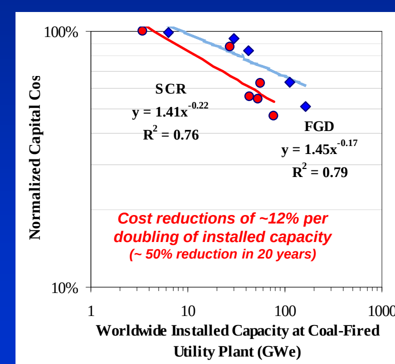
Estimated Cost of Two Advanced CO_2 Capture Systems





Historical Experience Curves for FGD and SCR Capital Costs

Substantial reductions seen in the cost of doing the same job at different points in time for the same power plant and fuel specifications



Application of Experience Curves to Future CCS Costs

(Percent cost reduction, 2001–2050, based on energy-economic modeling)*

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

* Range based on low and high global carbon price scenarios.

Source: van der Brock et al, 2010

Conclusions from CCS Cost Studies

- There is significant technical potential to reduce the cost of CCS for power plants and other industrial applications

but …

- Realization of that potential will require significant commercial deployment of CCS together with sustained R&D

Will CCS Save the Day?

- Very likely to soon see several large-scale demos of CCS, with continued R&D support; but …
- Widespread use will require strong policy drivers that create markets for CCS
- **WATCH THIS SPACE FOR UPDATES**

Thank You

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