The Cost of CO_2 Capture and Storage

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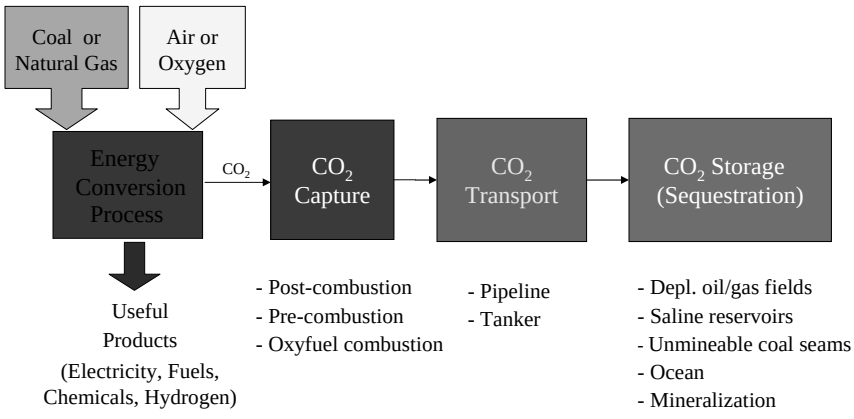
Motivating Questions

- What is the status of technologies for CO_2 capture and storage (CCS)?
- What is the current cost of CCS, and what are the factors that most influence cost?
- What is the impact of CCS on other environmental emissions and plant-level resource requirements?
- What is the outlook for future improvements that reduce CCS costs and impacts?

Schematic of a Typical CCS System



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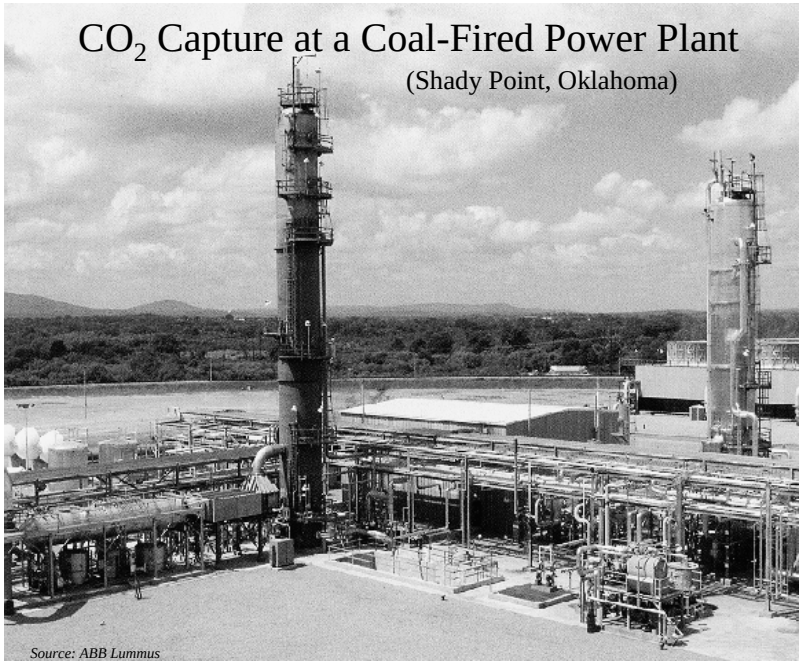
CO_2 Capture at a Coal-Fired Power Plant

(Shady Point, Oklahoma)



Source: ABB Lummus

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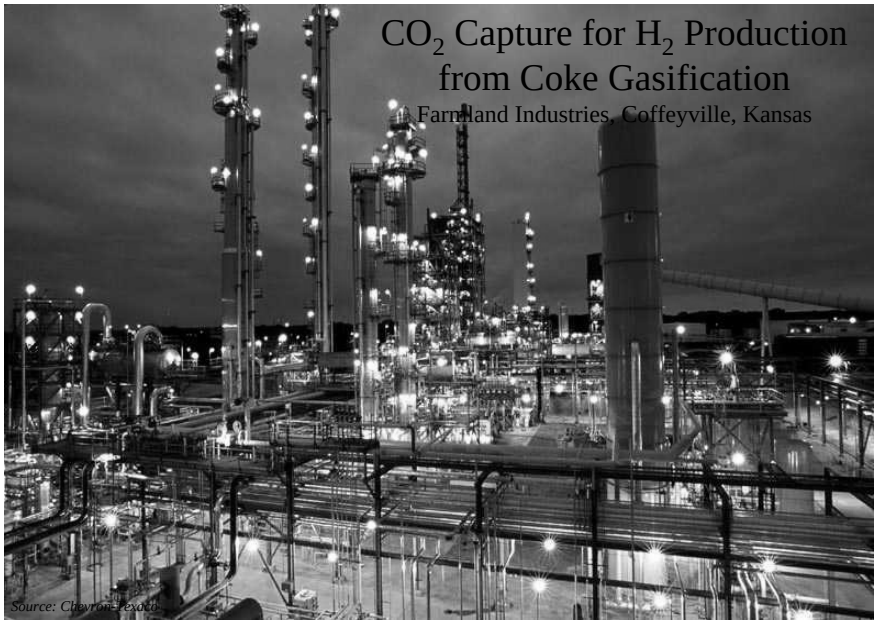
CO_2 Capture for H_2 Production from Coke Gasification

Farmland Industries, Coffeyville, Kansas



Source: Chevron-Texaco

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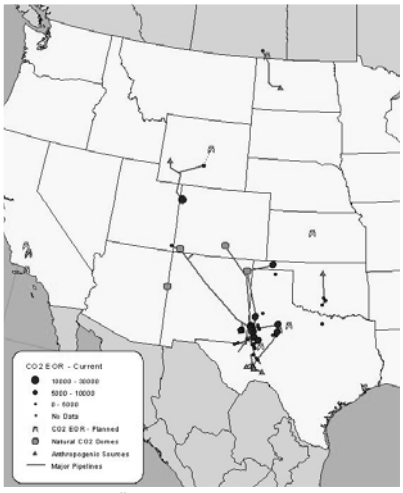
Existing CO_2 Pipelines for Enhanced Oil Recovery (EOR)



Source: USDOE/Battelle

Source: NRDC

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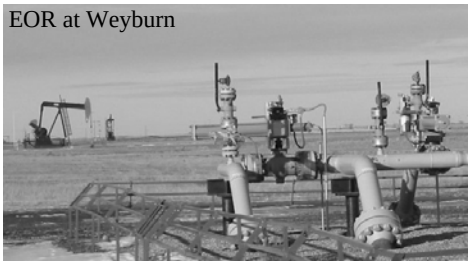
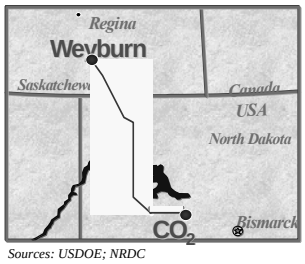
EOR at Weyburn



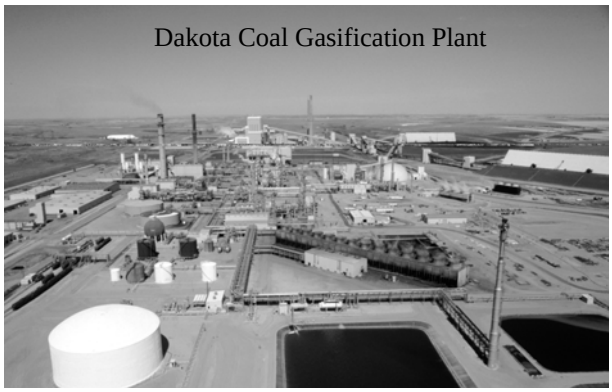
Weyburn CO_2 Pipeline & Storage Project

Geological Storage of CO_2 with Enhanced Oil Recovery



Sources: USDOE; NRDC

Dakota Coal Gasification Plant



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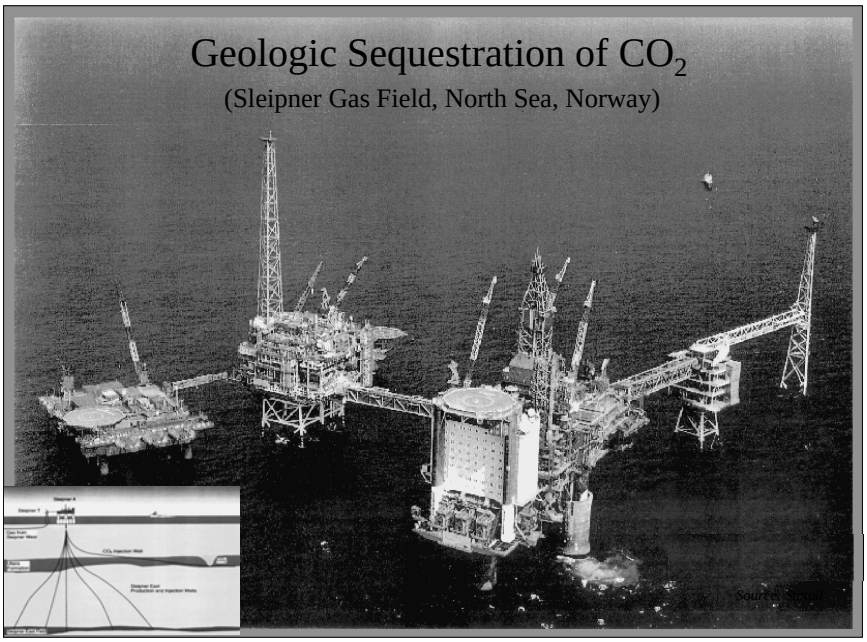
Geologic Sequestration of CO_2

(Sleipner Gas Field, North Sea, Norway)



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Status of CCS Technologies

- Technology for each major component of a CCS system (capture, transport, storage) can be found in commercial applications today, mainly in the petroleum and petrochemical process industries
- CO_2 capture also has been applied to flue gas streams from several coal-fired and gas-fired boilers, but at much smaller sizes than a modern power plant
- The integration of capture, transport and storage has been demonstrated, but not yet at an electric power plant
- R&D programs are underway worldwide to develop improved, lower-cost options for CO_2 capture

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Leading Candidates for CCS

- Fossil fuel power plants
  - Natural gas combined cycle (NGCC)
  - Pulverized coal combustion (PC)
  - Integrated coal gasification combined cycle (IGCC)
- Other large industrial sources of CO_2, e.g.,
  - Refineries and petrochemical plants
  - Hydrogen production plants
  - Pulp and paper plants
  - Etc.

Main focus on power plants as the largest source of CO_2

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What Does It Cost ?

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Many Factors Affect Reported Costs of CO_2 Capture & Storage

- Choice of 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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Different Measures of CCS Cost Often Adds to the Confusion

- Cost per Unit of Product (e.g., $/MWh)
- Cost of CO_2 Avoided ($/ton CO_2 avoided)
- Cost of CO_2 Captured ($/ton CO_2 captured)
- Cost of CO_2 Reduced ($/ton CO_2 reduced)

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Our Own Efforts to Improve Transparency & Understanding

- *The IEA Greenhouse Gas Programme (IEA GHG)* requires all contractors to use a consistent set of technical and economic premises when evaluating alternative CCS plants and processes
- *Carnegie Mellon University (CMU)* has developed a computer modeling tool to systematically evaluate plant-level performance and cost of alternative CCS options, based on user-specified inputs
  - Incorporates both current and advanced technologies
  - Integrates CCS with other environmental control systems
  - Characterize key uncertainties in performance and cost
  - Called IECM; Developed for USDOE; publicly available

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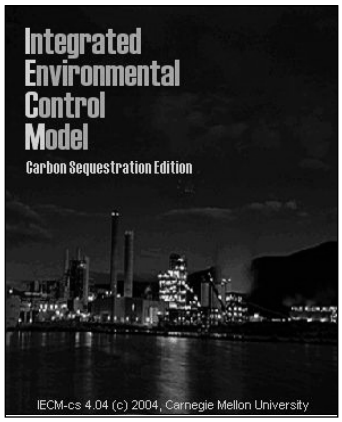
The IECM is Available At . . .

- **Free Web Download :**
  - www. iecm-online.com
- **Technical Support:**
  - PED.modeling@netl.doe.gov
- **Other Inquires:**
  - mikeb@cmu.edu
  - rubin@cmu.edu



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Approach for This Study

- Review and summarize recent (post-2000) CCS cost studies for fossil fuel power plants and other large industrial sources of CO_2

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Results of Literature Review

- A wide range of assumptions regarding power plant and capture system design parameters, plant utilization, economic and financial factors
- Most studies report only the cost of capture, excluding costs of CO_2 transport and storage
- Coal plant studies limited largely to bituminous coals (esp. for IGCC)
- Most studies are for new power plants; relatively few on retrofit or repowering of existing plants; relatively few studies of major industrial processes

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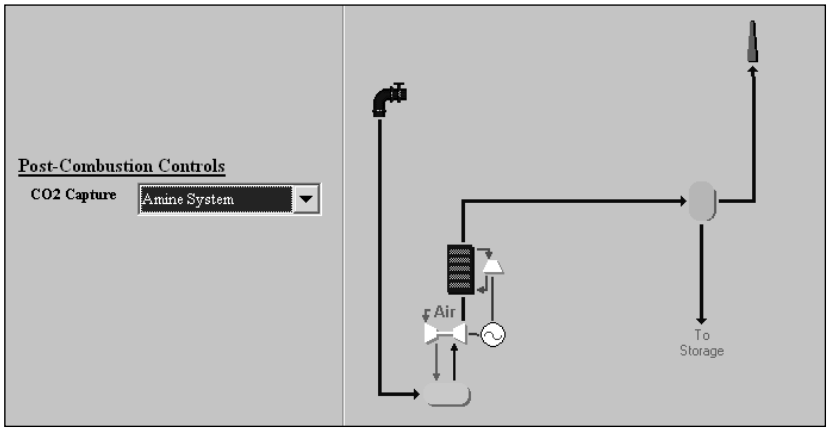
Results for New Power Plants (Current Technology)

NGCC Plant with CO_2 Capture



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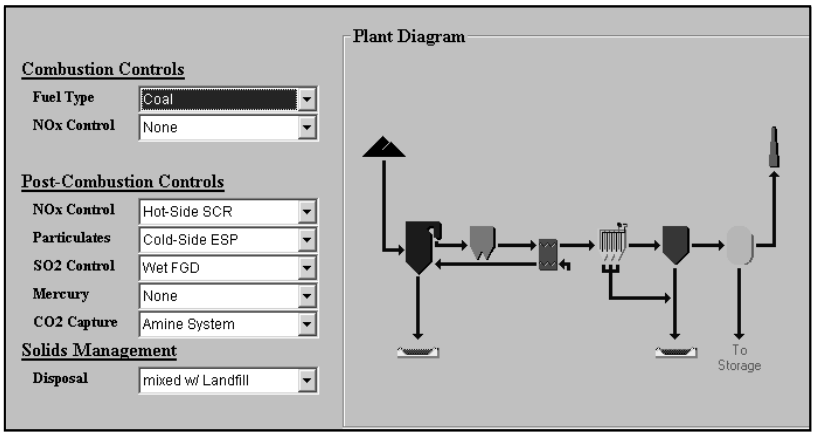
PC Plant with CO_2 Capture



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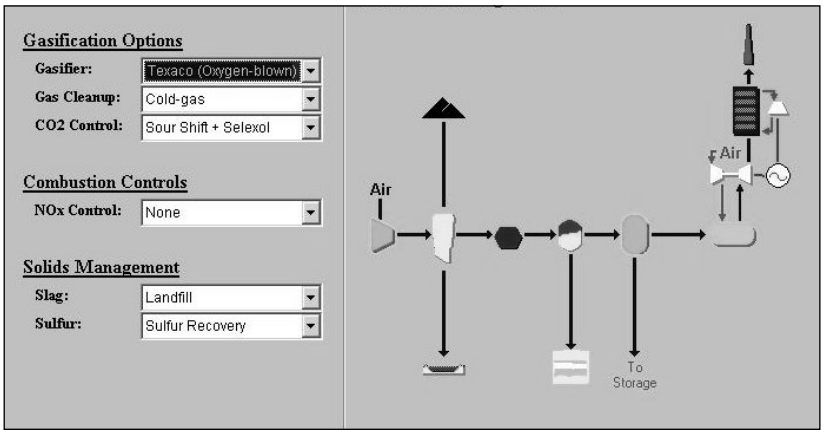
IGCC Plant with CO_2 Capture



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Assumptions in CCS Cost Studies

Parameter	***Range in Recent Studies***
Plant Size	300 – 800 MW
Base Plant Efficiency	Subcrit, supercrit, ultraSC, CC
Fuel Cost & Quality	NG, bitum, subbit, lignite
Plant Capacity Factor	50% – 95%
CO_2 Removal Efficiency	85% – 95%
Capital Charge Rate	11% – 16%

No single set of assumptions applies everywhere — differences in site-specific factors are the main source of variability in reported CO_2 capture costs

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Reminder

- No one has yet built and operated a CCS system at a large-scale power plant
- Hence, all the costs we're about to see are projections based on other applications; the "true" costs are not yet known

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Summary of Recent Studies of CO_2 Capture Cost *

(Excludes transport and storage costs; all costs in constant 2002 USD)

Cost and Performance Measures	NGCC Plant		PC Plant		IGCC Plant	
	Range low-high	*Rep. value*	**Range low-high**	*Rep. value*	**Range low-high**	*Rep. value*
Ref. plant emissions (kg CO_2/MWh)	344-379	*370*	736-811	*760*	682-846	*785*
Percent CO_2 reduction per MWh (%)	83-88	*86*	81-88	*85*	81-88	*85*
Capital cost w/o capture ($/kW)	515-724	*570*	1161-1486	*1290*	1169-1565	*1320*
Capital cost with capture ($/kW)	909-1261	*1000*	1894-2578	*2100*	1414-2270	*1800*
Percent increase in capital cost (%)	64-100	*76*	44-74	*63*	19-66	*36*
COE w/o capture ($/MWh)	31-50	*37*	43-52	*45*	41-61	*47*
COE with capture ($/MWh)	43-72	*54*	62-86	*73*	54-79	*63*
Percent increase in COE w/capture	37-69	*46*	42-84	*60*	20-55	*33*
Cost of CO_2 avoided ($/t CO_2)	37-74	*53*	29-55	*42*	13-37	*23*

** Costs include CO_2 compression; PC and IGCC data are for bituminous coals only; Natural gas prices range from $2.8-4.4/GJ (LHV); Coal prices approx. $1.2/GJ; Other assumptions vary across studies.*

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Transport & Storage Costs

- Pipeline transport of CO_2 is most widely studied option
- Annualized costs are typically in the range of:
  - \$1–5/ton CO_2 shipped for on-shore pipelines
  - 40–70% more for off-shore pipelines
- Main focus for CO_2 storage is geologic sequestration
- Storage costs are less well characterized and highly variable; most likely range is:
  - \$0.5–8.0/ton CO_2 stored for deep saline formations
  - Credits of \$10–16/ton CO_2 for enhanced oil recovery (EOR)

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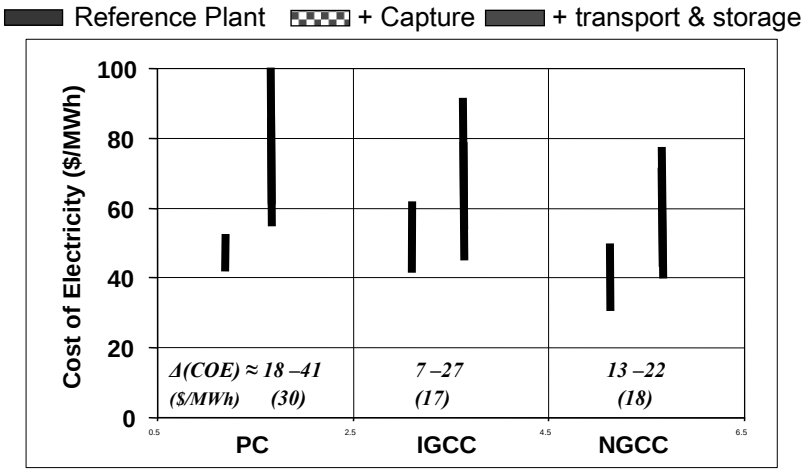
Range of Power Generation Costs Based on Recent Studies*



**Based on new plants, current technology, bituminous coals and supercritical PC units; Natural gas prices \$2.8-4.4/GJ (LHV), coal price ~\$1.2/GJ. Other assumptions vary across studies.*

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Importance of CCS Energy Penalty

- CCS plants require more fuel input/MWh, typically:
  - PC = +31 %; IGCC = +19%; NGCC = +16%
- This loss in efficiency increases the plant-level capital cost $(\$/kW)_{net}$ and cost of electricity $(\$/MWh)_{net}$
- CCS energy requirements also increase plant-level fuel use, reagent consumption, and environmental emissions (to air and land) relative to a similar plant without CCS; largest impacts are for PC plants
- However, …net impacts of CCS must be assessed in the context of a particular situation or scenario

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Results for Existing Power Plants (Current Technology)

CO_2 Capture at Existing Power Plants

- Retrofitting a CO_2 capture unit is technically feasible but higher in cost than for new plants; site-specific retrofit difficulties may limit applications
- Most cost-effective approaches appear to be:
  - Amine scrubber + supercritical boiler rebuild
  - Repowering with IGCC + CO_2 capture
- Further study is needed to assess & compare options, and their applicability to specific situations

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Advanced Technologies for CO_2 Capture

Examples of New or Improved Technologies Under Development

- Oxyfuel combustion systems
- Advanced (higher efficiency) power generation
  - NGCC, PC and IGCC systems
  - Integrated fuel cell-turbine and other hybrid systems
- Advanced post-combustion and pre-combustion capture technologies
- More efficient industrial processes for production of fuels, chemicals and other products

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Implications for Future CCS Costs

- Savings of at least 20 –30% are achievable in the near term
- Much more substantial cost reductions expected with continued R&D and the deployment of CCS technologies in the marketplace
- Government policies will play a key role in determining the magnitude and timing of future CCS deployment

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