The Economics of CO_2 Capture for Enhanced Oil Recovery and Climate Change Mitigation

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Washington, DC

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Outline of Talk

- Status of CO_2 capture technology
- Opportunities for enhanced oil recovery
- The costs of CO_2 captured and avoided
- The outlook for advanced capture systems
- Challenges moving forward

Status of CO_2 capture technology

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 CCUS

- Large industrial sources of CO_2 such as:
  - Gas processing, refineries, petrochemical plants
  - Hydrogen and ammonia production plants
  - Pulp and paper plants
  - Cement plants
- Fossil fuel power plants
  - Pulverized coal combustion (PC)
  - Natural gas combined cycle (NGCC)
  - Integrated coal gasification combined cycle (IGCC)

For these applications, various stages of technology development

- Commercial use
- Full-scale demonstration plant
- Pilot plant scale
- Laboratory or bench scale
- Conceptual design

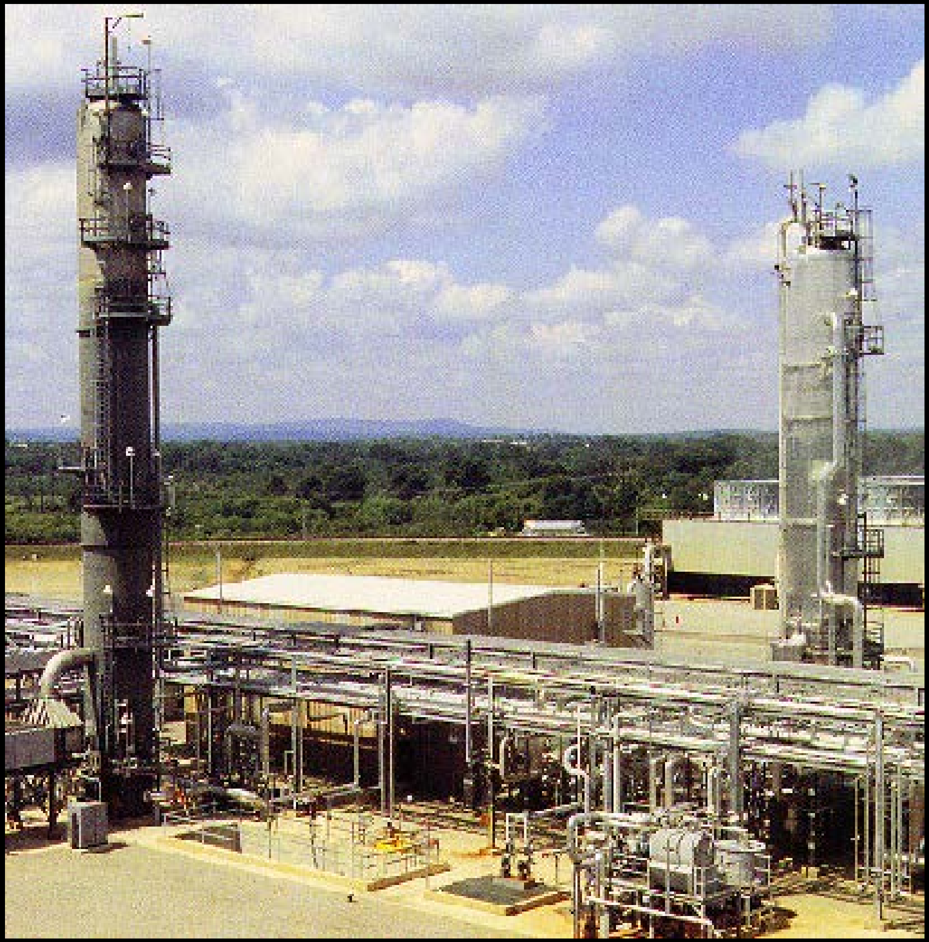
Commercial Post-Combustion Systems for Industrial CO_2 Capture

Source: IEA GHG, 2008

BP Natural Gas Processing Plant
(In Salah, Algeria)

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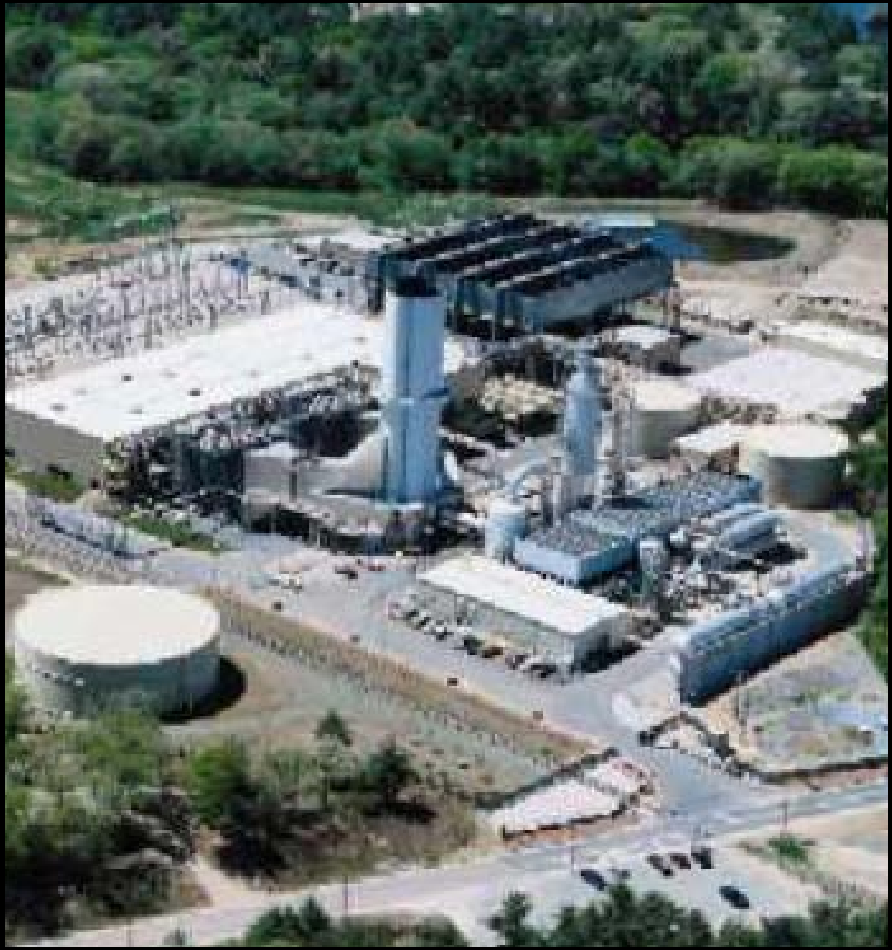
Post-Combustion CO_2 Capture at a Gas-Fired Power Plant



(Source: Suez Energy Generation))

(Source: Flour Daniel)

Bellingham Cogeneration Plant

(Bellingham, Massachusetts, USA)

Commercial 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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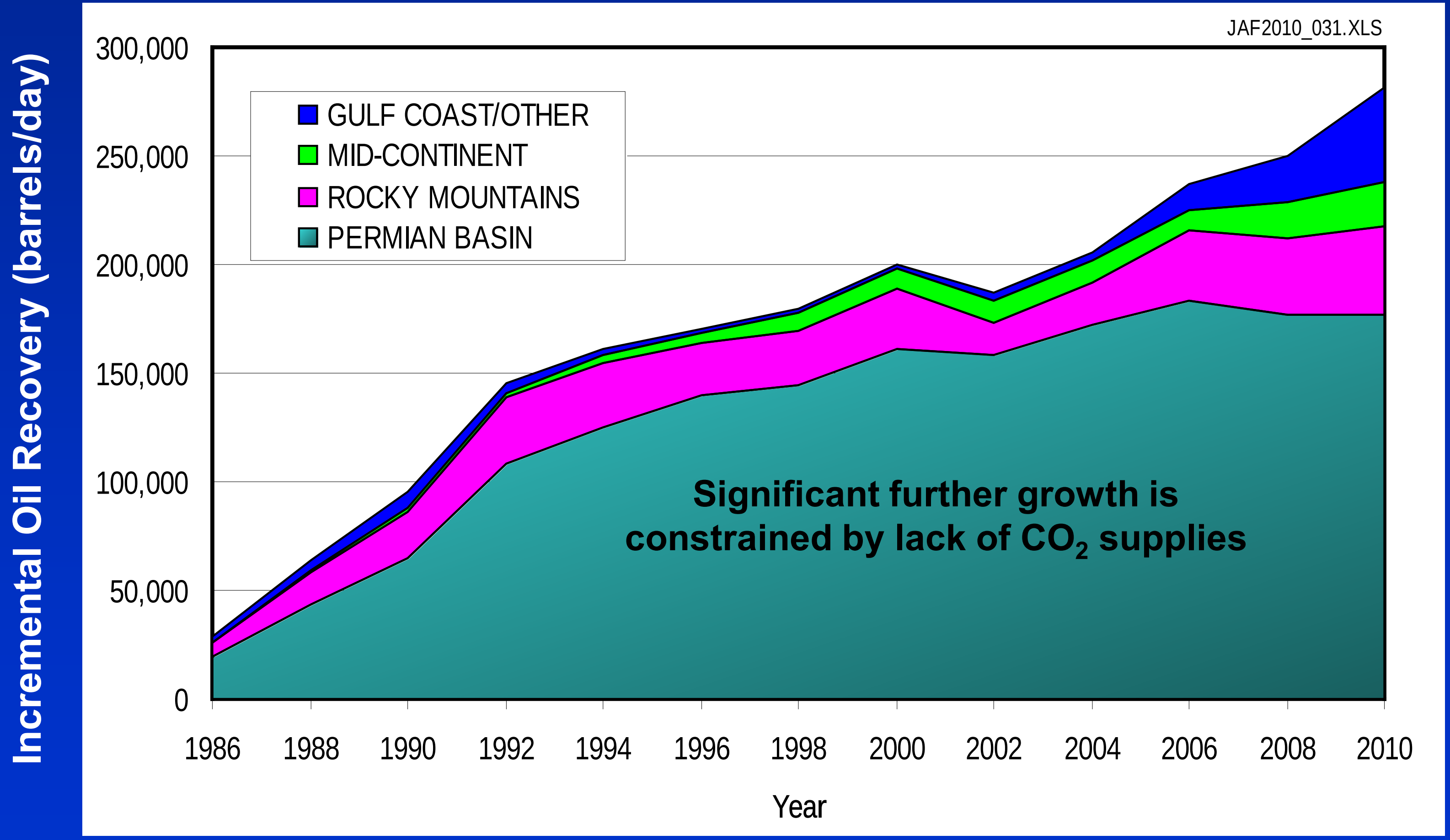
DOE-Supported Demonstrations

Performer	Location	Capture Technology	Capture Rate (m tons/y)	Target Formation	Start Date
PC Power Plants					
NRG Energy	Thompsons, TX	Amine	~0.5	EOR	2015
FutureGen Alliance	Meredosia, IL	Oxy	1.0	EOR/Saline	2015
IGCC Power Plants					
Summit Texas Clean Energy	Odessa, TX	Selexol	3.0	EOR	2014
Southern Company	Kemper County, MS	Selexol	2.0	EOR	2014
Hydrogen Energy California	Kern County, CA	Rectisol	2.0	EOR/Saline	2016
Industrial Processes					
Leucadia Energy Lake Charles	Lake Charles, LA	Rectisol	4.0	EOR	2014
Air Products	Port Arthur, TX	Amine	1.0	EOR	2013
Archer Daniels Midland	Decatur, IL	Amine	1.0	Saline	2014

Can EOR Stimulate Capture Technology Deployment?

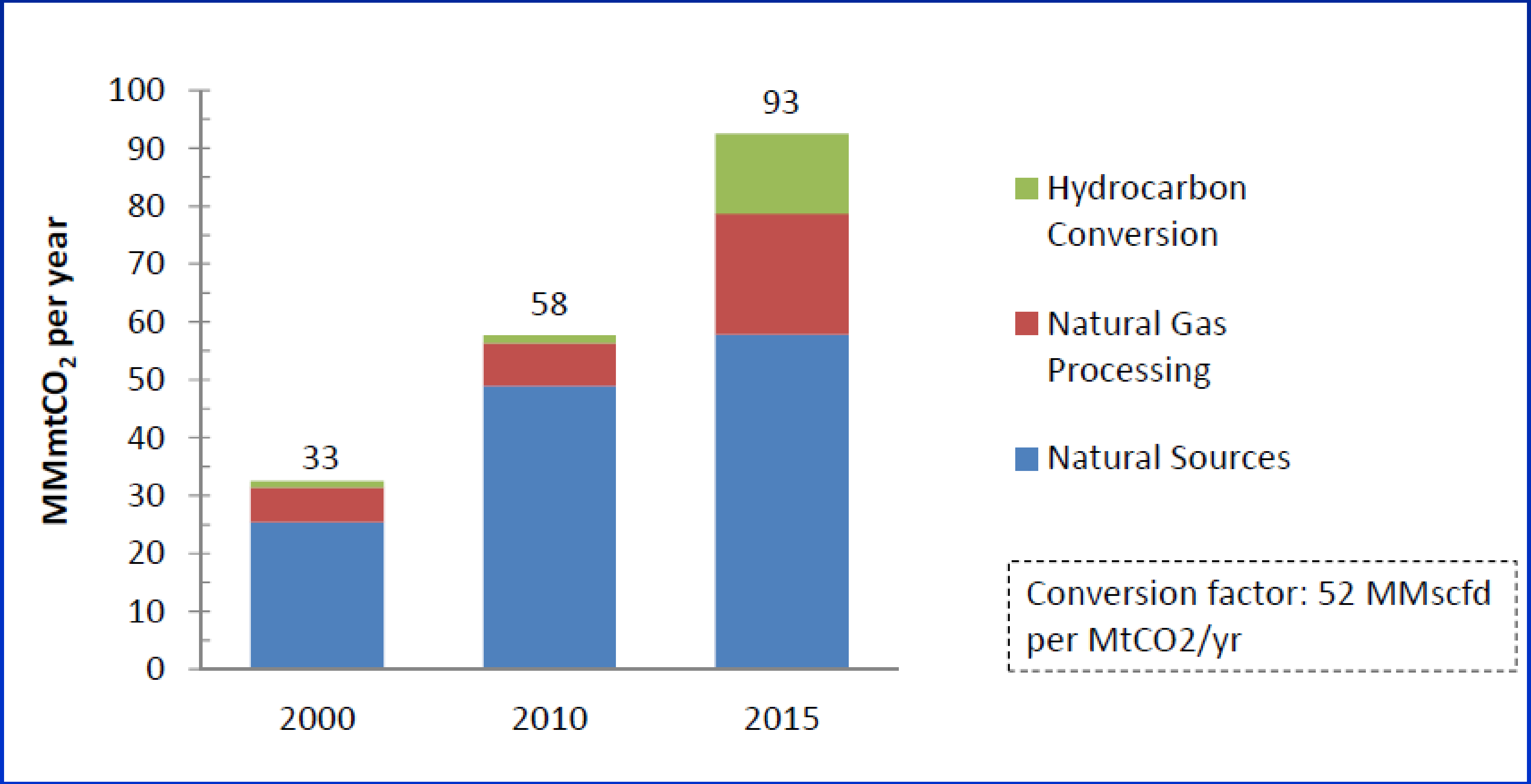
- What is the outlook for EOR production?
- What is the economic value of CO_2 for EOR?
- What is the availability and cost of providing CO_2 from various sources?
- Is there a significant role for power plants?
- In the context of climate change mitigation, is CO_2 -EOR a safe and secure method of carbon sequestration?

Growth of CO_2-EOR Production in the United States



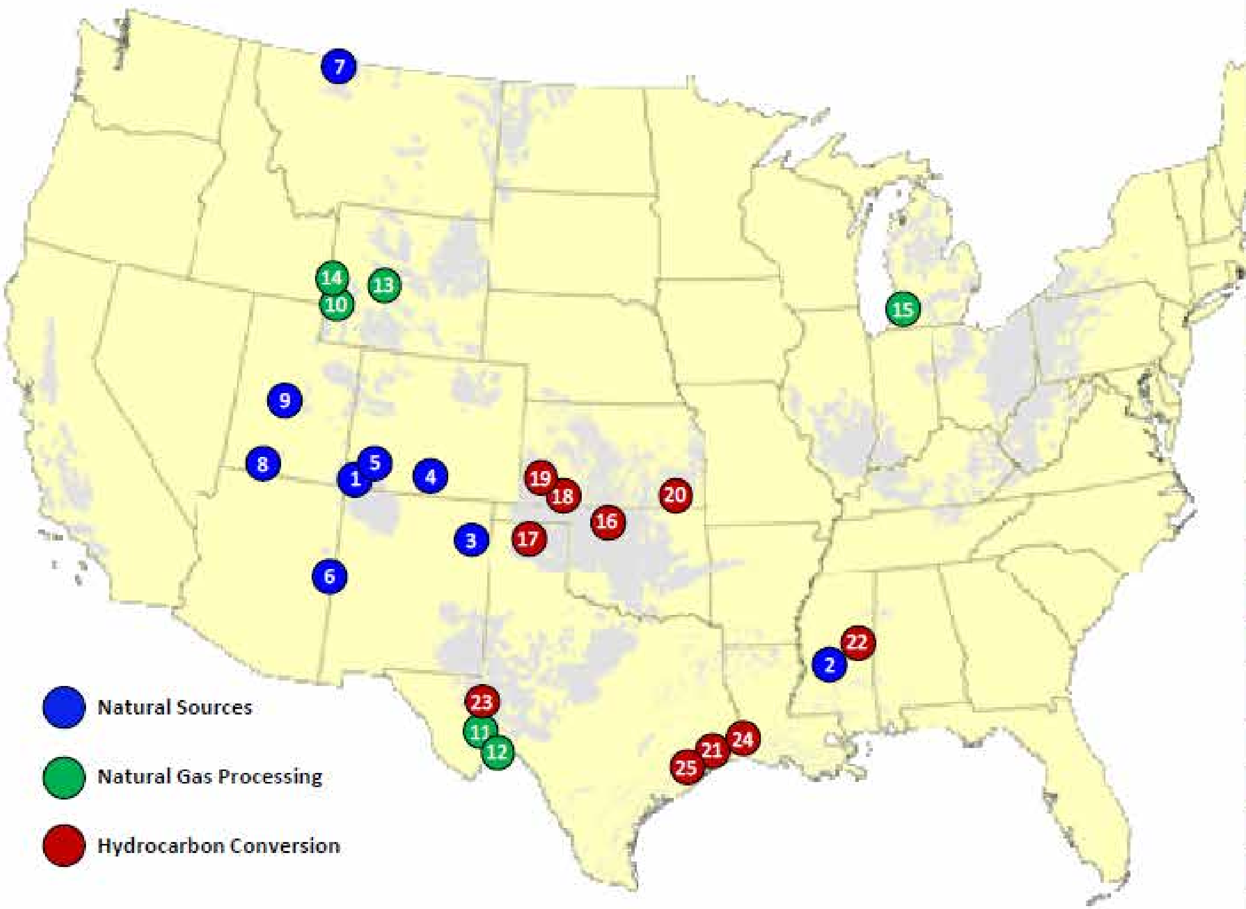
Source: Advanced Resources Int'l., 2011, based on Oil and Gas Journal, 2010.

Sources of CO_2 Supply for EOR Operations in the U.S.



Source: P. DiPietro, NETL, 2012

CO_2 Sources for EOR Floods



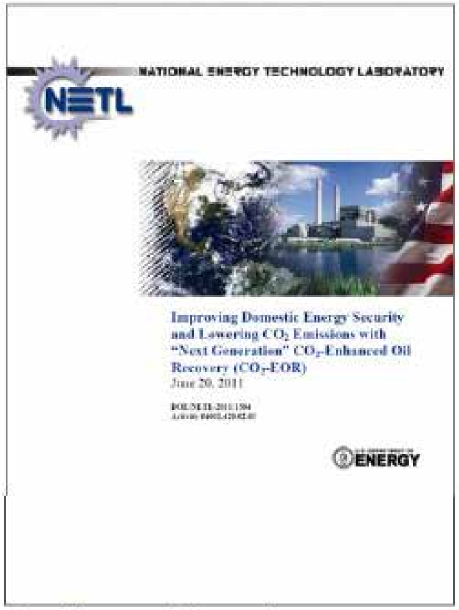
1. McElmo
2. Jackson
3. Bravo
4. Sheep
5. *Doe Canyon*
**6. St. John's*
**7. Kevin*
**8. Escalante*
*9. Gordon Creek
10. LaBarge
**11. Century*
12. TGRMP
*13. Lost Cabin
*14. Riley Ridge
15. Turtle Lake
16. Koch Nitrogen
17. Agrium, Inc.
18. Conestoga
19. Bonanza Energy
**20. CVR Energy*
**21. Air Products*
**22. Mississippi Power*
**23. Summit Texas*
**24. Leucadia*
**25. NRG*

* Not operational in 2010

Source: P. DiPietro, NETL, 2012

NETL/ARI CO_2 EOR Resource Assessment

- Field-to-field stream tube simulations of CO_2 EOR floods (CO_2 PROPHET)
- Screen for depth, crude gravity, and size
- Determine miscible/immiscible
- Economics based on 40 \$/mtCO_2 cost, 85 \$/bbl crude oil, 20% IRR



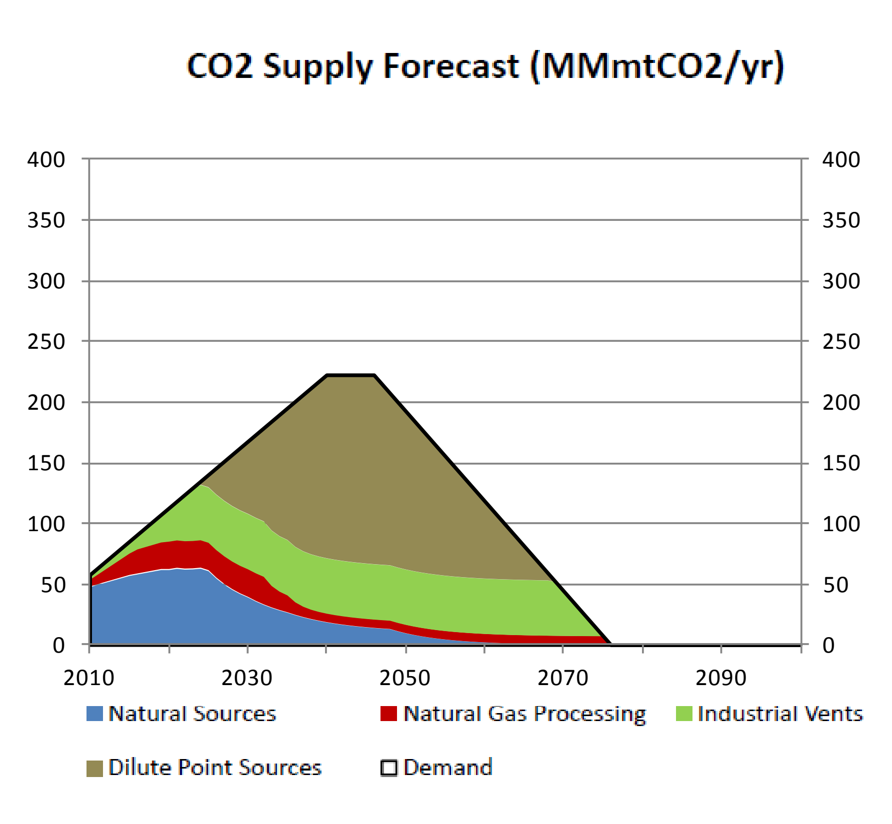
http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=391

CO2 EOR Resource Assessment Results: Lower 48 Onshore, Economically Recoverable			
	Crude oil production, Bbbls	CO2 Demand, BmtCO_2	Average Efficiency of CO2 Use (bbl/mt CO_2)
Current Best Practices	24	9	2.7
Next Generation CO_2 EOR technology	60	17	3.5

Source: P. DiPietro, NETL, 2012

Future CO_2 Supply Scenario

(Based on <u>Best Current Practices</u> for CO_2-EOR Technologies)



<u>Source</u>: P. DiPietro and C. Nichols, NETL, 2012

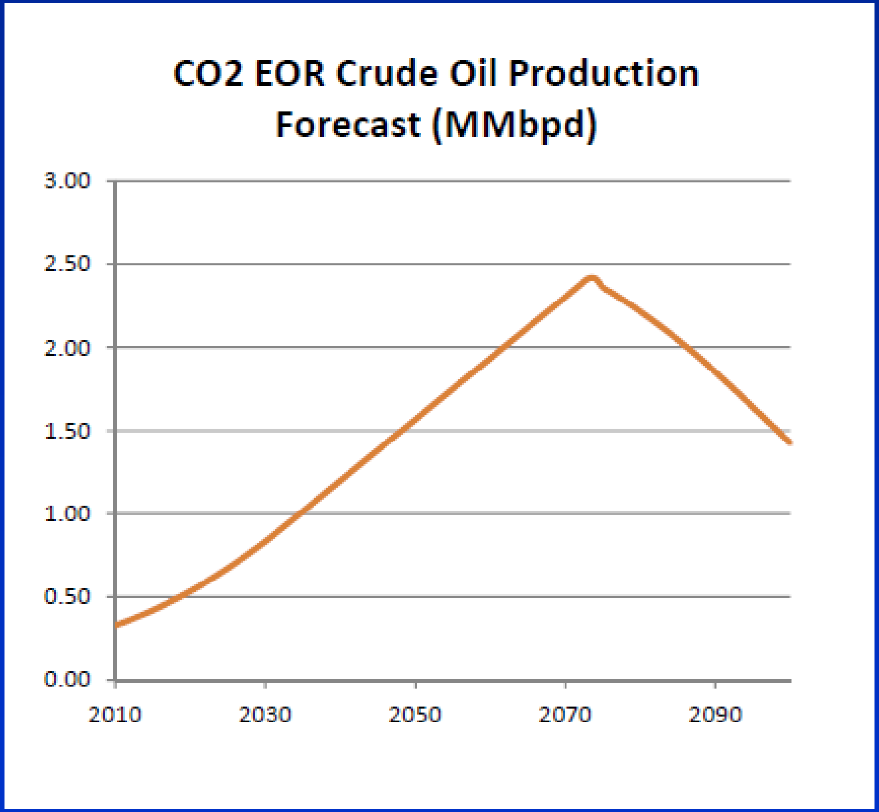
- 24 billion bbl of CO_2-EOR resources
- 9 B mt CO_2 demand
- 5.5 MMmt CO_2/yr growth in CO_2 demand
- 46 MMmtCO_2/yr from industrial vents
- Peak dilute sources is 156 MMmtCO_2/yr
- 45% of CO_2 from dilute sources

Future EOR Production Scenario

(Based on "Next Generation" CO_2-EOR Technologies)

Next Generation CO_2-EOR technologies:

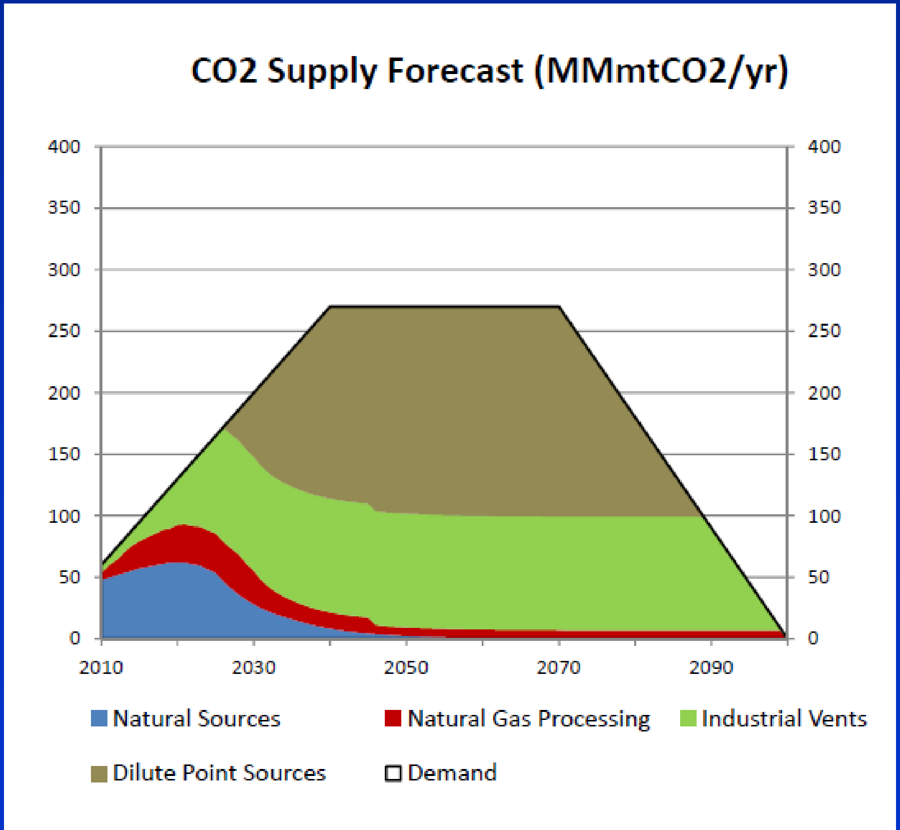
- Significant improvements to today's technology
- Application to residual oil zones (ROZs)
- Integration of CO_2-EOR and CO_2 storage
- Advanced near-miscible/immiscible technology
- Deployment in offshore oil fields and Alaska



Sources: V. Kuuskraa, ARI. 2011 and P. DiPietro, NETL, 2012;

Future CO_2 Supply Scenario

(Based on "Next Generation" CO_2-EOR Technologies)



Source: P. DiPietro and C. Nichols, NETL, 2012

- 60 billion bbl of CO_2-EOR resources
- 17 B mt CO_2 demand
- 7 MMmt CO_2 /yr growth in CO_2 demand
- 46 MMmtCO_2/yr from industrial vents
- Peak dilute sources is 214 MMmtCO_2/yr
- 63% of CO_2 from dilute sources

Significant potential for power plants to contribute to EOR CO_2 supplies after ~2030

The costs of capturing and sequestering CO_2

Many Recent CCS Cost Studies

- 2005: IPCC Special Report on CCS
- 2007: Rubin, et al., *Energy Policy*
- 2007: EPRI Report No. 1014223
- 2007: DOE/NETL Report 2007/1281
- 2007: MIT *Future of Coal* Report
- 2008: EPRI Report No. 1018329
- 2009: Chen & Rubin, *Energy Policy*
- 2009: ENCAP Report D.1.2.6
- 2009: IEAGHG Report 2009/TR-3
- 2009: EPRI Report No. 1017495
- 2010: Carnegie Mellon IECM v. 6.4
- 2010: UK DECC, Mott MacDonald Report
- 2010: Kheshgi, et al., SPE 139716-PP
- 2010: DOE/NETL Report 2010/1397
- 2010: DOE EIA Cost Update Report
- 2011: OECD/IEA Working Paper
- 2011: Global CCS Institute Update

My Observations

- Despite many recent studies on the cost of CO_2 capture and storage (CCS) there remain significant differences in underlying costing methods (as well as key assumptions) that are often not readily apparent.
- Such differences contribute to significant confusion, misunderstanding and (in some cases) the mis-representation of CO_2 abatement costs, especially among audiences unfamiliar with details of CCS costing.

Audiences for (and Sources of) Cost Estimates

Government

- Policymakers
- Analysts
- Regulators
- R&D agencies

Industry

- Operators
- Vendors
- A&E firms
- Venture capital
- Tech developers
- R&D orgs

NGOs

- Environmental
- Media
- Academia
- Foundations

Source: Based on Herzog, 2011

A Hierarchy of Methods to Estimate CCUS Costs

- Ask an expert
- Use published values
- Modify published values
- Derive new results from a model
- Commission a detailed engineering study

Common Measures of CCS Cost

- Cost of CO_2 avoided
- Cost of CO_2 captured
- Increased capital cost
- Increased cost of electricity

Dollars per Ton

- This is the metric most commonly used in technical and policy forums to quantify the cost of CCS (as well as other methods of reducing carbon emissions)
- Also the measure that is most easily misunderstood and misapplied

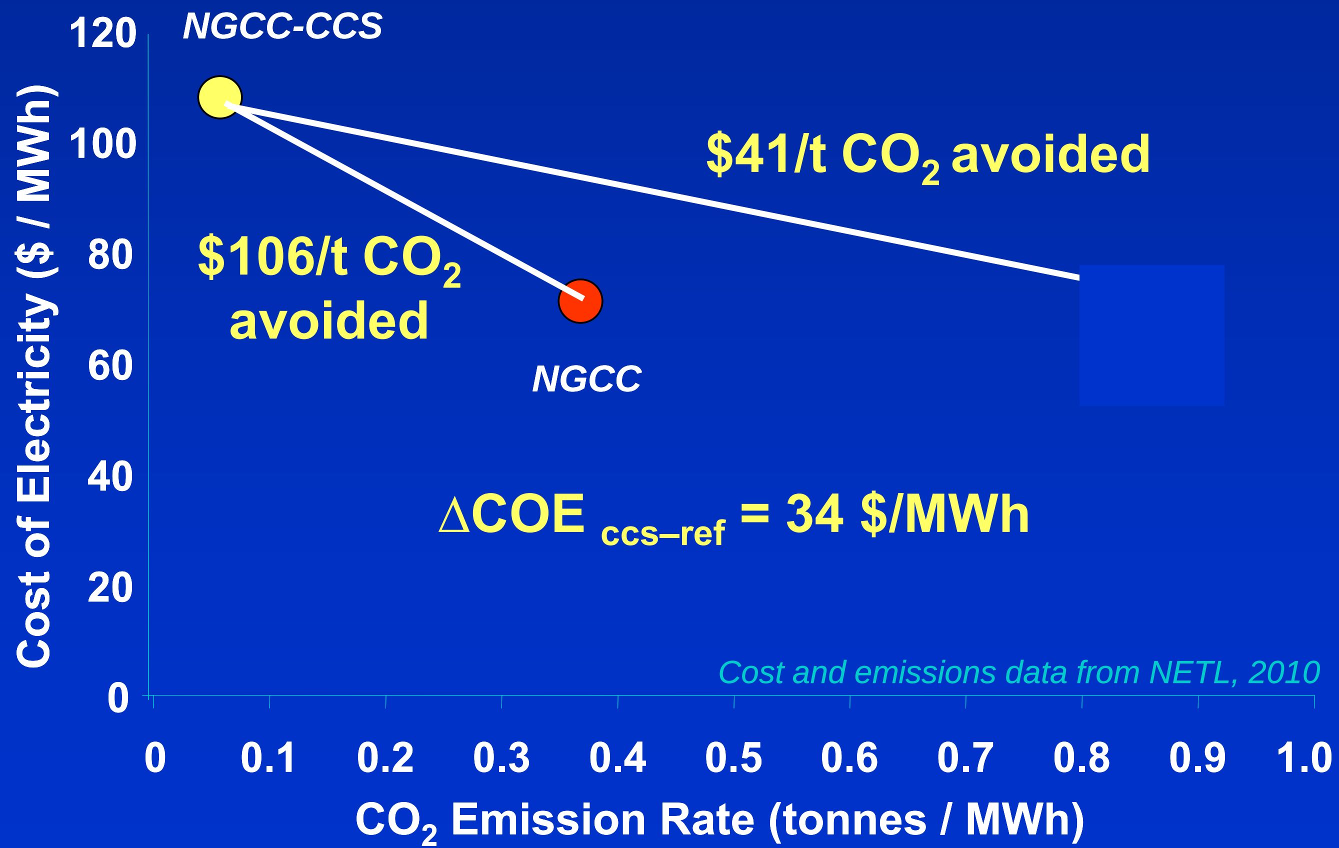
Cost of CO_2 Avoided

$$= \frac{(\$/\text{MWh})_{ccs} - (\$/\text{MWh})_{ref}}{(\text{t } CO_2/\text{MWh})_{ref} - (\text{t } CO_2/\text{MWh})_{ccs}} \quad (\$/\text{t } CO_2)$$

- This widely used metric gives the cost of reducing a ton of CO_2 emissions while still providing a unit of useful product (e.g., a MWh of delivered electricity)
- It should (but often does not) include the full chain of CCS processes, i.e., capture, transport and storage (emissions are not avoided until sequestered)
- It is a relative cost measure that is very sensitive to the choice of reference plant without CCS

Cost of CO_2 avoided is sensitive to assumed reference plant w/o CCS

Different questions require different reference plants



Two Additional Measures — Same Units, Different Meanings

- Cost of CO_2 Avoided ($/t CO_2)

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

- Cost of CO

Use with caution!

$$= \frac{\ldots)_{reference}}{\ldots_2/MWh)_{ccs,\ produced} \; - \; (t\ CO_2/MWh)_{ccs}}$$

- Cost of CO_2 Abated (Reduced) ($/t CO_2)

$$= \frac{(\$\ NPV)_{ccs} \; - \; (\$\ NPV)_{reference}}{(t\ CO_2)_{ref} \; - \; (t\ CO_2)_{ccs}}$$

Cost of Electricity (COE)

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

TCC = Total capital cost ($)

FCF = Fixed charge factor (fraction)

FOM = Fixed operating & maintenance costs ($/yr)

VOM = Variable O& M costs, excluding fuel cost ($/MWh)

HR = Power plant heat rate (MJ/MWh)

FC = Unit fuel cost ($/MJ)

CF = Annual average capacity factor (fraction)

MW = Net power plant capacity (MW)

Increase in COE

- A common metric for power plant CCS cost
- Typically reported on a “levelized” basis (LCOE)
  - Implies that all parameters in the COE equation (including FCF and CF) reflect their levelized value over the life of the plant
- Most studies report LCOE in constant dollars (no inflation effects); some report in current (nominal) dollars, which yield higher values
  - O&M costs are multiplied by a “levelization factor” calculated from specified rates of inflation and real cost escalations over the plant life.

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"

Ten Ways to Reduce CCUS Costs

(Inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume high EOR credits for CO_2 stored
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!*

Current Status of Costing Methods

- Various organizations have developed detailed procedures and guidelines for calculating power plant and CCS costs (capital, O&M, COE)
- Across different organizations, however, there are significant differences and inconsistencies in the costing methods that are used

Capital Cost Elements (Recent Studies)

EPRI (2009)	USDOE/NETL (2007)	USDOE/NETL (2010)	USDOE/EIA (2010)
Process facilities capital	Bare erected cost (BEC)	Bare erected cost (BEC)	Civil Structural Material & Installation
General facilities capital	Eng. & Home Office Fees	Eng. & Home Office Fees	Mechanical Equip. Supply & Installation
Eng'g, home office, overhead & fees	Project Contingency Cost	Project Contingency Cost	Electrical/I&C Supply and Installation
Contingencies—project and process	Process Contingency Cost	Process Contingency Cost	Project Indirects
Total plant cost (TPC)	**Total plant cost (TPC)**	**Total plant cost (TPC)**	EPC Cost before Contingency and Fee
AFUDC (interest & escalation)		Pre-Production Costs	Fee and Contingency
Total plant investment (TPI)		Inventory Capital	**Total Project EPC**
Owner's costs: royalties, preproduction costs, Inventory capital, Initial catalyst and chemicals, Land		Financing costs	Owner's Costs (excl. project finance)
		Other owner's costs	**Total Project Cost (excl. finance)**
Total Capital Requirement (TCR)		**Total overnight cost (TOC)**	

No consistent set of cost categories or nomenclature across studies

IEA GHG (2009)	ENCAP (2009)	UK DECC (2010)
Direct materials	EPC costs	Pre-licencing costs, Technical and design
Labour and other site costs	Owner's costs	Regulatory + licencing + public enquiry
Engineering fees	**Total Investment**	Eng'g, procurement & construction (EPC)
Contingencies		Infrastructure / connection costs
Total plant cost (TPC)		**Total Capital Cost (excluded IDC)**
Construction interest		
Owner's costs		
Working capital		
Start-up costs		
Total Capital Requirement (TCR)		

O&M Cost Elements in Recent Studies

Category	USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI (2009)
Fixed O&M	Operating labor	Operating labor	Operating labor
	Maintenance –labor	Maintenance –labor	Maintenance costs
	Admin. & support labor	Admin. & support labor	Overhead charges (admin & support labor)
		Property taxes and insurance	
Variable O&M (excl. fuel)	Maintenance – material	Maintenance – material	Maintenance costs
	Consumables (water, chemicals, etc.)	Consumables (water, chemicals, etc.)	Consumables (water, chemicals, etc.)
	Waste disposal	Waste disposal	Waste disposal
	Co- or by-product credit	Co- or by-product credit	Co- or by-product credit
	CO2 transport and storage	CO2 transport and storage	CO2 transport and storage

No consistent set of cost categories or nomenclature across studies

Category	IEA GHG (2009)	UK DECC (2010)
Fixed O&M	Operating labour	Operating labour
	Indicative cost	Planned and unplanned maintenance (additional labour, spares and consumables)
	Administrative and support labour	
	Insurance and local property taxes	Through life capital maintenance
	Maintenance cost	
Variable O&M (excl. fuel)	Consumables (water, chemicals, etc.)	Repair and maintenance costs
	By-products and wastes disposal	Residue disposal and treatment
	CO2 transport and storage	Connection & transmission charges
		Insurance
		CO2 transport and storage
		Carbon price

Elements of "Owner's Costs" in Several Recent Studies

USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI (2009)	IEA GHG (2009)	UK DECC (2010)
(None)	Preproduction (Start-Up) costs	Preproduction (Start-Up) costs	Feasibility studies	(None)
	Working capital	Prepaid royalties	Obtaining permits	
	Inventory capital	Inventory capital	Arranging financing	
	Financing cost	Initial catalyst/chem.	Other misc. costs	
	Land	Land	Land purchase	
	Other			

No consistent set of cost categories or nomenclature across studies

Key Assumptions Also Vary Across Studies

Parameter	USDOE/NETL 2007	USDOE/NETL 2010	EPRI 2009	IEA GHG 2009	UK DECC 2010
Plant Size (PC case)	550 MW (net)	550 MW (net)	750 MW (net)	800 MW (net)	1600 MW (gross)
Capacity Factor	85%	85%	85%	85% (yr 1= 60%)	varies yearly
Constant/Current $	Current	Current	Constant	Constant	Constant
Discount Rate	10%	10%	7.09%	8%	10%
Plant Book Life (yrs)	20	30	30	25	32-40 (FOAK) 35-45 (NOAK)
Capital Charge Factor					
no CCS	0.164	0.116	0.121	N/A	N/A
w/ CCS	0.175	0.124	0.121	N/A	N/A
Variable Cost Levelization Factor					
no CCS	1.2089 (coal) 1.1618 (other)	1.2676	1.00	1.00	N/A
- w/ CCS	1.2022 (coal) 1.1568 (other)	1.2676	1.00	1.00	N/A

N/A: not available

Transparency is critical for understanding

Uncertainty, Variability & Bias

- Variability and uncertainty can (in principle) be accounted for in costing methods, e.g., via parametric (sensitivity) analysis, choice of parameter values, and/or probabilistic analysis
- Bias can arise in project design specifications and choice of parameters and values for cost estimates
  - Can be difficult to detect or prove
  - Independent (3rd party) evaluations can be helpful

Especially important for evaluating new or emerging technologies

The Devil is in the Details

- Need to improve the consistency, reporting and transparency of costing methods and assumptions to enhance the understanding of CCS costs

A CCS Cost Task Force has recommended a path forward

Toward a Common Method of Cost Estimation for CO_2 Capture and Storage at Fossil Fuel Power Plants

**A White Paper Prepared by
the
Task Force on CCS Costing Methods**

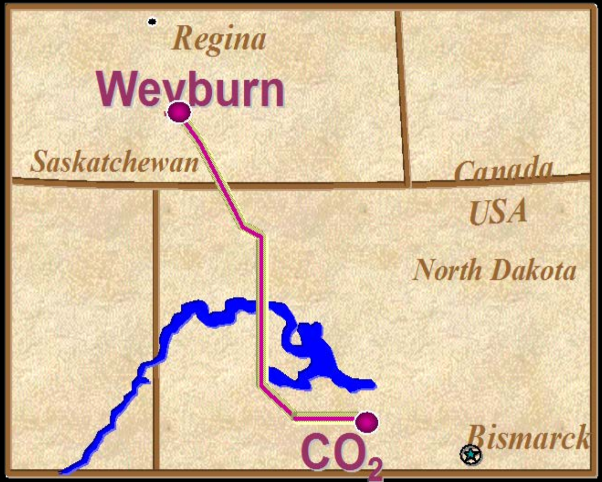
Ed Rubin (CMU) (Chair)
George Booras (EPRI)
John Davison (IEAGHG)
Clas Ekstrom (Vattenfall)
Mike Matuszewski (USDOE/NETL)
Sean McCoy (IEA)
Chris Short (GCCSI)

April 22, 2012

White Paper Contents:

- Defining Project Scope and Design
- Defining Nomenclature and Cost Categories for CCS Cost Estimates
- Quantifying Elements of CCS Cost
- Defining Financial Structure and Economic Assumptions
- Calculating the Costs of Electricity and CO_2 Avoided
- Guidelines for CCS Cost Reporting

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



Sources: IEAGHG; NRDC; USDOE

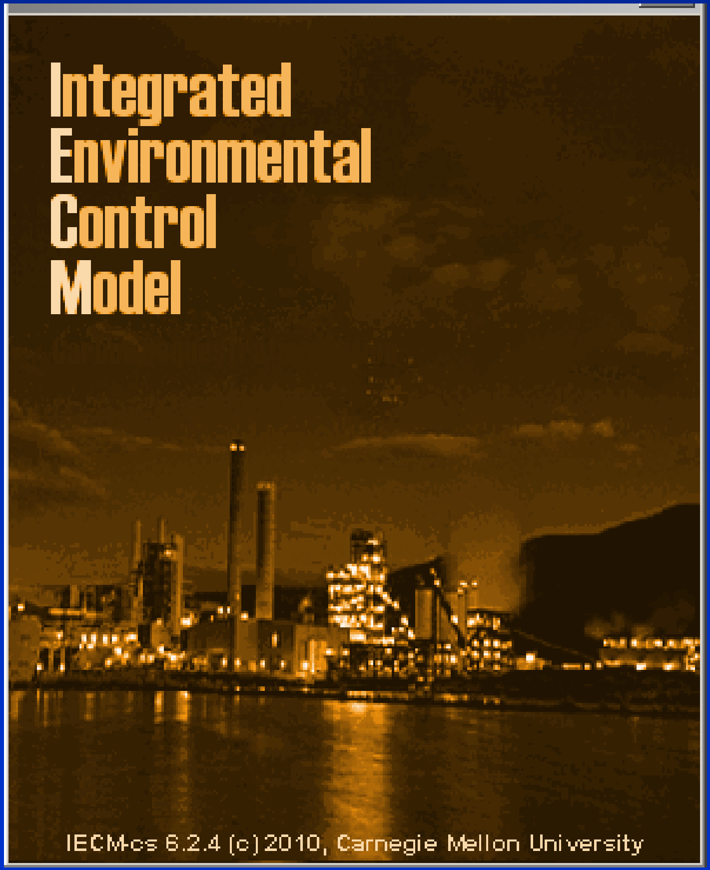
The cost of CCUS vs. CCS

Illustrative Cases Studies

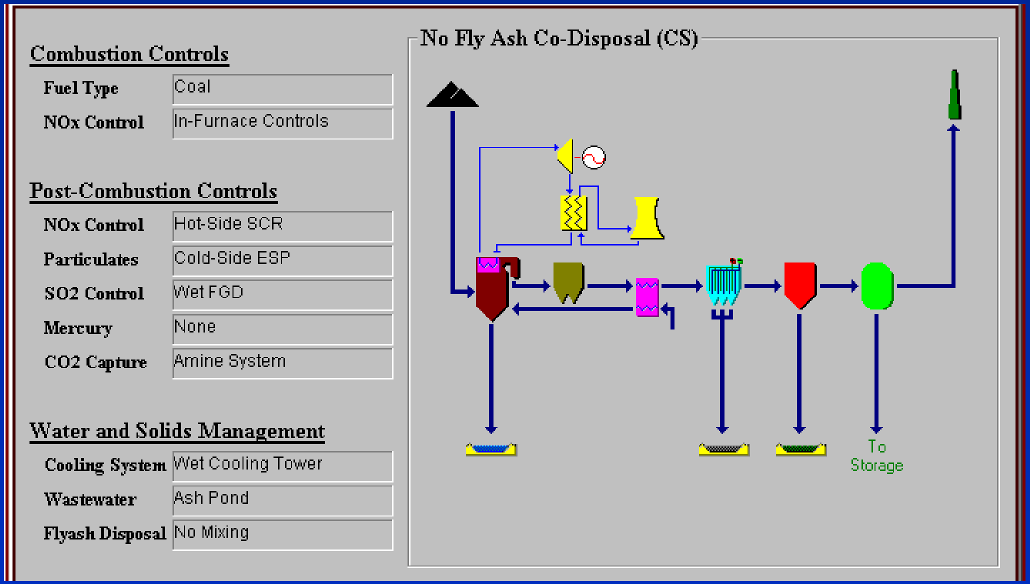
- Use the IECM to analyze effect on overall plant cost of varying the price of CO_2 sold for EOR for three plant types:
  - PC Plant
  - NGCC Plant
  - IGCC Plant

The Integrated Environmental Control Model (IECM)

- 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**

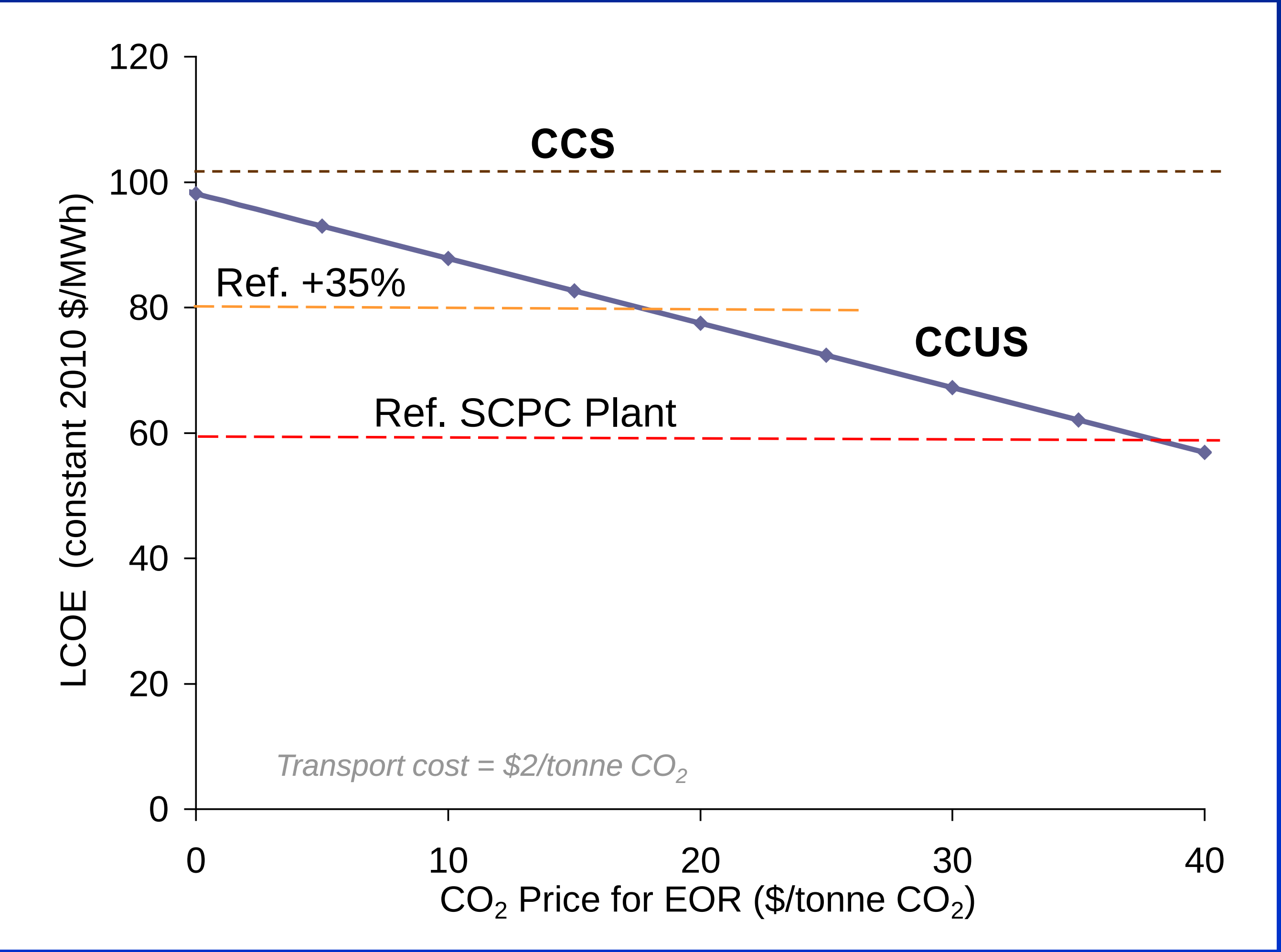


Illustrative Cases Studies *(1)*

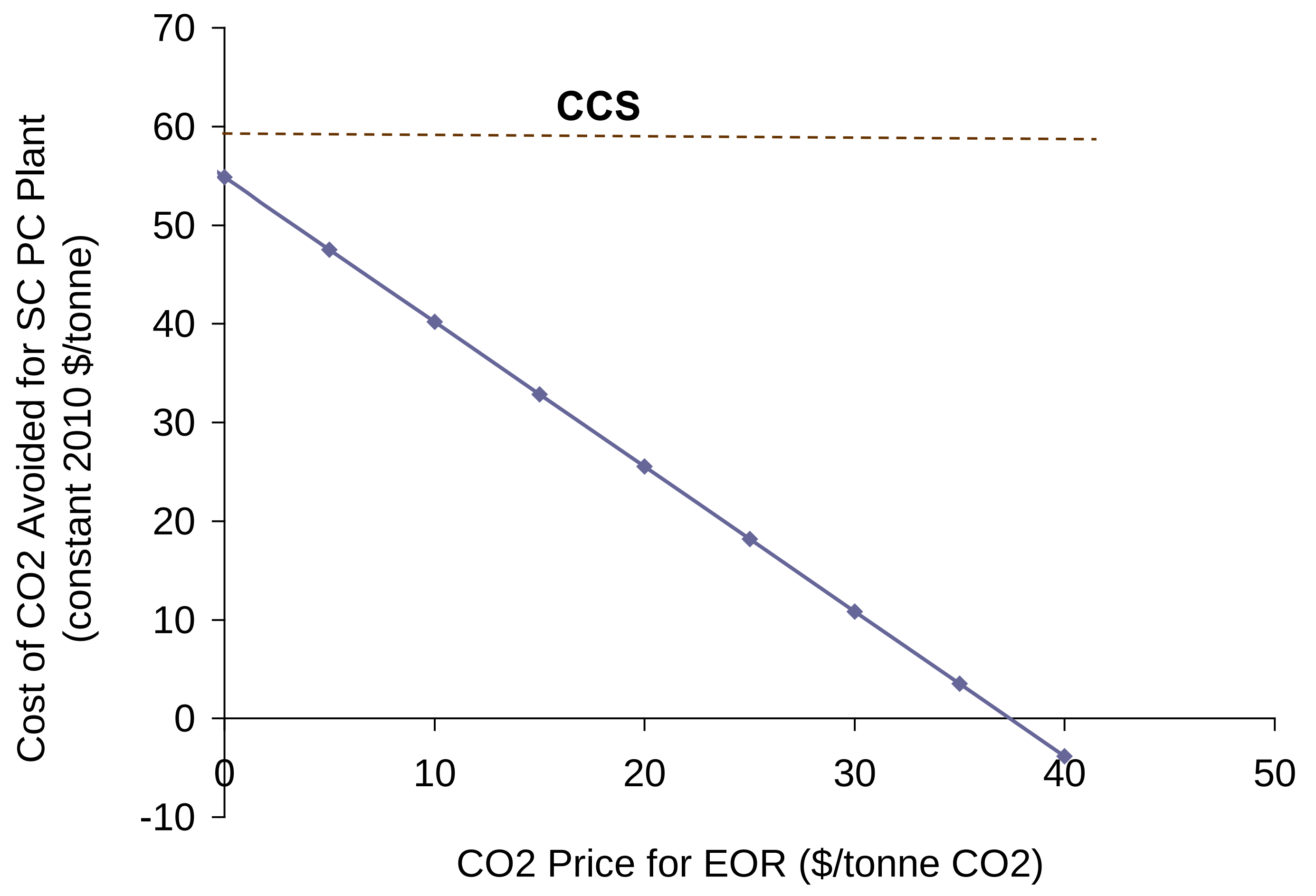


Plant Type	Supercritical PC
Coal Type	Illinois #6
Net Plant Capacity (Ref / CCS)	550 MW / 550 MW
CO_2 Capture System	Econamine FG+
Capacity Factor (levelized)	75%
Fixed Charge Factor (const $ / current $)	0.113 / 0.147

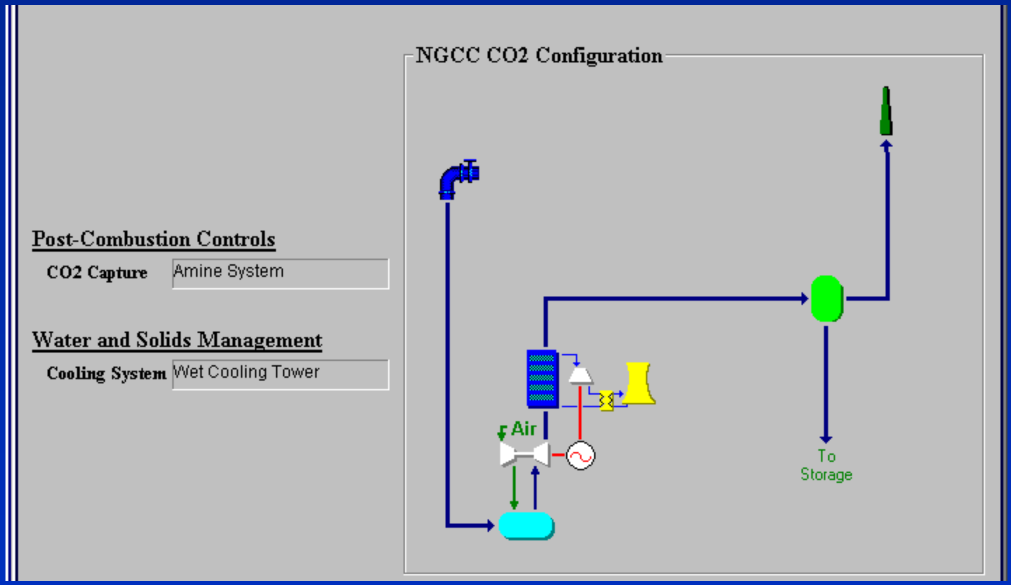
LCOE vs. CO_2 EOR Price
(SCPC Plant)



Avoidance Cost vs. CO_2 Price
(SCPC Plant)

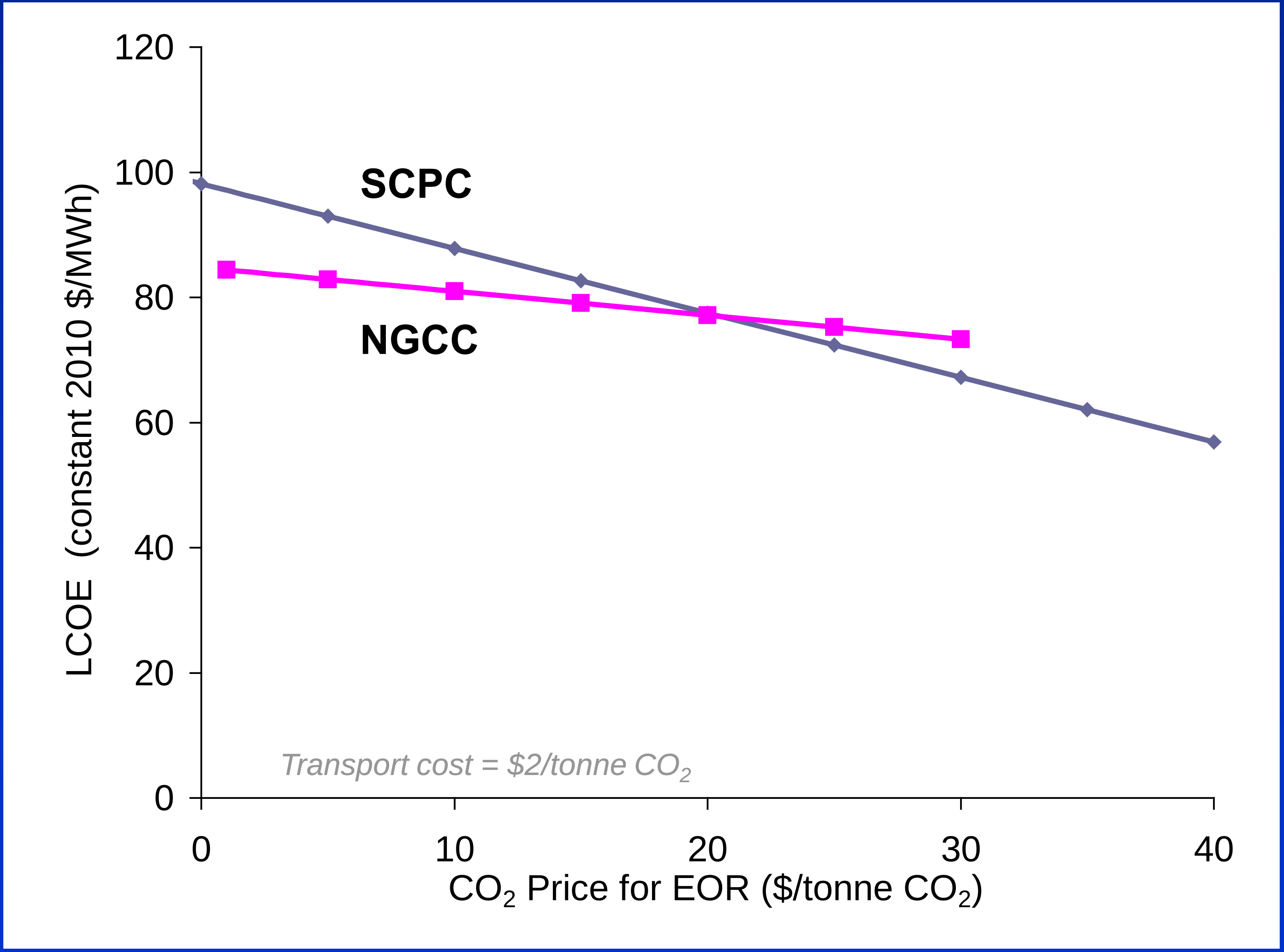


Illustrative Cases Studies *(2)*



Plant Type	NGCC
Gas Turbine Type	GE 7FB
Net Plant Capacity (Ref / CCS)	527 MW / 455 MW
CO_2 Capture System	Econamine FG+
Capacity Factor (levelized)	75%
Fixed Charge Factor (const \$ / current \$)	0.113 / 0.147

SCPC vs. NGCC



120
100
80
60
40
20
0
LCOE (constant 2010 $/MWh)
SCPC
NGCC
Transport cost = $2/tonne CO_2
0
10
20
30
40
CO_2 Price for EOR ($/tonne CO_2)

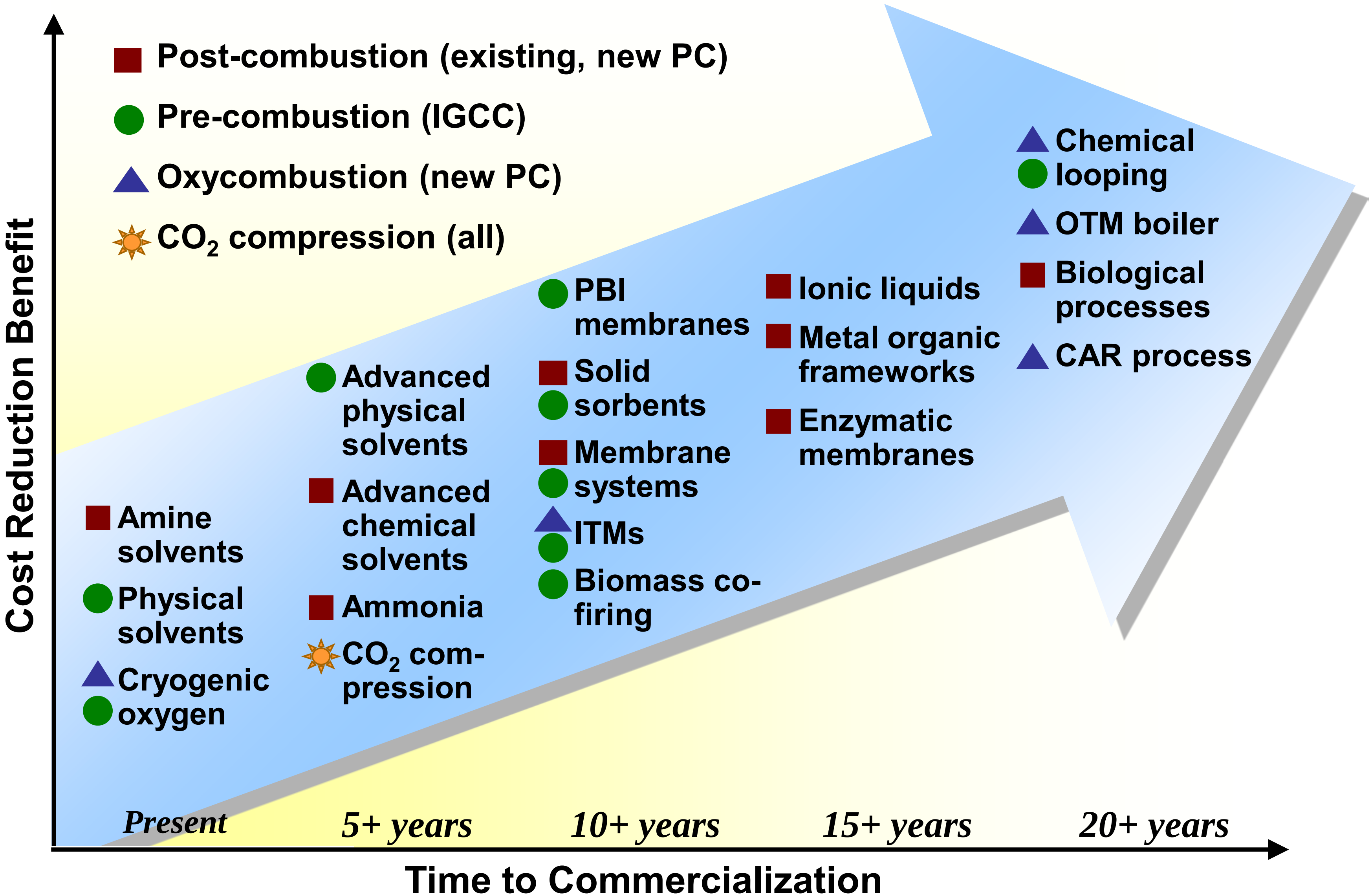
Sensitivity Cases

Case	LCOE (SCPC-CCS)	Avoidance Cost ($/t)	Cost of Capture ($/t)
Base CCS - constant $	101	59	36
current $, 3% inflation	134	78	47
+discount rate = 20%	143	84	51
+discount rate = 30%	154	90	54

Many other parameters can affect these results

What is the potential for advanced capture technology?

Better Capture Technologies Are Emerging



A New Paper Looks at Details

Progress in Energy and Combustion Science xxx (2012) 1–42

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Review

The outlook for improved carbon capture technology

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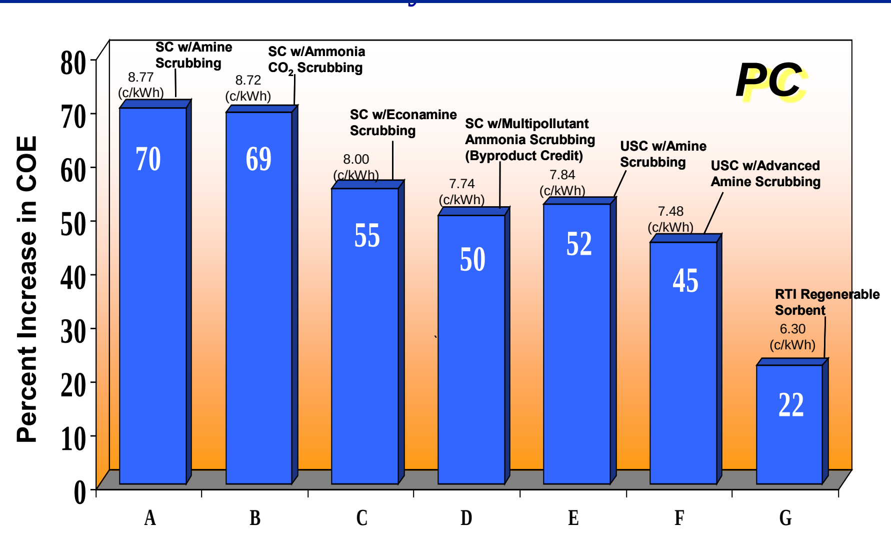
ABSTRACT

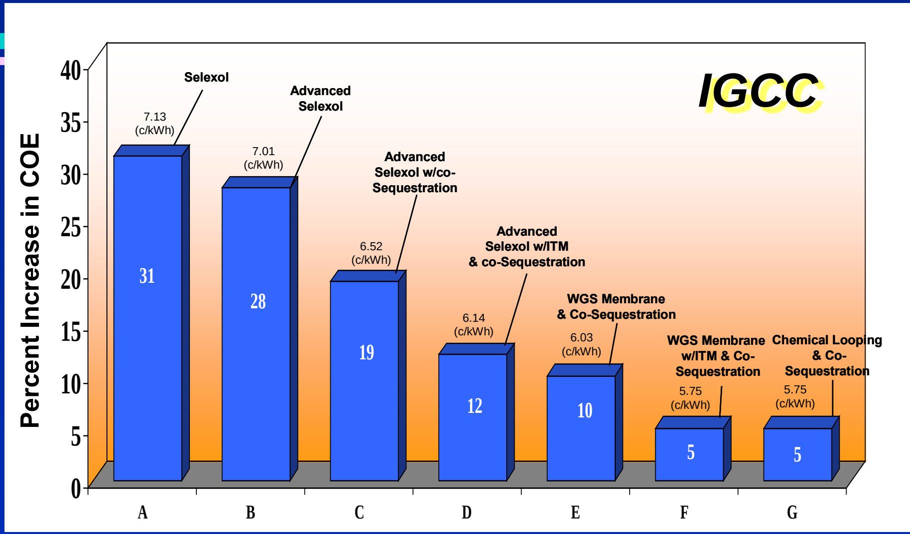
Carbon capture and storage (CCS) is widely seen as a critical technology for reducing atmospheric emissions of carbon dioxide (CO_2) from power plants and other large industrial facilities, which are major sources of greenhouse gas emissions linked to global climate change. However, the high cost and energy requirements of current CO_2 capture processes are major barriers to their use. This paper assesses the outlook for improved, lower-cost technologies for each of the three major approaches to CO_2 capture, namely, post-combustion, pre-combustion and oxy-combustion capture. The advantages and limitations of each of method are discussed, along with the current status of projects and processes at various stages in the development cycle. We then review a variety of "roadmaps" developed by governmental and private-sector organizations to project the commercial roll-out and deployment of advanced capture technologies. For perspective, we also review recent experience with R&D programs to develop lower-cost technologies for SO_2 and NO_x capture at coal-fired power plants. For perspective on projected cost reductions for CO_2 capture we further review past experience in cost trends for SO_2 and NO_x capture systems. The key insight for improved carbon capture technology is that achieving significant cost reductions will require not only a vigorous and sustained level of research and development (R&D), but also a substantial level of commercial deployment, which, in turn, requires a significant market for CO_2 capture technologies. At present such a market does not yet exist. While various incentive programs can accelerate the development and deployment of improved CO_2 capture systems, government actions that significantly limit CO_2 emissions to the atmosphere ultimately are needed to realize substantial and sustained reductions in the future cost of CO_2 capture.

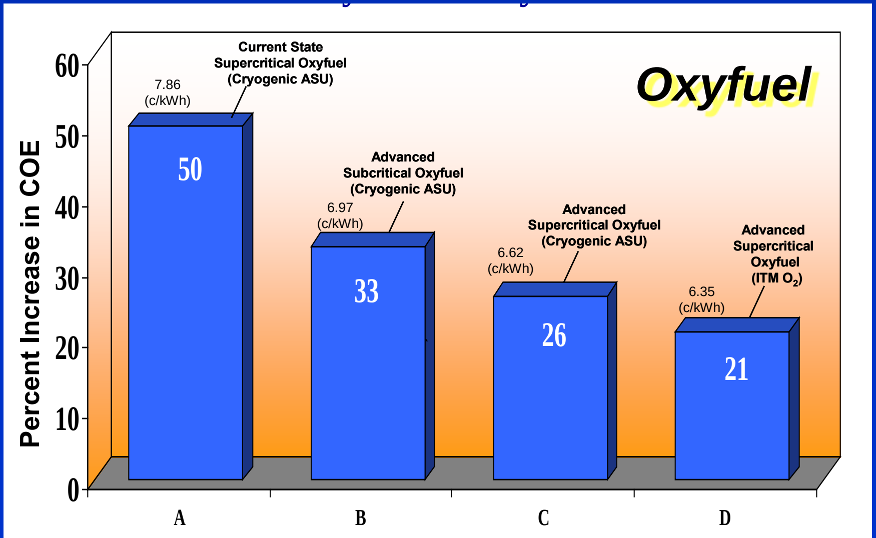
Two Approaches to Estimating Potential Cost Savings

- *<u>Method 1</u>:* Engineering-Economic Analysis
  - A "bottom up" approach based on engineering process models, informed by judgments regarding potential improvement in key parameters

Potential Cost Reductions Based on Engineering-Economic Analysis







19% -28% reductions in COE w/ CCS

Source: DOE/NETL, 2006

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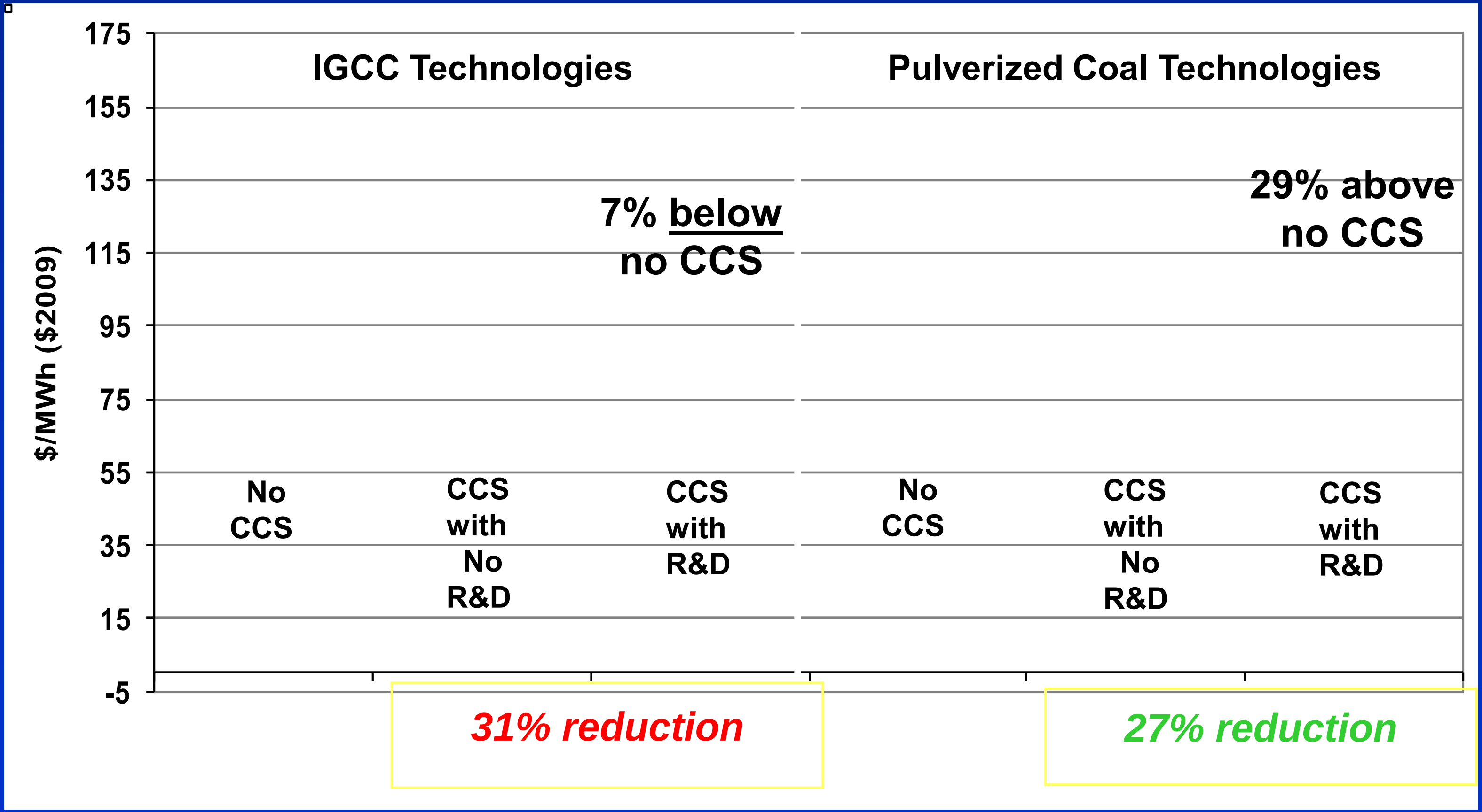
Potential Cost Reductions Based on Engineering-Economic Analysis



Source: DOE/ NETL, 2010

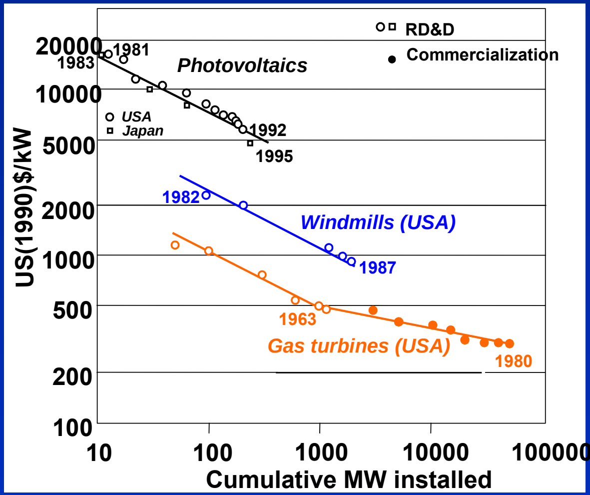
Two Approaches to Estimating Future Technology Costs

- *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

Empirical “Learning Curves”

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

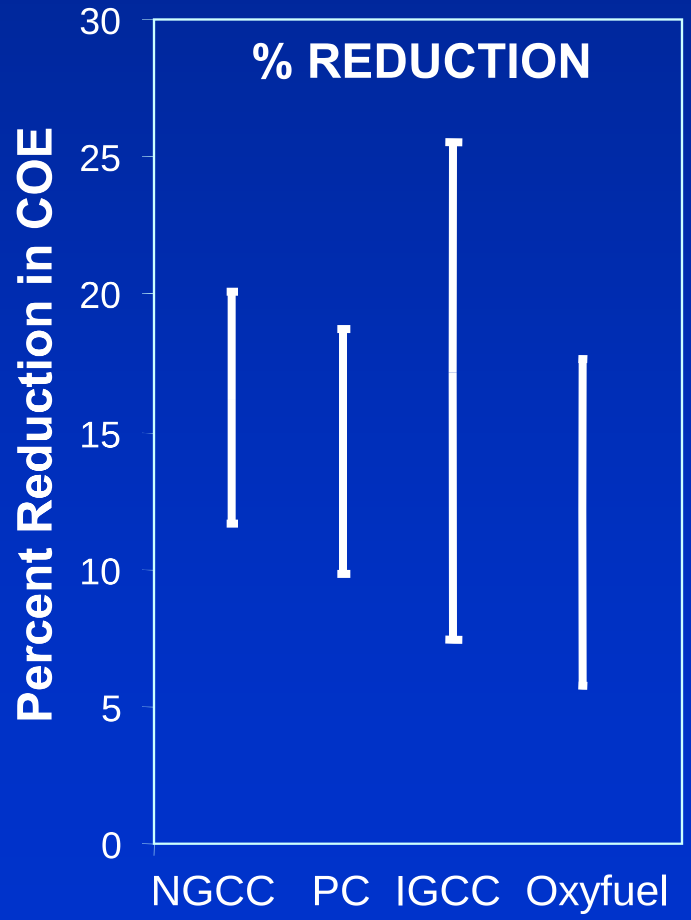


Source: IIASA, 1996

- 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)

Projected Cost Reductions for Power Plants with CO_2 Capture

(after 100 GW of cumulative CCS capacity worldwide)



- Plant-level learning curves developed from component-level analyses
- **Upper bound of ranges are similar to estimates from “bottom-up” analyses**

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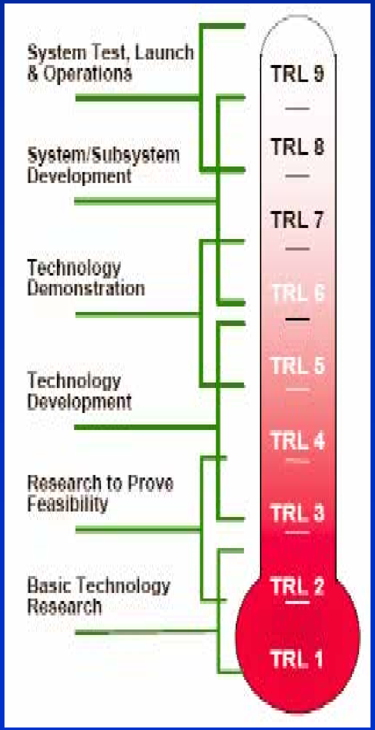
Conclusions

- Significant potential to reduce the cost of carbon capture via:
  - New or improved CO_2 capture technologies
  - Improved plant efficiency and utilization

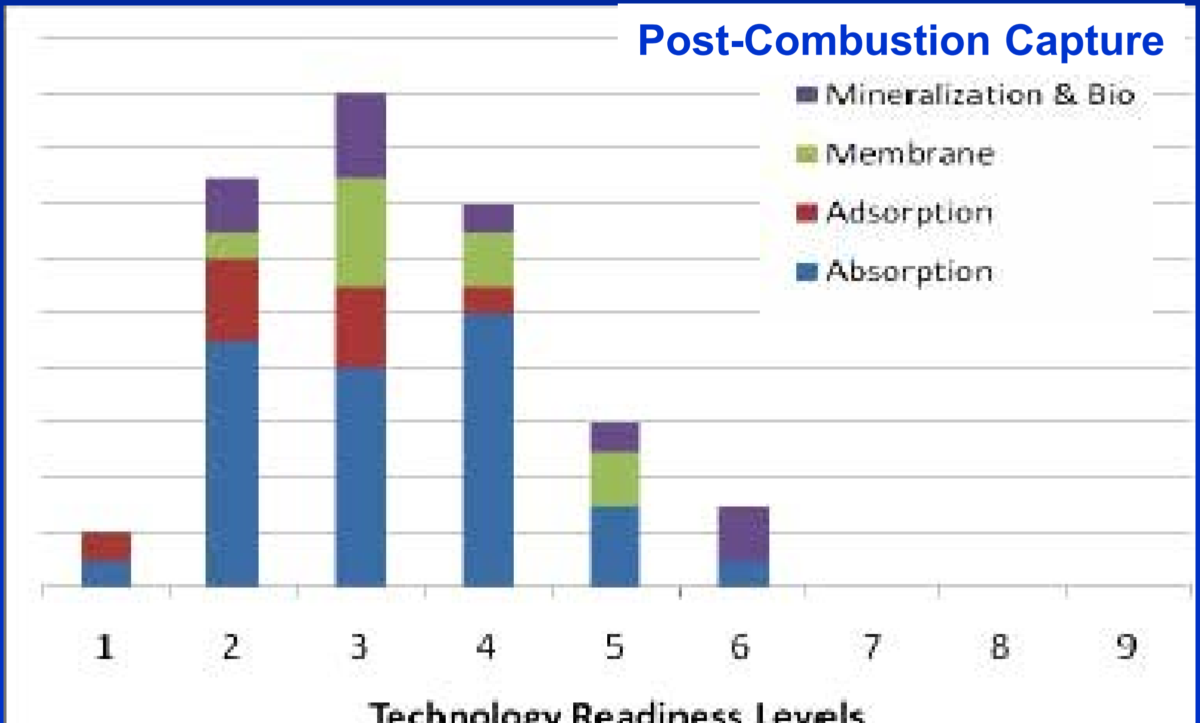
Challenges for advanced CCS technology

Most New Capture Concepts Are Far from Commercial Availability

Technology Readiness Levels

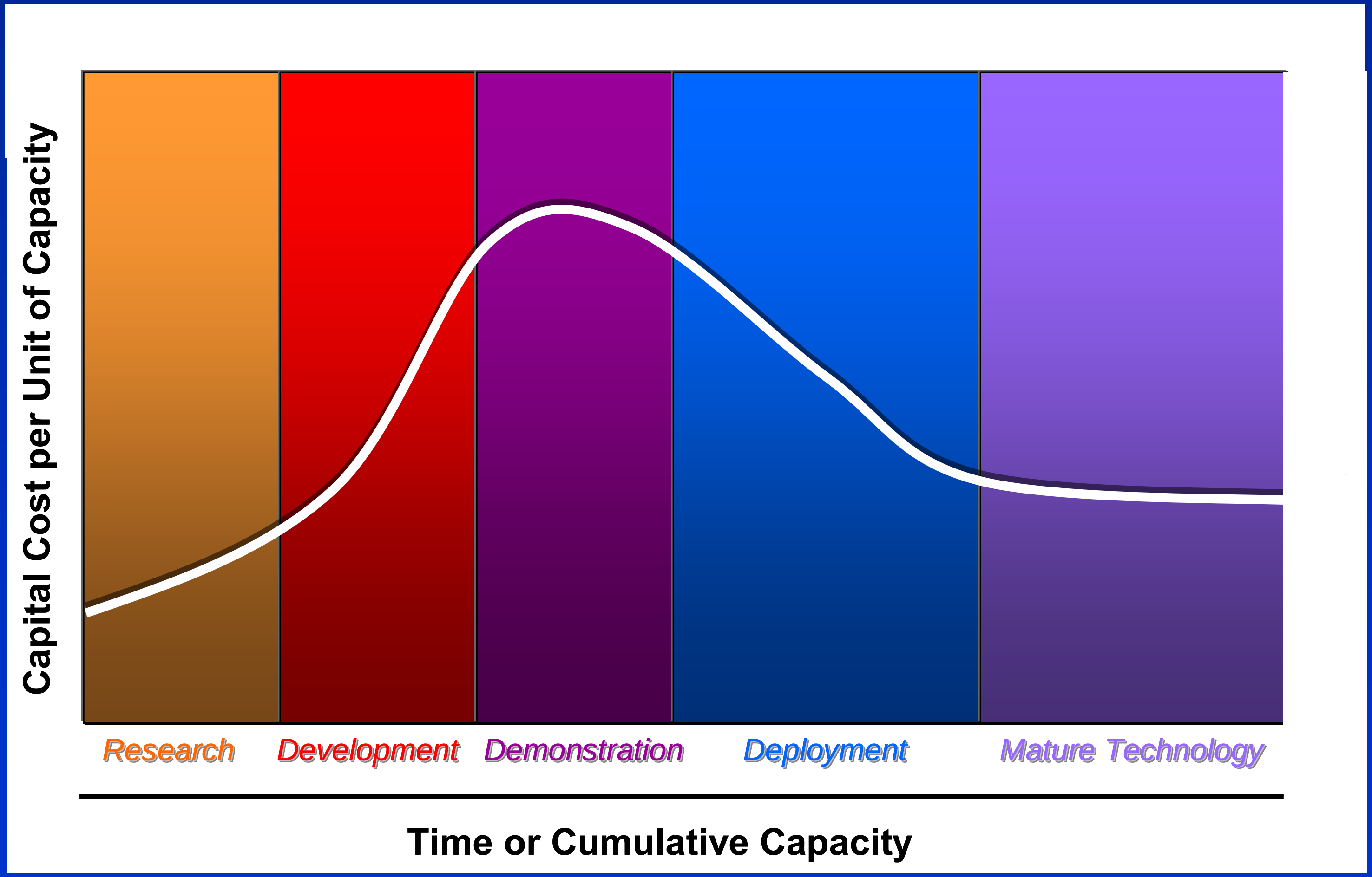


Source: NASA, 2009



***Source*: EPRI, 2009**

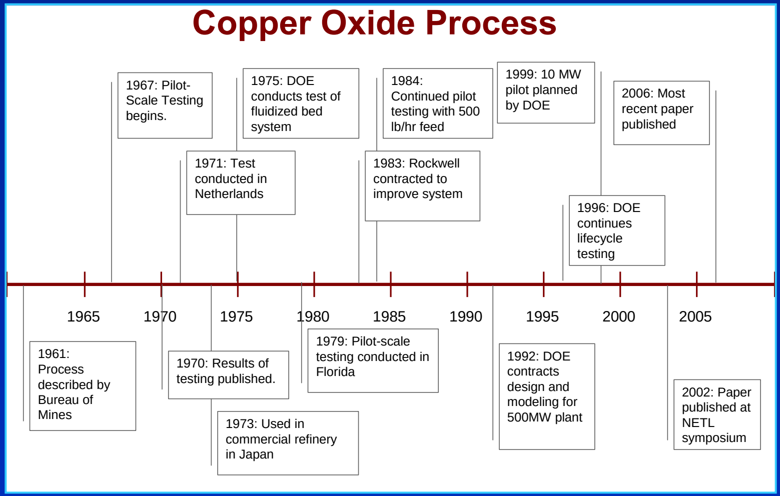
Typical Cost Trend for a New Technology

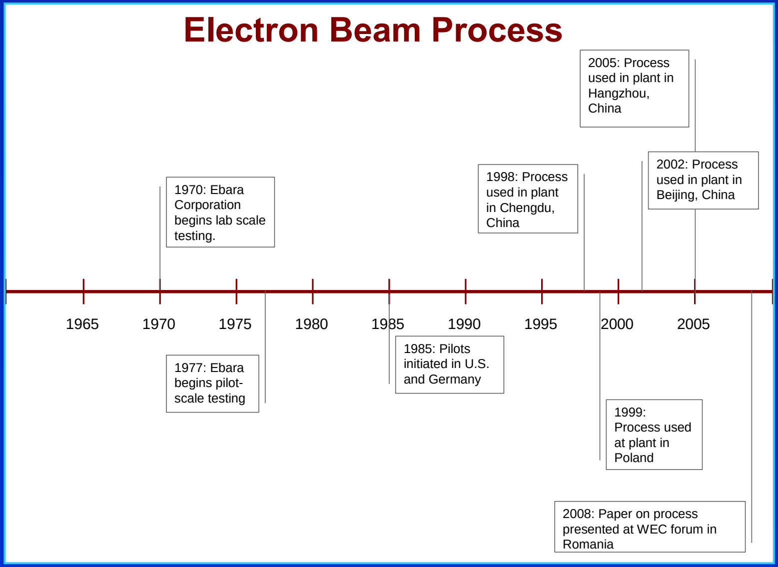


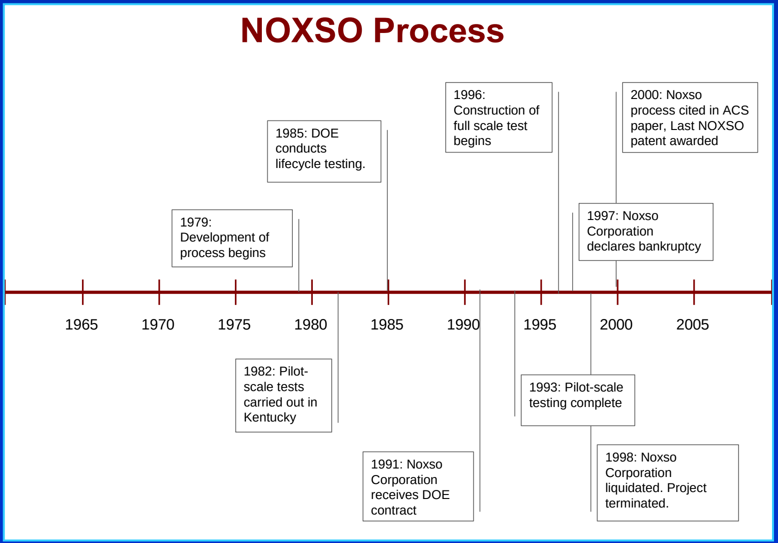
Source: Based on EPRI, 2008

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

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







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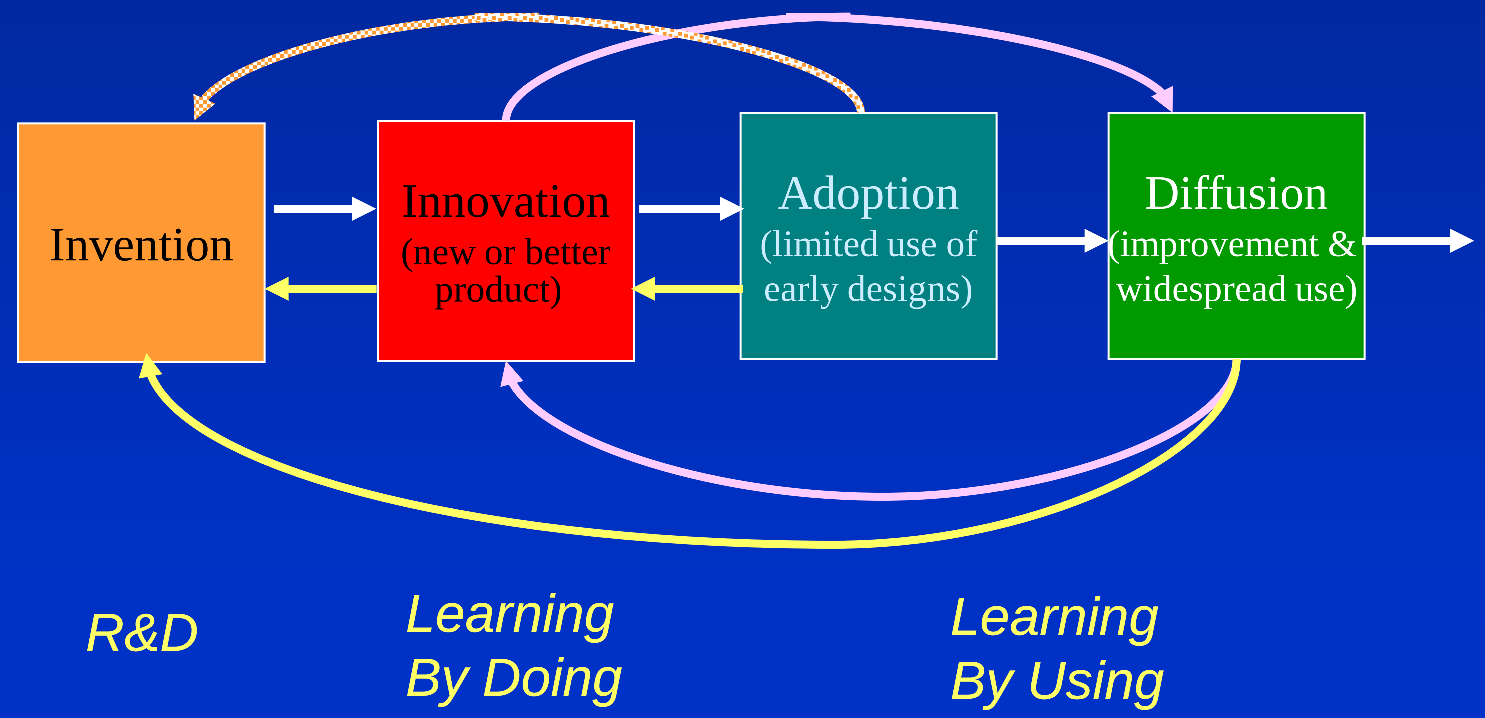
Need to Accelerate the Pace of Innovation



The CCSI Initiative to Accelerate New Capture Systems

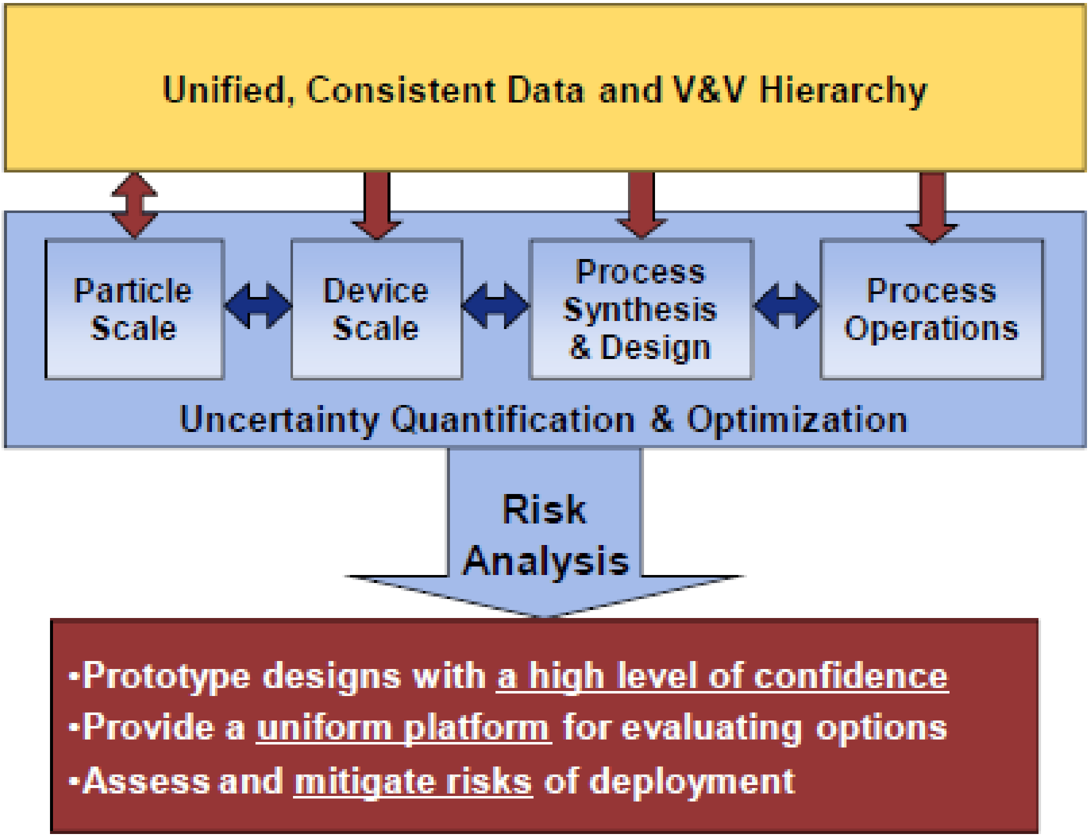


Figure 1.3 CCSI innovations for computational modeling of carbon capture systems

Source: DOE/ NETL, 2011

The Critical Role of Policy

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

Thank You

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