The Outlook for Advanced Post-Combustion CCS Processes

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Background

- Our research group at Carnegie Mellon has been looking at and modeling a variety of current and advanced technologies for carbon capture and storage (CCS) as a greenhouse gas mitigation option for power plants using fossil fuels or biomass, including:
  - Pre-combustion
  - Post-combustion, and
  - Oxy-combustion processes for CO_2 capture

Advanced Capture Technology Models Under Development*

- Post-Combustion Capture
  - Advanced membranes
  - Calcium looping
  - Solid sorbents
    - Amine-based
    - Activated carbon-based
    - Metal organic frameworks
  - Ionic liquids
- Oxy-Combustion Capture
  - Oxygen production
  - Carbon processing unit
  - Gas recycle options
- Pre-Combustion Capture
  - Chemical looping
  - Ionic liquids
  - Sorbent-enhanced WGS

*In projects supported by DOE/NETL and Stanford/GCEP

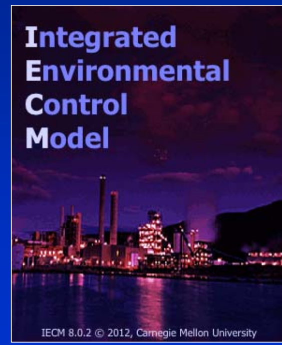
Objective of This Talk

- Focus on post-combustion CO_2 capture
- Summarize preliminary findings on the potential of advanced technologies to significantly reduce the cost of CO_2 capture relative to current amine-based systems

The IECM Framework

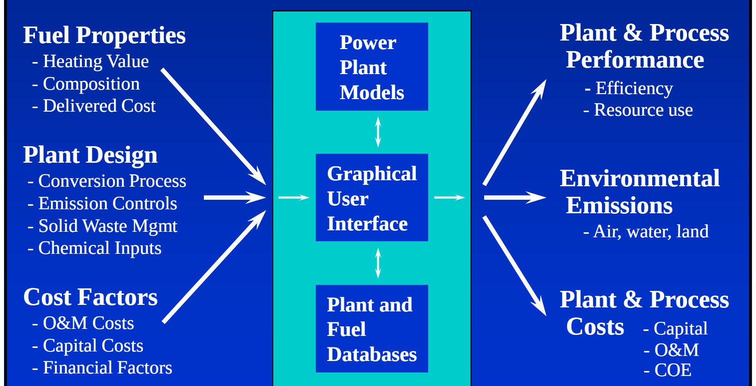
IECM: A Tool for Analyzing Power Plant Design Options

- 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**



USED WORLDWIDE BY INDUSTRY, GOVERNMENT, ACADEMIA & OTHERS

IECM Software Package



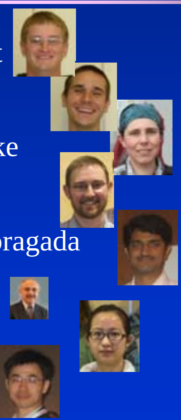
Technologies Currently in IECM
(Version 8.0.2)

CO_2 Capture & Storage Systems*	Coal Combustion Plants		Gasification Plants (IGCC)	IGCC and NGCC Plants
Post-Combustion Capture Conv. Amine; Adv. amines (FG+); Chilled ammonia; Membrane systems; Aux. NG steam or power gen. (optional) Oxy-Combustion Capture Flue gas recycle; ASU; Chemical processing units Pre-Combustion Capture Water gas shift + Selexol CO_2 Compressor CO_2 Transport Pipelines (6 U.S. regions); Other (user-specified) CO_2 Storage Deep saline formation; Geol.Storage w/ EOR; Other (user-specified)	Boiler/Turbine Systems Subcritical; Supercritical; Ultra-supercritical Furnace Firing Tangential; Wall; Cyclone Furnace NOx Control LNB; SNCR; SNCR+LNB; Gas reburn Flue Gas NOx Removal Hot-side SCR Mercury Removal Carbon/sorbent injection	Particulate Removal Cold-side ESP; Fabric filter (Reverse air; Pulse jet) SO_2 Removal Wet limestone (Conv.; F. oxidation; Additives); Wet lime; Lime spray dry Solids Management Ash pond; Landfill; Co-mixing; useful byproducts Cooling and Wastewater Systems Once-thru cooling; Wet cooling tower; Dry cooling; Chemical treatment; Mech. treatment	Air Separation Unit Cryogenic Slurry Preparation & Coal Pretreatment Gasification Slurry-fed gasifier (GE-Q); Dry-fed gasifier (Shell) Syngas Cooling and Particulate Removal Mercury Removal Activated carbon H_2S Removal Selexol; Sulfinol Sulfur Recovery Claus plant; Beavon-Stretford unit	Gas Turbine GE 7FA; GE 7FB Heat Recovery Steam Generator Steam Turbine Boiler Feedwater System Process Condensate Treatment Cooling Water System Once-through; Wet cooling tower; Dry cooling Aux. Equipment

*Additional capture options under development include solid sorbent and calcium looping systems for post-combustion (PC or NGCC plants), a chemical looping system for IGCC, and an advanced oxy-combustion system

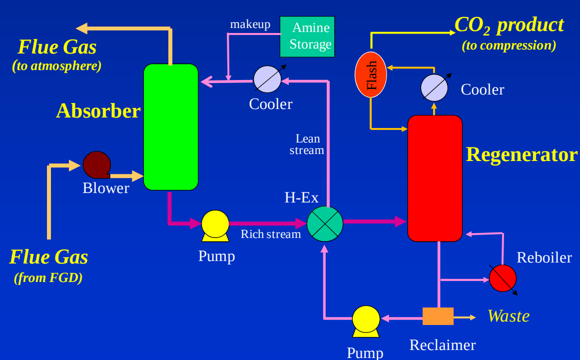
The CMU Project Team

- Kyle Borgert
- Justin Glier
- Karen Kietzke
- John Kitchin
- Hari Mantripragada
- Ed Rubin
- Wenqin You
- Haibo Zhai



Current Post-Combustion Capture Technology

CO_2 Capture Using an Amine-Based System



CO_2 Capture Systems on Power Plants

(Slip streams of ~10-20 MW)

(Source: Flour Daniel) (Source: IEA GHG) (Source: Southern Co.)

First Large-Scale Demonstration Project Now Operating

- Sask Power Boundary Dam (Canada); 110 MW coal-fired unit;
- 90% capture +EOR (~ 1 Mt CO_2/yr); Startup September 2014


Sask Power, 2014

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Cost of Post-Combustion 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	Supercritical Pulverized Coal Plant	Natural Gas Combined Cycle
% Increases in power generation cost ($/kWh)*	**~ 60–80%**	**~ 30–45%**

- ***Capture accounts for most (~80%) of the total cost***

**Added cost to consumers will be much smaller, reflecting the CCS capacity in the generation mix at any given time. Retrofit of existing plants typically has a higher cost*

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Advanced CO_2 Capture Technologies

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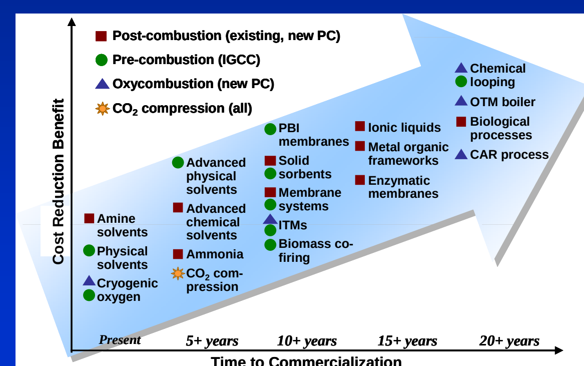
Examples of Advanced Technologies: Everything beyond *Present*



Source: USDOE, 2010

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Characteristics of Advanced Carbon Capture Systems

- The technology is not yet deployed or available for purchase at a commercial scale
  - Current stage of development may range from concept to large pilot or demonstration project
- Process design details still preliminary or incomplete
- Process performance not yet validated at scale, or under a broad range of conditions
- May require new components and/or materials that are not yet manufactured or used at a commercial scale

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IECM Technologies for Post-Combustion CO_2 Capture

- Liquid solvent systems
  - Amines (MEA, FG+)
  - Chilled ammonia
  - Ionic liquids*
- Solid sorbent systems
  - Amine-based*
  - Activated carbons*
  - Metal organic frameworks*
  - Calcium looping*
- Membrane systems
  - Once-through systems
  - Sweep gas (recycle) systems*
- Process energy supply options:
  - Plant generator and steam cycle
  - Auxiliary NG boiler or power plant
  - Purchased off-site

* Under development for Version 9.0 or later

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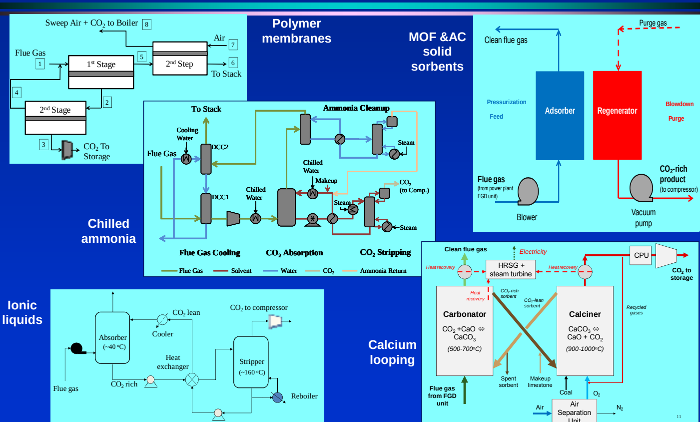
In recent papers and presentations we analyzed several advanced technologies



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Preliminary Findings for Overall Plant Performance

For designs achieving 90% CO_2 capture:

- Many of the advanced processes for post-combustion capture have energy penalties comparable to current amine systems, based on the current state of technology
- The two systems with better performance than amines were an advanced membrane design (2-stage, 2-step with air sweep) and a calcium looping system
  - *Caveat:* Effects of flue gas impurities on process and system performance remains to be determined

Preliminary Conclusion:
Better capture materials and process designs are needed to get major performance improvements

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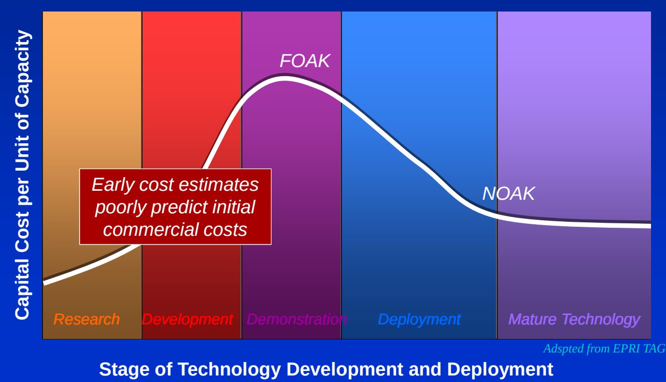
Typical Cost Trend of a New Technology



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How can we do a better job of estimating the cost of advanced technologies ?

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Seven Simple Steps to Improve Cost Estimates for New Technologies

1. Use non-cost metrics for earliest-stage technologies
2. Define the proper system boundary for cost estimates
3. Use standard costing methods
4. Quantify cost elements appropriately for FOAK plant
5. Use learning curves when estimating NOAK costs
6. Characterize and quantify uncertainties
7. Report cost metrics that are useful and unambiguous

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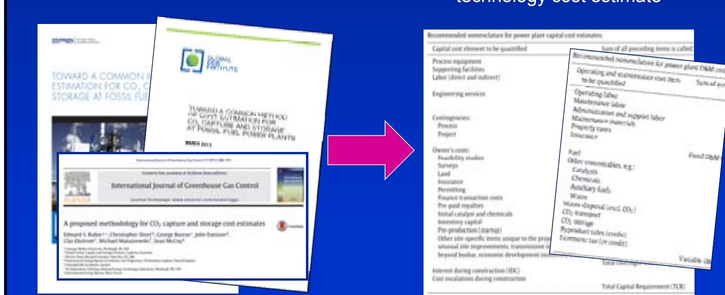
A Standardized Costing Method is Now Available

Recent guidelines from International Task Force

Items to be included in a power plant or capture technology cost estimate



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DOE/EPRI Guidelines for Process and Project Contingency Cost

Current Technology Status	Process Contingency (% of process capital)
New concept with limited data	40+
Concept with bench-scale data	30-70
Small pilot plant data	20-35
Full-sized modules operated	5-20
Process is used commercially	0-10

- "Factor applied … to quantify the uncertainty in the technical performance and cost of the commercial-scale equipment" based on the current state of technology. *- EPRI TAG*

Most studies of advanced capture systems assume ***much smaller*** process contingencies (e.g., 0 to <20%)

EPRI Cost Classification	Design Effort	Project Contingency (% of total process capital, eng'g. &home office fees, and process contingency)
Class I (~AACE Class 5/4)	Simplified	30–50
Class II (~AACE Class 3)	Preliminary	15–30
Class III (~ AACE Class 3/2)	Detailed	10–20
Class IV (~AACE Class 1)	Finalized	5–10

- "Factor covering the cost of additional equipment or other costs that would result from a more definitive design of a more detailed design of a definitive project at an actual site." *- EPRI TAG*

Most Class I-III studies assume ≤10%

Source: EPRI, 1993; AACE, 2011; NETL, 2011

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Contingency Costs Assumptions for Advanced Capture Technology

Should be based on the current state of technology and design detail

Parameter	Typical Assumption	EPRI/DOE Guidelines*	Capital Cost Increase
Process Contingency (%TPC)	10%	~40%	***~30%***
Project Contingency (%TPC)	10%	~30%	***~20%***
TOTAL Contingency (%TPC)	**20%**	**~70%**	***~50%***

*Based on current state of technologies for membrane, solid sorbents, and other post-combustion processes with limited data.

The total contingency cost for advanced capture processes is significantly under-estimated in most cost studies, leading to systematically low capital cost estimates

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Insights on Technology Innovation

- Research on technology innovation shows that in addition to sustained R&D, "learning by doing" is needed to achieve commercial cost reductions. Thus, …
- To realize N^{th}-of-a-kind costs you have to build *N* plants

Conclusion: High capital costs will hinder the entry of new technologies

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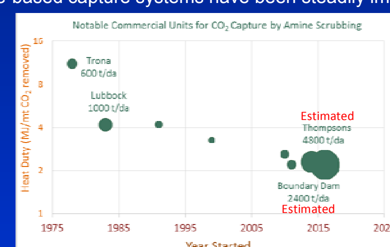
Another Challenge for New Technology: Baseline technology does not stand still

Amine-based capture systems have been steadily improving



Source: G.Rochelle, GHGT-12, 2014

Conclusion: Advanced post-combustion capture technologies face stiff headwinds on the path to commercialization

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Thank You

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