A Modeling Framework to Assess Costs and Uncertainties of Carbon Capture Technology Options

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Presentation to the
Department of Chemical and Biomolecular Engineering
University of Notre Dame
South Bend, Indiana
April 2, 2013

Outline of Talk

• The problem of global climate change
• The potential role of carbon capture and storage
• Current status and cost of CCS technology
• The promise of advanced capture technology
• Evaluating options with the IECM
• Plans and directions for future work

The problem of global climate change

Major Greenhouse Gases (GHGs) Emitted from Human Activities

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Common Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
<td>Fossil fuel combustion, forest clearing, cement production, etc.</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
<td>Landfills, production and distribution of natural gas &amp; petroleum, fermentation from the digestive system of livestock, rice cultivation, fossil fuel combustion, etc.</td>
</tr>
<tr>
<td>N₂O</td>
<td>Nitrous Oxide</td>
<td>Fossil fuel combustion, fertilizers, nylon production, manure, etc.</td>
</tr>
<tr>
<td>HFC’s</td>
<td>Hydrofluorocarbons</td>
<td>Refrigeration gases, aluminum smelting, semiconductor manufacturing, etc.</td>
</tr>
<tr>
<td>PFC’s</td>
<td>Perfluorocarbons</td>
<td>Aluminum production, semiconductor industry, etc.</td>
</tr>
<tr>
<td>SF₆</td>
<td>Sulfur Hexafluoride</td>
<td>Electrical transmissions and distribution systems, circuit breakers, magnesium production, etc.</td>
</tr>
</tbody>
</table>

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

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

Source: IPCC, 2001

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 concentrations.

- Global emissions must be reduced significantly, no matter what stabilization target is selected!

Analogy: 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 (>2°C 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”
Focus on CO₂ from Energy Use — the Dominant Greenhouse Gas

U.S. Greenhouse Gas Emissions weighted by 100-yr Global Warming Potential (GWP)

- 7.4% Electricity + Vehicles
- 6.5% CH₄
- 2.2% N₂O
- Others

Total in 2005 = 7.26 Gt CO₂ equiv.

Source: USEPA, 2007

Electricity + Vehicles emit ≈ 75% of all CO₂

83.9%

The potential role of carbon capture and storage (CCS)

Options to Mitigate CO₂ 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 CO₂ at large industrial sources to prevent its release to the atmosphere

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 major changes in the U.S. energy system are needed

CCS PLAYS A MAJOR ROLE
Cost-Effective Global Strategies Also Require CCS in the Portfolio

Models show increasing need for CCS as stabilization goal tightens.

Without CCS the cost of stabilization increases sharply.

Source: IPCC, 2007

Current status and cost of CCS technology

Current status and cost of CCS technology

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 CO₂ 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 CO₂ --
Status of CCS Technology

- Pre- and post-combustion CO₂ capture technologies are commercial and widely used in industrial processes; also at several gas-fired and coal-fired power plants, at small scale; CO₂ capture efficiencies are typically 85-90%. Oxyfuel capture is undergoing development/scaleup.
- CO₂ transport via pipelines is a mature technology.
- Geological storage of CO₂ is commercial on a limited basis, mainly for EOR; several projects in deep saline formations are operating at scales of ~1 Mt CO₂ /yr.
- Large-scale integration of CO₂ capture, transport and geological sequestration has been demonstrated at several industrial sites (outside the U.S.), and at electric power plants at small scale (~25-40 MW).

Post-Combustion Technology for Industrial CO₂ Capture

BP Natural Gas Processing Plant
(In Salah, Algeria)

Post-Combustion CO₂ Capture at a Gas-Fired Power Plant

Bellingham Cogeneration Plant
(Bellingham, Massachusetts, USA)

Post-Combustion CO₂ Capture at Coal-Fired Power Plants

Shady Point Power Plant
(Panama, Oklahoma, USA)

Warrior Run Power Plant
(Cumberland, Maryland, USA)
Examples of Pre-Combustion CO₂ Capture Systems

- Petcoke Gasification to Produce H₂ (Beulah, North Dakota, USA)
- Coal Gasification to Produce SNG (Beulah, North Dakota, USA)

Pre-Combustion Capture at IGCC Plants

- Puertollano IGCC Plant (Spain)
- Buggenhur IGCC Plant (The Netherlands)

CO₂ Pipelines in the Western U.S.

- > 3000 miles of pipeline
- ~50 MtCO₂/yr transported

Geological Storage of Captured CO₂ in a Deep Saline Formation

- Sleipner Project (Norway)
**Geological Storage of Captured CO₂ in a Depleted Gas Formation**

In Salah /Krechba (Algeria)

![Image](source)

**Geological Formations in North America**

- **Oil & Gas Fields**
- **Deep Saline Formations**

![Image](source)

**Geological Storage of Captured CO₂ with Enhanced Oil Recovery (EOR)**

Dakota Coal Gasification Plant, ND

![Image](source)

**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 (CO₂ only vs. all GHGs)
  - Power plant only vs. partial or complete life cycle
- Time Frame of Interest
  - First-of-a-kind plant vs. nth plant
  - Current technology vs. future systems
  - Consideration of technological “learning”

![Image](source)
Measures of CCS Cost

- Increased cost of electricity
- Cost of CO₂ avoided
- Cost of CO₂ captured
- Capital cost
- Dispatch (variable) cost

Definition of Key Costs

- Cost of CO₂ Avoided ($/ton CO₂ avoided)
  \[
  \frac{(\text{$/MWh})_{\text{CCS}} - (\text{$/MWh})_{\text{reference}}}{(\text{CO}_2 \text{MWh})_{\text{ref}} - (\text{CO}_2 \text{MWh})_{\text{CCS}}}
  \]

- Cost of Electricity Generation ($/MWh)
  \[
  \frac{(\text{TCC})(\text{FCF}) + \text{FOM}}{\text{(CF)}(8760)\text{(MW)}} + \text{VOM} + (\text{HR})(\text{FC})
  \]

Many factors influence the cost of CCS

Ten Ways to Reduce CCS Cost

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel price
7. Assume EOR credits for CO₂ storage
6. Omit certain capital costs
5. Report $/ton CO₂ 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!

Incremental Cost of CCS for New Coal-Based Plants Using Current Technology

Increase in levelized cost for 90% capture

| Incremental Cost of CCS, relative to name 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)
Typical Cost of CO₂ Avoided
(Relative to a SCPC reference plant w/o CCS)

<table>
<thead>
<tr>
<th>Power Plant System (relative to a SCPC plant without CCS)</th>
<th>New Supercritical Pulverized Coal Plant</th>
<th>New Integrated Gasification Combined Cycle Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS with deep saline aquifer storage</td>
<td>~ $70 /tCO₂</td>
<td>~ $50 /tCO₂</td>
</tr>
<tr>
<td>CCS w/ enhanced oil recovery (EOR) storage</td>
<td>Cost reduced by ~ $20–30 /tCO₂</td>
<td></td>
</tr>
</tbody>
</table>

Source: Based on IPCC, 2005; Rubiño et al, 2007; DOE, 2007

The promise of advanced capture technology

CCS Cost for New NGCC Plants (Current Technology)

Increase in levelized cost for 90% capture

<table>
<thead>
<tr>
<th>Cost Measure</th>
<th>New NGCC Cost Increase with CCS</th>
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<tbody>
<tr>
<td>% Increase in generation cost ($/kWh) (relative to NGCC w/o CCS)</td>
<td>~ 30–45%</td>
</tr>
<tr>
<td>Cost of CO₂ Avoided: Relative to NGCC:</td>
<td>~$100 /tCO₂</td>
</tr>
<tr>
<td>Cost of CO₂ Avoided: Relative to SCPC:</td>
<td>~$40 /tCO₂</td>
</tr>
</tbody>
</table>

Better Capture Technologies Are Emerging

<table>
<thead>
<tr>
<th>Cost Reduction Benefit</th>
<th>Present</th>
<th>5+ years</th>
<th>10+ years</th>
<th>15+ years</th>
<th>20+ years</th>
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<tbody>
<tr>
<td>Post-combustion (existing, new PC)</td>
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<tr>
<td>Pre-combustion (IGCC)</td>
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<tr>
<td>Oxycombustion (new PC)</td>
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<td>CO₂ compression (all)</td>
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<td>Amine solvents</td>
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<td>Advanced physical solvents</td>
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<td>Advanced chemical solvents</td>
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<td>Ammonia</td>
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<tr>
<td>Carbonate</td>
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<td>Cryogenic</td>
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<td>Carbon capture</td>
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<tr>
<td>Chemical looping</td>
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<tr>
<td>OTM boiler</td>
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<tr>
<td>Biological processes</td>
<td></td>
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<tr>
<td>CAR process</td>
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</tbody>
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OFFICE OF FOSSIL ENERGY
Most New Capture Concepts Are Far from Commercial Availability

Typical Cost Trend for a New Technology

IECM: A Tool for Analyzing Power Plant Design Options

Evaluating options with the IECM
Motivating Questions

- What technologies are currently available to reduce emissions of pollutant $P$ for a particular power plant?

- For each technology and plant type:
  - What level(s) of emissions reduction are possible?
  - What are the impacts on plant-level emissions, efficiency, resource requirements, and cost?

- Can Advanced Technology X achieve lower cost and/or improved performance relative to current systems?

- Can it meet goals for “high risk, high payoff” technology?

IECM Modeling Approach

- Systems Analysis Approach
- Process Performance Models
- Engineering Economic Models
- Advanced Software Capabilities
  - User-friendly graphical interface
  - Probabilistic analysis capability
  - Versatile input/output features

IECM Software Package

Fuel Properties
- Heating Value
- Composition
- Delivered Cost

Plant Design
- Conversion Process
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

Cost Factors
- O&M Costs
- Capital Costs
- Financial Factors

Power Plant Models

Graphical User Interface

Plant & Process Performance
- Efficiency
- Resource use

Environmental Emissions
- Air, water, land

Plant & Process Costs
- Capital
- O&M
- COE

Plant and Fuel Databases

IECM Technologies for PC Plants (excluding CO$_2$ capture, transport and sequestration)

Boiler/Turbine Types
- Subcritical
- Supercritical
- Ultra-supercritical

Furnace Firing Types
- Tangential
- Wall
- Cyclone

Furnace NO$_x$ Controls
- LNB
- SNCR
- SNCR + LNB
- Gas scrub

Flue Gas NO$_x$ Removal
- Hot-side SCR

Mercury Removal
- Carbon/sorbent injection

Particulate Removal
- Cold-side ESP
- Fabric filter
- Electrostatic Jet, Pulse Jet

SO$_x$ Removal
- Wet limestone
- Conventional, Forced oxidation
- Additives
- Wet lime
- Lime spray dryer

Solid waste Management
- Ash pond, Landfill, Co-mixing
- Byproducts (for export)

Cooling and Wastewater Systems
- Once-through cooling
- Wet cooling tower
- Dry cooling tower
- Chemical treatment
- Mechanical treatment
IECM Technologies for IGCC Plants
(excluding CO₂ capture, transport and sequestration)

- **Air Separation Unit**
  - Cryogenic
- **Shale Preparation**
- **Coal Pretreatment**
- **Gasification**
  - Slurry-feed gasifier (GE-Q)
  - Dry-feed gasifier (Shell)
- **Syngas Cooling and Particulate Removal System**
- **Mercury Removal**
  - Activated carbon
- **H₂S Removal System**
  - Selexol
  - Sulfinol
- **Sulfur Recovery System**
  - Flue Plant
  - Beavon-Stretford Unit
- **Gas Turbine**
  - GE 7FA
  - GE 7FB
- **Heat Recovery Steam Generator**
- **Steam Turbine**
- **Boiler Feedwater System**
- **Process Condensate Treatment**
- **Auxiliary Equipment**
  - Cooling Water System
    - Once-through
    - Wet cooling tower
    - Air cooled condenser

Pulverized Coal Power Plant with Post-Combustion CO₂ Capture

- **PC Boiler**
- **Air Pollution Control Systems**
  - NOₓ, PM, SO₂
- **CO₂ Capture**
  - Amine
  - Amine/CO₂
  - Selexol
  - Sulfinol
  - Chemical looping
  - Auxiliary NG boiler or power plant (optional)
- **CO₂ Transport Options**
  - Pipelines (six U.S. regions)
- **CO₂ Sequestration Options**
  - Geologic: Deep Saline or Other Formations
  - Geologic: Enhanced Oil Recovery (EOR)

IGCC Power Plant with Pre-Combustion CO₂ Capture

- **Air Separation Unit**
- **Coal Gasifier**
- **Quench System**
- **SNR Reactor**
- **Sulfur Recovery**
  - Selexol
  - Sulfinol
- **CO₂ Capture**
  - Selexol/CO₂
  - CO₂ Compression
  - CO₂ to storage

IECM Technologies for CCS

- **CO₂ Capture Options**
  - **Pre-Combustion (IGCC):**
    - Water gas shift + Selexol
    - Chemical looping
  - **Oxy-Combustion (PC):**
  - **Post-Combustion (PC, NGCC):**
    - Amine systems (MEA, FG+)
    - Chilled ammonia
    - Membrane systems
    - Chemical looping
    - Auxiliary NG boiler or power plant (optional)
- **CO₂ Transport Options**
  - Pipelines (six U.S. regions)
- **CO₂ Sequestration Options**
  - Geologic: Deep Saline or Other Formations
  - Geologic: Enhanced Oil Recovery (EOR)
Process Performance Models

- Detailed mass and energy balances for each major component and overall plant
- For components with complex chemistry and/or heat integration schemes, multi-variate regression or other reduced-order models are derived from experimental data and detailed process models
- Approximately 10-20 performance parameters for each component technology

IECM Performance Parameters for Amine Capture System

- Flue gas composition
- Flue gas temp/pressure
- CO₂ removal efficiency
- SO₂ removal efficiency
- NO₂ removal efficiency
- HCl removal efficiency
- Sorbent concentration
- Lean solvent loading
- Acid gas sorbent loss
- Sorbent oxidation loss
- Nominal sorbent makeup
- Ammonia generation
- Cooling water makeup
- Reclaimer chemical reqn’t
- Flue gas pressure drop
- Fan efficiency
- Sorbent pumping head
- Pump efficiency
- Regeneration heat
- Equiv. elec. requirement
- CO₂ product pressure
- CO₂ product purity
- Compressor efficiency
- Compression energy

Performance Model for Amine Capture System

Captured CO₂:
\[ \eta_{\text{CO₂}} = f(L/G, C, y_{\text{in}}, \phi_{\text{lean}}, T_{\text{fg}}, T_{\text{solv}}, H, D) \]

Wet Tower Performance Model

Cooling water quantity:
\[ m_{w} = \frac{(H_P - 3413) \cdot MW_{w} \cdot 1000 \cdot (1 + \mu_{\text{w}})}{\Delta T_{f}} \]

Makeup water quantity:
\[ m_{\text{makeup}} = m_{\text{cycle}} + m_{\text{CG}} + m_{\text{cond}} \]
\[ m_{\text{cycle}} = 0.001 \% \cdot m_{\text{f}} \]
\[ m_{\text{cond}} = \frac{m_{\text{cycle}}}{CC - 1} \]
\[ m_{\text{makeup}} = m_{\text{cycle}} \cdot \left( \frac{W_{f} - W_{g}}{W_{f}} \right) \]

where:
- \( \mu_{\text{w}} \) = auxiliary cooling load
- \( \mu_{\text{f}} \) = steam cycle heat rate
- \( MW_{w} \) = plant gross output
- \( \Delta T_{f} \) = water temp. change
- \( m_{\text{f}} \) = air flow rate
- \( W_{f} \) = inlet air humidity
- \( W_{g} \) = outlet air humidity
- \( CC \) = cycle of concentration

Cost models based on NETL Baseline Study
IECM Performance Model of Evaporative Loss for Wet Tower

Evaporation loss is estimated based on steady-state energy and mass balances for a differential volume segment:

\[ m_{aw}dh = (m_e - m_i)(W_2 - W)\big|_{dh} + (m_{aw}W')\big|_{dh} \]

**Assumptions**
- Negligible heat transfer through walls
- Constant specific heats (water and dry air)
- Uniform water temp. at any cross section
- Constant Lewis number across the tower

**Model Inputs**
- Tower inlet water temperature
- Tower outlet water temperature
- Dry bulb air temperature
- Wet bulb air temperature
- Recirculation cooling water flow rate

**Model Output**
- Evaporation loss

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Technology Cost Models

- Direct cost models for each major process area (typically 5-10 areas per technology) based on detailed engineering design studies
- Explicit links to process performance models via key parameters (e.g., flow rate, temp., pressure, etc.)
- Calculate total capital cost, variable O&M costs, fixed O&M costs and annualized cost of electricity
- Approximately 20-30 cost elements per technology

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IECM Cost Model Parameters for Amine Capture System

- Process Area Costs (12)
- Process Facilities Cost
- Eng’g. & Home Office
- General Facilities
- Contingency Costs (2)
- Interest during Construction
- Royalty Fees
- Pre-production Costs
- Inventory (startup) Cost
- Total Plant Cost
- Total Capital Req’n’t
- Operating Labor
- Maintenance Labor
- Admin./Support Labor
- Maintenance Materials
- Amine Sorbent Cost
- Other Chemicals Cost
- Waste Disposal Cost
- Water Cost
- (Power Cost)*
- CO₂ Transport Cost
- CO₂ Storage Cost

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Probabilistic Capability

- Allows users to explicitly model and quantify the effects of uncertainty and/or variability on component and system performance, emissions and cost
- Values for user-selected parameters are specified as a probability distribution function, which is sampled using a selected method and sample size
- Results are displayed as a cumulative distribution function, yielding confidence intervals and probability of different outcomes for selected parameters
Probabilistic Results: Uncertainty in COE

IECM Users and Uses

The IECM Team

Recent Applications

- Performance and Cost Models of Advanced CO2 Capture Systems
  - Advanced liquid solvents  (Peter Versteeg)
  - Solid sorbent systems  (Justin Glier)
  - Membrane capture systems  (Haibo Zhai)
  - Advanced oxy-combustion  (Kyle Borgert)
  - Chemical looping combustion  (Hari Mantripragada)
- Software Development & Dist.  (Karen Kitzke)

- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning
- Teaching/Education

- A techno-economic assessment of polymer membrane systems for post-combustion carbon capture at coal-fired power plants.
- Comparative performance and cost assessments of coal-and natural gas-fired power plants under a CO2 emission performance standard regulation.
- Chemical looping for pre-combustion CO2 capture—performance and cost analysis.
- Oxyfuel combustion: technical and economic considerations for the development of carbon capture from pulverized coal power plants.
- The cost of carbon capture and storage for natural gas combined cycle power plants.
- A technical and economic assessment of ammonia-based post-combustion CO2 capture at coal-fired power plants.
- Water use at pulverized coal power plants with post-combustion carbon capture and storage.
Illustrative Results

Sweep-based 2-Stage, 2-Step Membrane System Model

Effect of Membrane Properties on Cost of CO₂ Avoided
Effect of Membrane Facilities Price on Cost of CO2 Avoided

![Graph showing the relationship between Membrane Facilities Price and Cost of CO2 Avoided.](image)

Ammonia-Based CO2 Capture System
(Detailed performance model in Aspen Plus)

![Diagram of Ammonia-Based CO2 Capture System](image)

Illustrative Results from Ammonia System Aspen Model

![Graphs illustrating illustrative results from Ammonia System Aspen Model](image)

Ammonia-Based CO2 Capture System
(Reduced Order Model in IECM)

![Diagram of Ammonia-Based CO2 Capture System](image)
Some of the IECM Parameters for the New Chilled Ammonia Capture System Model

Probabilistic Research Questions

Questions about a particular technology, e.g.:

- What is the likelihood that Technology A will meet a specified performance and/or cost target?

Questions of a comparative nature, e.g.:

- What is the likelihood that Technology A will cost X% less (or perform Y% better) than Technology B when both systems have uncertainties?
**Stochastic Simulation**

Parameter Uncertainty Distributions → Stochastic Sampler → Results

**SAMPLING LOOP**

(1 iterations)

Power Plant Model

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**Case Study 1:**
SCPC Plants with and w/o CCS

(13 uncertain parameters specified)

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**Question:** What's the probability that the added cost of CCS will be no more than $40/MWh?

IECM Probabilistic Cost Difference Capability
(accounting for all correlated variables)

- 10% chance of ≤ $40/MWh

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**Case Study 2:**
Ammonia vs. Amine Capture:
How likely that ammonia will be cheaper?

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Difference in Plant Levelized Cost of Electricity for Ammonia versus Amine CO₂ Capture (2010 $/MWh)

- < 20% chance that ammonia system cheaper than amine
Future Work

- New model developments under DOE sponsorship:
  - Solid sorbents
  - Advanced oxy-combustion
  - Chemical looping combustion
  - Public workshops/tutorials
- New systems analysis under Stanford/GCEP project:
  - Ionic liquids (Notre Dame)
  - Metal organic frameworks (Northwestern)
  - Biomimetic sorbents (Stanford)
  - Life cycle assessments

Thank You

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