Integrated Modeling of Carbon Management Technologies for Electric Power Systems

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Some Questions to be Addressed

- What carbon management technologies may be used in a particular application (e.g., existing vs. new plants)?
- What are the key parameters that affect the performance, emissions, and cost of a given option?
- How do the alternative options compare in terms of performance, reliability, and cost?
- What are the uncertainties and technological risks of different carbon management options?
- What are the priorities and benefits of R&D to reduce key uncertainties in new process designs?
Scope and Objectives

- Identify potential options for power generation with carbon capture and sequestration, suitable for, (a) existing plants, and (b) new plants
- Develop a model to quantify performance, emissions, and cost of alternative options, and their dependency on key plant and technology design parameters, operating parameters, and carbon management methods
- Characterize uncertainty in key parameters of the carbon management system
- Integrate carbon management technologies with other plant environmental control systems
- Conduct case studies to illustrate model applications
Current Applications

- **Enhanced oil recovery (EOR)**
  - Dow MEA (Some plants in TX and NM, now shut down)
  - Common in 1970s and 1980s (100-1200 tons CO₂/d)
- **Fertilizer industry**
  - H₂ and CO₂ separation ⇒ Urea production
  - Dow MEA (Indo Gulf Fertilizer Co.) - 150 tons CO₂/d
- **Carbonation of brine (soda ash)**
  - Kerr-McGee MEA (North American Chemical Co., operational since 1978) - 800 tons CO₂/d
- **Food-grade**
  - Fluor Daniel / Dow MEA (Northeast Energy Associates, MA) - 320 tons CO₂/d
- **Commercial CO₂ capture and sequestration facility**
  - Injection into deep saline aquifer (Sleipner West gas field, Norway, installed in 1996) - ~3000 tons CO₂/d
Power Generation Options Using Fossil Fuels

Power Generation Technologies

Fuel
- Coal
  - Combustion-based
  - Gasification-based
- Gas
  - Direct Combustion
  - Gas Reforming

Oxidant
- Air
- Pure Oxygen

Technology
- Simple Cycle
  - Pulverized Coal
  - Gas Turbines
- Combined Cycle
  - Gas Turbines
  - Coal Gasification
  - Fuel Cells
  - Other
CO₂ Capture Technologies

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
    Polyphenylenoxide
    Polydimethylsiloxane
  Gas Absorption
    Polypropelene
  Ceramic Based Systems

 Microbial/Algal Systems
CO₂ Sequestration Options

**CO₂ Disposal / Storage Options**

- **Geological Sequestration**
  - Deep Saline Reservoirs
  - Exhausted Oil and Gas Wells
  - Abandoned Coal Seams

- **Ocean Sequestration**
  - Very Deep Ocean Injection
  - Unconfined Release (@ ~ 1000 m)
  - Dense Plume Formation (shallow)
  - Dry Ice Injection

- **Biological Sequestration**
  - Forests and Terrestrial Systems
  - Marine Alga

- **Other Methods**
  - Storage as a solid in an Insulated Repository
  - Utilization Schemes (e.g. Polymerization)
Modeling Framework for Carbon Management Options

- **Power Generation**
  - Coal or Natural Gas
  - Air or Pure O₂

- **CO₂ Capture**
  - Absorption
  - Adsorption
  - Cryogenics
  - Membranes

- **CO₂ Transport**
  - Pipeline
  - Other

- **CO₂ Storage or Disposal**
  - Deep Saline Reservoirs
  - Oil and Gas Wells
  - Deep Coal Seams
  - Oceans
  - Byproduct Utilization

Simple Cycle
Combined Cycle
Energy Considerations

- Total Energy Requirement
- Process Heat
- Compression
- Transport
- Storage/Disposal

Important Factors:
- Gas Stream Flow and Composition
- Choice of CO₂ Capture Technology
- Desired CO₂ Capture Efficiency
- Process Parameters
- Desired CO₂ Product Specifications
- Mode of Transport
- Transportation Distance
- Choice of Disposal Method

~ 60-80% cost of separation & capture
Current Status

- Developed preliminary models (performance, emissions, and cost) for several CO\textsubscript{2} capture options, CO\textsubscript{2} transport options, and CO\textsubscript{2} storage options.
- Initial focus on modeling of current commercial technologies (amine scrubbing systems) for combustion-based power systems.
- Integrated the new CO\textsubscript{2} module with the IECM combustion-based power plant model developed for the USDOE.
Integrated Environmental Control Model (IECM)

Coal Cleaning

Combustion Controls

Flue Gas Cleanup & Waste Management

- NOx Removal
- Particulate Removal
- SO2 Removal
- Combined SOx/NOx Removal
- Advanced Particulate Removal
Objectives

- Develop a comprehensive modeling framework to estimate the performance, environmental emissions, and cost of coal-based power generation technologies

- Develop a method for comparing alternative options on a systematic basis, including the effects of uncertainty
Probabilistic Software Capability

- Allows you to specify parameter values as distribution functions, as well as conventional deterministic (point) estimates
- Allows you to explicitly quantify the effects of uncertainty in performance, emissions, and cost, yielding confidence intervals for uncertain results
Conventional Process Modeling (Deterministic Simulation)
Parameter Uncertainty Distributions

- **NORMAL**
- **UNIFORM**
- **LOGNORMAL**
- **TRIANGULAR**
- **BETA**
- **FRACTILE**
Stochastic Simulation

Parameter Uncertainty Distributions → Stochastic Modeler → Results

SAMPLING LOOP

Process Model
Expert Judgments on Key Model Parameters

- Sorbent Sulfur Loading
- Gasifier Fines Carryover
- Carbon Retention in Bottom Ash

![Probability Density](image-url)

- Sorbent Sulfur Loading, wt-%
- Fines Carryover, % of coal feed
- Carbon Retention in Bottom Ash, % of coal feed carbon
Total Plant Capital Cost

Cumulative Probability

Total Capital Requirement ($1994/kW)

Probabilistic

DOE (1989)

524 MW net
Value of Targeted Research

Input Uncertainty Assumptions
- Base Case Uncertainties
- Reduced Uncertainties in Selected Performance and Cost Parameters

Cumulative Probability

Levelized Cost of Electricity, Constant 1989 mills/kWh
Probabilistic Comparison of Competing Technologies

The graph shows the cumulative probability of total cost savings relative to baseline technology (S/MWh). The x-axis represents the total cost savings, while the y-axis shows the cumulative probability. Two technologies, A and B, are compared, with Technology B generally offering a higher cumulative probability for higher cost savings.
The IECM is Available for Downloading

- **Web Access:**
Preliminary IECM User Group

- ABB Power Plant Control
- American Electric Power
- Consol, Inc.
- Energy & Env. Research Corp.
- Exportech Company, Inc.
- FirstEnergy Corp.
- FLS Miljo A/S
- Foster Wheeler Development Corp.
- Lehigh University
- Lower Colorado River Authority
- McDermott Technology, Inc.
- Mitsui Babcock Energy LTD.
- National Power Plc.
- Niksa Energy Associates
- Pacific Corp.
- Pennsylvania Electric Association
- Potomac Electric Power Co.
- Savvy Engineering
- Sierra Pacific Power Co.
- Southern Company Services, Inc.
- Stone & Webster Engineering Corp.
- Tampa Electric Co.
- University of California, Berkeley
- US Environmental Protection Agency
**Configure Plant**

**Combustion Controls**
- **Furnace Type:** Tangential
- **NOx Control:** Low NOx Burners

**Post-Combustion Controls**
- **NOx Control:** Hot-Side SCR
- **Particulates:** None
- **SO2 Control:** None
- **SO2/NOx:** None

**Solids Management**
- **Recovery:** None
- **Fly Ash Disposal:** mixed w/ Landfill
**Combustion Controls**
- **Furnace Type:** Tangential
- **NOx Control:** Low NOx Burners

**Post-Combustion Controls**
- **NOx Control:** Hot-Side SCR
- **Particulates:** Cold-Side ESP
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- **Particulates:** Cold-Side ESP
- **SO2 Control:** Wet FGD
- **SO2/NOx:** None
- **CO2 Control:** Absorption - MEA

**By-Product Management**

- **Recovery:** None
- **Fly Ash Disposal:** Mixed w/ Landfill
- **CO2 Storage:** Depleted Oil Wells
Current Coal
Name: Appalachian Medium Sulfur
Rank: Bituminous
Source: Model Default Coals

Composition (wt% as fired) and Higher Heating Value (Btu/lb)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Heating Value</td>
<td>1.326e+04</td>
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<tr>
<td>Carbon</td>
<td>73.81</td>
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<tr>
<td>Hydrogen</td>
<td>4.880</td>
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<tr>
<td>Oxygen</td>
<td>5.410</td>
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<tr>
<td>Chlorine</td>
<td>7.000e-02</td>
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<tr>
<td>Sulfur</td>
<td>2.130</td>
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<tr>
<td>Nitrogen</td>
<td>1.420</td>
</tr>
<tr>
<td>Ash</td>
<td>7.230</td>
</tr>
<tr>
<td>Moisture</td>
<td>5.050</td>
</tr>
<tr>
<td>Cost ($/ton)</td>
<td>32.07</td>
</tr>
</tbody>
</table>

Favorite Coals
Name: Wyoming Powder River Basin
Rank: Sub-Bituminous

<table>
<thead>
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<th>Value</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>Carbon</td>
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<td>Hydrogen</td>
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<td>Oxygen</td>
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<td>Chlorine</td>
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<td>Sulfur</td>
<td>0.3700</td>
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<tr>
<td>Nitrogen</td>
<td>0.7000</td>
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<tr>
<td>Ash</td>
<td>5.320</td>
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<tr>
<td>Moisture</td>
<td>30.24</td>
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<tr>
<td>Cost ($/ton)</td>
<td>12.46</td>
</tr>
<tr>
<td>Title</td>
<td>Units</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Gross Electrical Output</td>
<td>MWg</td>
</tr>
<tr>
<td>Steam Cycle Heat Rate</td>
<td>Btu/kWh</td>
</tr>
<tr>
<td>Boiler Efficiency</td>
<td>%</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>%</td>
</tr>
<tr>
<td>Excess Air For Furnace</td>
<td>% stoich.</td>
</tr>
<tr>
<td>Leakage Air at Preheater</td>
<td>% stoich.</td>
</tr>
<tr>
<td>Gas Temp. Exiting Economizer</td>
<td>deg. F</td>
</tr>
<tr>
<td>Gas Temp. Exiting Air Preheater</td>
<td>deg. F</td>
</tr>
<tr>
<td>Ambient Air Temperature</td>
<td>deg. F</td>
</tr>
<tr>
<td>Ambient Air Pressure</td>
<td>psia</td>
</tr>
<tr>
<td>Ambient Air Humidity</td>
<td>lb H2O/lb dry air</td>
</tr>
<tr>
<td>Collected Bottom Ash Solids</td>
<td>%</td>
</tr>
<tr>
<td>Base Plant Energy Requirements</td>
<td></td>
</tr>
<tr>
<td>Coal Pulverizer</td>
<td>% MWg</td>
</tr>
<tr>
<td>Steam Cycle Pumps</td>
<td>% MWg</td>
</tr>
<tr>
<td>Forced Draft Fans</td>
<td>% MWg</td>
</tr>
<tr>
<td>Cooling System</td>
<td>% MWg</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>% MWg</td>
</tr>
</tbody>
</table>
### Uncertainty Editor

<table>
<thead>
<tr>
<th>Plant Parameter</th>
<th>Units</th>
<th>Value</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum SO2 Removal Efficiency</td>
<td>%</td>
<td>95</td>
<td>90</td>
<td>99</td>
</tr>
</tbody>
</table>

#### Distribution:
- Triangular
- Normal
- Uniform
- Fractiles

#### Distribution Details:
- **Normalized:**
  - Min: 0.9000
  - Mode: 1.0000
  - Max: 1.023
- **Nominal:**
  - Min: 85.50
  - Mode: 95.00
  - Max: 97.18

#### Description:
Triangular(a,b,c) describes a triangular-shaped distribution where the values a, b, and c represent the minimum, most likely and maximum values, respectively.

#### Uncertainty Areas:
- Base Plant
- Air Preheater
- Solid Waste Mgmt.
- NOx Control
- Particulate Control
- SO2 Control
- SO2/NOx Control

### Uncertainty Tools: Untitled

- **Sample Size:** 50
- **Sampling Method:** Median LHS
Example: CDF Graph of Total Variable Costs (M$/yr)

Mean: 2.410
2.5 percentile: 1.900
Median (50th percentile): 2.353
97.5 percentile: 3.148
Concentrated CO2 (mton/yr) = 2.711e+06
CO₂ Module Results

- Flue gas (out) composition
- CO₂ emission level (kg CO₂/hr)
- Amount of CO₂ product (ton/hr)
- Purity of CO₂ product (%)
- Solvent circulation rate (m3/hr)
- Make-up solvent rate (kg MEA/hr)
- Make-up rate relative to the circulation rate (%)
- Waste generation rate (kg/hr)
- Energy penalty (% of MWg)
- Net power generation
- Cost of CO₂ captured ($/ton CO₂ captured)
- Cost increase in electricity (cents/kWh)
- Cost of CO₂ avoided ($/ton CO₂ avoided)
Additional Technology Options

- **Just Completed**
  - Combustion NO\textsubscript{x} Controls
    - Selective Non-Catalytic Reduction (SNCR)
    - Low NO\textsubscript{x} Burners (LNB)
    - LNB + Overfire air
    - LNB + SNCR
    - Natural Gas Reburn
    - Tangential, Wall & Cyclone Firing

- **Just Started**
  - Post-Combustion Controls
    - Air Toxics (mercury)
  - Other Fossil Fuels
  - Alternative Power Generation Systems
  - CO2 Sequestration Options
Future Developments:
A Menu of Technology Options
Select Gasification Combined Cycle (IGCC) Options

Choose Power System

Please Choose a Power System:

- Conventional Combustion
- Gasification Comb. Cycle
- Advanced Combustion
- Fuel Cells
- Vision 21 Plant
ASSEN Model of an IGCC System

- **Coal Handling**
  - Coal
  - Ash

- **Gasification, Particulate & Ash Removal, Fines Recycle**
  - Raw Syngas
  - Gasifier Air
  - Captured Fines

- **Steam Cycle & SCR**
  - Boiler Feedwater Return Water
  - Gasifier Steam
  - Shift & Regen. Steam

- **Zinc Ferrite Process**
  - Cyclone
  - Cyclone Clean Syngas
  - Off-Gas

- **Sulfuric Acid Plant**
  - Tailgas
  - Sulfuric Acid
  - Air

- **Steam Turbine**
  - Cooling Water Makeup
  - Exhaust Gas

- **Gas Turbines**
  - Cooling Water Blowdown
  - Net Electricity Output

- **Boiler Feedwater Treatment**
  - Blowdown
  - Exhaust Gas

- **Internal Electric Loads**
  - Air

- **Raw Water**
  - Blowdown
  - Exhaust Gas

- **Sulfuric Acid Plant**
  - Tailgas
  - Sulfuric Acid
  - Air
Response Surface Model for an IGCC System
Desktop Model of an IGCC System

- **Goal:** Optimization
- **Gasification Options**
  - Gasifier: KRW
  - Oxidant: Oxygen
  - Gas Cleanup: Hot
- **Post-Combustion Controls**
  - NOx Control: SCR
- **Solids Management**
  - Slag: Landfill
  - Sulfur: Sulfur, Landfill, Sulfuric Acid

Plant Diagram
Model Applications

- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning
A Hierarchy of Process Models

- Mechanistic/Empirical Models
- Component Models
- Integrated Models
- System Models
- Enterprise

Validation — Communication