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
CO$_2$ Sequestration 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
Energy Considerations

Total Energy Requirement
- Process Heat
- Electricity

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$_2$ capture options, CO$_2$ transport options, and CO$_2$ storage options
- Initial focus on modeling of current commercial technologies (amine scrubbing systems) for combustion-based power systems
- Integrated the new CO$_2$ 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 Values → Process Model → Results
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**
  - Probability Density
  - Sorbent Sulfur Loading, wt-%

- **Gasifier Fines Carryover**
  - Fines Carryover, % of coal feed

- **Carbon Retention in Bottom Ash**
  - Carbon Retention, % of coal feed carbon
Calculated Plant Efficiency

Cumulative Probability

Net Plant Efficiency (% HHV basis)

- Probabilistic
- Deterministic
Total Plant Capital Cost

Cumulative Probability

Total Capital Requirement ($1994/kW)

Probabilistic
DOE (1989)
524 MW net

524 MW net
Value of Targeted Research

Levelized Cost of Electricity, Constant 1989 mills/kWh

Cumulative Probability

Input Uncertainty Assumptions
- Base Case Uncertainties
- Reduced Uncertainties in Selected Performance and Cost Parameters
Probabilistic Comparison of Competing Technologies

The diagram shows the cumulative probability of total cost savings relative to the baseline technology for two technologies, A and B. The x-axis represents the total cost savings relative to the baseline technology in dollars per MWh, while the y-axis represents the cumulative probability.
IECM Software Package

Fuel Properties
- Heating Value
- Composition
- Delivered Cost

Plant Design
- Furnace Type
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

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

Power Plant Model

Graphical User Interface

Session & Fuel Databases

Plant & Process Performance

Environmental Emissions

Plant & Process Costs
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
Welcome to the DOE Integrated Environmental Control Model
IECM Interface

Configure Plant

Set Parameters

Get Results

Combustion Controls

Furnace Type: Tangential
NOx Control: Low NOx Burners

Post-Combustion Controls

NOx Control: None
Particulates: None
SO2 Control: None
SO2/NOx: None

Solids Management

Recovery: None
Fly Ash Disposal: mixed w/ Landfill

Plant Diagram
**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
- SO2 Control: None
- SO2/NOx: None

Solids Management
- Recovery: None
- Fly Ash Disposal: mixed w/ Landfill
Configure Plant

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

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

**Solids Management**
- **Recovery:** None
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Plant Diagram
### Combustion Controls

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

### Post-Combustion Controls

- **NOx Control:** Hot-Side SCR
- **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
<table>
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<th>No.</th>
<th>Title</th>
<th>Units</th>
<th>Unc</th>
<th>Value</th>
<th>Calc</th>
<th>Min</th>
<th>Max</th>
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<td>Gross Electrical Output</td>
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<td>150</td>
<td>400</td>
<td>300</td>
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<td>-50</td>
<td>130</td>
<td>80</td>
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<td>psia</td>
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<td>14.7</td>
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<td>12</td>
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<td>lb H2O/lb dry air</td>
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<td>0</td>
<td>4</td>
<td>1.5</td>
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<td>1.3</td>
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<td>0</td>
<td>4</td>
<td>1.3</td>
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<td>Maximum</td>
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<td>Maximum SO2 Removal Efficiency</td>
<td>%</td>
<td>95</td>
<td>90</td>
<td>99</td>
<td></td>
<td></td>
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</table>

**Distribution:**
- Triangular
- Normal
- Uniform
- Fractiles

**Nominal:**
- Min: 85.50
- Mode: 95.00
- Max: 97.18

**Normalized:**
- Min: 0.9000
- Mode: 1.000
- Max: 1.023

**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.

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

**Sample Size:** 50

**Sampling Method:** Median LHS
<table>
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<tr>
<th>Stack Gas Component</th>
<th>Flow Rate (ton/hr)</th>
<th>Overall Flow Component</th>
<th>Flow Rate (ton/hr)</th>
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<tr>
<td>1 N2</td>
<td>1771</td>
<td>1 Coal</td>
<td>166.5</td>
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<tr>
<td>2 O2</td>
<td>149.0</td>
<td>2 Lime/Limestone</td>
<td>9.729</td>
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<tr>
<td>3 H2O</td>
<td>252.7</td>
<td>3 Ammonia</td>
<td>0.3460</td>
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<td>4 CO2</td>
<td>454.3</td>
<td>4 Total</td>
<td>178.6</td>
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<td>5 CO</td>
<td>0.0</td>
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<td>6 HCl</td>
<td>2.395e-02</td>
<td>6 Bottom Ash</td>
<td>3.997</td>
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<td>7 SO2</td>
<td>1.300</td>
<td>7 Fly Ash</td>
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<td>8 SO3</td>
<td>3.137e-02</td>
<td>8 FGD Waste</td>
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<td>9 NO</td>
<td>0.2053</td>
<td>9 By-Product Ash</td>
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<td>10 NO2</td>
<td>1.656e-02</td>
<td>10 By-Product Gypsum</td>
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<tr>
<td>11 Ash</td>
<td>3.313e-02</td>
<td>11 By-Product Sulfur</td>
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<tr>
<td>12 Total</td>
<td>2629</td>
<td>12 By-Product Acid</td>
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<td>13</td>
<td></td>
<td>13 Total</td>
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<td>14 SOx</td>
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<td>15 NOx</td>
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<td>Technology</td>
<td>Capital Cost (M$)</td>
<td>Capital Cost ($/kW)</td>
<td>O&amp;M Cost (M$/yr)</td>
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<td>NOx Control</td>
<td>24.04</td>
<td>52.97</td>
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<td>TSP Control</td>
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<td>SO2 Control</td>
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<td><strong>Subtotal</strong></td>
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<td><strong>237.6</strong></td>
<td><strong>15.03</strong></td>
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<td>964.2</td>
<td>58.29</td>
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<td><strong>Total</strong></td>
<td><strong>545.5</strong></td>
<td><strong>1202</strong></td>
<td><strong>73.32</strong></td>
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</table>

Costs are in Constant 1996 dollars.
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 ($/tonCO₂ captured)
- Cost increase in electricity (cents/kWh)
- Cost of CO₂ avoided ($/tonCO₂ 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

Please Choose a Power System:
- Conventional Combustion
- Gasification Comb. Cycle
- Advanced Combustion
- Fuel Cells
- Vision 21 Plant
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
Response Surface Model for an IGCC System
Desktop Model of an IGCC System

Configure Plant

Set Objectives

Set Parameters

Get Results

**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
Model Applications

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