Overview of the Integrated Environmental Control Model

$\text{CO}_2$ Capture Option (IECM-CS)

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for
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Current Modeling Activities

• Development and Application of the Integrated Environmental Control Model (IECM)
  ▪ focus on current multi-pollutant environmental controls

• An Integrated Modeling Framework for Carbon Management Technologies (IECM–CS)
  ▪ includes CO₂ controls for combustion and gasification systems

• Development of the Vision 21 Planner (V21P)
  ▪ advanced systems for high-efficiency, zero-emission plants
Modeling Objectives

Focus on electric power systems using fossil fuels:

- Provide a reliable and easy-to-use tool to estimate the performance, emissions, and cost of meeting multi-pollutant environmental requirements at a given facility, using either current or advanced technologies.

- Provide a framework for comparing alternative options on a systematic basis, including the effects of uncertainty, at the preliminary stage of technology design or selection.
Modeling Approach

• Systems Analysis Framework
• Process Technology Models
• Engineering Economic Models
• Advanced Software Capabilities
  - Probabilistic analysis capability
  - User-friendly graphical interface
  - Easy to add or update models
The IECM: Control Options for Regulated Pollutants
Integrated Environmental Control Model (IECM) Framework

Coal Cleaning

Combustion Controls

Flue Gas Cleanup & Waste Management

NO\textsubscript{x} Removal

Mercury Removal

Particulate Removal

SO\textsubscript{2} Removal

Combined SO\textsubscript{x}/NO\textsubscript{x} Removal

Advanced Particulate Removal
Current IECM Technologies

**Furnace Types**
- Tangential
- Wall
- Cyclone

**Furnace NO\textsubscript{x} Controls**
- LNB
- SNCR
- SNCR + LNB
- Gas reburn

**NO\textsubscript{x} Removal**
- Hot-side SCR

**Mercury Removal**
- Carbon injection
- Carbon + water

**Particulate Removal**
- Cold-side ESP
- Fabric filter
  - Reverse Air
  - Pulse Jet

**SO\textsubscript{2} Removal**
- Wet limestone
  - Conventional
  - Forced oxidation
  - Additives
- Wet lime
- Lime spray dryer

**Combined SO\textsubscript{2}/NO\textsubscript{x} Removal**
- Copper oxide
- NOXSO

**Solids Management**
- Ash pond
- Landfill
- Stacking
- Co-mixing
- Byproducts
  - Ash
  - Gypsum
  - Sulfuric Acid
Multi-Pollutant Interactions

Criteria Air Pollutants

Hazardous Air Pollutants

Greenhouse Gas Emissions

PM
SO₂
NOₓ

Hg
HCl
H₂SO₄

CO₂
CH₄

PM
SO₂
NOₓ

Hg
HCl
H₂SO₄

CO₂
CH₄
Model Software Package

- Fuel Properties
  - Heating Value
  - Composition
  - Delivered Cost

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

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

- Power Plant Models

- Graphical User Interface

- Plant and Fuel Databases

- Plant & Process Performance
  - Efficiency
  - Resource use

- Environmental Emissions
  - Air, water, land

- Plant & Process Costs
  - Capital
  - O&M
  - COE
IECM User Group

ABB
AEP-SCR Engineering
Airborne Technologies
Akzo Nobel Functional Chem
Alberta Economic Development
Alberta Environment
ALCOA Power Generating, Inc.
Allegheny Energy Supply
Alliant Energy
Alstom Power Inc.
American Electric Power
Apogee Scientific, Inc.
Applied Technology Services
Argonne National Laboratory
ATCO Power
Babcock Borsig Power, Inc.
Babcock & Wilcox Co.
Bechtel Power Corp.
Black & Veatch Corp.
BOC Gases
Boiler Systems Engineering
Canada Environment
Canada Natural Resources
Carnegie Mellon University
Cinergy Power Generation
Clean Energy Int.
Cogentrix Energy, Inc.
CONSOL Energy, Inc.
Consumers Energy
CP&L
CPG, Inc.
CQ, Inc.
Croll-Reynolds
Department of Environmental Prot
Detroit Edison Co.
Diamond Power Specialty Co
Doyen & Associates, Inc.
Duke Engineering & Services
Duke Fluor Daniel
Dynegy Midwest Generation
Electric Energy, Inc. (EEI)
Electricity de France
Emera Inc.
Emery Recycling Corporation
Enel Produzione
EnerenUE
Energy & Environ Research Corp.
Energy & Environ Strategies
Energy Systems Associates
Energy Technology Enterprises
ENS, Inc.
Environmental Defense
Envirol & Renewable Energy Syst
EPR, Palo Alto
Exportech Company, Inc.
FirstEnergy Corp.
Florida Power & Light Co.
FLS Milto A/S
Fortum Power and Heat Oy
Fossil Energy Research Corp.
Foster Wheeler Development
Foster Wheeler USA Corp.
Fuel Tech, Inc.
General Electric Company
Goodwin Environmental
Great River Energy
Gyeongsang National University
H&W Management Science
Hamon Research Cottrell, Inc.
Harza Engineering
Holland Board of Public Works
IEA Coal Research
Illinois Clean Coal Institute
Illinois Dept. of Natural Resources
Illinois EPA
Illinois Institute of Technology
Indiana Dept. of Env. Mgmt.
Intermountain Power Service Corp.
Jack R. McDonald, Inc.
Kansas City Power & Light Co.
KEMA Nederland B.V.
Kinecrtics
Korea Electric Power Corporation
Korea Institute of Energy Research
Korea Western Power Co.
Krupp Polysius Corp.
LAB SA
Lehigh University
Lower Colorado River Authority
Mail Station PA838
Mcdermott Technology, Inc.
MidAmerican Energy Co.
Minnkota Power Cooperative, Inc.
Mitsubishi Heavy Industries, Ltd.
Mitsui Babcock Energy Ltd.
National Park Service
National Power Plc.
NESCAUM
New Hampshire Dept. of Env.
SVC
New Jersey DEP
Nicholson Environmental, Inc.
Niksa Energy Associates
NIPSCO
Niro A/S
North Carolina DENR
North Carolina State Univ
Ontario Power Generation
Pacific Corp.
Parsons Technology
Pavillon Technologies, Inc.
Pennsylvania Electric Assoc
PEPCO
PG&E National Energy Group
Pinnacle West Energy
Potomac Electric Power Co.
PowerGen
PPL Generation, LLC
PPL Montana, LLC
Predict Maintenance Tech
Princeton University
Progress Materials, Inc.
PSEG Power LLC
Public Power Institute
Reaction Engineering Intl
Research Triangle Institute
Rheinbraun Brennstoff GmbH
Sargent & Lundy, LLC
SaskPower
Savvy Engineering, LLC
Scientech
Sierra Pacific Power Co.
Southern Company Services, Inc.
State of New Jersey
Stone & Webster Engineering Corp.
Superior Adsorients, Inc.
Syncrude
Tampa Electric Co.
Tennessse Valley Authority
Texas Natural Resource Conv Comm
TNO Envit, Energy & Process Innov
TransAlta
TXU Electric
U.S. DOE
U.S. EPA
University of California
University of New Orleans
University of Pittsburgh
URS Corporation
Utah Dept. of Env. Quality
W.L. Gore & Associates, Inc.
Washington Power
Western Kentucky Energy Corp.
Wheelabrator Air PollControl
Wisconsin Dept. of Nat Resources
Wisconsin Electric Power Co.
Wisconsin Energy Corp.
Wisconsin Public Service Corp.
Wisvest-Connecticut, LLC
Model Applications

- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning
The IECM-CS:
Expanded Options for Power Generation and Carbon Sequestration
Project Objectives

- Expand IECM framework to include CO₂ capture and storage options for combustion-based and gasification-based power plants
- Develop performance and cost models for current and advanced CO₂ capture systems
- Integrate carbon management technologies with other environmental control systems
- Characterize key uncertainties in performance and cost for selected technologies
CO$_2$ Capture & Storage Module

Coal or Natural Gas

Power Generation System

Air or Oxygen

CO$_2$ Capture

CO$_2$ Transport

CO$_2$ Storage (Sequestration)

Useful Products (Electricity, Byproducts)
Power Generation Options Under Development

Power Generation Systems

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

Oxidant
- Air
- Oxygen

Technology
- Simple Cycle
  - Pulverized Coal
  - Gas Turbines
- Combined Cycle
  - Gas Turbines
  - Coal Gasification
CO₂ Capture & Storage Options

- CO₂ Capture Technologies
  - Amine-based (MEA) systems (for PC or NGCC)
  - Selexol system (for IGCC)
  - Oxyfuel combustion (available in 2003)
  - Membrane separation (available in 2003)
- CO₂ Transport via Pipeline
- CO₂ Storage Options
  - Geologic Reservoir
  - Enhanced Oil Recovery
  - Enhanced Coal Bed Methane Recovery
  - Deep Ocean
Technical Basis of the IECM
Process Performance Models

- Employ detailed mass and energy balances for the overall plant and individual components
- Employ empirical or semi-empirical relationships and other models for complex process chemistry
- Calculate component and system mass flows, energy flows, and efficiency
- Calculate multi-media environmental emissions
- Approximately 10-20 performance parameters for each process technology
• The IECM parameter input specifications start at the turbine-generator set and “work backwards” to calculate the required energy and mass flows to provide a specified amount of gross power output.

• The key input parameters for calculating plant mass and energy flow rates are the user-specified:
  - Gross plant electrical capacity ($MW_g$)
  - Steam cycle heat rate ($HR_s$) (Btu/kWh)

• Thermal energy input to steam turbine is then:

$$Q_{steam} \text{ (Btu/hr)} = MW_g \times HR_s \times 1000$$
Power Plant Heat and Fuel Input

- Fuel heat input to furnace then calculated based on the boiler efficiency:

\[ Q_{fuel} \ (\text{Btu/hr}) = \frac{Q_{steam}}{\eta_{boiler}} \]

- Fuel flow rate into the furnace (at full capacity) is then calculated from the heat input requirement and fuel heating value:

\[ \dot{m}_{fuel} \ (\text{lbs/hr}) = \frac{Q_{fuel}}{HHV} \]
Power Plant Flue Gas Flow Rate

- Flue gas flow rate, properties and composition are then calculated from a combustion equation based on the:
  - Fuel flow rate
  - Fuel composition
  - Excess air fraction
  - Furnace partition/emission factors
  - Thermodynamic properties of component gases

\[
C_x H_y O_z N_i S_j Cl_k + (1 + e) (O_2 + 3.76 N_2) + Ash \\
\rightarrow CO_2 + CO + H_2O + SO_2 + SO_3 + HCl + \\
N_2 + NO + NO_2 + O_2 + Ash (1 - f_{bottom})
\]
Criteria Pollutant Emissions

- Stack emission rate (lb/MBtu) for SO$_2$, NO$_x$ and particulates may be user-specified or calculated (default = NSPS).
- Removal efficiency of control technologies may be user-specified, or calculated to meet the specified stack emission limit.
Performance Model for a Plant Component or Control Technology

- \( m_{\text{pollutant, in}} \)
- \( m_{\text{reagents}} \)
- \( m_{\text{pollutant, out}} \)
- \( m_{\text{removed}} \)
- Energy

Emission Control Technology
Performance Model for an Emission Control Technology

\[ m_{\text{pollutant, out}} = (1 - \eta) m_{\text{pollutant, in}} \]

\[ \eta = \text{pollutant removal efficiency} \]
\[ = f(\text{process parameters, } p_i) \]

\[ m_{\text{reagent}} = f(\eta, p_i) \]

\[ \text{Energy} = f(\eta, p_i) \]
**Example 1: Performance Model for Wet Limestone FGD**

\[
\ln \left( 1 - \eta_{SO_2} \right) = -0.725 \\
+ 2.5 \times 10^{-4} \left( [SO_2]_{inlet} - 2000 \right) \\
- \left( 10 \Phi - 10.3 \right) \\
- 0.0175 \left( \frac{L}{G} \right) \\
+ 5.14 \times 10^{-6} \left( [Cl] - 25,000 \right) \\
- 0.00042 \left[ DBA \right]
\]

*for \([SO_2] > 1000 \text{ ppm}\)
\[ \eta_{\text{CO}_2} = f(L/G, C, y_{\text{in}}, \phi_{\text{lean}}, T_{\text{fg}}, T_{\text{solv}}, H, D) \]

**Example 2: Performance Model for MEA System**

**Absorber**
- Flue Gas In: \( G, T_{\text{fg}}, y_{\text{in}} \)
- \( L, T_{\text{solv}}, C, \phi_{\text{lean}} \)
- \( \phi_{\text{max}} \)

**Regenerator**
- Captured CO\(_2\) (99.8% pure)
- \( Q_{\text{reg}} \)
- \( \phi_{\text{lean}} \)
- Regenerated Solvent
Technology Cost Models

- Direct cost models for each major process area (typically 5-10 areas per technology)
- Explicit links to process performance models
- Calculate total capital cost
- Calculate variable operating costs
- Calculate fixed operating costs
- Calculate annualized cost of electricity
- Approximately 20-30 cost parameters for each technology modeled
Capital Cost Models

Direct Cost (DC) per process area, $i$

$= f(\text{key flowsheet parameters, e.g., plant size, gas flow rate, temp, etc}) \times (\text{Retrofit cost factor})$

Total Process Capital (TPC) = $\sum (DC)_i$

Indirect Cost Elements = $f(\text{TPC})$

Total Capital Requirement = $\sum (DC)_i + \sum (IC)_i$
O&M Cost Models

Variable Cost = Reagent Costs + Other Input Costs + Energy Cost*

Fixed Cost = Labor Cost + Maintenance Materials

*Based on net power loss to plant
Probabilistic Analysis Features
Probabilistic Software Capability

- Allows you to explicitly model and quantify the effects of uncertainty in performance, emissions and cost
- Allows you to specify input parameter values as distribution functions, as well as conventional deterministic values
- Probabilistic results are displayed as cumulative distribution functions, yielding confidence intervals for uncertain results
Value of Probabilistic Analysis

- Handle uncertainties explicitly
- Represent current understanding
- Systematic thinking about possible outcomes
- Quantify uncertain outcomes--help avoid surprises
- Predict effects of process or parameter variability
- Identify most important parameters
- Help focus discussion and debate
- Quantify or assess risks
- Identify robust strategies and conclusions
- Plan for contingencies
- Prioritize R&D activities to reduce uncertainty
Modeling Uncertainty

- IECM is designed to easily handle uncertainties in:
  - Model parameters (different values for a particular variable)
  - Model structure (different representations of a given process)
- Parameter uncertainties can be modeled using:
  - Sensitivity analysis
  - Probability distributions
- No single “best way” to model uncertainty -- best approach depends on the questions being asked
Representing Uncertainties

Types of uncertainties

- Random error
- Systematic error
- Variability
- Lack of empirical base

• Sources of information

- Data analysis
- Published literature
- Expert judgment
Examples of Parameter Uncertainty Distributions

NORMAL

UNIFORM

LOGNORMAL

TRIANGULAR

BETA

FRACTILE
## IECM Uncertainty Functions

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Mean, std. dev.</td>
</tr>
<tr>
<td>Lognormal</td>
<td>Median, geom. std. dev.</td>
</tr>
<tr>
<td>Uniform</td>
<td>min, max</td>
</tr>
<tr>
<td>Fractiles</td>
<td>n values</td>
</tr>
<tr>
<td>Triangular</td>
<td>min, middle, max</td>
</tr>
<tr>
<td>Wedge</td>
<td>min, max</td>
</tr>
<tr>
<td>Half Normal</td>
<td>mean, std. dev.</td>
</tr>
</tbody>
</table>
Stochastic Simulation

Parameter Uncertainty Distributions → Stochastic Sampler → Results → SAMPLING LOOP → Process Model
Example of a Probabilistic Result

Cumulative Probability

Total Capital Requirement ($/kW)

Probabilistic Result
Illustrative Case Study

• Look at cost of current CCS technology:
  ▪ Amine-based CO₂ capture for combustion
  ▪ Pipeline transport
  ▪ Geologic sequestration

• Include *uncertainty* and *variability* in selected performance and cost parameters of the:
  ▪ Base power plant
  ▪ CO₂ capture system
  ▪ CO₂ transport system
  ▪ CO₂ storage system
Case Study Plant w/ CO₂ Capture

Combustion Controls
- Fuel Type: Coal
- NOx Control: None

Post-Combustion Controls
- NOx Control: Hot-Side SCR
- Particulates: Cold-Side ESP
- SO₂ Control: Wet FGD
- Mercury: None
- CO₂ Capture: Amine System

Solids Management
- Disposal: mixed w/ Landfill
Process Performance Parameters

*italics* denotes uncertain or variable parameters

- Flue gas composition
- Flue gas temp/pressure
- $CO_2$ removal efficiency
- $SO_2$ removal efficiency
- $NO_2$ removal efficiency
- $HCl$ removal efficiency
- MEA concentration
- Lean solvent loading
- Acid gas sorbent loss
- MEA oxidation loss
- Nominal MEA make-up
- Ammonia generation
- Reclaimer chemical reqm’t
- Cooling water makeup
- Flue gas pressure drop
- Fan efficiency
- Solvent pumping head
- Pump efficiency
- Regeneration heat (calc)
- Equiv. elec. requirement
- $CO_2$ product pressure
- $CO_2$ product purity
- Compressor efficiency
- Compression energy
## Amine System Performance Parameter Uncertainties

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Units</th>
<th>Data (Range)</th>
<th>Nominal Value</th>
<th>Unc. Representation (Distribution Function)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ removal efficiency</td>
<td>%</td>
<td>Mostly 90</td>
<td>90</td>
<td>Uniform (85,95)</td>
</tr>
<tr>
<td>SO₂ removal efficiency</td>
<td>%</td>
<td>Almost 100</td>
<td>99.5</td>
<td>Uniform (99,100)</td>
</tr>
<tr>
<td>NO₂ removal efficiency</td>
<td>%</td>
<td>20-30</td>
<td>25</td>
<td>Uniform (20,30)</td>
</tr>
<tr>
<td>HCl removal efficiency</td>
<td>%</td>
<td>90-95</td>
<td>95</td>
<td>Uniform (90,95)</td>
</tr>
<tr>
<td>Particulate removal eff.</td>
<td>%</td>
<td>50</td>
<td>50</td>
<td>Uniform (40,60)</td>
</tr>
<tr>
<td>MEA concentration</td>
<td>wt%</td>
<td>15-50</td>
<td>30</td>
<td>Uniform (20,30)</td>
</tr>
<tr>
<td>Lean solvent CO₂ loading</td>
<td>mol CO₂/mol MEA</td>
<td>0.15-0.30</td>
<td>0.22</td>
<td>Triangular (0.17,0.22,0.25)</td>
</tr>
<tr>
<td>Nominal MEA make-up</td>
<td>kg MEA/tonne CO₂</td>
<td>0.5-3.1</td>
<td>1.5</td>
<td>Triangular (0.5,1.5,3.1)</td>
</tr>
<tr>
<td>MEA loss (SO₂)</td>
<td>mol MEA/mol SO₂</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>MEA loss (NO₂)</td>
<td>mol MEA/mol NO₂</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>MEA loss (HCl)</td>
<td>mol MEA/mol HCl</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>MEA loss (exhaust gas)</td>
<td>ppm</td>
<td>1-4</td>
<td>2</td>
<td>Uniform (1,4)</td>
</tr>
<tr>
<td>NH₃ generation</td>
<td>molNH₃/molMEA ox</td>
<td>0.13</td>
<td>0.13</td>
<td>-</td>
</tr>
<tr>
<td>Caustic for MEA reclaimer</td>
<td>kg NaOH/tonneCO₂</td>
<td>0.13</td>
<td>0.13</td>
<td>-</td>
</tr>
<tr>
<td>Cooling water makeup</td>
<td>M³/tonne CO₂</td>
<td>0.5-1.8</td>
<td>0.8</td>
<td>Triangular (135,200,480)</td>
</tr>
<tr>
<td>Solvent pumping head</td>
<td>kPa</td>
<td>35-250</td>
<td>207</td>
<td>Triangular (150,207,250)</td>
</tr>
<tr>
<td>Pump efficiency</td>
<td>%</td>
<td>70-75</td>
<td>75</td>
<td>Uniform (70,75)</td>
</tr>
<tr>
<td>Gas-phase pressure drop</td>
<td>kPa</td>
<td>14-30</td>
<td>26</td>
<td>Triangular (14,26,30)</td>
</tr>
<tr>
<td>Fan efficiency</td>
<td>%</td>
<td>70-75</td>
<td>75</td>
<td>Uniform (70,75)</td>
</tr>
<tr>
<td>Equiv. elec. requirement</td>
<td>% regeneration heat</td>
<td>9-19</td>
<td>14</td>
<td>Uniform (9,19)</td>
</tr>
<tr>
<td>CO₂ product purity</td>
<td>wt%</td>
<td>99-99.8</td>
<td>99.5</td>
<td>Uniform (99,99.8)</td>
</tr>
<tr>
<td>CO₂ product pressure</td>
<td>MPa</td>
<td>5.86-15.16</td>
<td>13.79</td>
<td>Triangular (5.86,13.79,15.16)</td>
</tr>
<tr>
<td>Compressor efficiency</td>
<td>%</td>
<td>75-85</td>
<td>80</td>
<td>Uniform (75,85)</td>
</tr>
</tbody>
</table>
Process Cost Parameters

(italics denotes uncertain parameters)

- Process Area Costs (12)
- Process Facilities Cost
- Eng’g & Home Office
- General Facilities
- Contingency Costs
- Interest d/ Construction
- Royalty Fees
- Pre-production Costs
- Inventory (startup) Cost
- Total Plant Cost
- Total Capital Reqm’t
- Operating Labor
- Maintenance Labor
- Admin./Support Labor
- Maintenance Materials
- Reagent (MEA) Cost
- Chemicals Cost
- Waste Disposal Cost
- Water Cost
- (Power Cost)*
- CO₂ Transport Cost
- CO₂ Storage Cost
## CCS Cost Parameter Uncertainties

<table>
<thead>
<tr>
<th>Capital Cost Elements</th>
<th>Nom. Value*</th>
<th>O&amp;M Cost Elements</th>
<th>Nom. Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Area Costs (9 areas)</td>
<td>PFC(^b)</td>
<td>Total Maintenance Cost</td>
<td>2.5 % TPC(^j)</td>
</tr>
<tr>
<td>Total Process Facilities Cost</td>
<td>7 % PFC(^c)</td>
<td>Maintenance cost allocated to labor</td>
<td>40% of total maint. cost</td>
</tr>
<tr>
<td>Engineering and Home Office</td>
<td>7 % PFC(^c)</td>
<td>Admin. &amp; support labor</td>
<td>30% of total labor</td>
</tr>
<tr>
<td>General Facilities</td>
<td>10 % PFC(^c)</td>
<td>Operating Labor</td>
<td>2 jobs/shift(^b)</td>
</tr>
<tr>
<td>Project Contingency</td>
<td>15 % PFC(^c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Contingency</td>
<td>5 % PFC(^c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Plant Cost (TPC) = sum of above</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Fixed O&M Costs (FOM)

<table>
<thead>
<tr>
<th>Variable O&amp;M Costs (VOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest During Construction</td>
</tr>
<tr>
<td>Royalty Fees</td>
</tr>
<tr>
<td>Pre-production Costs</td>
</tr>
<tr>
<td>Inventory (startup) Cost</td>
</tr>
<tr>
<td>Total Capital Reqmt (TCR) = sum of above</td>
</tr>
</tbody>
</table>

### Nom. Value* |

- Process Area Costs (9 areas): flue gas blower, absorber, regenerator, solvent processing area, MEA reclaimer, steam extractor, heat exchanger, pumps, CO₂ compressor. The sum of these is the total process facilities cost (PFC). The uncertainty distributions used are: \(^b\)Normal (1.0,0.1), \(^c\)Triangular (5,7,15), \(^d\)Triangular (5,10,15), \(^e\)Triangular (10,15,20), \(^f\)Triangular (2,5,10), \(^g\)Triangular (0.5,0.5,0.5), \(^h\)Triangular (0.5,1,1), \(^i\)Triangular (0.4,0.5,0.6), \(^j\)Triangular (1,2.5,5), \(^k\)Triangular (1,2,3), \(^l\)Uniform (1150,1300), \(^m\)Triangular (0.004,0.02,0.06), \(^n\)Chance distribution (-10(p=0.25), -5(p=0.25), 3(p=0.05), 5(p=0.35), 8(p=0.1))
# Case Study Plant Parameters

*(italics denotes uncertain or variable parameters)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross plant size (MW)</td>
<td>500</td>
<td>Emission standards</td>
<td>2000 NSPS</td>
</tr>
<tr>
<td><em>Gross plant heat rate (kJ/kWh)</em></td>
<td>9600&lt;sup&gt;a&lt;/sup&gt;</td>
<td>NO&lt;sub&gt;x&lt;/sub&gt; controls</td>
<td>LNB+SCR</td>
</tr>
<tr>
<td><em>Levelized capacity factor (%)</em></td>
<td>75&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Particulate control</td>
<td>ESP</td>
</tr>
<tr>
<td><strong>Coal Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HHV (kJ/kg)</td>
<td>Low-S: 19346</td>
<td>Hi-S: 25300</td>
<td></td>
</tr>
<tr>
<td>% S</td>
<td>0.48</td>
<td>% C</td>
<td>47.9</td>
</tr>
<tr>
<td>% C</td>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt; control</td>
<td>FGD</td>
</tr>
<tr>
<td><strong>Delivered cost ($/tonne)</strong></td>
<td>23.19&lt;sup&gt;c&lt;/sup&gt;</td>
<td>41.37&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>CO&lt;sub&gt;2&lt;/sub&gt; storage method</strong></td>
<td>Geologic</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Distance to storage</strong></td>
<td>165 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cost year (const.$)</strong></td>
<td>2000</td>
<td><strong>Fixed charge factor</strong></td>
<td>0.15&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Nominal case is a sub-critical unit. Uncertainty case includes supercritical unit. The uncertainty distributions used are:  
<sup>a</sup>Unc = Chance(8968(p=0.5), 9600(p-0.5));  
<sup>b</sup>Unc = Triangular(65,75,85);  
<sup>c</sup>Unc = Triangular(15.94,23.19,26.81);  
<sup>d</sup>Unc = Triangular (35.31, 41.97, 51.96)  
<sup>e</sup>Corresponds to a 30-year plant life with a 14.8% real interest rate (or, a 20-year life with 13.9% interest);  
Unc = Uniform(0.10,0.20)
Common Measures of Cost

• Cost of CO₂ Avoided ($/ton CO₂ avoided)

$$\frac{($/\text{MWh})_{\text{capture}} - ($/\text{MWh})_{\text{reference}}}{(\text{CO}_2/\text{MWh})_{\text{ref}} - (\text{CO}_2/\text{MWh})_{\text{capture}}}$$

• Cost of Electricity ($/\text{MWh}$)

$$\frac{(TCR)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC)$$
Case Study Results: Cost of CO₂ Avoided

Low-S Coal Case

Key variables:
- CO₂ capture efficiency
- steam elect. penalty
- compressor efficiency
- lean sorbent loading
- process facilities cost
- CO₂ storage cost
- variable operating costs

Uncertainty/Variability in:
- MEA Performance Pars.
- + MEA Cost Parameters

Cumulative Probability

CO₂ Mitigation Cost ($/tonne CO₂ avoided)