IECM Overview and Update

Edward S. Rubin
Department of Engineering and Public Policy
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, Pennsylvania

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NETL CO_2 Capture Technology Meeting
Pittsburgh, Pennsylvania

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Company Background Slide:

The Carnegie Mellon University campus

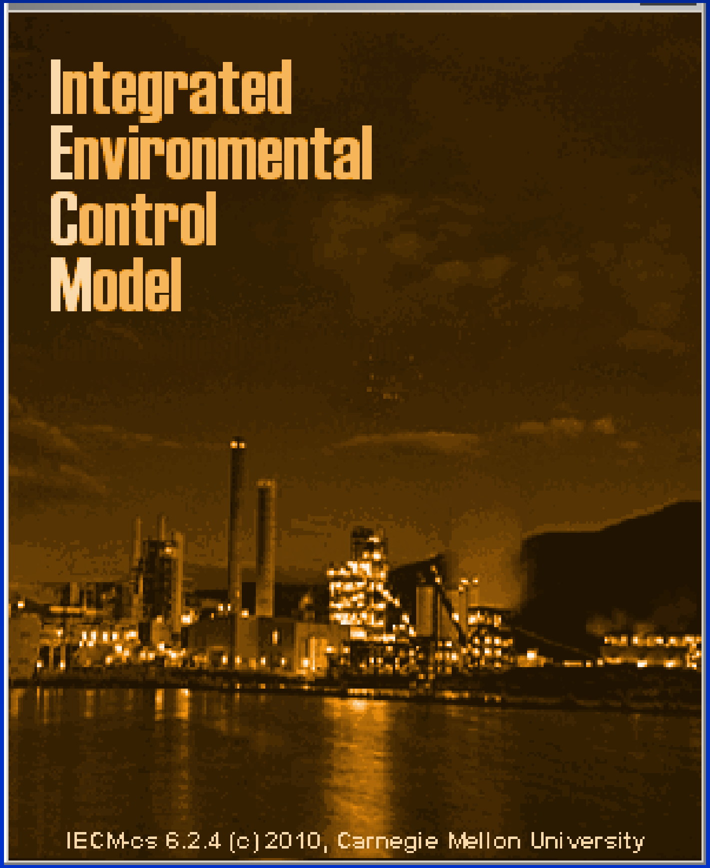
Project Overview

- *Title:* Integrated Environmental Control Model (IECM)
- *DOE Funding (via URS) :* $245,300
- *Performance Dates:* Nov 15, 2011 – Nov 14, 2012

- *Also a related project:* "The Role of Simulation and Modeling in Accelerating CO_2 Capture Technology"

The Integrated Environmental Control Model (IECM)

- 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**



IECM Modeling Approach

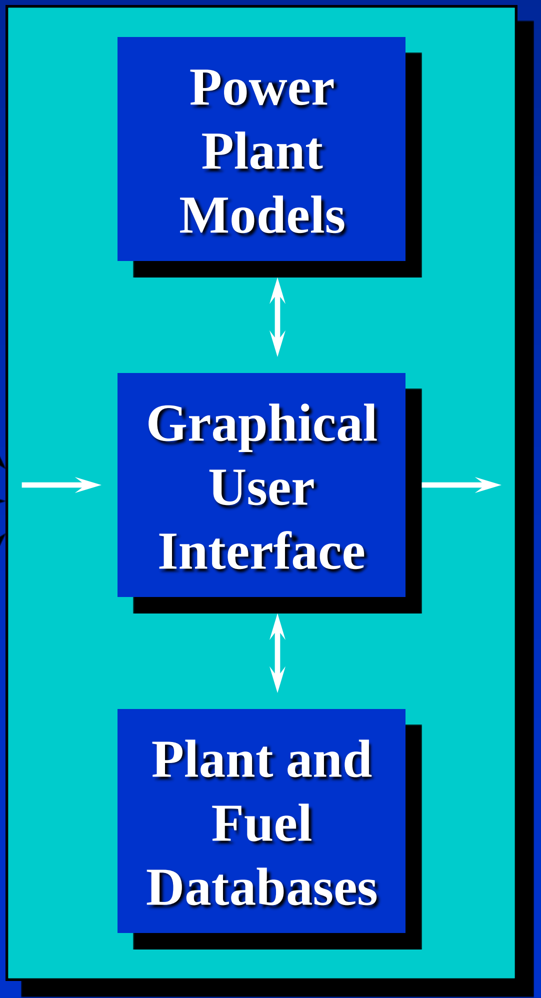
- Systems Analysis Approach
- Process Performance Models
- Engineering Economic Models
- Advanced Software Capabilities
  - User-friendly graphical interface
  - Probabilistic analysis capability
  - Versatile input/output features

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



Plant & Process Performance
- Efficiency
- Resource use

Environmental Emissions
- Air, water, land

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

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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 reburn

Flue Gas NO_x 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
  - Conventional, Forced oxidation
  - Additives
- Wet lime
- Lime spray dryer

Solids 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 CO_2 capture, transport and sequestration)

Air Separation Unit
- Cryogenic

Slurry Preparation

Coal Pretreatment

Gasification
- Slurry-feed gasifier (GE-Q)
- Dry-feed gasifier (Shell)

Syngas Cooling and Particulate Removal System

Mercury Removal
- Activated carbon

H_2S Removal System
- Selexol
- Sulfinol

Sulfur Recovery System
- Claus 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

IECM Technologies for CCS

- <u>CO_2 Capture Options</u>
  - *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)
- <u>CO_2 Transport Options</u>
  - Pipelines (six U.S. regions)
- <u>CO_2 Sequestration Options</u>
  - 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
- CO_2 removal efficiency
- SO_2 removal efficiency
- NO_2 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 reqm’t
- Flue gas pressure drop
- Fan efficiency
- Sorbent pumping head
- Pump efficiency
- Regeneration heat
- Equiv. elec. requirement
- CO_2 product pressure
- CO_2 product purity
- Compressor efficiency
- Compression energy

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

IECM Cost Model Parameters for Amine Capture System

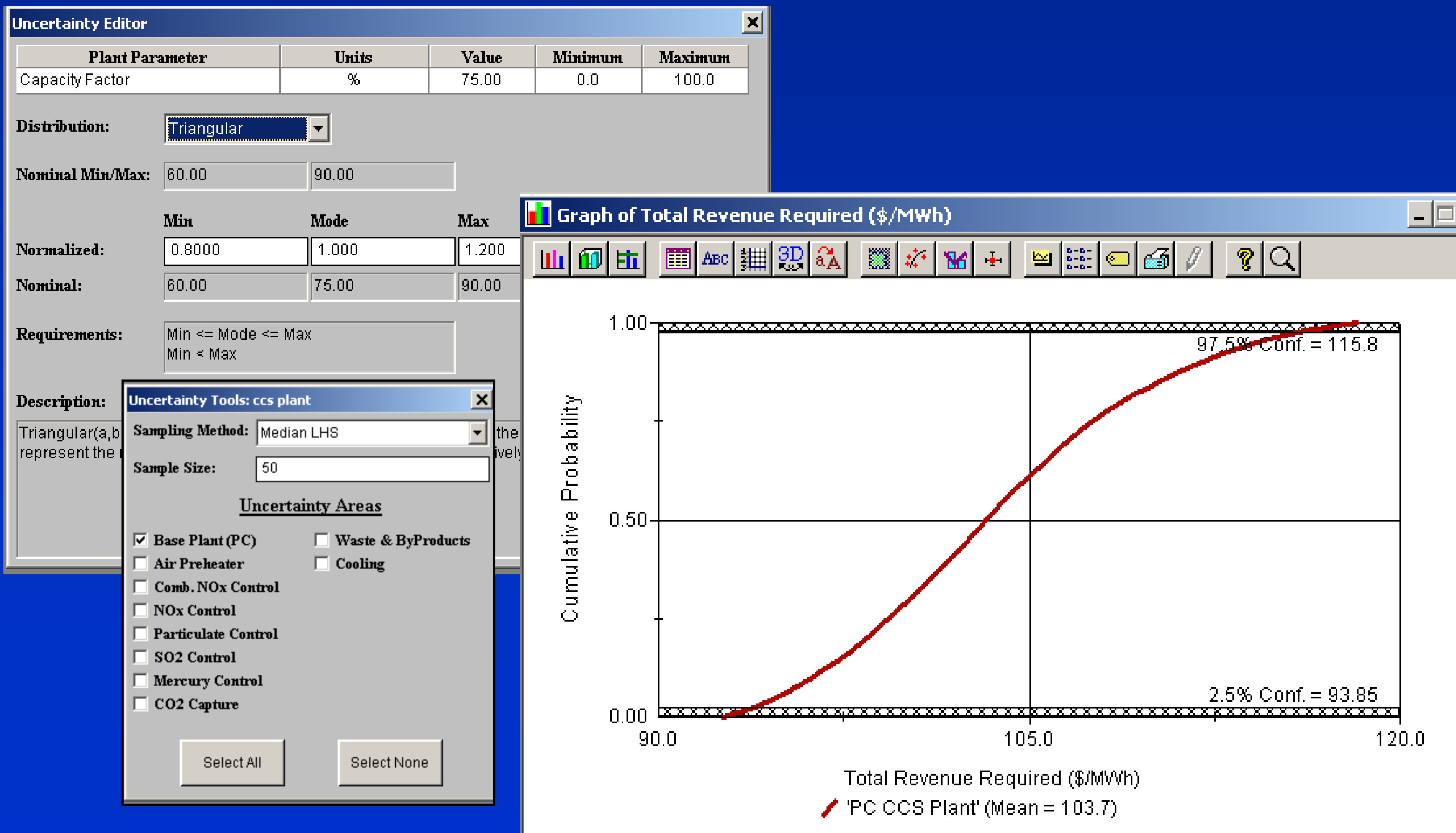
- Process Area Costs (12)
- Process Facilities Cost
- Eng'g. & Home Office
- General Facilities
- Contingency Costs (2)
- Interest during Construction
- Royalty Fees
- Pre-production Costs
- Inventory (startup) Cost
- Total Plant Cost
- Total Capital Reqm't

- Operating Labor
- Maintenance Labor
- Admin./Support Labor
- Maintenance Materials
- Amine Sorbent Cost
- Other Chemicals Cost
- Waste Disposal Cost
- Water Cost
- *(Power Cost)**
- CO_2 Transport Cost
- CO_2 Storage Cost

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*



Model Applications

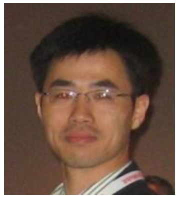
- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning

Recent IECM versions downloaded by:
>2200 individuals in >800 organizations in > 50 countries

The IECM Team

- Performance and Cost Models of Advanced CO_2 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 Kietzke)*






Recent Developments

Since Last Year's Meeting *(1)*

- Developed reduced order models (ROMs) for several advanced CO_2 capture processes, now implemented in new IECM test versions:
  - Chilled ammonia process (post-comb.)
  - Membrane capture system (post-comb.)
  - Chemical looping system (pre-comb.)
- Additional process models under development:
  - Advanced oxy-combustion system
  - Solid sorbent capture system (post-comb.)
  - Chemical looping system (post-comb.)
- Prepared draft technical reports documenting new CO_2 capture process models

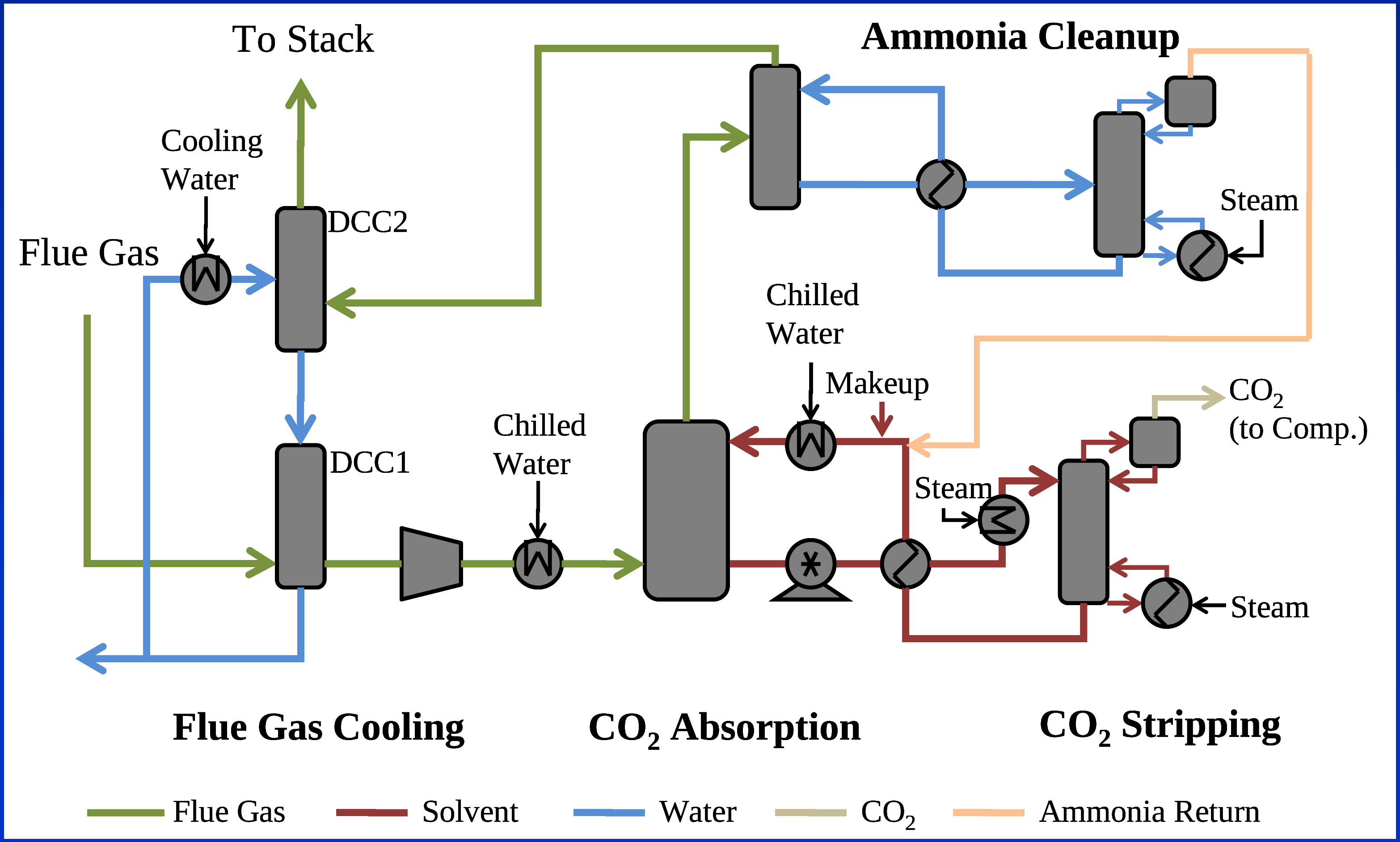
Since Last Year's Meeting *(2)*

- Posted beta version 7.0 for testing
  - >500 downloads to date
- Additional new capabilities in v. 7.1.0, being used for two IECM workshops at this meeting
- Conducted case studies of CCS designs to characterize performance, cost, and uncertainties, including:
  - CCS costs for NGCC plants
  - Effect of proposed CO_2 NSPS for coal plants
  - Effect of EOR credits on capture system cost
  - Comparisons of advanced capture technologies with current amine-based systems

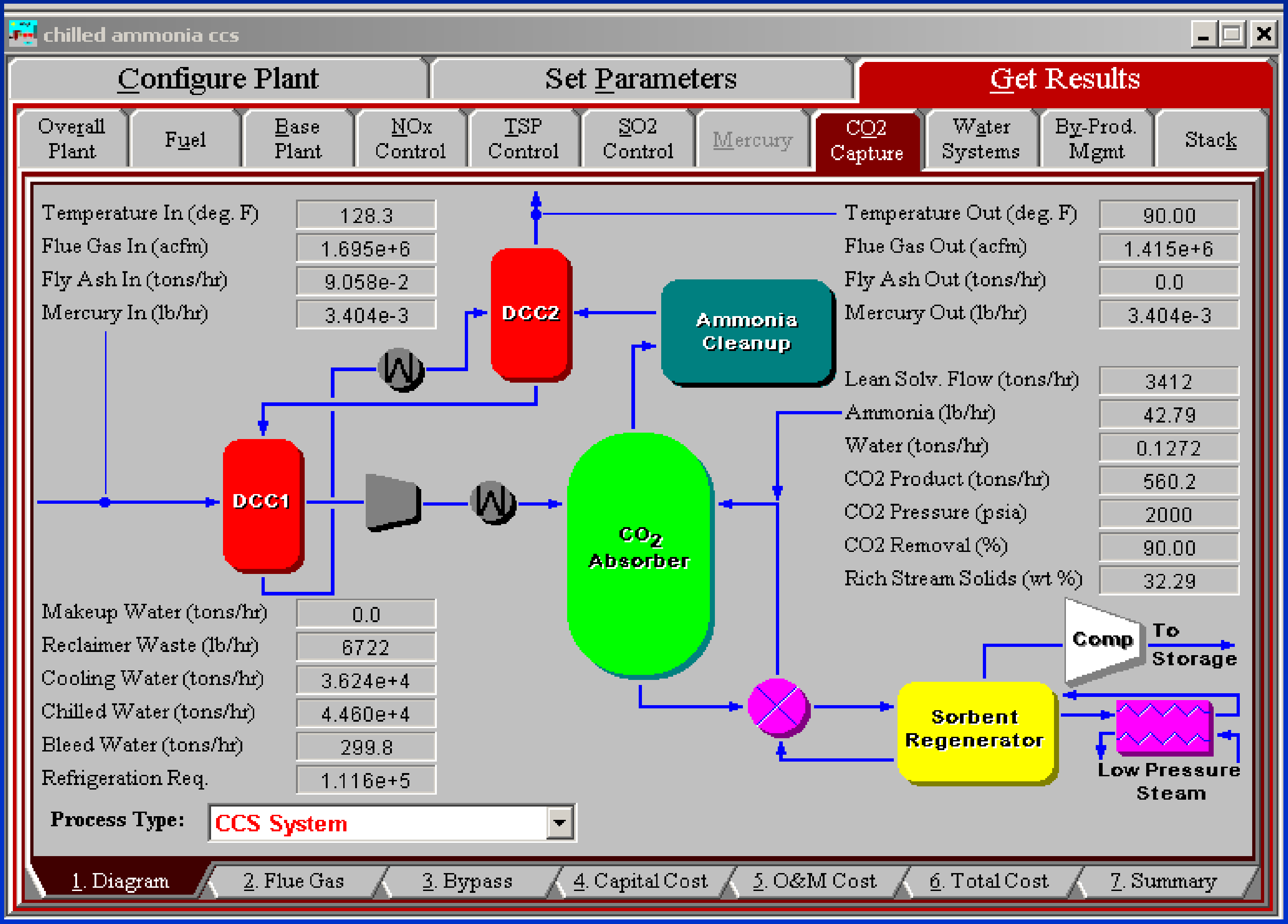
Illustrative Results: Sensitivity Analyses

(Deterministic Cases)

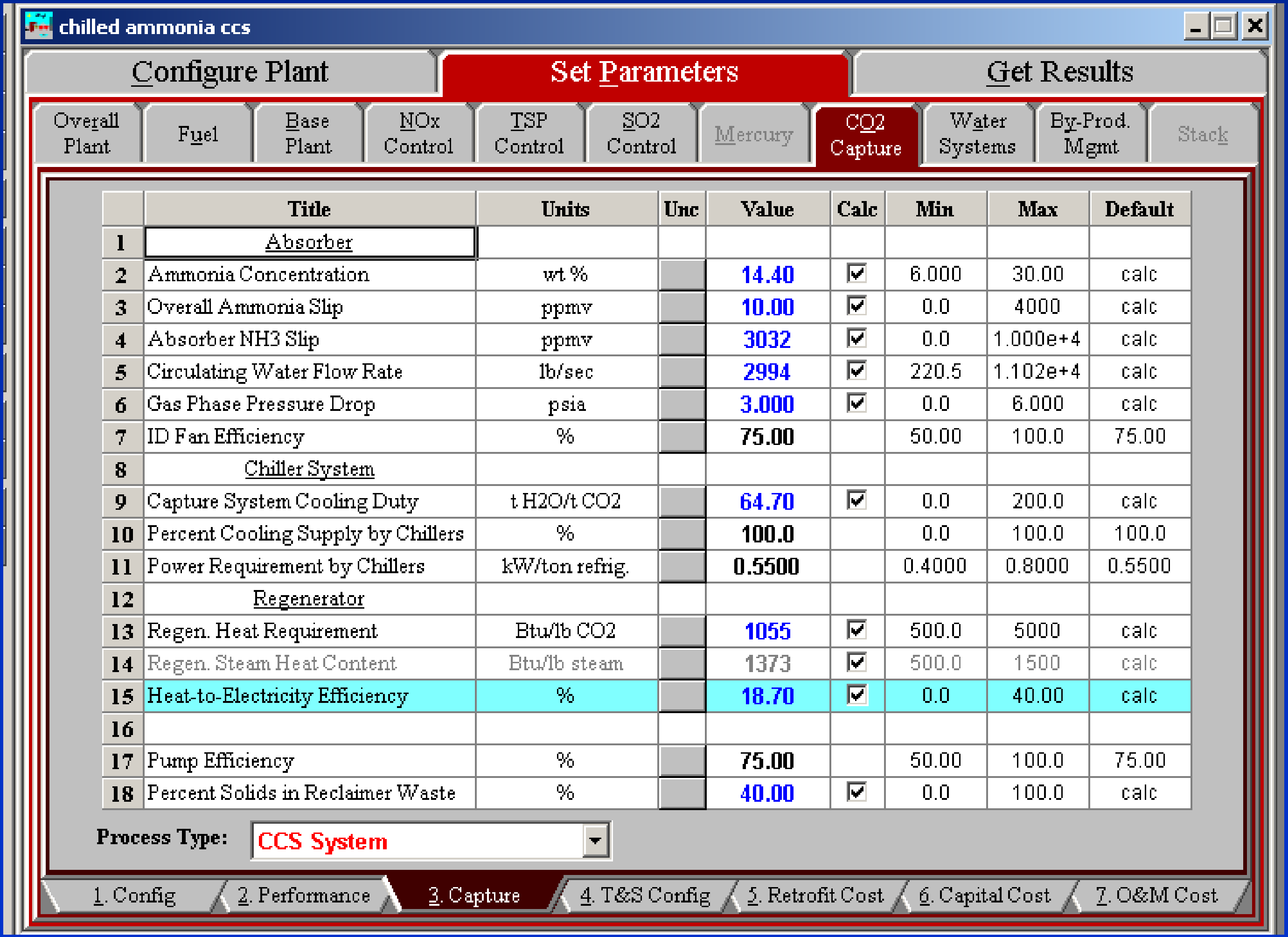
Ammonia-Based CO_2 Capture System
(Detailed performance model in Aspen Plus)



Ammonia-Based CO_2 Capture System
(Reduced Order Model in IECM)

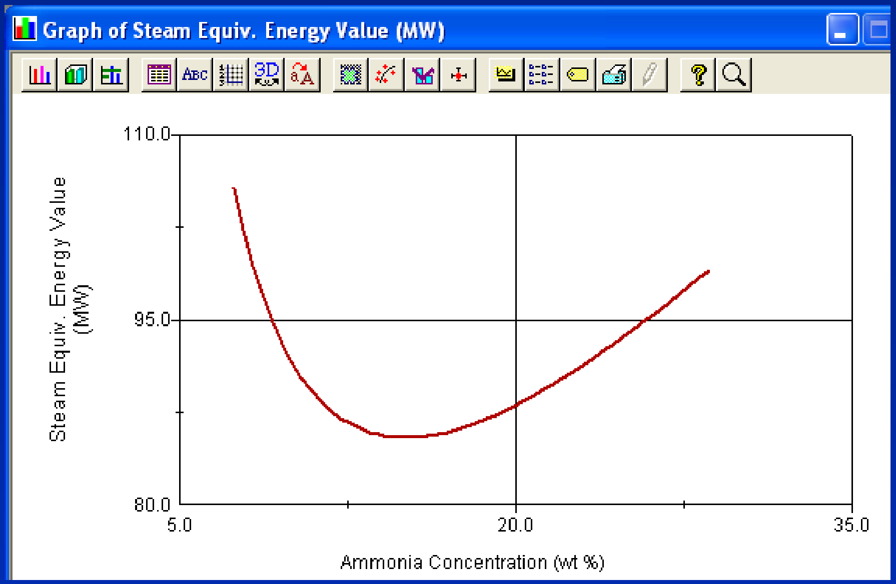


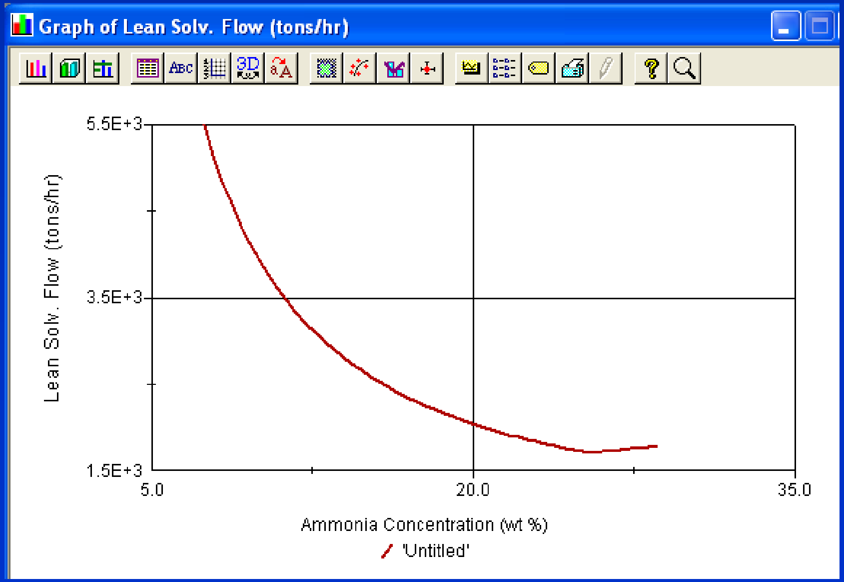
Some of the IECM Parameters for the New Chilled Ammonia Capture System Model

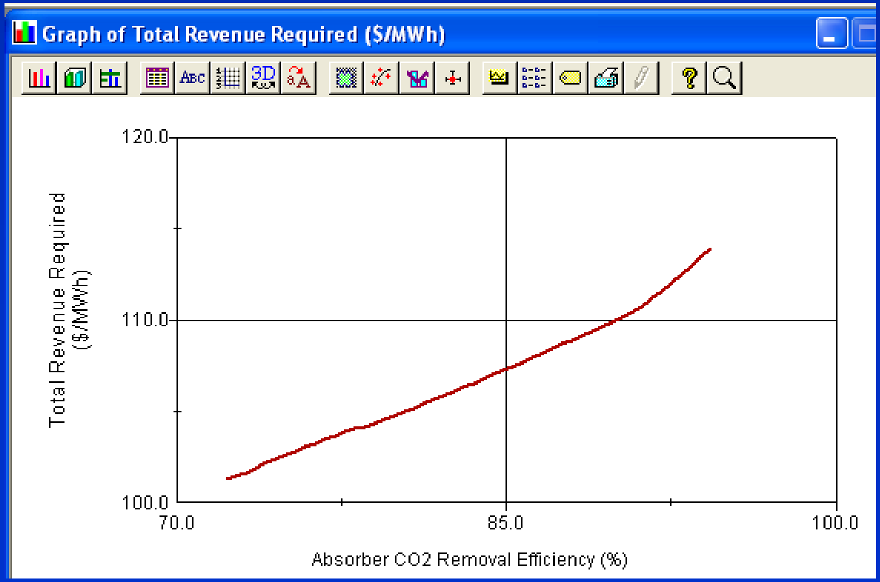


	Title	Units	Unc	Value	Calc	Min	Max	Default
1	Absorber							
2	Ammonia Concentration	wt %		14.40	☑	6.000	30.00	calc
3	Overall Ammonia Slip	ppmv		10.00	☑	0.0	4000	calc
4	Absorber NH3 Slip	ppmv		3032	☑	0.0	1.000e+4	calc
5	Circulating Water Flow Rate	lb/sec		2994	☑	220.5	1.102e+4	calc
6	Gas Phase Pressure Drop	psia		3.000	☑	0.0	6.000	calc
7	ID Fan Efficiency	%		75.00		50.00	100.0	75.00
8	Chiller System							
9	Capture System Cooling Duty	t H2O/t CO2		64.70	☑	0.0	200.0	calc
10	Percent Cooling Supply by Chillers	%		100.0		0.0	100.0	100.0
11	Power Requirement by Chillers	kW/ton refrig.		0.5500		0.4000	0.8000	0.5500
12	Regenerator							
13	Regen. Heat Requirement	Btu/lb CO2		1055	☑	500.0	5000	calc
14	Regen. Steam Heat Content	Btu/lb steam		1373	☑	500.0	1500	calc
15	Heat-to-Electricity Efficiency	%		18.70	☑	0.0	40.00	calc
16								
17	Pump Efficiency	%		75.00		50.00	100.0	75.00
18	Percent Solids in Reclaimer Waste	%		40.00	☑	0.0	100.0	calc

Sensitivity of performance and cost results to selected ammonia system parameters*

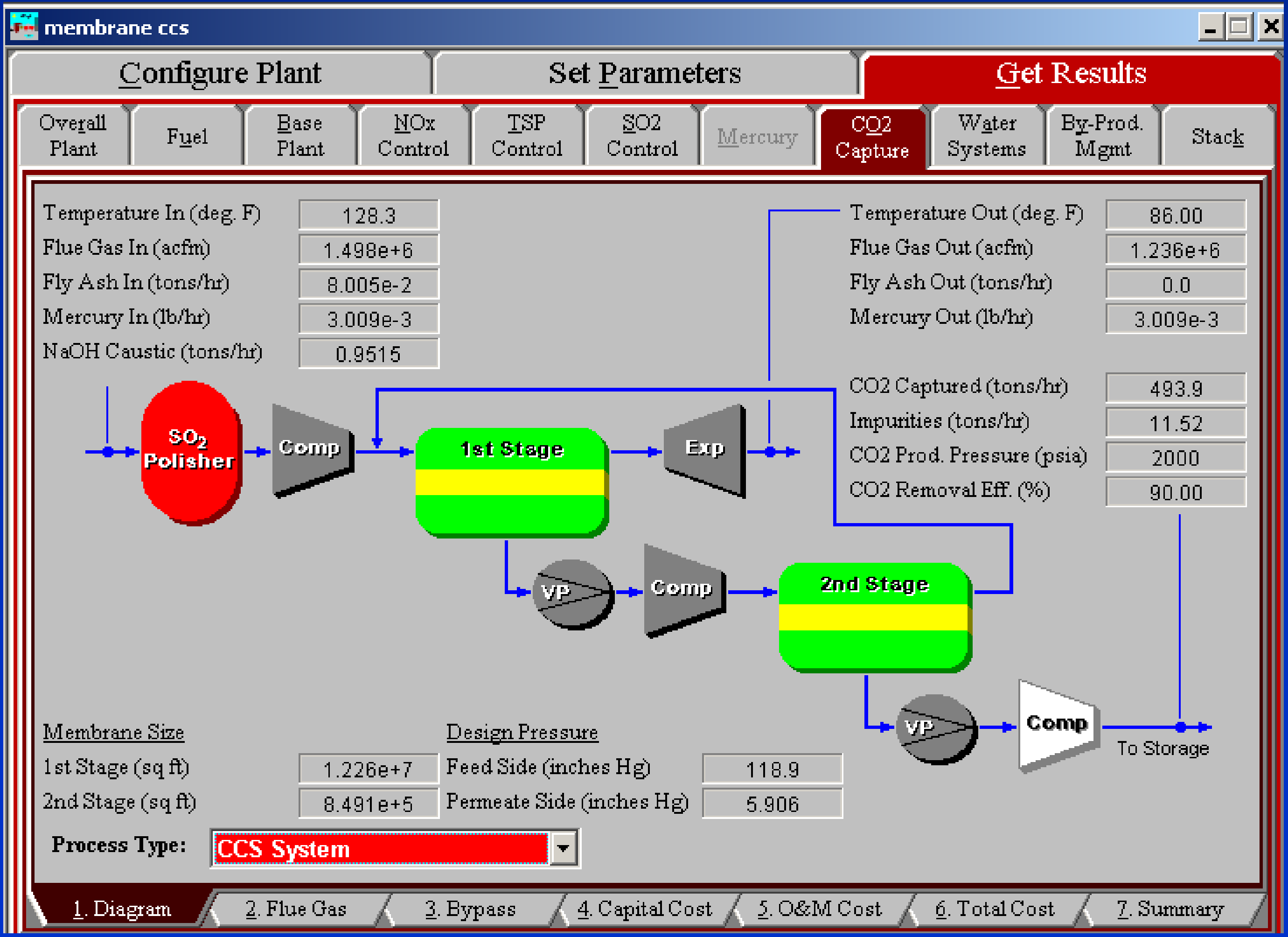




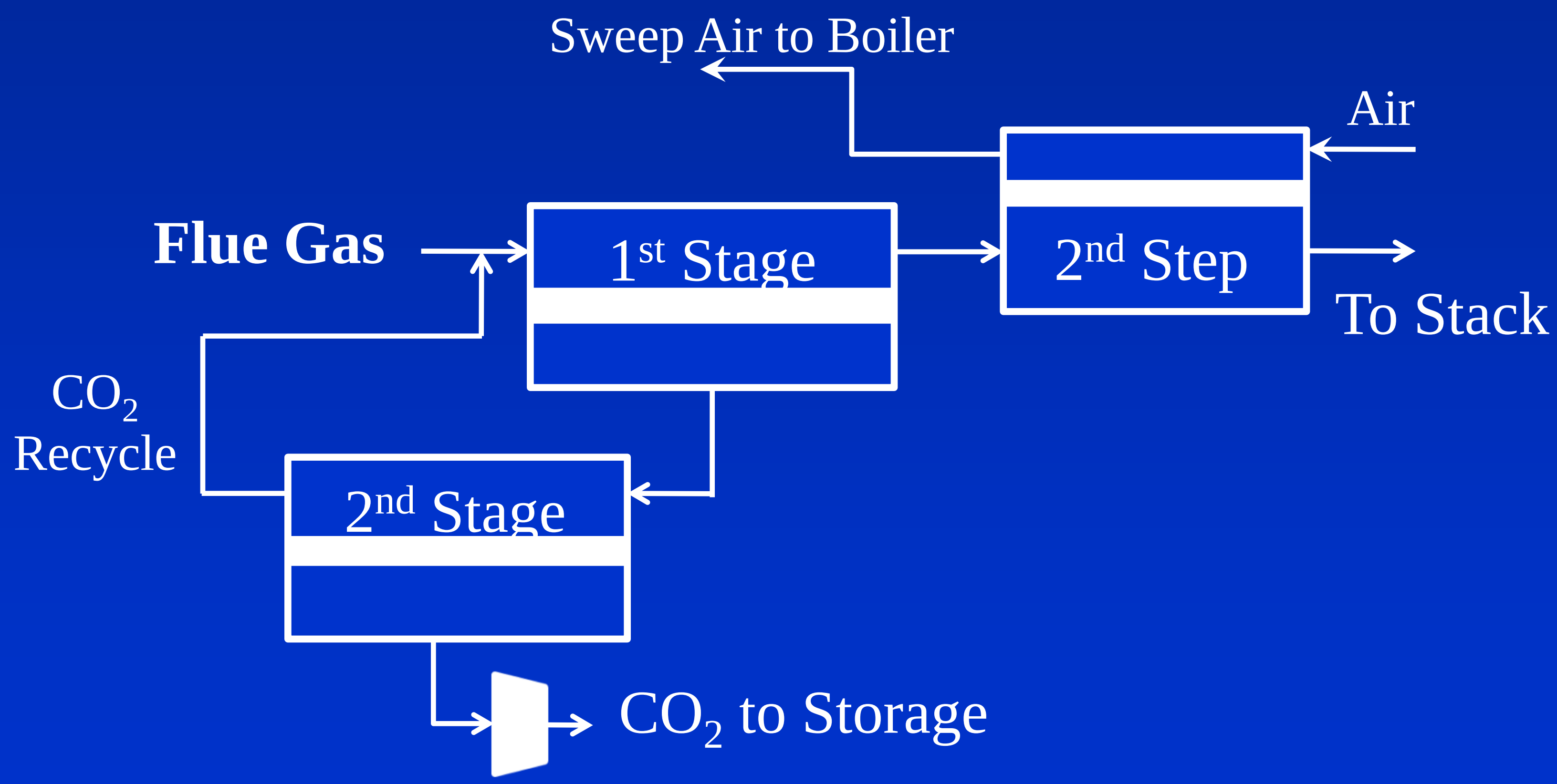


*All other parameters held constant

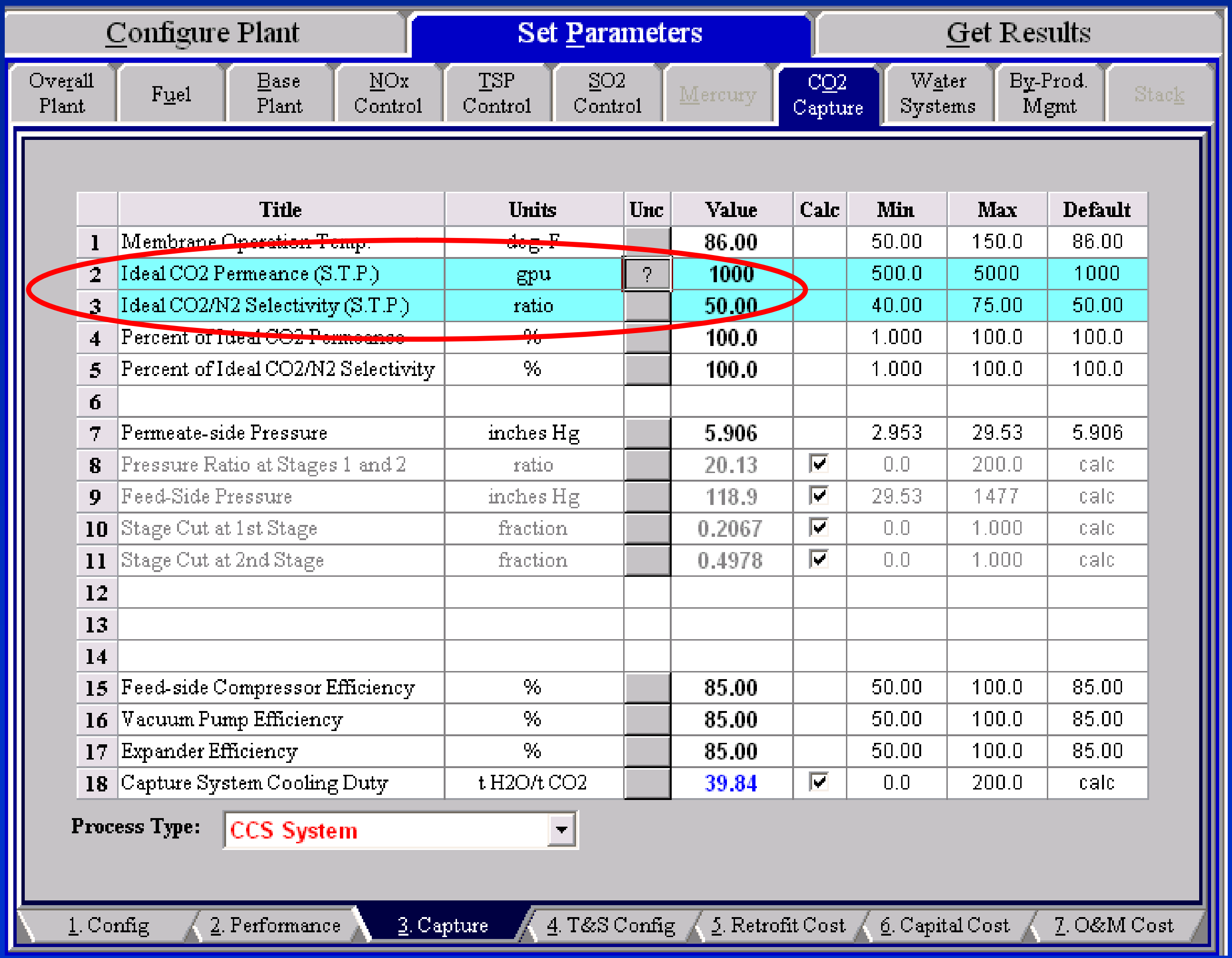
New 2-Stage Membrane System Model in IECM



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



Some IECM Parameters for the New Membrane Capture System Model



	Title	Units	Unc	Value	Calc	Min	Max	Default
1	Membrane Operation Temp.	deg. F		86.00		50.00	150.0	86.00
2	Ideal CO2 Permeance (S.T.P.)	gpu	?	1000		500.0	5000	1000
3	Ideal CO2/N2 Selectivity (S.T.P.)	ratio		50.00		40.00	75.00	50.00
4	Percent of Ideal CO2 Permeance	%		100.0		1.000	100.0	100.0
5	Percent of Ideal CO2/N2 Selectivity	%		100.0		1.000	100.0	100.0
6								
7	Permeate-side Pressure	inches Hg		5.906		2.953	29.53	5.906
8	Pressure Ratio at Stages 1 and 2	ratio		20.13	☑	0.0	200.0	calc
9	Feed-Side Pressure	inches Hg		118.9	☑	29.53	1477	calc
10	Stage Cut at 1st Stage	fraction		0.2067	☑	0.0	1.000	calc
11	Stage Cut at 2nd Stage	fraction		0.4978	☑	0.0	1.000	calc
12								
13								
14								
15	Feed-side Compressor Efficiency	%		85.00		50.00	100.0	85.00
16	Vacuum Pump Efficiency	%		85.00		50.00	100.0	85.00
17	Expander Efficiency	%		85.00		50.00	100.0	85.00
18	Capture System Cooling Duty	t H2O/t CO2		39.84	☑	0.0	200.0	calc

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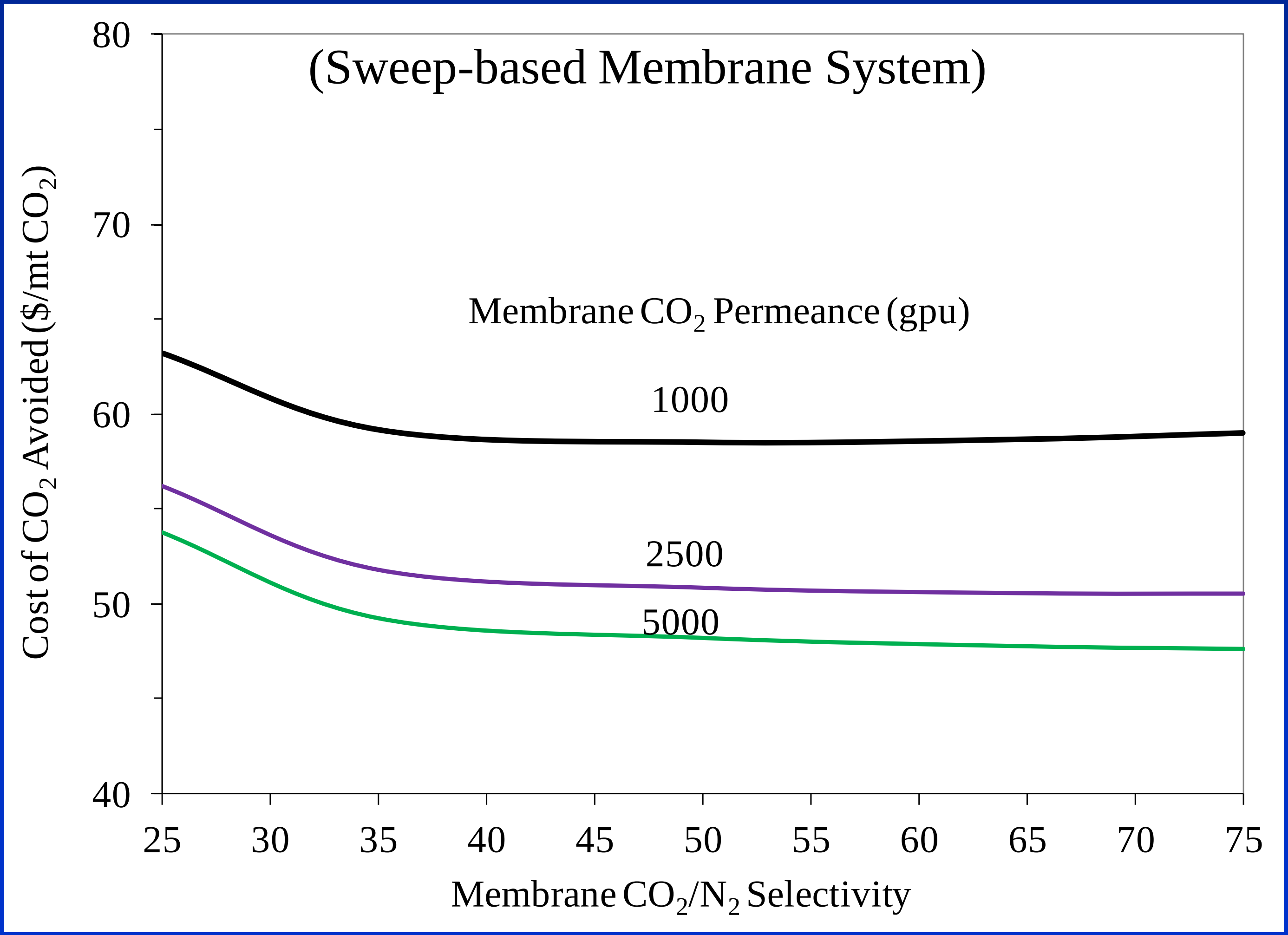
Effect of Membrane Properties on Cost of CO_2 Avoided



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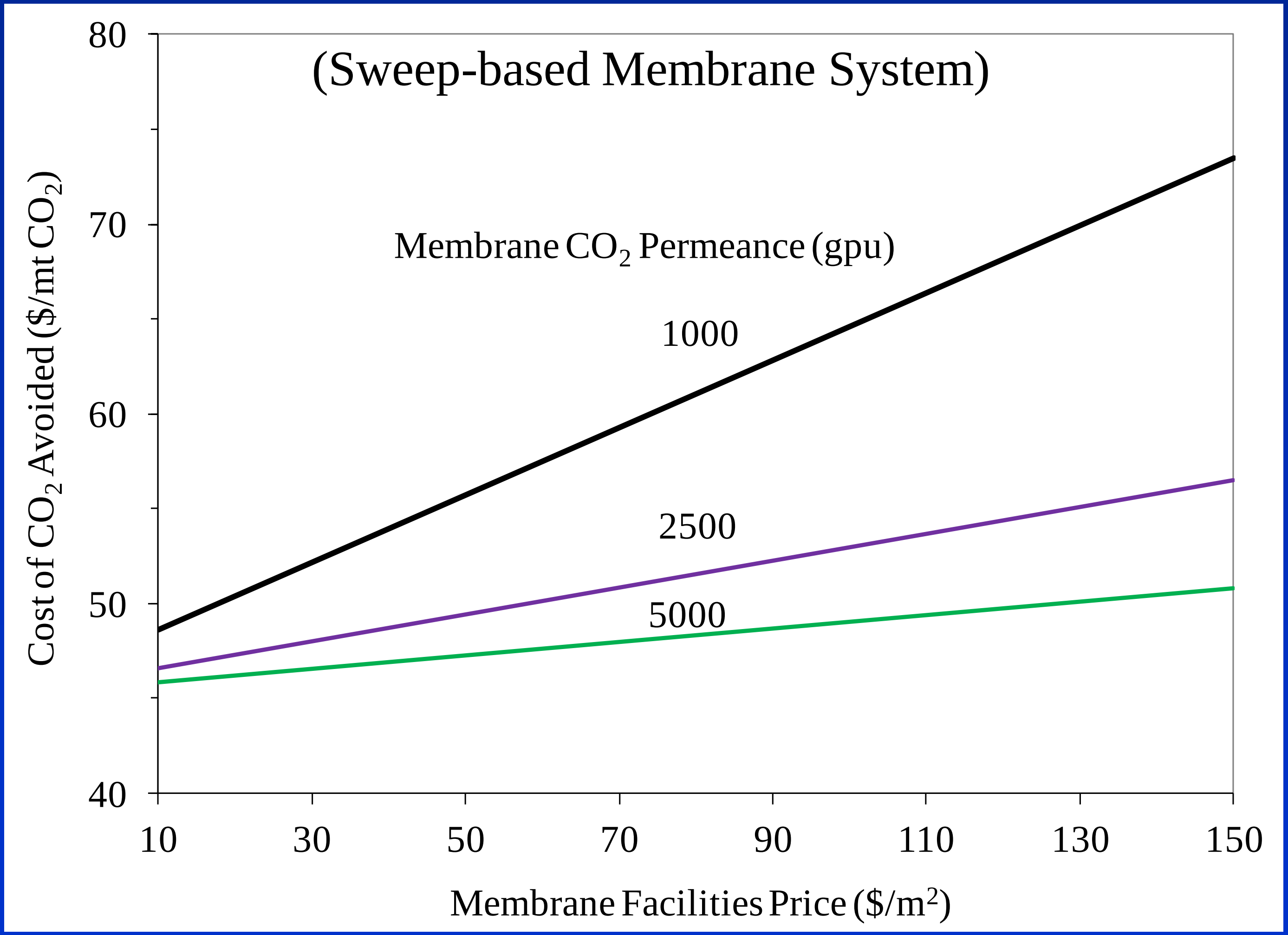
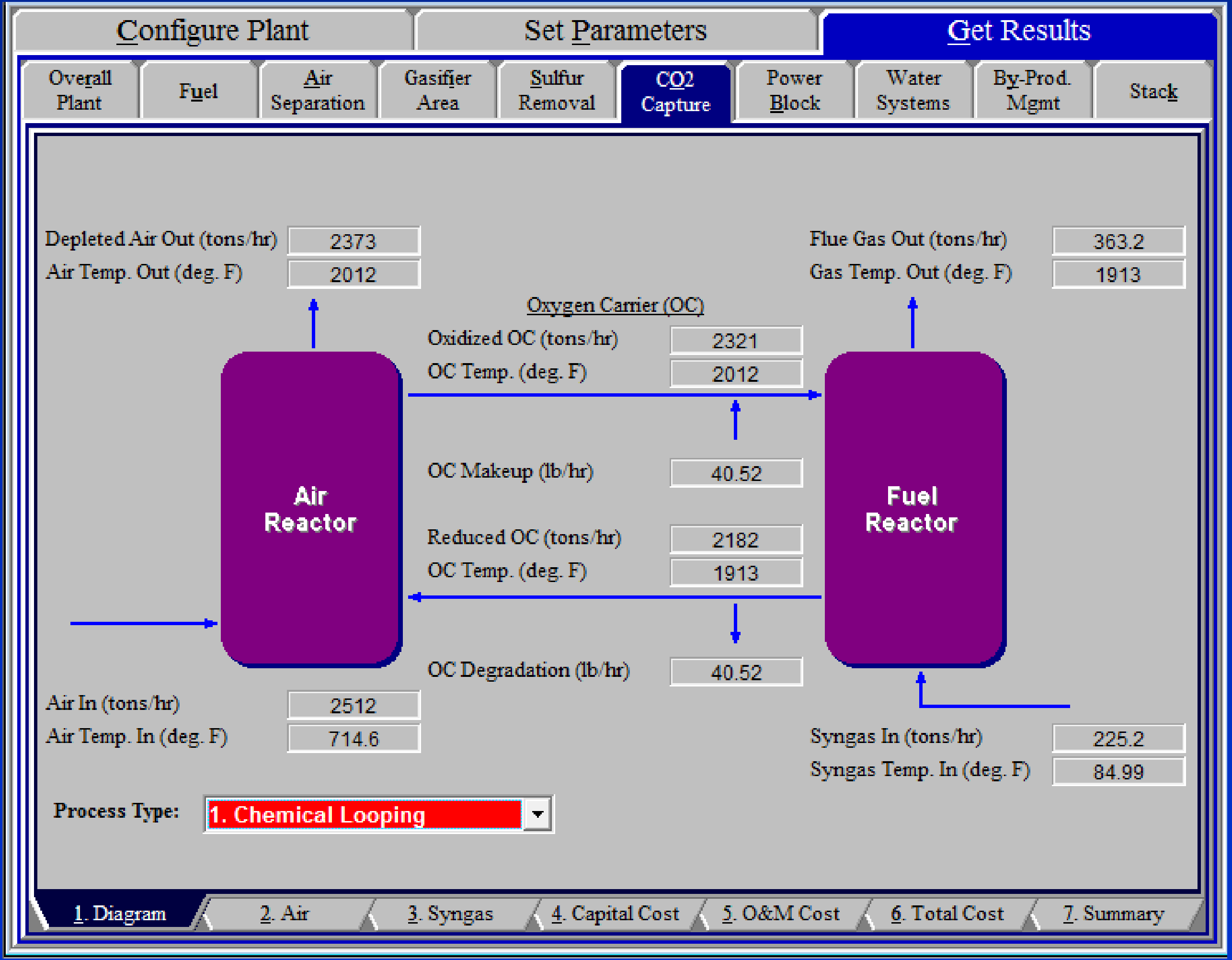
Effect of Membrane Facilities Price on Cost of CO_2 Avoided



New Chemical Looping Capture System Model in IECM



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Some IECM Parameters for the New CLC Capture System Model

Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel | Air Separation | Gasifier Area | Sulfur Removal | CO2 Capture | Power Block | Water Systems | By-Prod. Mgmt | Stack

	Title	Units	Unc	Value	Calc	Min	Max	Default
1	*Air Reactor*							
2	Air Reactor Temperature	deg. F		2012		Menu	Menu	2012
3	Inlet Excess MeO	mol MeO/mol OC		0.3000		0.0	0.9000	0.3000
4	Excess Air Ratio	ratio		3.204	☑	None	None	calc
5	Superficial Gas Inlet Velocity	ft/sec		22.97		16.40	32.81	22.97
6	Residence Time of Solids	seconds		5.000		4.000	10.00	5.000
7	*Fuel Reactor*							
8	Fuel Reactor Temperature	deg. F		1913	☑	None	None	calc
9	Stoichiometric Ratio	mol O2/mol fuel		0.3842	☑	None	None	calc
10	Combustion Efficiency	%		99.22	☑	0.0	100.0	calc
11	Residence Time of Solids	seconds		60.00		50.00	70.00	60.00
12	OC Degradation Rate	%/hr		2.700e-2		0.0	1.000	2.700e-2
13								
14	Maximum Train Diameter	feet		26.25		0.0	52.49	26.25
15	Number of Operating Trains	integer		1	☑	Menu	Menu	Calc
16	Number of Spare Trains	integer		0		Menu	Menu	0
17								
18	CLC Power Requirement	% MWg		9.731	☑	0.0	100.0	calc

Process Type: 1. Chemical Looping

1. Config | 2. Performance | 3. T&S Config | 4. Retrofit Cost | 5. Capital Cost | 6. O&M Cost

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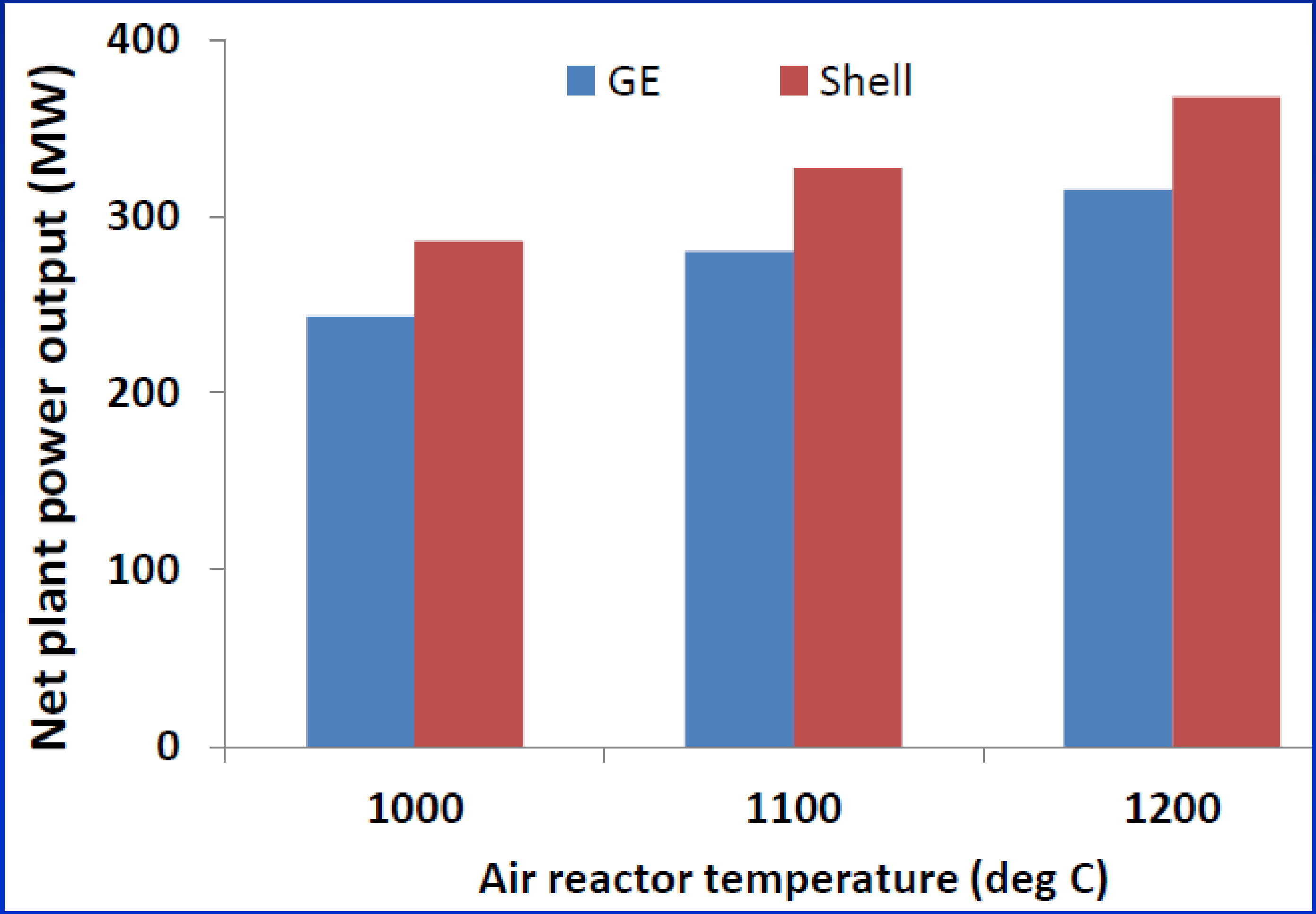
Effect of Air Reactor Temperature on Net Power Output of IGCC Plant



Illustrative Results:
Full Uncertainty Analyses
(Probabilistic Cases)

Two Classes of Research Questions

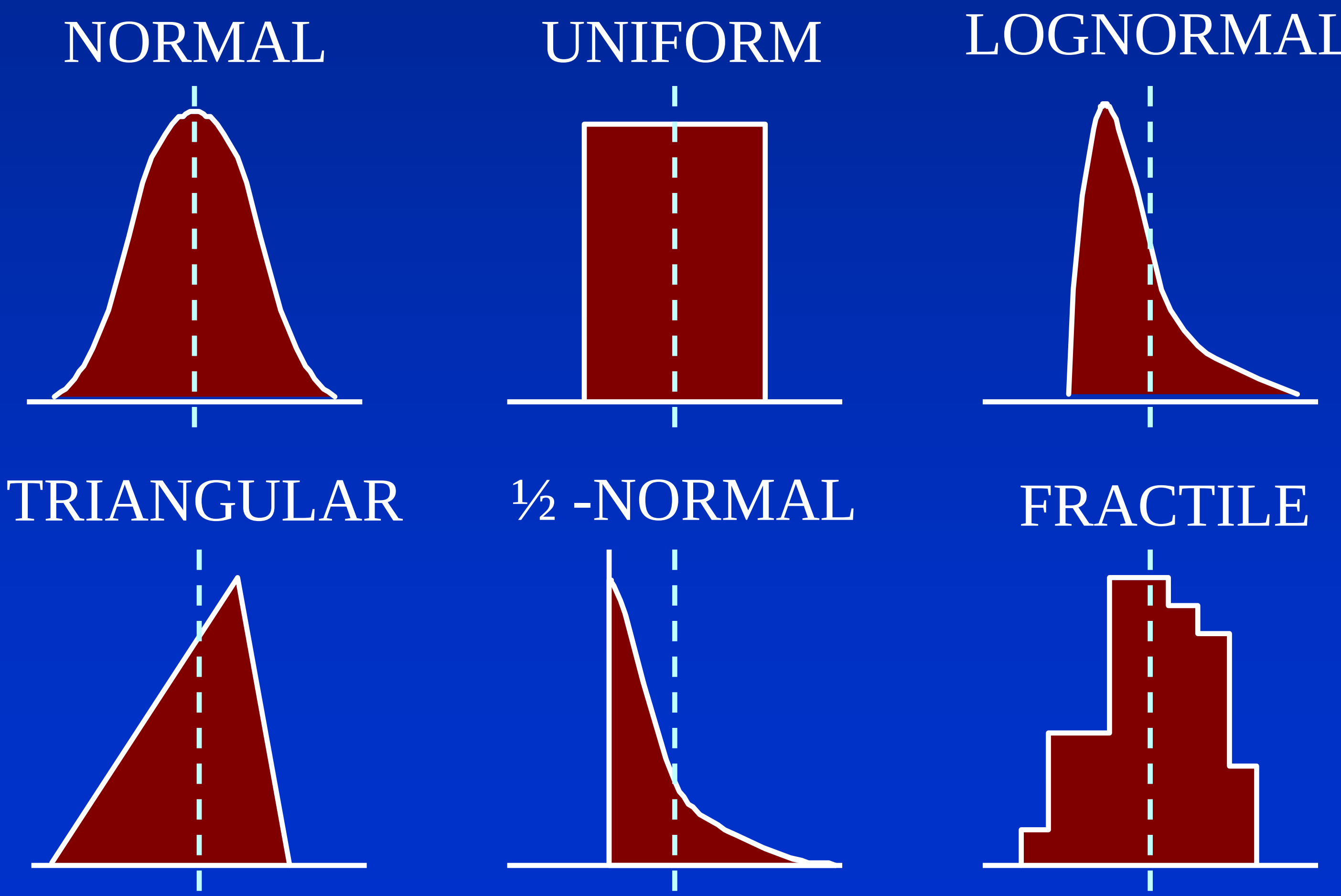
Questions about a particular technology, e.g.:

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

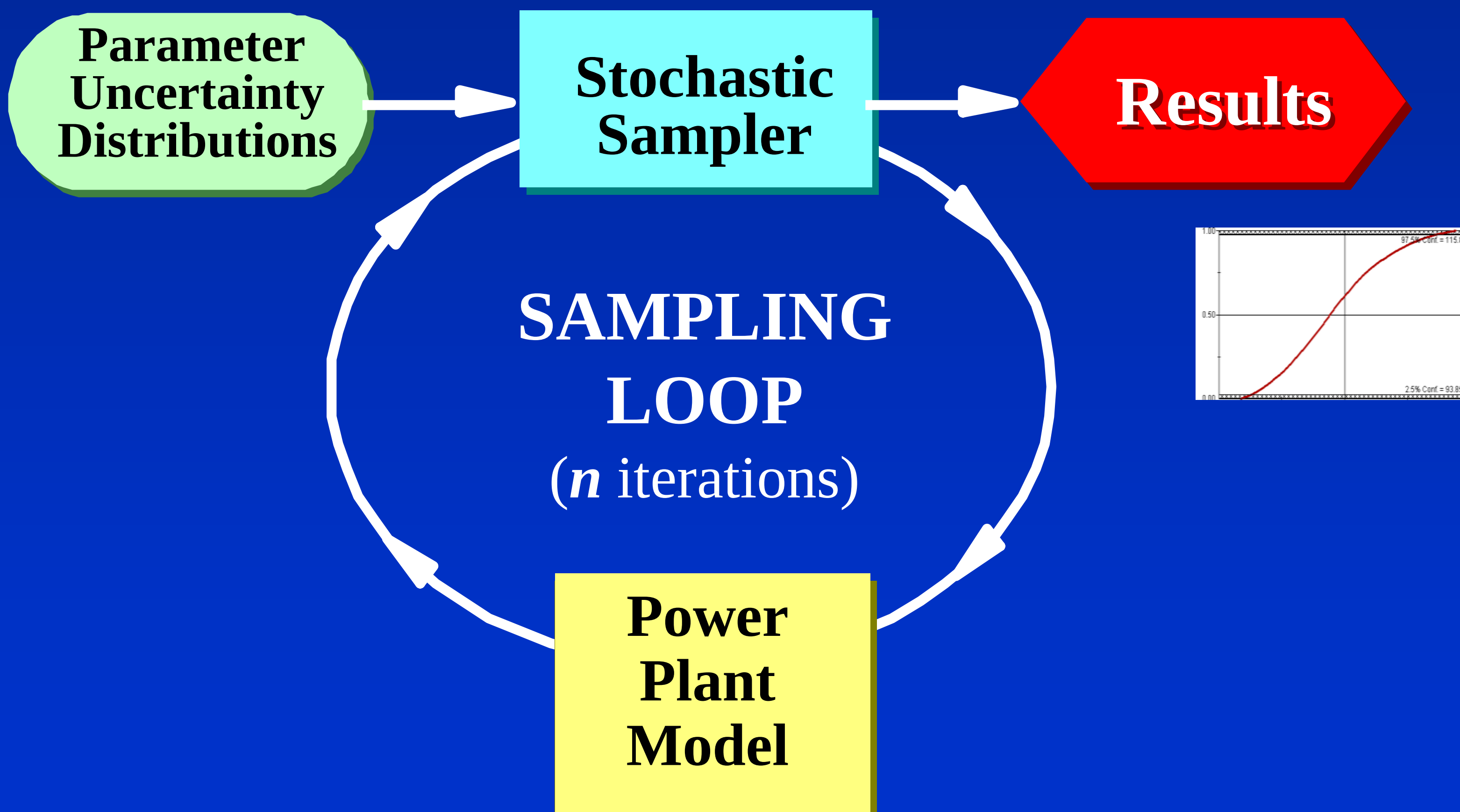
Questions of a comparative nature, e.g.:

- What is the likelihood that Technology A will cost X% less, or perform Y% better, than Technology B in a particular application ?

Examples of IECM Parameter Uncertainty Distributions

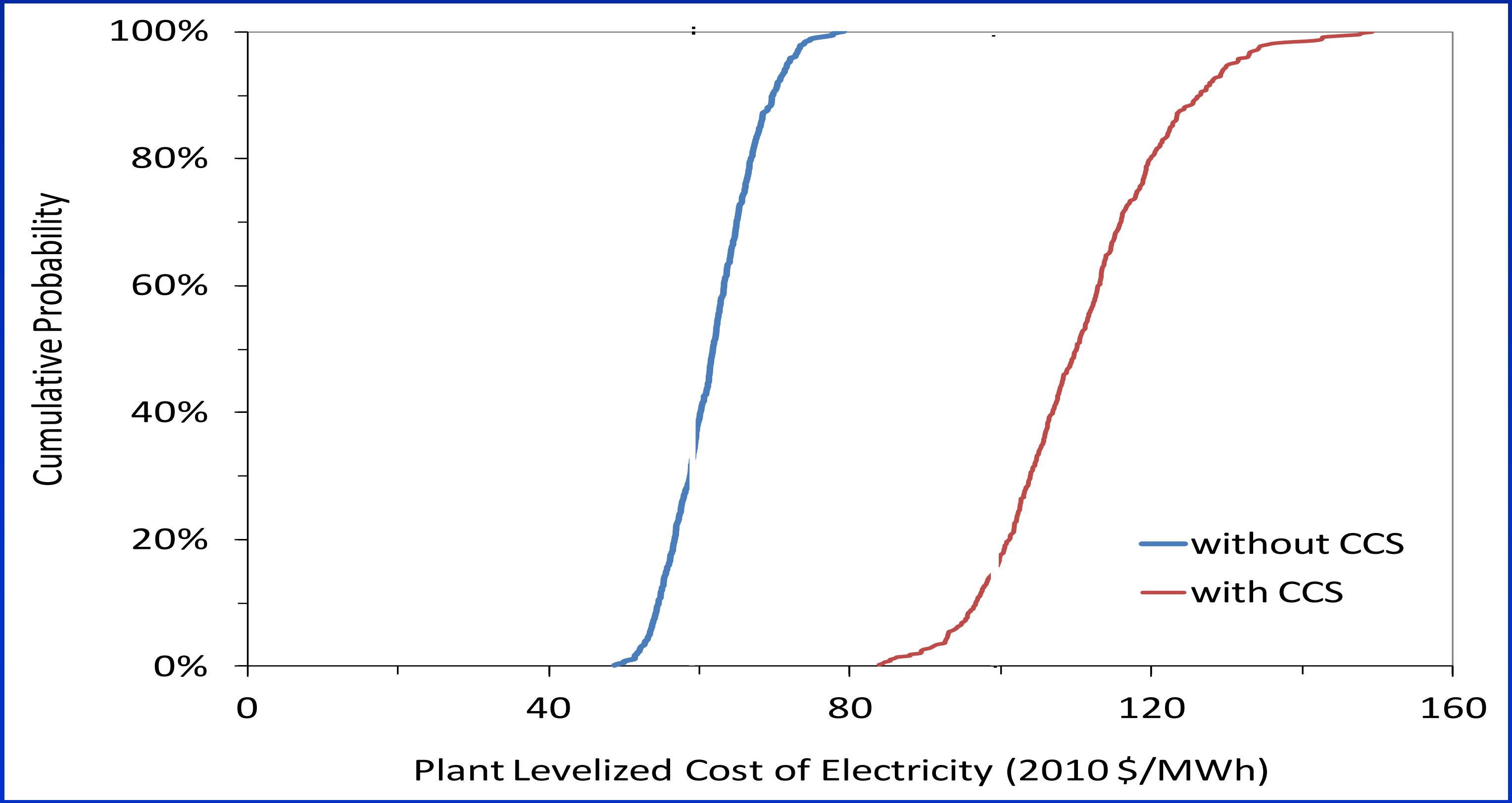


Stochastic Simulation



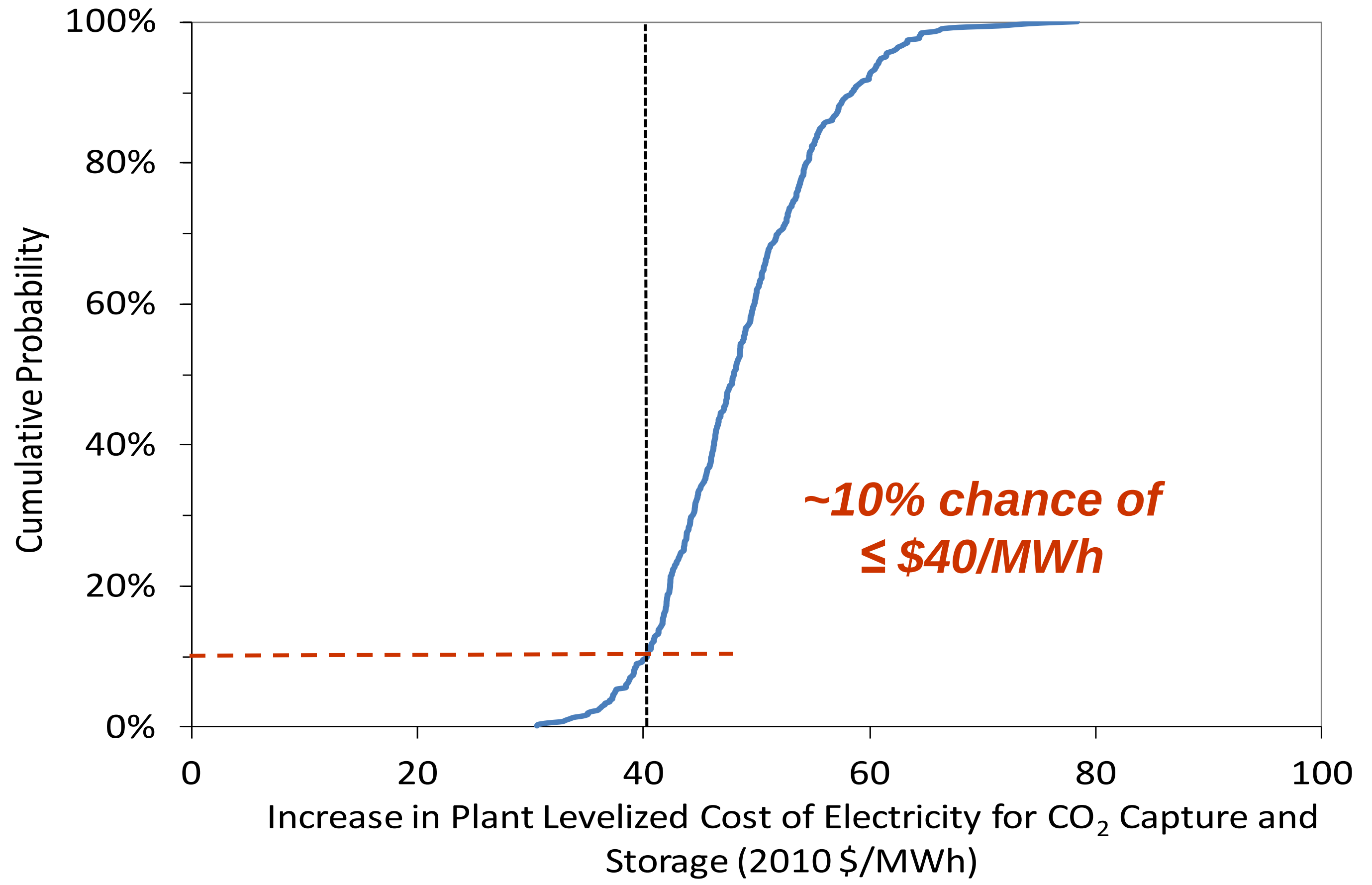
Case Study:
SCPC Plants with and w/o CCS
(13 uncertain parameters specified)

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

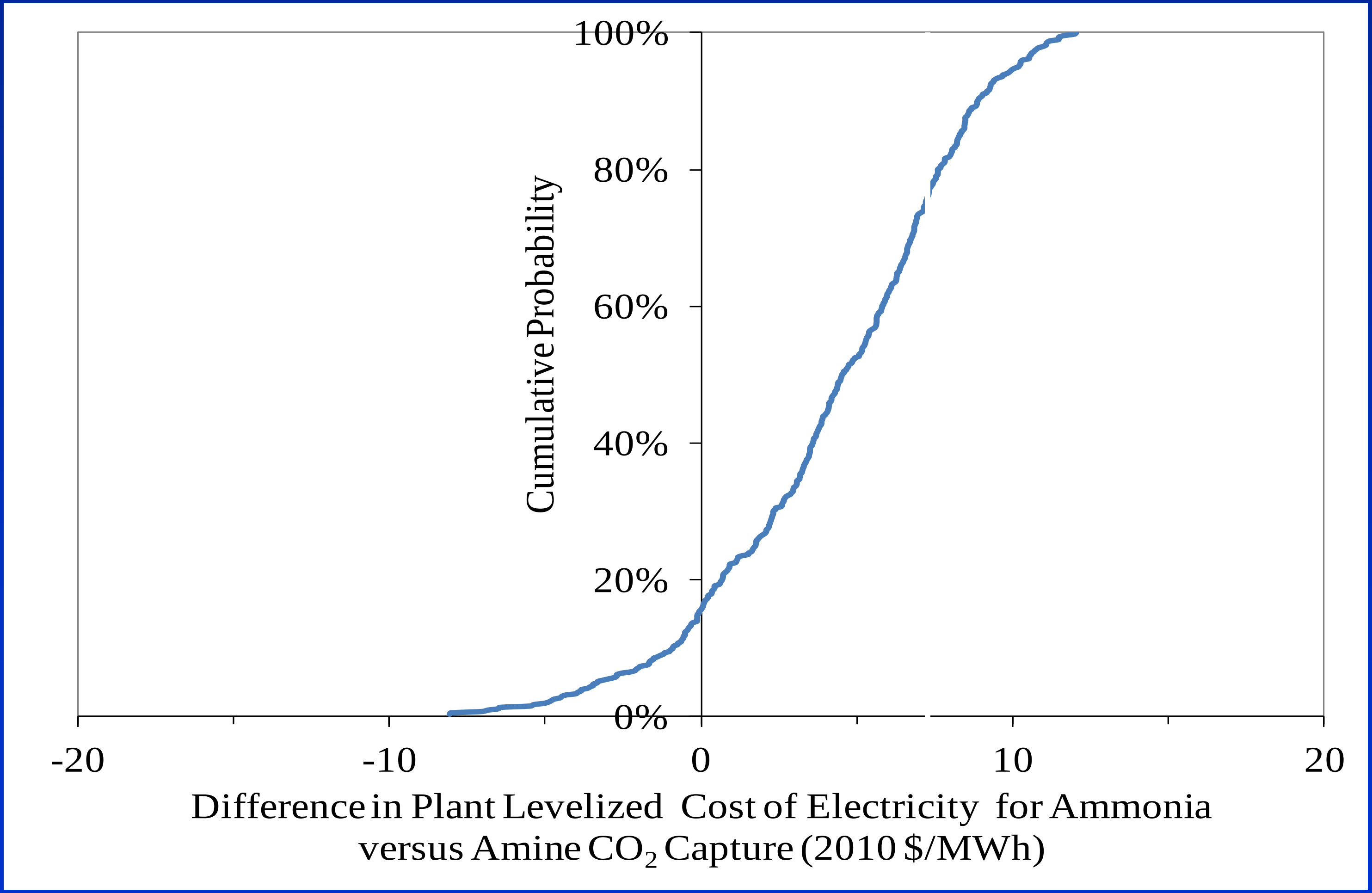


IECM Probabilistic Cost Difference

(accounting for all correlated variables)



Probabilistic Difference in LCOE for Ammonia vs. Amine Capture



Future Work This Year

- Workshop session II for IECM users (today)
  - Intermediate/Advanced; 530p – 730p
- New IECM release this fall with:
  - Final performance and cost models of chilled ammonia process, post-combustion membrane capture, and chemical looping pre-combustion system
  - Other updates and enhancements (e.g., capability for probabilistic *difference* between two uncertain systems)
  - Technical reports and model documentation
- Continued model development, including:
  - Preliminary models for post-combustion solid sorbents, advanced oxy-combustion systems, and post-comb. CLC

Acknowledgments

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  - Jared Ciferno
  - Robert Romanosky
  - Lynn Brickett
  - Chris Guenther
  - Madhava Syamlal

Thank You

rubin@cmu.edu