CCSI

Carbon Capture Simulation Initiative

Risk-Based Cost Methods

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Carbon Capture Challenge

- The **traditional pathway** from discovery to commercialization of energy technologies is long[1], i.e., ~ 20-30 years.
- Technology innovation increases the cost growth, schedule slippage, and the probability of operational problems.[2]
- President's plan[3] requires that barriers to the widespread, safe, and cost-effective deployment of CCS be overcome within 10 years.
- To help realize the President's objectives, new approaches are needed for taking concepts from lab to power plant, quickly, at low cost and with minimal risk.

Bench Research ~ 1 kWe

Small pilot < 1 MWe

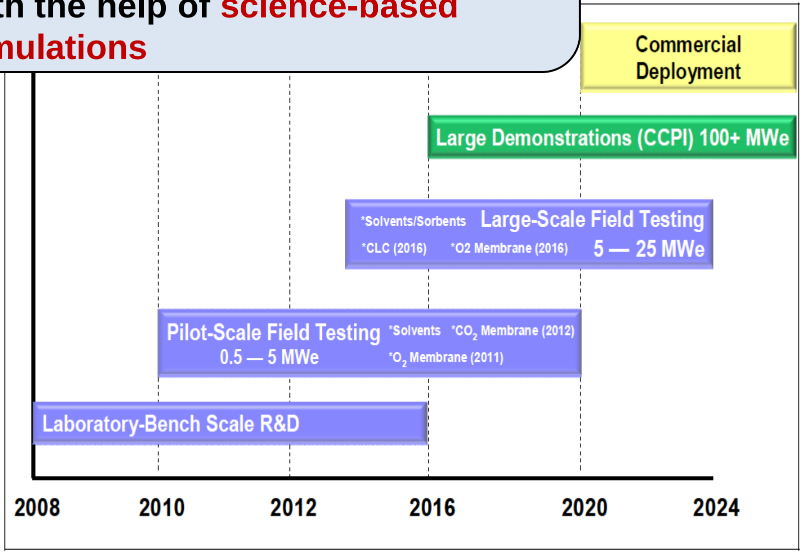
Medium pilot 1 – 5 MWe

Semi-works pilot 20-35 MWe

First commercial plant, 100 MWe

Deployment, >500 MWe, >300 plants

CCSI will accelerate the development of CCS technology, from discovery through deployment, with the help of science-based simulations



Source: Ciferno, "DOE/NETLs Existing Plants."

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1. International Energy Agency Report: Experience Curves for Energy Technology Policy," 2000
2. RAND Report: "Understanding the Outcomes of Mega-Projects," 1988;
3. http://www.whitehouse.gov/the-press-office/presidentialmemorandum-a-comprehensive-federal-strategy-carbon-capture-and-storage

For Accelerating Technology Development

Identify promising concepts → Reduce the time for design & troubleshooting → Quantify the technical risk, to enable reaching larger scales, earlier → Stabilize the cost during commercial deployment

National Labs

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Academia

Carnegie Mellon

Princeton University

West Virginia University

Boston University

The University of Texas at Austin

Industry

ADA Environmental Solutions

ALSTOM

B&W thebabcock&wilcoxcompany

GE

EPRI Electric Power Research Institute

Southern California Edison An Edison International Company San Onofre Nuclear Generating Station

FLUOR

Southern Company

Phillips 66

AEP American Electric Power

Chevron

ExxonMobil

URS

Air Products

Eastman

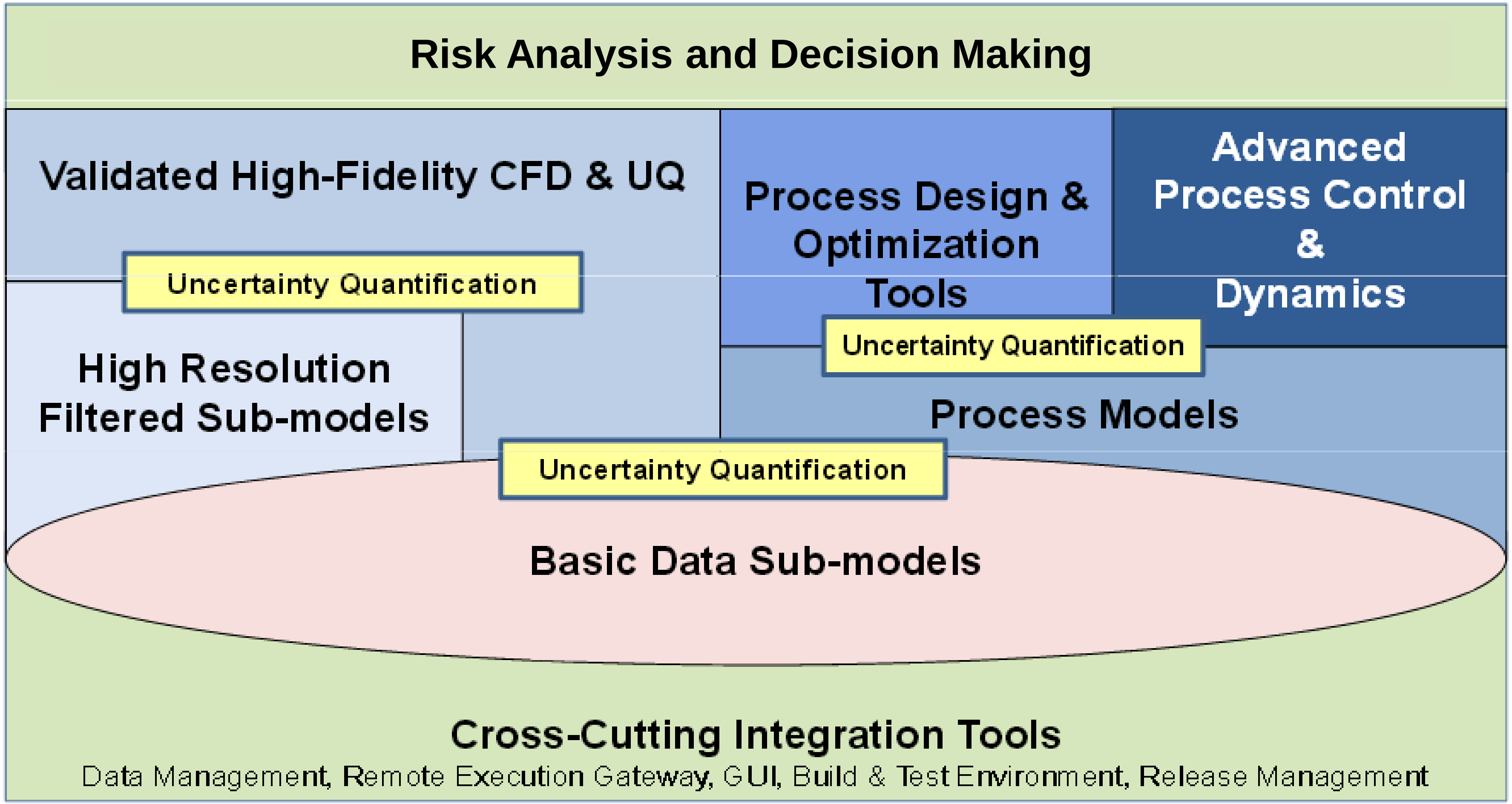
ANSYS

PSE

aspentech

invensys

Advanced Computational Tools to Accelerate Next Generation Technology Development


Risk Analysis and Decision Making

Validated High-Fidelity CFD & UQ

Uncertainty Quantification

High Resolution Filtered Sub-models

Process Design & Optimization Tools

Advanced Process Control & Dynamics

Uncertainty Quantification

Process Models

Uncertainty Quantification

Basic Data Sub-models

Cross-Cutting Integration Tools

Data Management, Remote Execution Gateway, GUI, Build & Test Environment, Release Management

CCSI Carbon Capture Simulation Initiative

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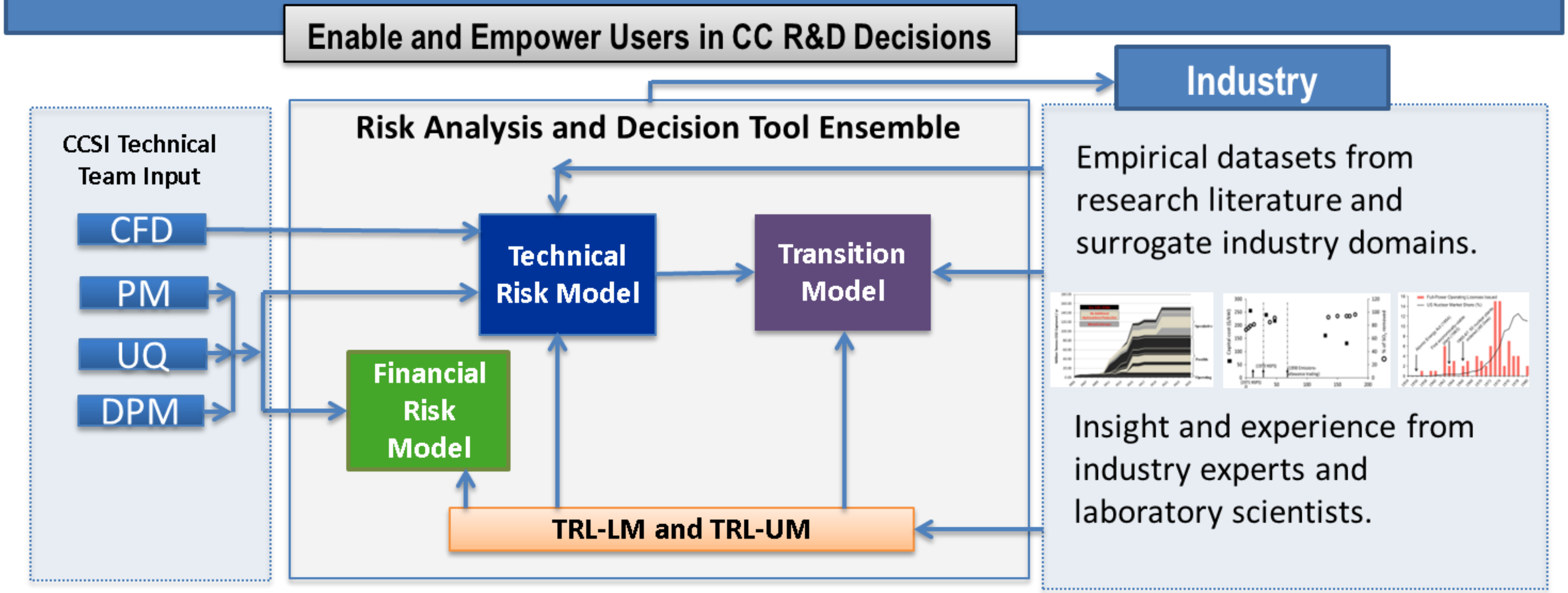
Risk Analysis Role in Facilitating Acceleration

Risk Analysis Role in Facilitating Acceleration

Enable industry users to incorporate their current state of knowledge, resources, and capabilities into the Risk Analysis and Decision Making Tool Ensemble to make sound judgment about R&D directions—moving along the TRL scales or skipping scales—with confidence and resolve, without comprising system reliability, maintainability, and supportability objectives.



Enable and Empower Users in CC R&D Decisions

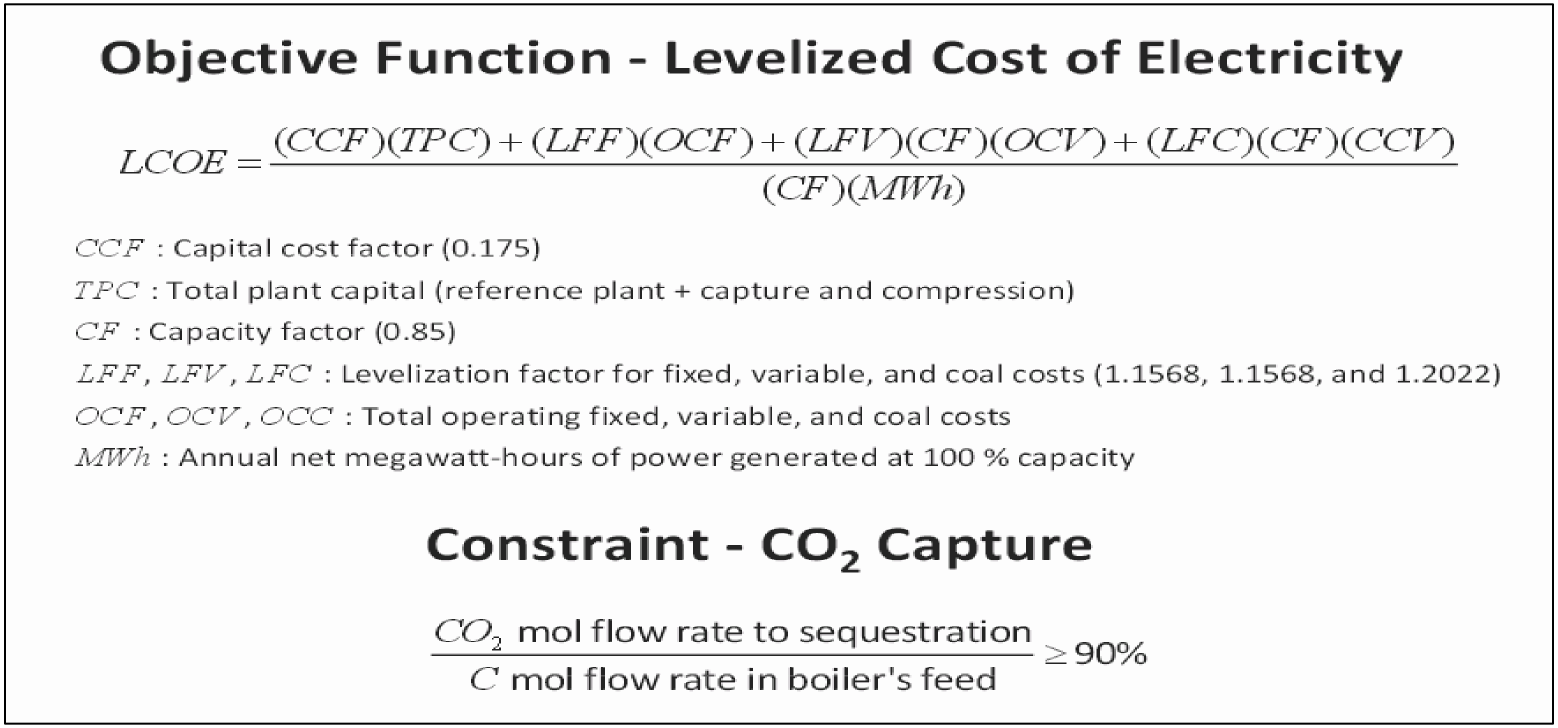
Empirical datasets from research literature and surrogate industry domains.

Insight and experience from industry experts and laboratory scientists.

Development Roadmap and Value to End Users

Process Modeling and Optimization
Cost Model

Cost is calculated using an optimized steady-state system process model (Aspen plus) as shown below:



Objective Function - Levelized Cost of Electricity

$$LCOE = \frac{(CCF)(TPC) + (LFF)(OCF) + (LFV)(CF)(OCV) + (LFC)(CF)(CCV)}{(CF)(MWh)}$$

CCF : Capital cost factor (0.175)

TPC : Total plant capital (reference plant + capture and compression)

CF : Capacity factor (0.85)

LFF, LFV, LFC : Levelization factor for fixed, variable, and coal costs (1.1568, 1.1568, and 1.2022)

OCF, OCV, OCC : Total operating fixed, variable, and coal costs

MWh : Annual net megawatt-hours of power generated at 100 % capacity

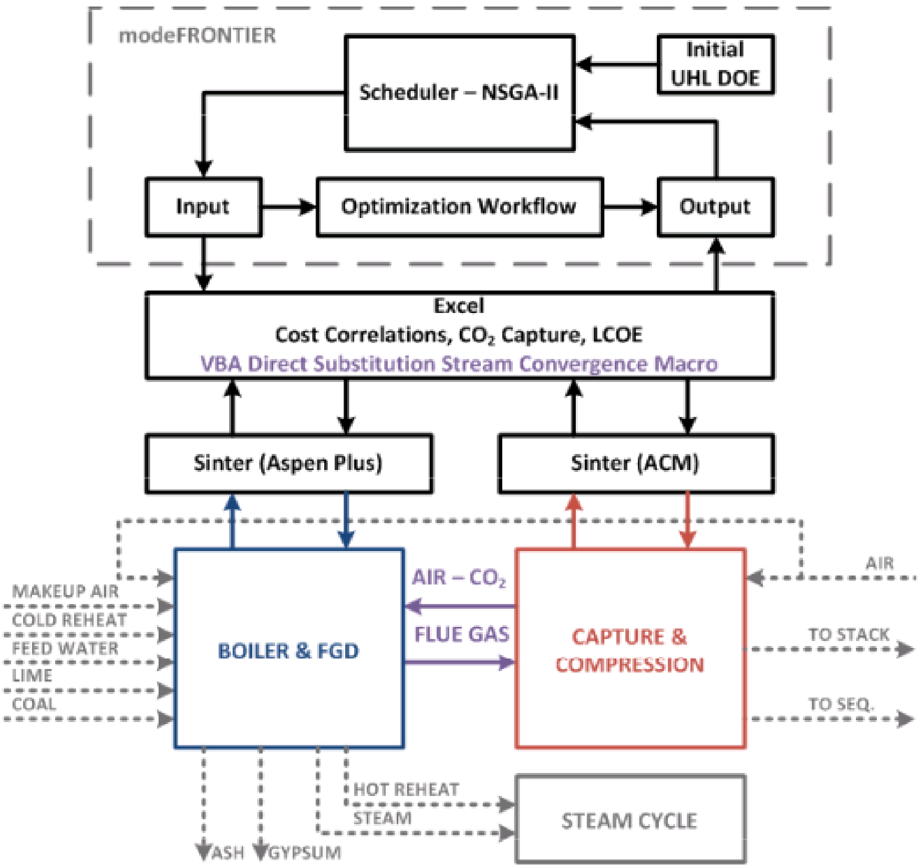
Constraint - CO_2 Capture

$$\frac{CO_2 \text{ mol flow rate to sequestration}}{C \text{ mol flow rate in boiler's feed}} \geq 90\%$$

Cost is then passed to the Risk Analysis models for use in the Financial Risk Model

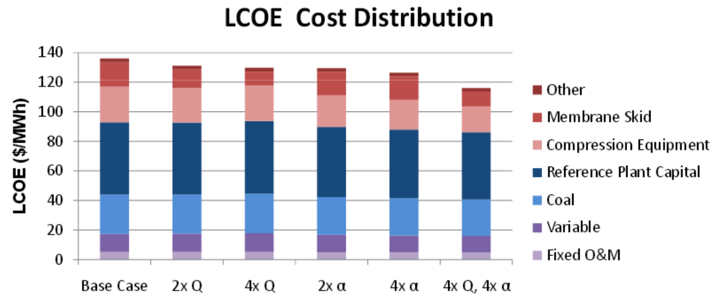
Process Modeling and Optimization Cost Model

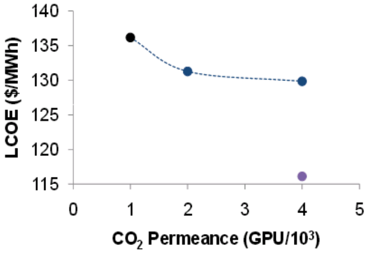
Modular Framework
Retrofit to a 550 MW Subcrital PC Plant

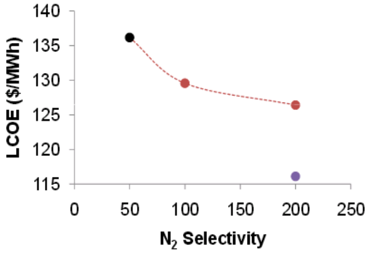


Sample Results

	Typical	Base Case	2x *Q*	4x *Q*	2x α	4x α	4x *Q*,4x α
CO_2 Permeance (GPU)	10-10000†	1000‡	2000	4000	1000	1000	4000
Ar Selectivity	N/A	20	20	20	40	80	80
H_2O Selectivity	<1	0.5	0.5	0.5	0.5	0.5	0.5
N_2 Selectivity	4-150†	50‡	50	50	100	200	200
O_2 Selectivity	N/A	20	20	20	40	80	80
LCOE ($/MWh)	N/A	**136**	**131**	**130**	**130**	**126**	**116**
LCOE inc Reference Plant (%)	N/A	**113**	**105**	**103**	**103**	**97**	**81**

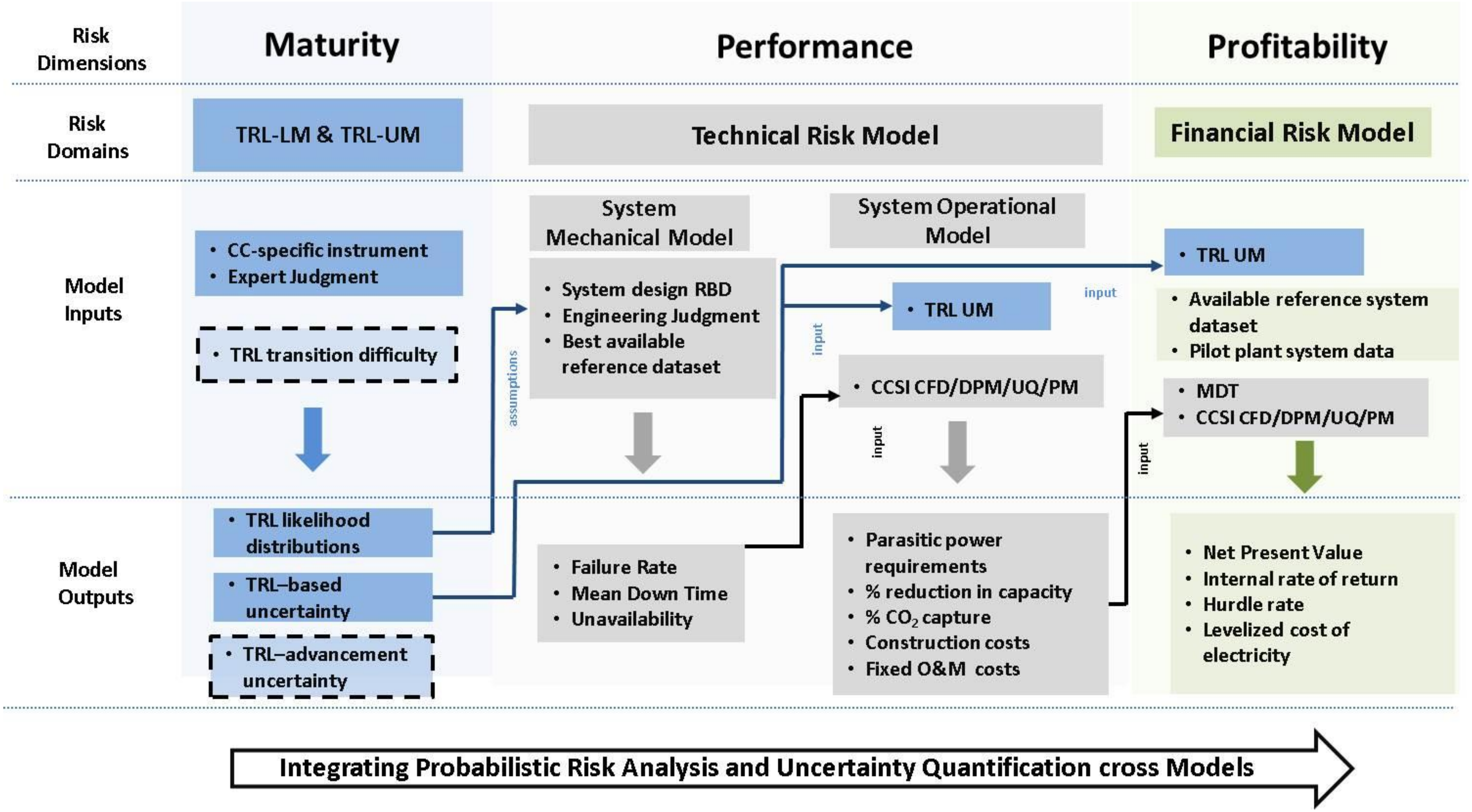






Result (units)	Base Case	2x *Q*	4x *Q*	2x α	4x α	4x *Q*,4x α
Relative vol. increase of FG (%)	16	18	21	12	11	13
Makeup air ($m^3/hr/10^3$)	83	112	163	52	36	68
Oxygen depletion (%)	2.8	4.1	6.9	1.3	0.7	2.2
FG CO_2 concentration (mol%)	17	17	17	18	18	18
Membrane area ($m^2/10^6$)	1.13	0.85	0.64	1.14	1.16	0.75
Membrane skid cost ($\$/10^6$)	57	43	32	57	58	36
Compression eq. cost ($\$/10^6$)	83	81	82	75	72	64
Net Output (MW)	409	411	407	422	430	440

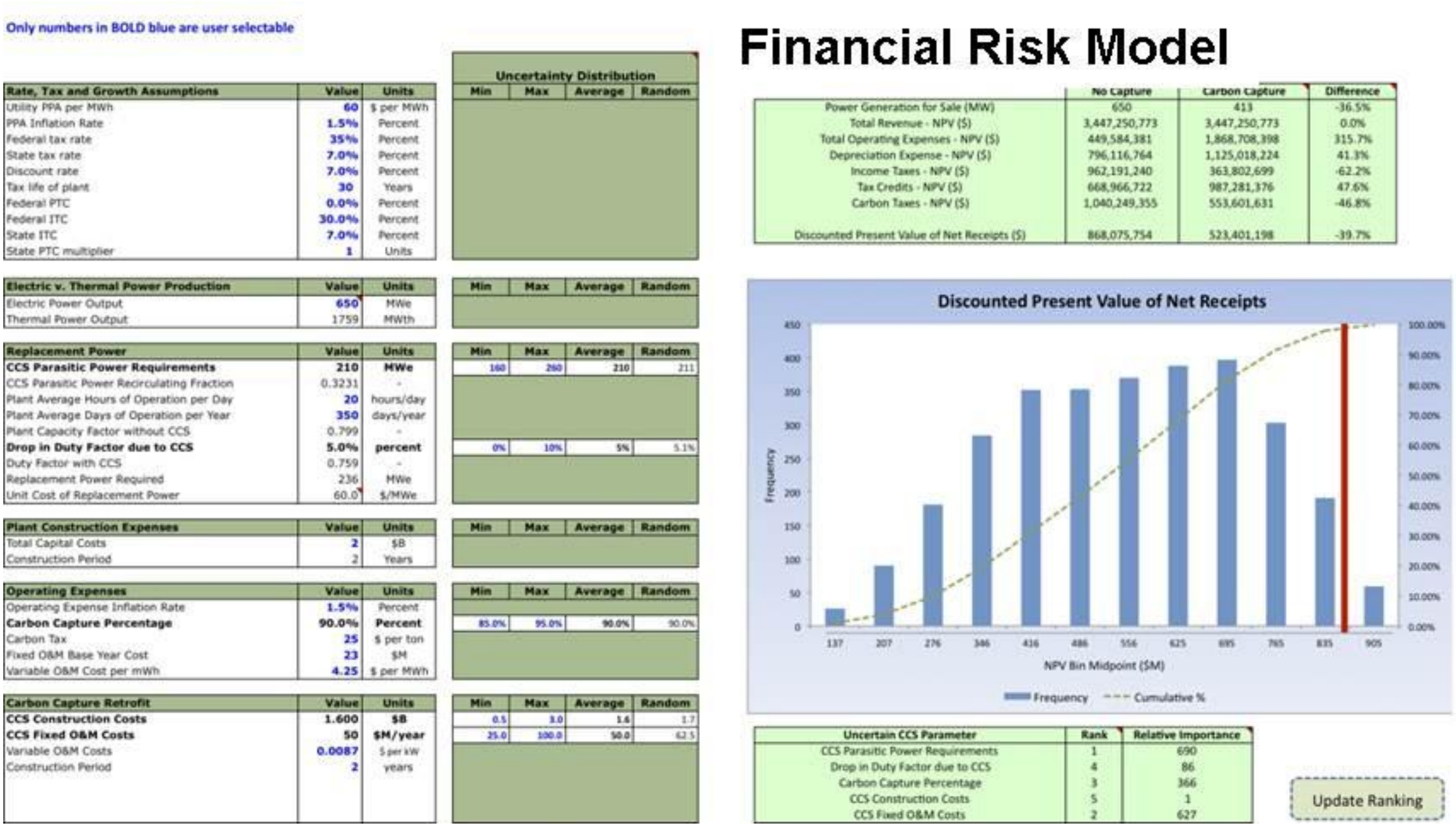
Coupled CCSI Risk Analysis and Decision-Making Framework



Risk Dimensions	Maturity	Performance		Profitability
Risk Domains	TRL-LM & TRL-UM	Technical Risk Model		Financial Risk Model
Model Inputs	• CC-specific instrument • Expert Judgment • TRL transition difficulty	System Mechanical Model • System design RBD • Engineering Judgment • Best available reference dataset	System Operational Model • TRL UM • CCSI CFD/DPM/UQ/PM	• TRL UM • Available reference system dataset • Pilot plant system data • MDT • CCSI CFD/DPM/UQ/PM
Model Outputs	• TRL likelihood distributions • TRL–based uncertainty • TRL–advancement uncertainty	• Failure Rate • Mean Down Time • Unavailability	• Parasitic power requirements • % reduction in capacity • % CO_2 capture • Construction costs • Fixed O&M costs	• Net Present Value • Internal rate of return • Hurdle rate • Levelized cost of electricity

Integrating Probabilistic Risk Analysis and Uncertainty Quantification cross Models

Financial Risk Model



Only numbers in BOLD blue are user selectable

			Uncertainty Distribution			
Rate, Tax and Growth Assumptions	**Value**	**Units**	**Min**	**Max**	**Average**	**Random**
Utility PPA per MWh	**60**	$ per MWh				
PPA Inflation Rate	**1.5%**	Percent				
Federal tax rate	**35%**	Percent				
State tax rate	**7.0%**	Percent				
Discount rate	**7.0%**	Percent				
Tax life of plant	**30**	Years				
Federal PTC	**0.0%**	Percent				
Federal ITC	**30.0%**	Percent				
State ITC	**7.0%**	Percent				
State PTC multiplier	**1**	Units				

Electric v. Thermal Power Production	**Value**	**Units**	**Min**	**Max**	**Average**	**Random**
Electric Power Output	**650**	MWe				
Thermal Power Output	1759	MWth				

Replacement Power	**Value**	**Units**	**Min**	**Max**	**Average**	**Random**
CCS Parasitic Power Requirements	**210**	**MWe**	160	260	210	211
CCS Parasitic Power Recirculating Fraction	0.3231	-				
Plant Average Hours of Operation per Day	**20**	hours/day				
Plant Average Days of Operation per Year	**350**	days/year				
Plant Capacity Factor without CCS	0.799	-				
Drop in Duty Factor due to CCS	**5.0%**	**percent**	0%	10%	5%	5.1%
Duty Factor with CCS	0.759	-				
Replacement Power Required	236	MWe				
Unit Cost of Replacement Power	60.0	$/MWe				

Plant Construction Expenses	**Value**	**Units**	**Min**	**Max**	**Average**	**Random**
Total Capital Costs	**2**	$B				
Construction Period	2	Years				

Operating Expenses	**Value**	**Units**	**Min**	**Max**	**Average**	**Random**
Operating Expense Inflation Rate	**1.5%**	Percent				
Carbon Capture Percentage	**90.0%**	**Percent**	85.0%	95.0%	90.0%	90.0%
Carbon Tax	**25**	$ per ton				
Fixed O&M Base Year Cost	**23**	$M				
Variable O&M Cost per mWh	**4.25**	$ per MWh				

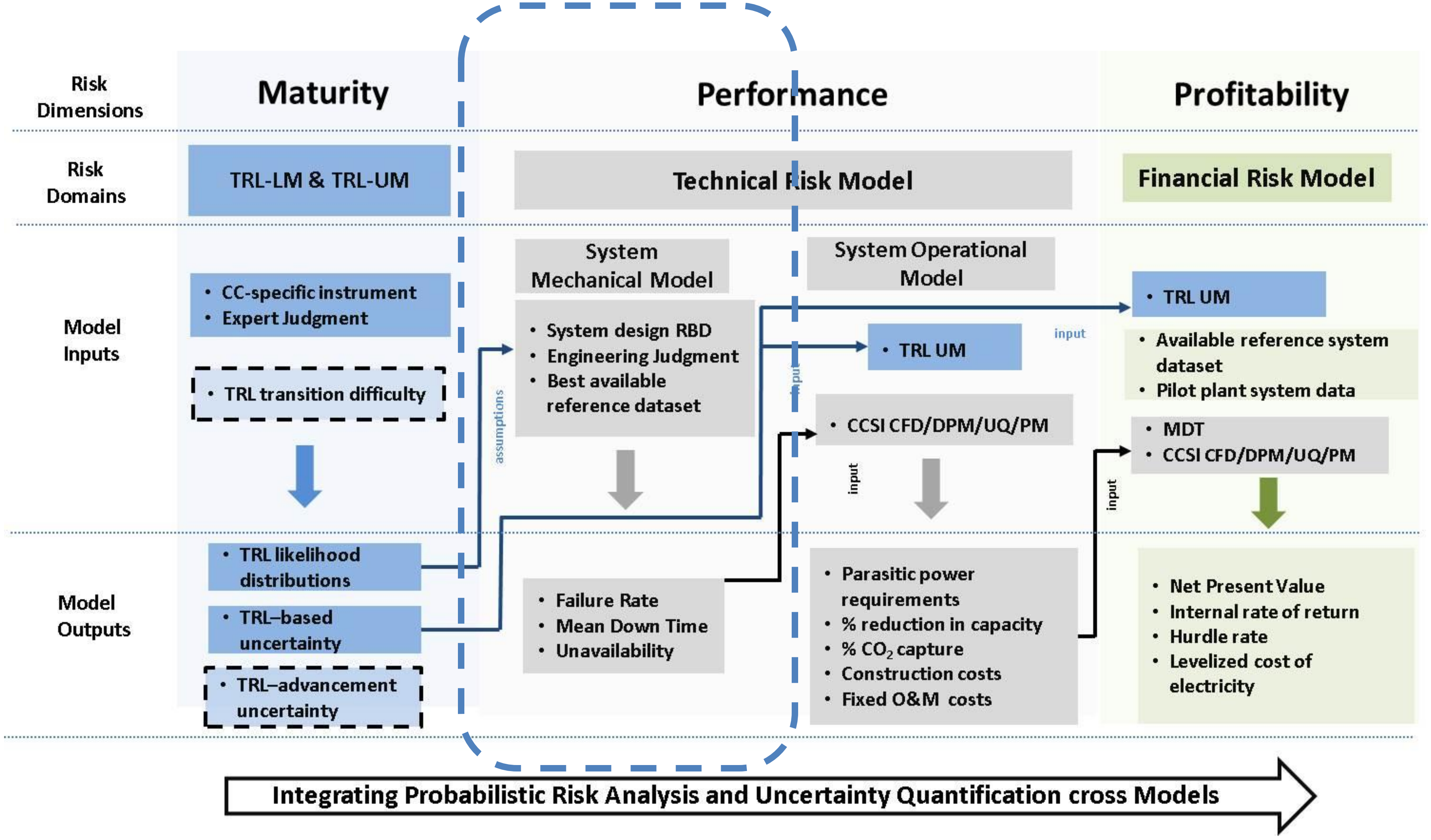
Carbon Capture Retrofit	**Value**	**Units**	**Min**	**Max**	**Average**	**Random**
CCS Construction Costs	**1.600**	**$B**	0.5	3.0	1.6	1.7
CCS Fixed O&M Costs	**50**	**$M/year**	25.0	100.0	50.0	62.5
Variable O&M Costs	**0.0087**	$ per kW				
Construction Period	**2**	years				

Financial Risk Model

	No Capture	Carbon Capture	Difference
Power Generation for Sale (MW)	650	413	-36.5%
Total Revenue - NPV ($)	3,447,250,773	3,447,250,773	0.0%
Total Operating Expenses - NPV ($)	449,584,381	1,868,708,398	315.7%
Depreciation Expense - NPV ($)	796,116,764	1,125,018,224	41.3%
Income Taxes - NPV ($)	962,191,240	363,802,699	-62.2%
Tax Credits - NPV ($)	668,966,722	987,281,376	47.6%
Carbon Taxes - NPV ($)	1,040,249,355	553,601,631	-46.8%
Discounted Present Value of Net Receipts ($)	868,075,754	523,401,198	-39.7%

Discounted Present Value of Net Receipts

Uncertain CCS Parameter	Rank	Relative Importance
CCS Parasitic Power Requirements	1	690
Drop in Duty Factor due to CCS	4	86
Carbon Capture Percentage	3	366
CCS Construction Costs	5	1
CCS Fixed O&M Costs	2	627



Risk Dimensions

- Maturity
- Performance
- Profitability

Risk Domains

- TRL-LM & TRL-UM
- Technical Risk Model
- Financial Risk Model

Model Inputs

Maturity:

- CC-specific instrument
- Expert Judgment
- TRL transition difficulty

System Mechanical Model

- System design RBD
- Engineering Judgment
- Best available reference dataset

System Operational Model

- TRL UM
- CCSI CFD/DPM/UQ/PM

Profitability:

- TRL UM
- Available reference system dataset
- Pilot plant system data
- MDT
- CCSI CFD/DPM/UQ/PM

assumptions

input

input

input

input

Model Outputs

Maturity:

- TRL likelihood distributions
- TRL–based uncertainty
- TRL–advancement uncertainty

System Mechanical Model:

- Failure Rate
- Mean Down Time
- Unavailability

System Operational Model:

- Parasitic power requirements
- % reduction in capacity
- % CO_2 capture
- Construction costs
- Fixed O&M costs

Profitability:

- Net Present Value
- Internal rate of return
- Hurdle rate
- Levelized cost of electricity

Integrating Probabilistic Risk Analysis and Uncertainty Quantification cross Models

Technical Risk
System Mechanical Model

- Application based on a prototype hybrid solid sorbent system
- A series of RBD describes the system as interconnected functional blocks; failure of any block prevents the operation of the system.
- The estimation of failure rate and MDT of each component /function block allows a calculation of MTBF, MDT, and U for any components, blocks, combinations of blocks, or for the whole system.

$$U_s = \frac{\sum_i \lambda_i MDT_i}{1 + \sum_i \lambda_i MDT_i}$$

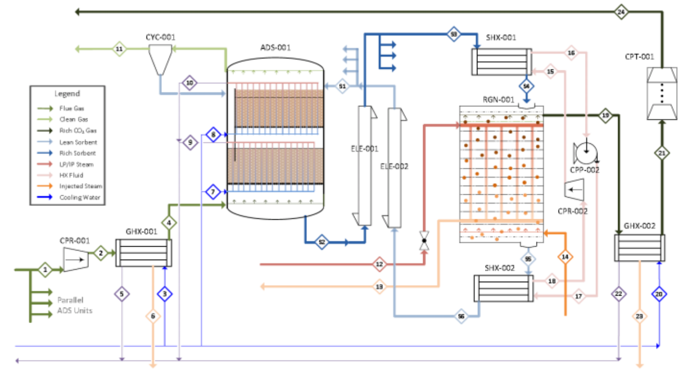


Figure A.1 Process Flow Diagram (Lee *et al.* 2012, p. 16)

Prepare Flue Gas

- Flue gas composition
- Compressor
- Gas heat exchanger
- Gas piping (3)
- Gas valves (2)
- Gas valve controller(2)
- Water pump
- Water piping (3)
- Water valves (3)
- Water controller (2)

Adsorb CO_2 from Flue Gas by Sorbent (Adsorber)

- Cooling water piping (3)
- Water valves (3)
- Water valve controller (3)
- Water pump
- Flue gas pipe/inlet
- Gas valve
- Gas valve controller
- Clean gas pipe/outlet
- Clean gas valve
- Clean gas controller
- Cyclone unit and fines return
- Sorbent in and out:
  -piping (2)
  -valves (2)
  -level controllers (2)
- Upper HX
- Lower HX
- Passive mechanical structures (failure modes:

Sorbent Transport – Pneumatic System

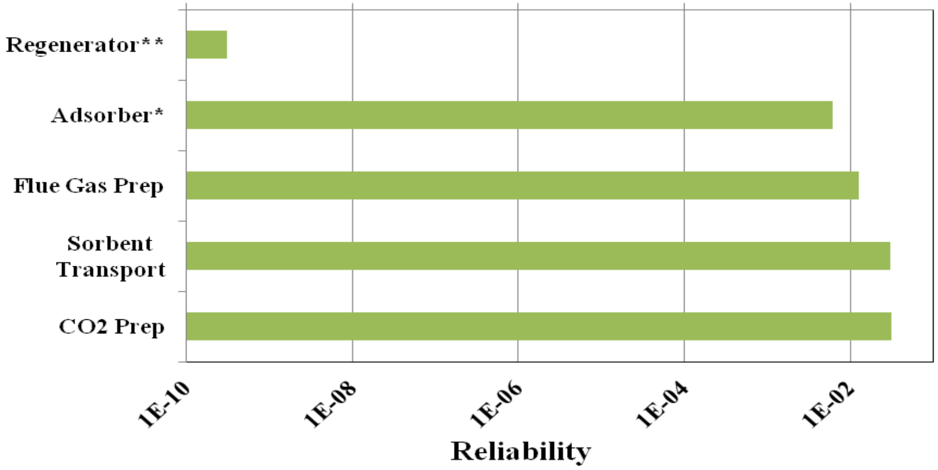
- Sorbent piping (4)
- Sorbent valve (4)
- Sorbent valve controller(4)
- Transport gas piping (4)
- Gas valve (2)
- Gas valve controller (2)
- Compressor (2)
- Air cooler (2)
- Pneumatic pipe (solids and gas) (2)
- Sorbent collection hoppers (2)

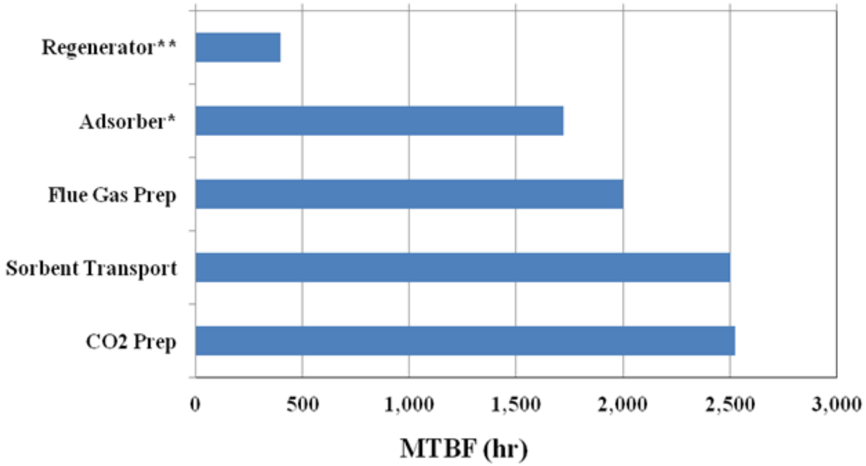
Desorption of CO_2 from Sorbent (Regenerator)

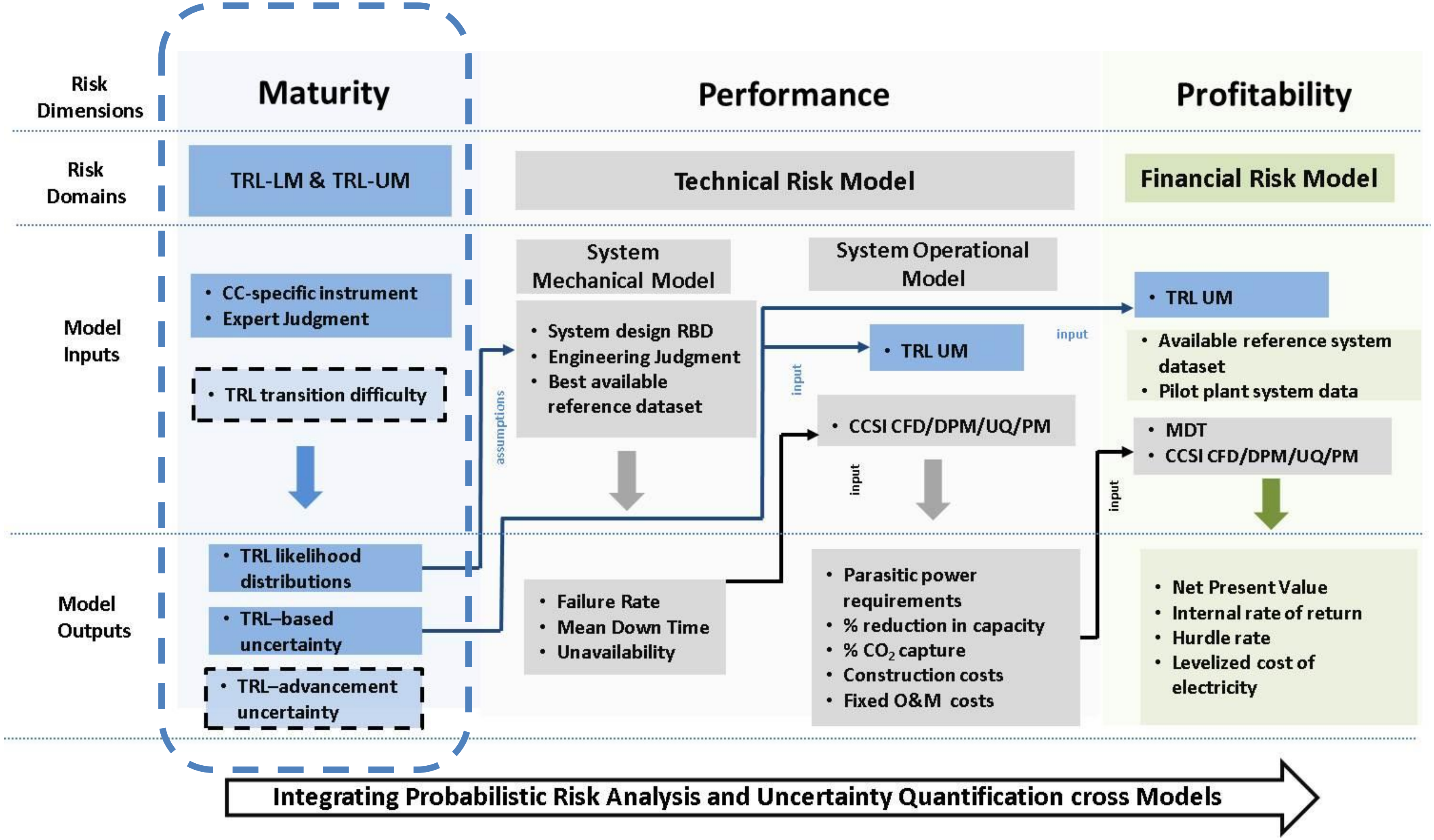
- Sorbent in and out:
  -piping (4)
  -valves (4)
  -level controllers (4)
- Solid heat exchangers (2)
- Compressor
- Centrifugal pump
- Temperature controller
- Plant hot steam:
  -piping (2)
  -valves(2)
  -level controllers (2)
- Mild steam:
  -piping (2)
  -valve
  -valve controller
  -blower
- Solid HX fluid (steam/ water)
  -piping(4)

Prepare CO_2 for Compression Train

- Product CO_2 gas collector
- Gas piping (2)
- Gas valve (2)
- Gas valve controller (2)
- Gas heat exchanger
- Cooling water pump
- Water piping (2)
- Water valve (2)
- Water level controller (2)







Risk Dimensions

Maturity

Performance

Profitability

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TRL-LM & TRL-UM

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Financial Risk Model

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- Expert Judgment

- TRL transition difficulty

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- TRL UM

- Available reference system dataset
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- TRL likelihood distributions
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- Failure Rate
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- Parasitic power requirements
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- % CO_2 capture
- Construction costs
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- Net Present Value
- Internal rate of return
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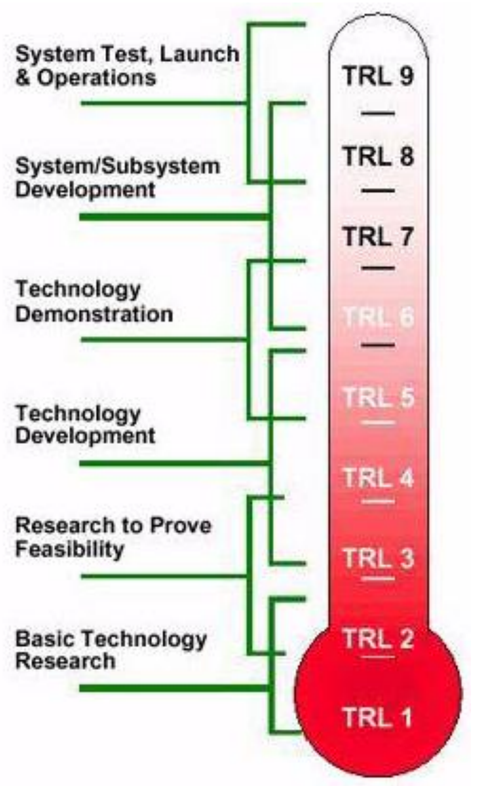
Integrating Probabilistic Risk Analysis and Uncertainty Quantification cross Models

Maturity Modeling: Technology Readiness Level

Major Objectives of Risk Analysis and Decision Making

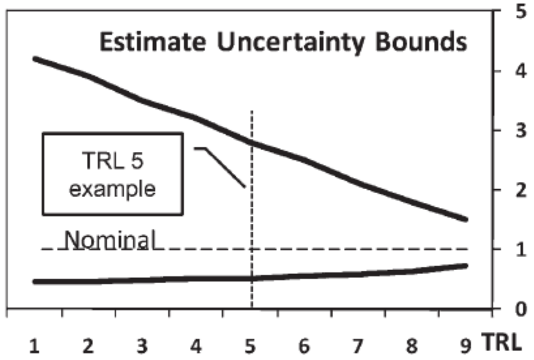
1. Formulate risk acceptance metrics and processes relevant to capital investors and other stakeholders that can be integrated into the simulation framework (CCSI Objective 3)
2. Provide connectivity between plant-cost scaling factors for each technology option and economic market influences such as finite resources of specialized labor and materials (CCSI Objective 1)
3. Combine technical risk and financial risk factors into an integrated decision analysis framework that naturally handles propagation of uncertainties into a variety of decision metrics (CCSI Objective 1 & 3)



Technology Readiness Level (TRL)

Measure used to assess the maturity of evolving technologies prior to incorporating the technology into a system/subsystem (Mankins, 1995, NASA). The qualitative TRL can be used to roughly estimate the uncertainty bounds in a comparison of technologies (Mathews, 2010). This methodology will be used to help quantify technical risks and used to accomplish Risk Analysis Objectives 2 and 3.

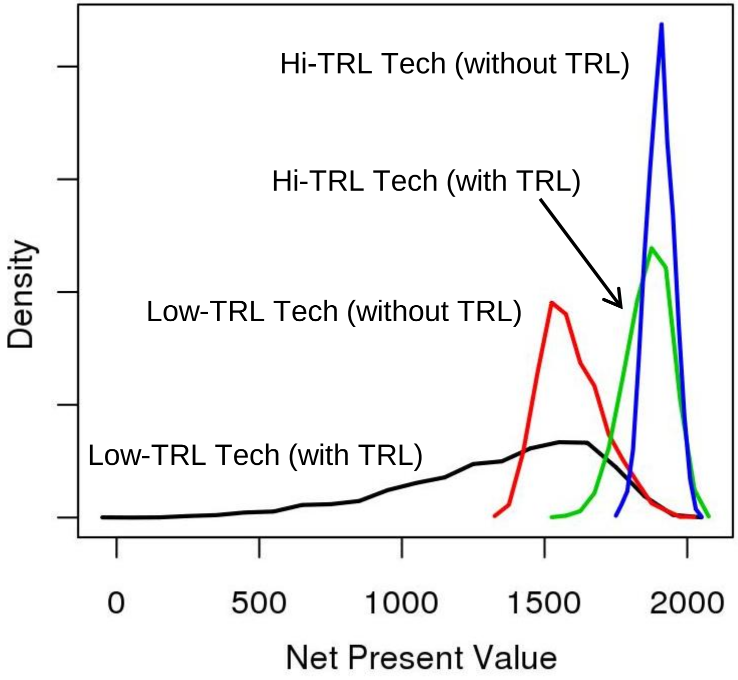
- **Yard stick to measure accelerated development against traditional development**
- **Introduce uncertainty into framework of technical risk model**



Technology Maturity Models

Significance

- Technology maturity modeling is the foundational step in CCSI Probabilistic Risk Analysis
- Without including the maturity uncertainties, models under-estimate uncertainties and possibly over-estimate performance and profitability estimates, especially at low TRLs



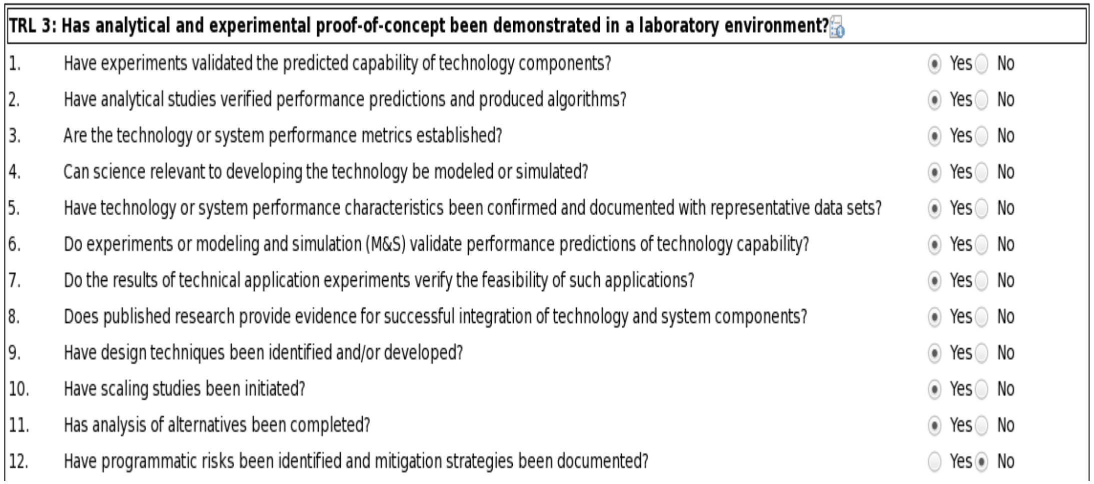
Methods

- TRL input is entered into the GUI of the expert elicitation system
- The model calculates the likelihood of the technology being at a certain maturity level
- Uncertainty factor distributions (ranges) are then modeled for each maturity level and used in the uncertainty analysis to simulate uncertainty factors to be used in the modeling of the technical and financial risks.

TRL Likelihood Model

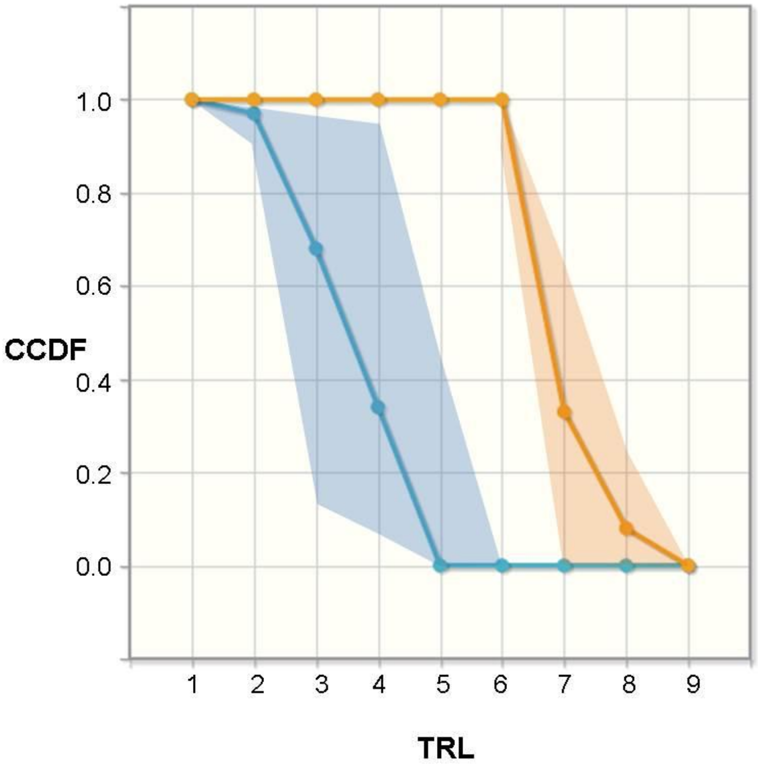
Technology Readiness Levels		
9	Commercial operation in relevant environment	
8	Commercial demonstration, full scale deployment in final form	650 MW
7	System prototype in an operational environment	>100 MW
6	Fully integrated pilot (prototype) tested in a relevant environment	10 - 50 MW
5	Component validation in relevant environment (coal plant)	1 MW
4	Component validation tests in laboratory environment	1 KW
3	Analytical and experimental critical function proof-of-concept	
2	Formulation of application	
1	Basic principals	

$$P(TRL_i) = \binom{n}{k} p^k (1-p)^{n-k}$$



TRL 3: Has analytical and experimental proof-of-concept been demonstrated in a laboratory environment?

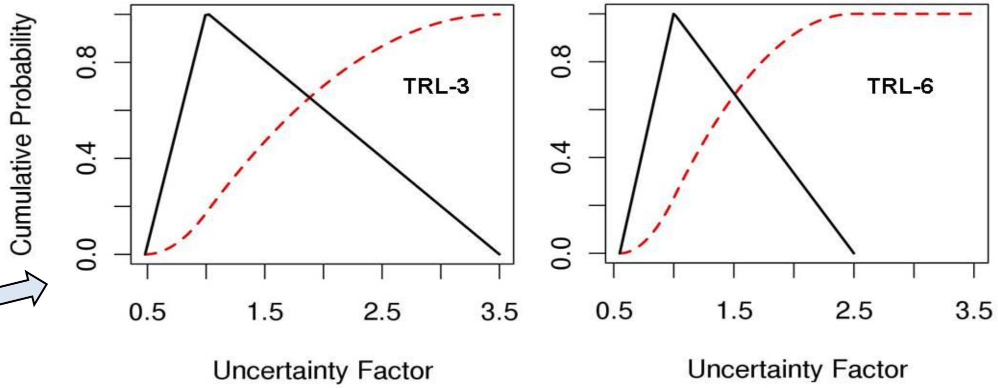
1. Have experiments validated the predicted capability of technology components? ● Yes ○ No
2. Have analytical studies verified performance predictions and produced algorithms? ● Yes ○ No
3. Are the technology or system performance metrics established? ● Yes ○ No
4. Can science relevant to developing the technology be modeled or simulated? ● Yes ○ No
5. Have technology or system performance characteristics been confirmed and documented with representative data sets? ● Yes ○ No
6. Do experiments or modeling and simulation (M&S) validate performance predictions of technology capability? ● Yes ○ No
7. Do the results of technical application experiments verify the feasibility of such applications? ● Yes ○ No
8. Does published research provide evidence for successful integration of technology and system components? ● Yes ○ No
9. Have design techniques been identified and/or developed? ● Yes ○ No
10. Have scaling studies been initiated? ● Yes ○ No
11. Has analysis of alternatives been completed? ● Yes ○ No
12. Have programmatic risks been identified and mitigation strategies been documented? ○ Yes ● No

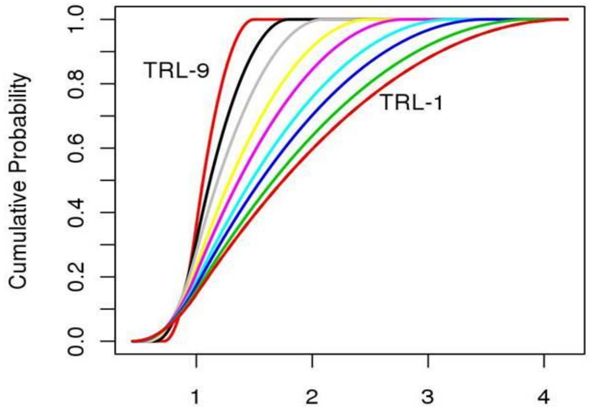


TRL Uncertainty Model

TRL uncertainty Factors

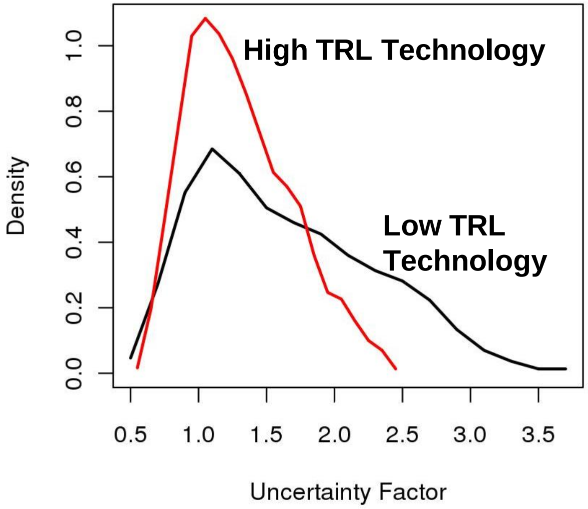
TRL	Min	Max	Mode	P(mode)
0	0.44	7.0	1.0	0.3
1	0.45	4.2	1.0	0.3
2	0.46	3.9	1.0	0.3
3	0.48	3.5	1.0	0.3
4	0.50	3.2	1.0	0.3
5	0.52	2.8	1.0	0.3
6	0.55	2.5	1.0	0.3
7	0.58	2.1	1.0	0.3
8	0.64	1.8	1.0	0.3
9	0.72	1.5	1.0	0.3



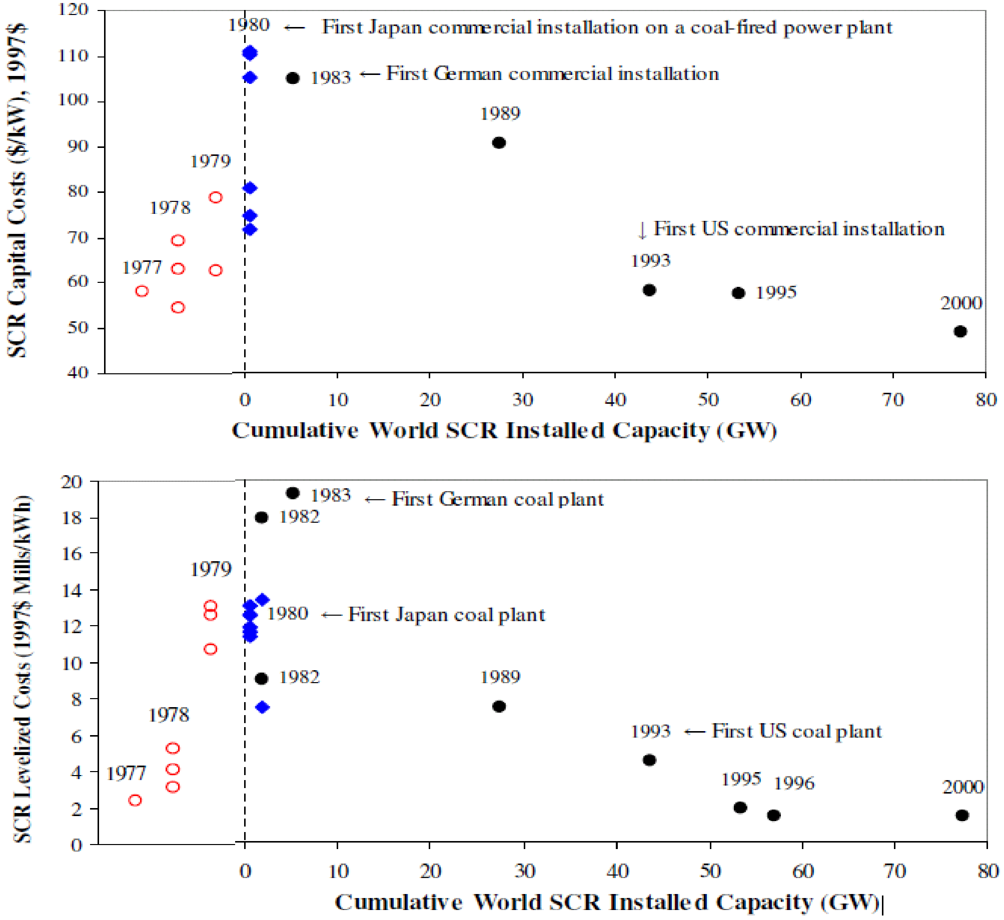


$$U = \gamma_0 F(x_0) + \gamma_1 F(x_1) + \ldots + \gamma_9 F(x_9)$$

$$\gamma_i = \alpha_i \prod_{j=i+1}^{9} (1 - \alpha_j)$$



(Cost) Uncertainty Factor Distributions



TRL uncertainty Factors

TRL	Min	Max	Mode	P(mode)
0	0.44	7.0	1.0	0.3
1	0.45	4.2	1.0	0.3
2	0.46	3.9	1.0	0.3
3	0.48	3.5	1.0	0.3
4	0.50	3.2	1.0	0.3
5	0.52	2.8	1.0	0.3
6	0.55	2.5	1.0	0.3
7	0.58	2.1	1.0	0.3
8	0.64	1.8	1.0	0.3
9	0.72	1.5	1.0	0.3

Capital and levelized costs of a SCR system for a standard (500 MWe, burning medium sulfur coal, 80% NOx removal) new coal-fired power plant.
SCR: selective catalytic reduction systems at standard U.S. coal-fired utility plants, used for the removal of NO_X.

- Studies based on low-sulfur coal plant, which requires lower SCR capital cost
- Studies evaluated prior to any commercial SCR installation on a coal-fired utility plant

Yeh, S, E Rubin, et al. Uncertainties in Technology Experience Curves for Integrated Assessment Models. *Environmental Science & Technology*, Vol. 43, No. 18, pp. 6907-6914, 2009.

Implications for Cost Modeling

- Costs are calculated/simulated using a steady-state optimal system process model. The simulations incorporate parameter (aleatory) uncertainties (call these known unknowns)
- This modeling ignores uncertainties due to lack of knowledge caused by the lack of technical maturity (epistemic uncertainties or unknown unknowns)
- Our risk analysis models incorporate the TRL uncertainty modeling to address the epistemic uncertainties and the mechanical risk model to address the reliability (maintenance) of the system.
- Without incorporating these models, the results under-estimate the uncertainties of the system and possibly over-estimate the performance

  provides more realistic comparison of technologies and identifies large sensitive areas (processes and parameters) to help accelerate the technology development

Future Development

- Transition model to identify potential TRL up-scaling pathways and challenges
- Incorporate likelihood model uncertainties
- Develop multi-process maturity modeling capability (e.g., adsorber, regenerator, and transport)
- Operationalize the System Flow Diagram for CCSI Decision Making Framework

Disclaimer

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