

Probabilistic Performance and Cost Modeling for Concentrating Solar Power Plants

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Overview

- **Introduction**
- **Probabilistic Modeling Approach**
- **Probabilistic Modeling Examples in CSP**
- **Summary**



Introduction

- **Performance and cost models have typically used deterministic models**
 - No quantification of uncertainty and confidence
 - Sensitivity (one-off) analyses provides limited insight
- **Probabilistic modeling**
 - Quantification of uncertainties and likelihood of achieving cost and performance metrics
 - Identification and ranking of the most important parameters and processes



Previous Work

- **Becker and Klimas (eds.), 1993**
 - Probabilistic power tower and cost model
 - Annual insolation not varied
 - Low number of realizations
- **Ho and Kolb (ASME ES2009, JSEE 2011)**
 - Probabilistic power tower and cost model
 - Annual insolation not varied
 - SOLERGY run manually
- **Ho et al. (SolarPACES 2009, Solar Energy 2011)**
 - Probabilistic power tower performance model
 - SOLERGY runs automated in batch mode with LHS inputs
 - Annual insolation varied using 30-year data



Previous Work

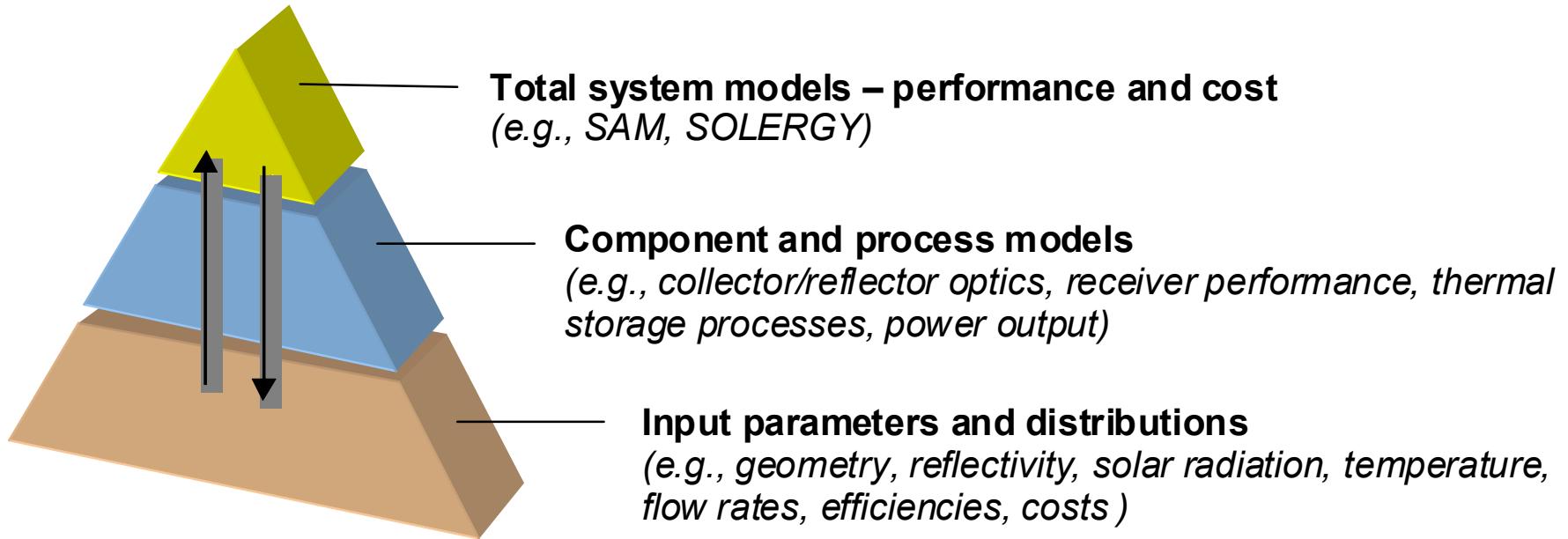
- **Ho and Dobos (SolarPACES 2010)**
 - Implementation of probabilistic methods in System Advisor Model (SAM)
 - Parabolic trough performance and cost model
 - Annual insolation varied using 30-year data
- **Finch and Ho (SolarPACES 2011)**
 - Applied stochastic SAM model to power tower
 - Evaluated impact of technology improvement opportunities (TIOs) on levelized cost of electricity



Overview

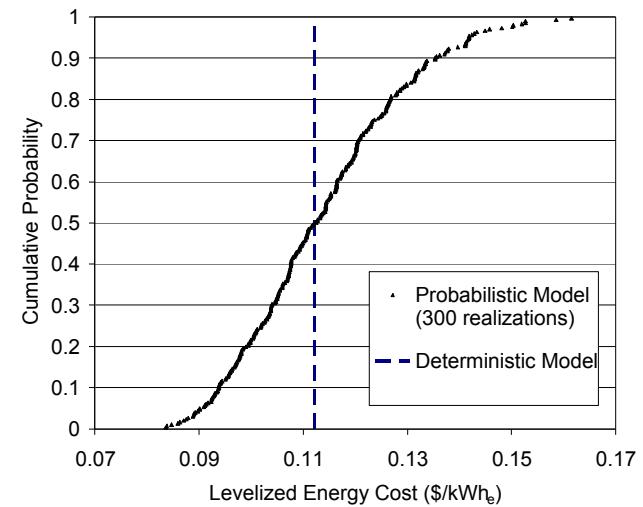
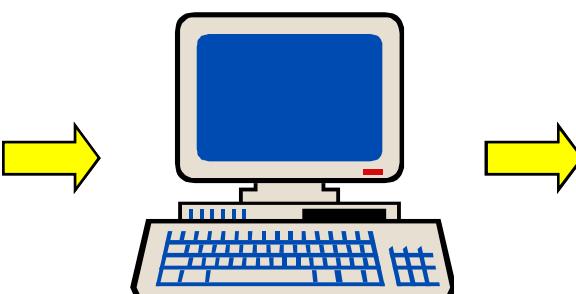
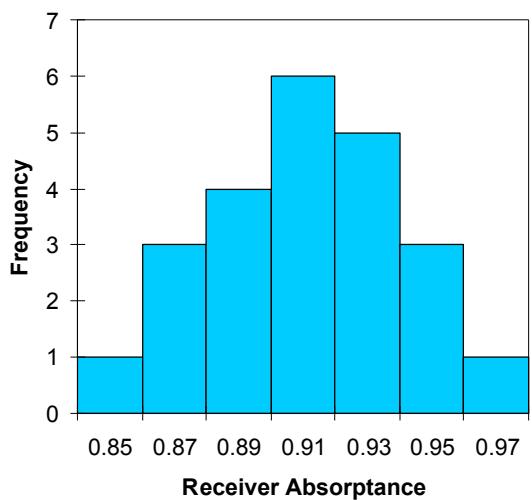
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Total System Modeling Pyramid



Need to honor uncertainties in component and process models to improve reliability of total-system models

Probabilistic Modeling



Stochastic Inputs
(Latin Hypercube Sampling)

Multiple Computer Simulations
(e.g., SOLERGY, SAM)

Distribution of Results
(Multiple Simulations)



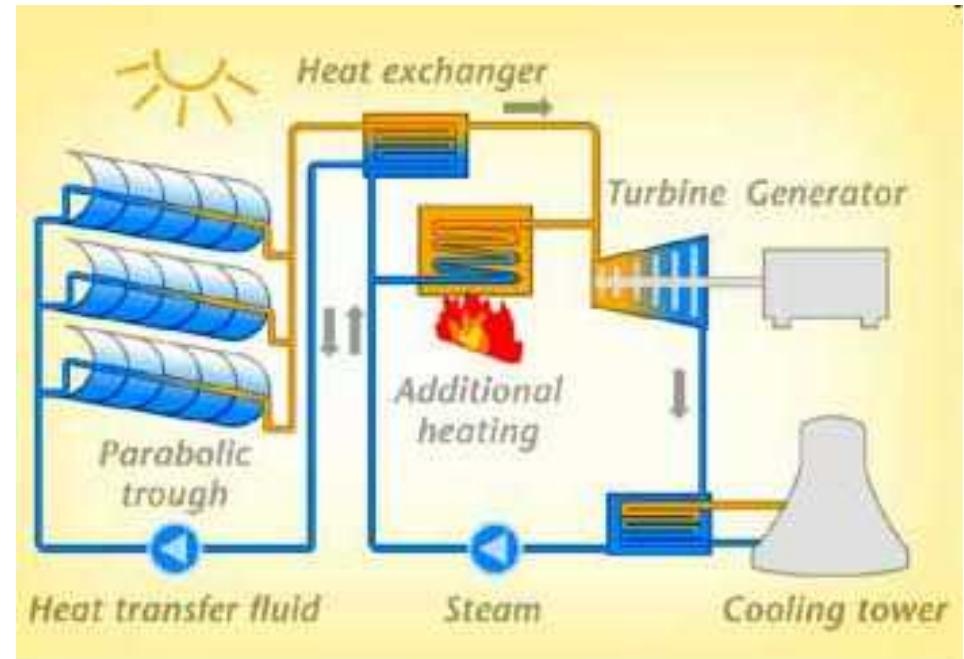
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Parabolic Trough Example

(Ho and Dobos, 2010)

- **64 MW_e Parabolic Trough Plant (e.g., Nevada Solar One)**
 - 30-year plant life
 - No explicit storage
 - Eleven parameters chosen for uncertainty analysis

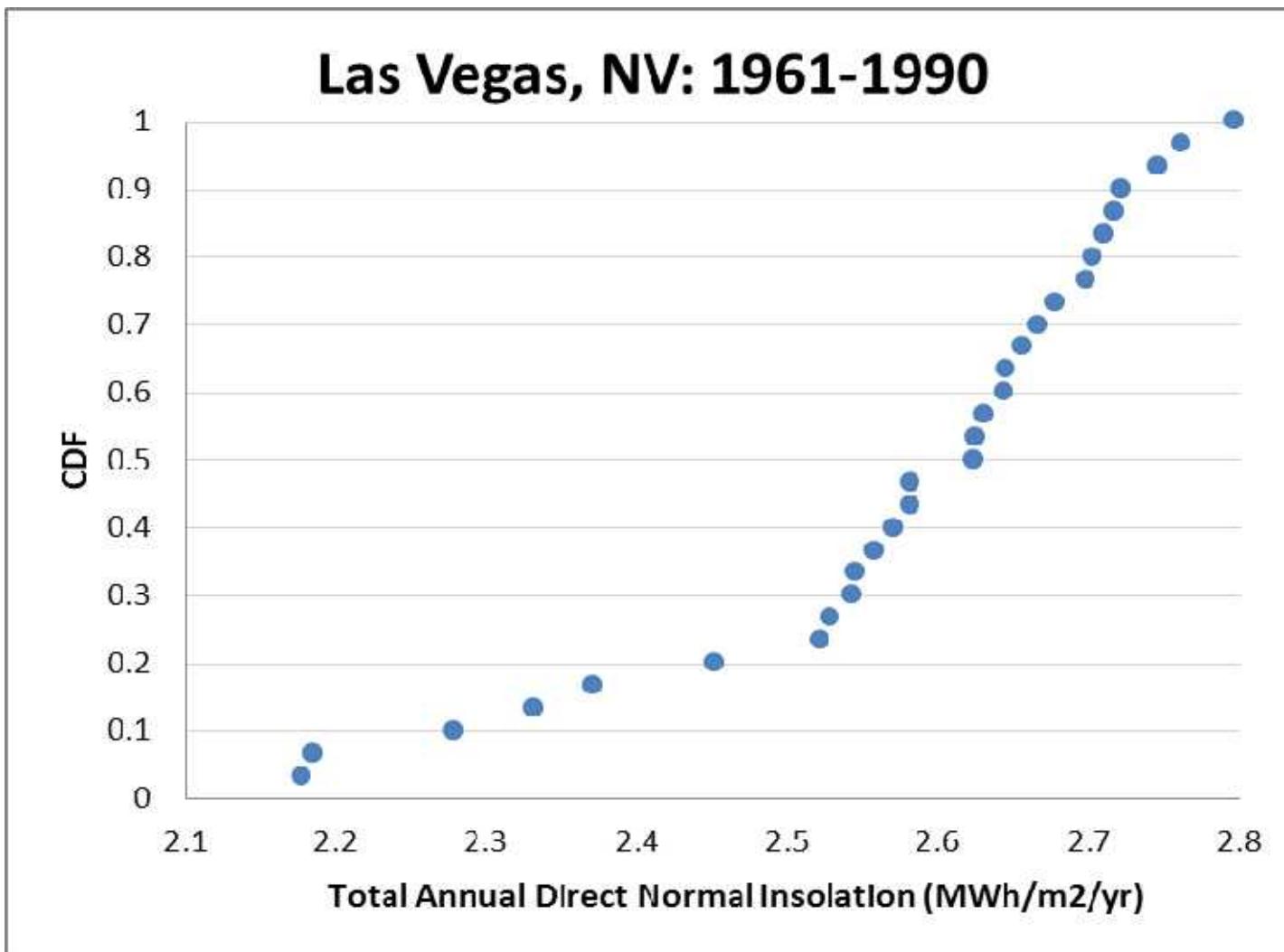


Uncertainty Distributions for Input Parameters

Parameter	Nominal Value	Distribution
Mirror Reflectance	0.935	Uniform, 0.91 - 0.96
Receiver Absorptance	0.96	Uniform, 0.93 - 0.97
Fraction of Broken Glass Receivers	0.01	Uniform, 0.01 - 0.15
Power Block Startup Time	0.5 hour	Normal, Mean = 0.5 std. dev. = 0.2
Overall System Availability	96 %	Uniform, 88 - 96
Fixed Parasitic Load	0.0055 %	Uniform, 0.003 - 0.01
Total Annual Insolation	2.62 MWh/m ²	User Defined CDF
Real Discount Rate	8.0 %	Uniform, 5.5 - 8.5
Inflation Rate	2.5 %	Uniform, 1.5 - 3.5
Fixed O&M Cost per Year	80 \$/kW (nameplate capacity)	Uniform, 70 - 100
Engineering, Procurement, Construction	15 % (of direct cost)	Uniform, 15% - 20%

Insolation Uncertainty

(Cumulative Distribution Function for 30 years)



Stochastic Sampling

(Latin Hypercube Sampling)

SAM 2010.7.29: C:\Documents and Settings\ckho\My Documents\Technical Reports\SolarPACES\2010 - Pe...

File Case Results Developer Help

Welcome Uncertainty Analysis Helper Functions Variable Setup NSO - Physical Model - Original NSO - Phy: ▾

Select Technology and Market... [CSP Trough Physical, Utility IPP]

System Summary Σ

Climate
Location: LAS_VEGAS, NV
Lat: 36.1 Long: -115.2 Elev: 664.0 m

Financing
Analysis: 30 years

Tax Credit Incentives
Fed. ITC

Payment Incentives

Annual Performance
Degradation: 0 %
Availability: 96 %

Trough System Costs
Total Installed: \$ 282,734,475
Est. per Capacity (\$/kW): \$ 4,443

Solar Field
Solar Multiple: 1.29486
Number of Loops: 95

Parametrics Sensitivity Optimization Statistical Multiple Systems Excel Exchange Simulator Opti

Add Statistical Simulation Clear All

Analysis Setup

Select an output metric: LCOE(real)

Select input distributions

Add... Edit... Remove

Availability (Uniform [0.88,0.96])
Mirror reflectance (Uniform [0.91,0.96])
Power block startup time (Normal [0.5,0.2])
Variation 1 Absorber Absorptance (Uniform [0.93,0.94])
Variation 1 Broken Glass (Uniform [0.01,0.15])

Select correlations:
Add... Edit... Remove

Remove Simulation
 Enable this simulation
Compute Samples...

Number of sampled values per variable: 100
Seed value (-1 for random): -1

Next Step Back Step Home

Stochastic Sampling

(Latin Hypercube Sampling)

SAM 2010.7.29: C:\Documents and Settings\ckho\My Documents\Technical Reports\SolarPACES\2010 - Pe...

File Case Results Developer Help

Uncertainty Analysis

LHS Input Vectors

Select Technology and Market...

System Summary

	Availability	Mirror reflectance	Power block start
1	0.889451	0.91966	0.463219
2	0.891594	0.959367	0.729273
3	0.949793	0.910196	0.307466
4	0.918744	0.936687	0.504148
5	0.941899	0.945132	0.649214
6	0.915235	0.938736	0.520264
7	0.901445	0.915261	0.58033
8	0.917989	0.923458	0.622315
9	0.892413	0.955147	0.387037
10	0.893838	0.923894	0.440993
11	0.905292	0.916164	0.452696
12	0.907131	0.944187	0.342203
13	0.948539	0.947739	0.100516
14	0.940337	0.915579	0.514072
15	0.947849	0.933421	0.493314
16	0.903898	0.930781	0.408379
17	0.923019	0.951675	0.231767
18	0.912109	0.944649	0.156188

Rows... Copy Paste

Climate

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Solar Field

Solar Multiple: 1.29486

Number of Loops: 95

OK Cancel

Physical Model - Original

NSO - Phy

Multiple Systems Excel Exchange Simulator Opti

Remove Simulation

Enable this simulation

Compute Samples...

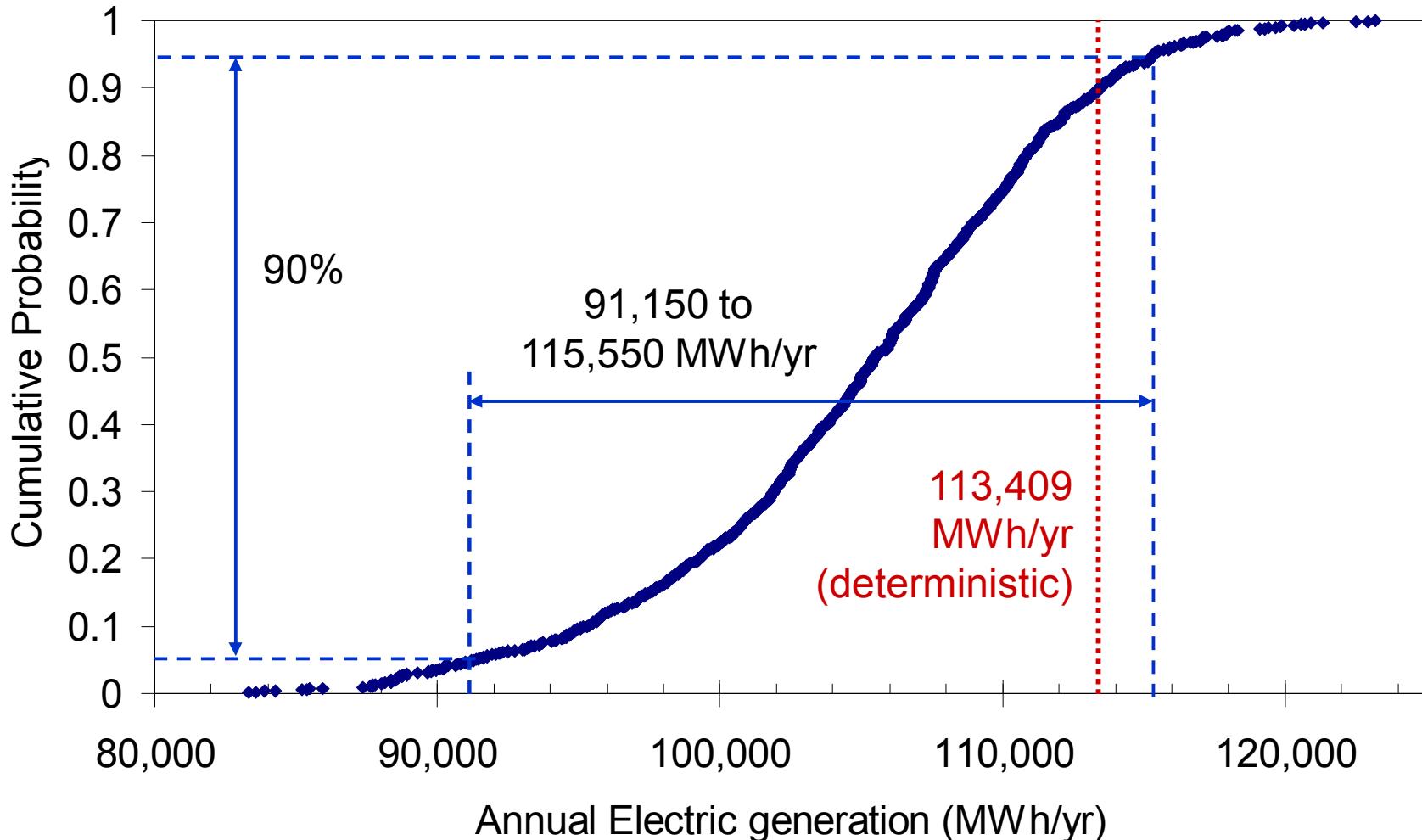
variable: 100

random: -1

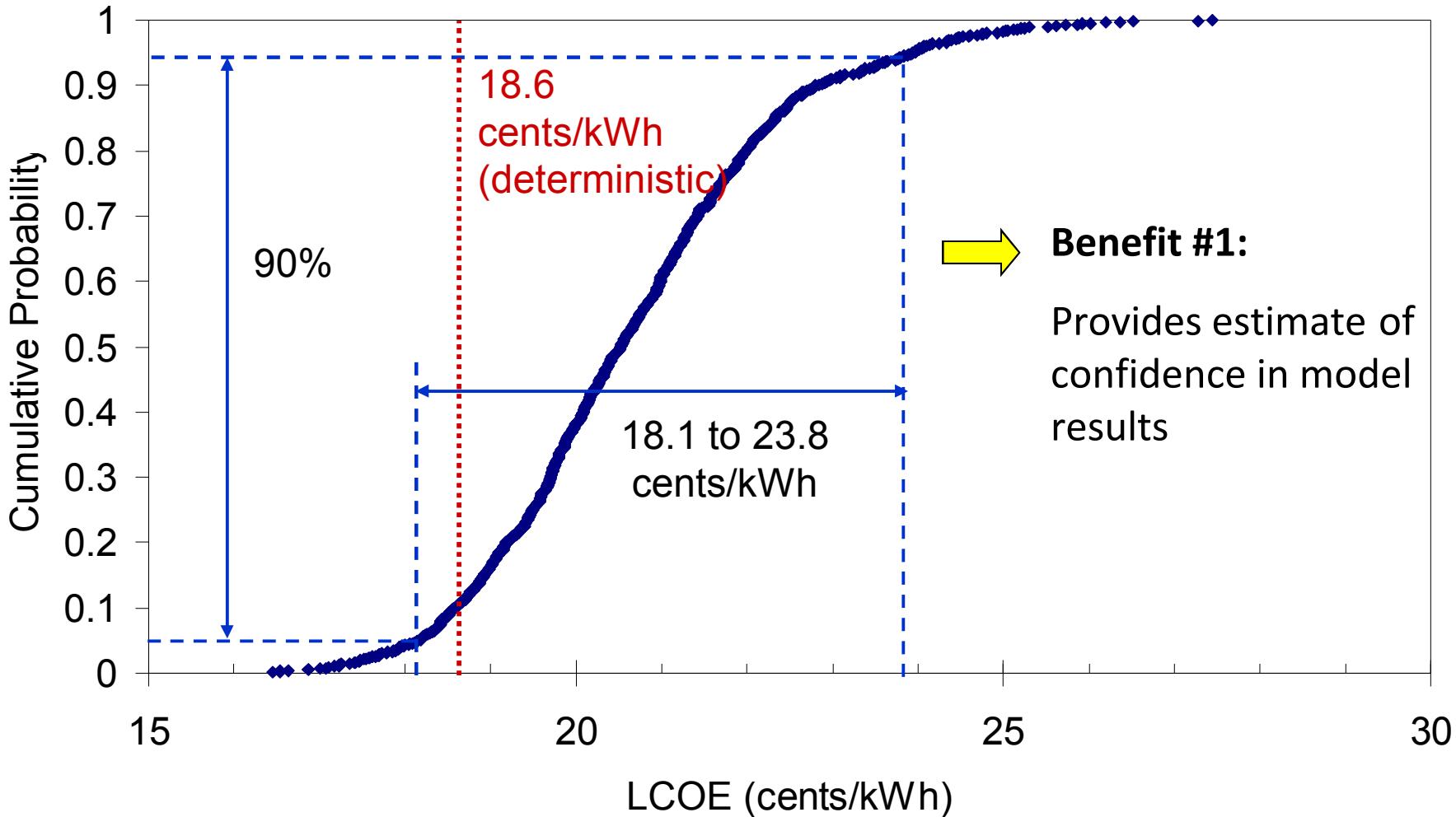


Results (1000 realizations)

Results: Annual Electric Generation



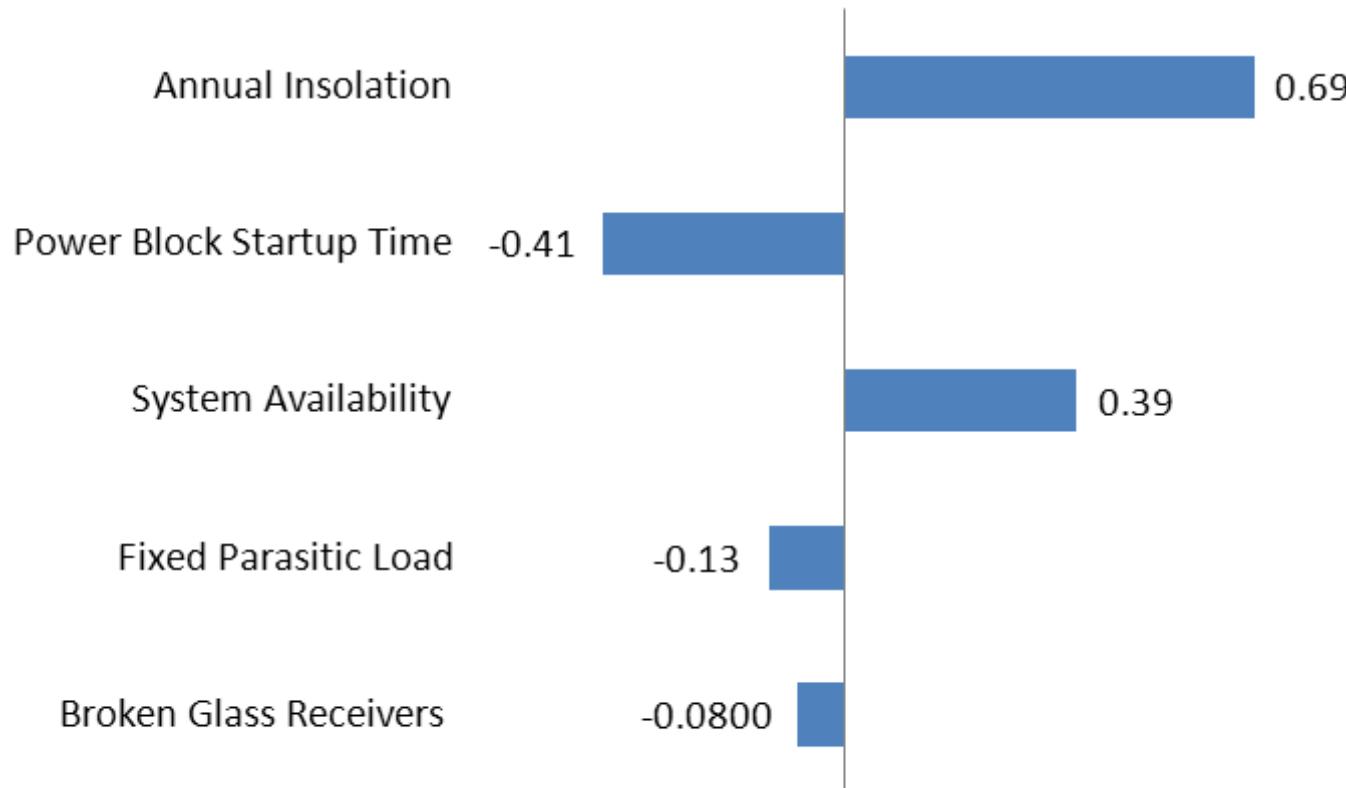
Results: LCOE (real)



Sensitivity Analysis:

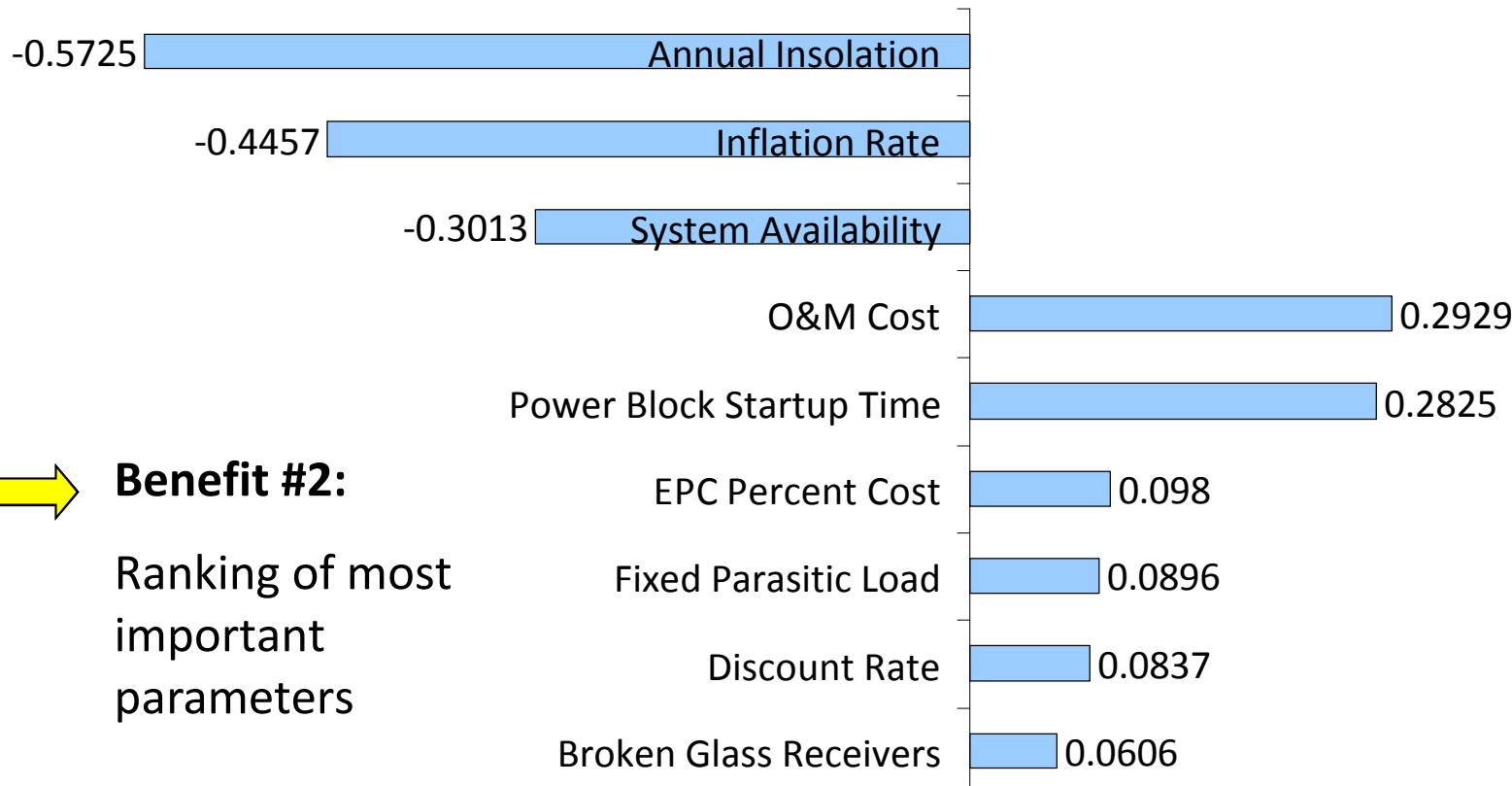
Annual Electric Generation

Standard Rank Regression Coefficient (β) Annual Generation



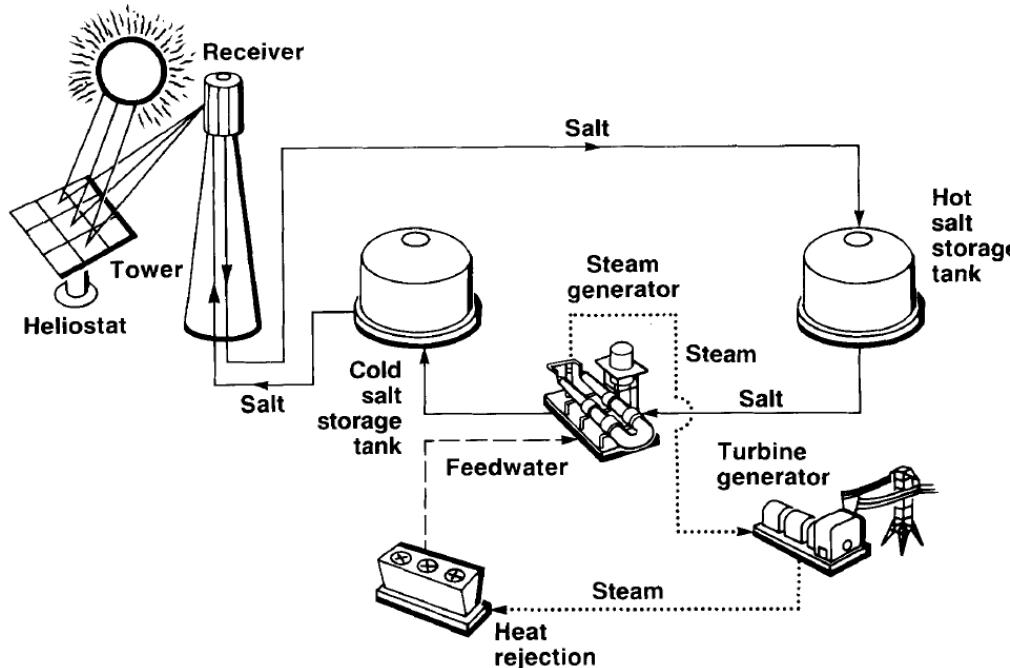
Sensitivity Analysis: LCOE (real)

Standardized Rank Regression Coefficient (β) Levelized Cost of Electricity



Power Tower Example

(Finch and Ho, 2011)



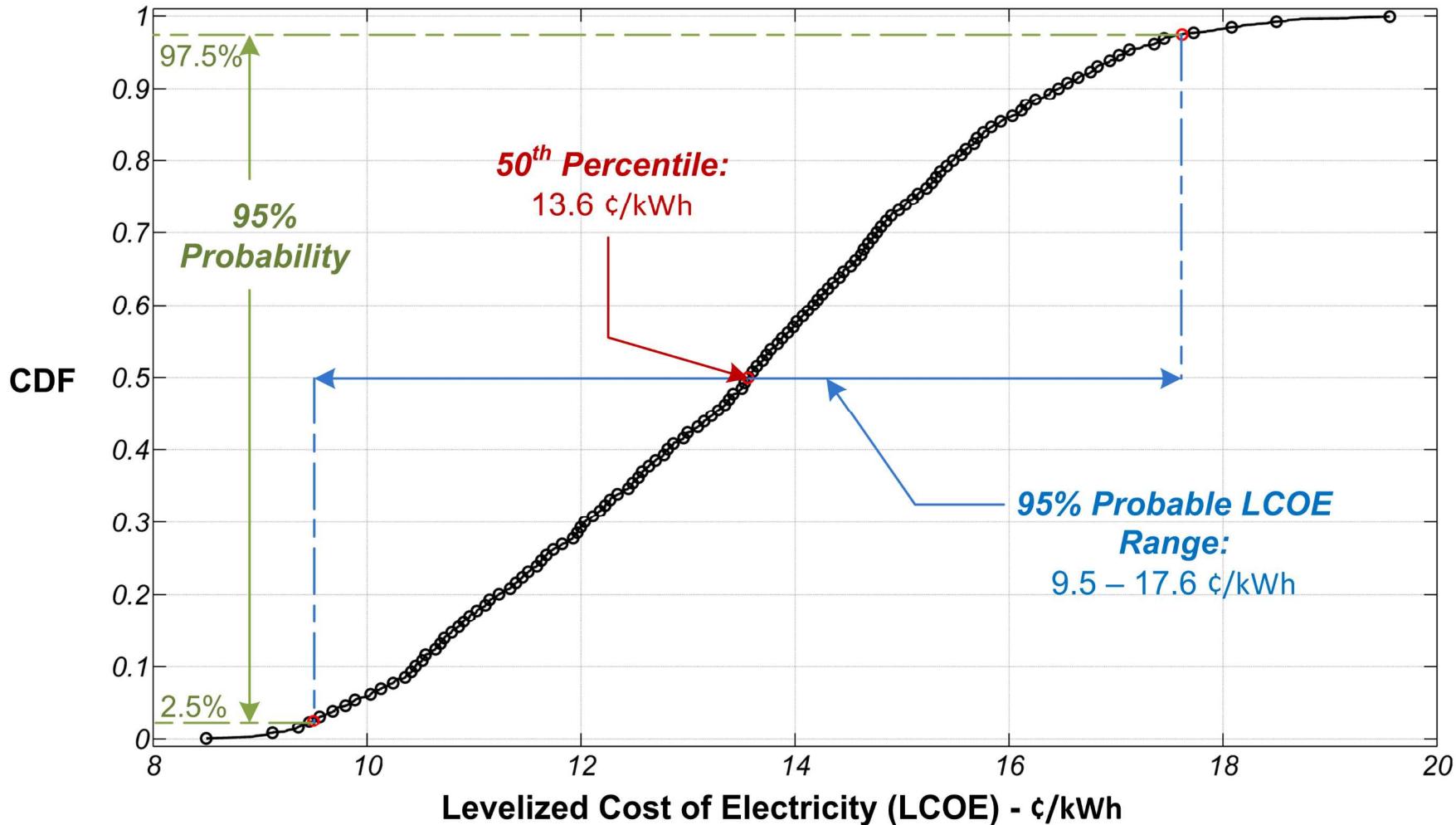
- 100 MWe molten-salt power tower system
 - 30 year plant life
 - Storage capacity of 9 hours
 - TMY weather data from Daggett, CA
 - Direct normal insolation = 2.8 MWh/m²/yr



Uncertain Parameters

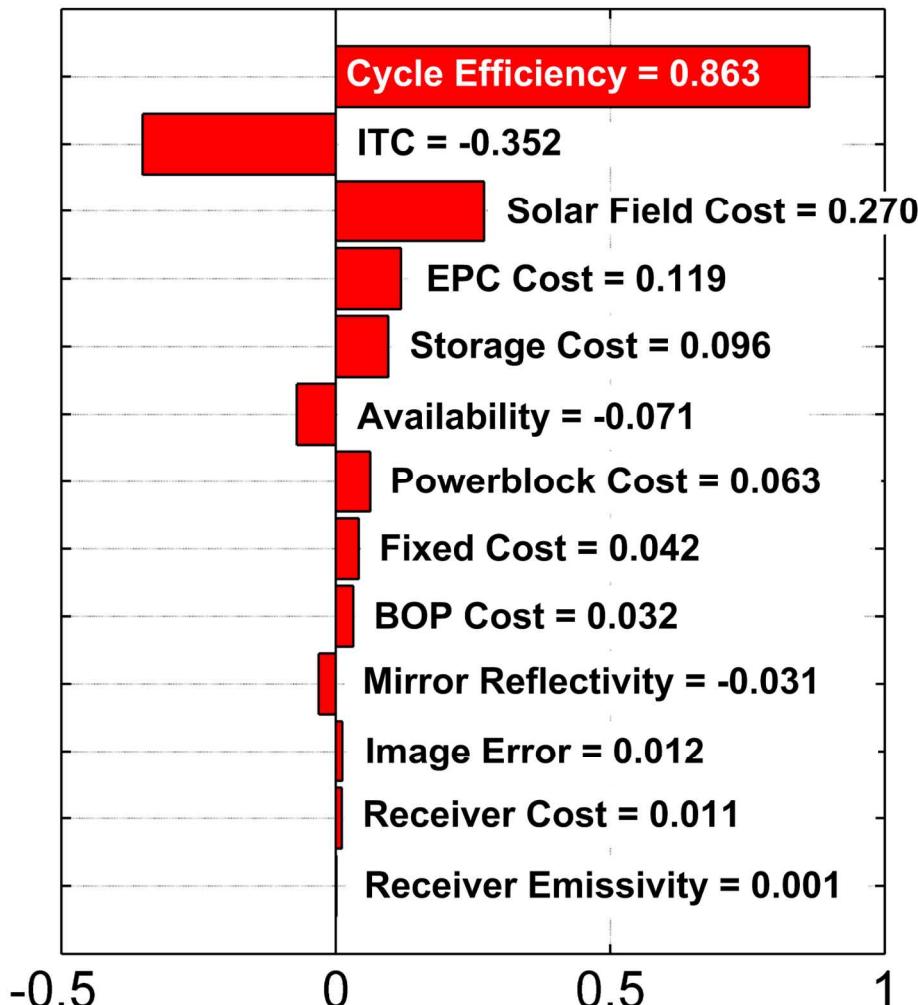
SAM Input (TIO)		Present Day	Future Goal
Availability	(%)	90	94
Balance of Plant (BOP) Cost	(\$/kWe)	350	250
Cycle Efficiency	(%)	42.5	48
EPC and Owner Cost	(%)	25	15
Fixed Costs by Capacity	(\$/kW-yr)	65	50
Image Error	(mrad)	1.53	1.25
Investment Tax Credit (ITC)	(%)	30	10
Mirror Reflectance and Soiling	(%)	89.3	92.6
Powerblock Cost	(\$/kWe)	1000	800
Receiver Emissivity	(%)	88	44
Receiver Cost Scaling Exponent	-	0.7	0.53
Solar Collector Field Cost	(\$/m ²)	200	120
Storage Cost	(\$/kWt)	30	20

Results: LCOE Uncertainty



Results: LCOE Sensitivity

Standardized Regression Coefficients (β)



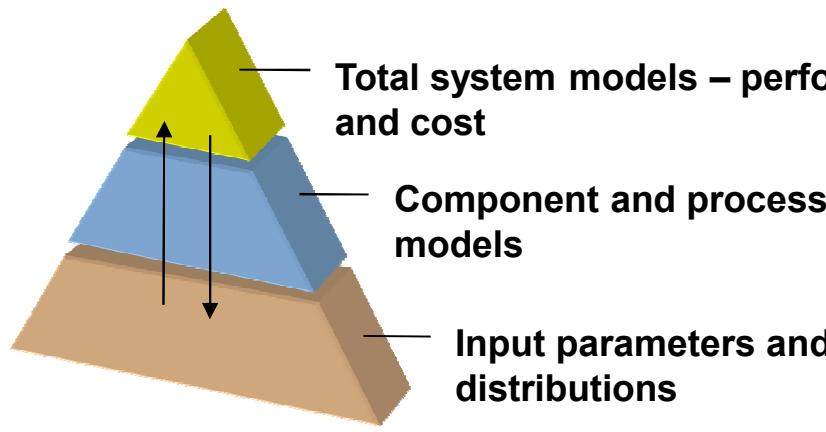


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Summary

- **Need to honor and propagate uncertainties through total system**
- **Probabilistic modeling for CSP**
 - Uncertainty analyses will provide companies with more confidence and reliability in their cost/performance models
 - Quantify likelihood of achieving cost and performance metrics
 - Sensitivity analyses will prioritize R&D to focus on system components that have the most impact
- **Probabilistic modeling has been incorporated into SAM**



Ongoing Work

- **Develop database of uncertainty distributions and CSP modeling protocols**
 - SolarPACES Task 1: Guidelines for CSP Modeling
 - Towers, troughs, dishes, weather
- **Evaluate reliability models and uncertainty distributions**
 - Incorporation into SAM