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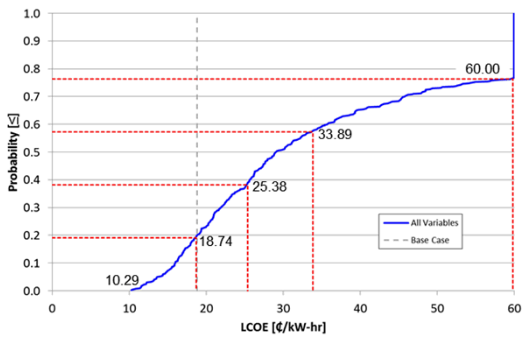

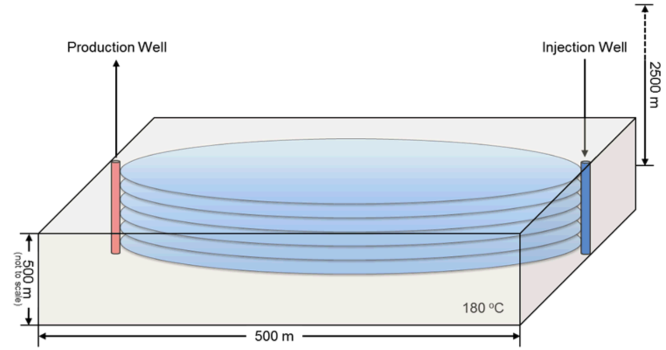

A Probabilistic Assessment of Enhanced Geothermal Systems, Uncertainty, and Levelized Cost of Electricity

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Introduction

According to the U.S. Energy Information Administration (EIA) exploration and production risk is one of the factors responsible for slow development of EGS resources (http://(www.eia.gov):

- Even in well-characterized resource areas, there is significant exploration and production risk, which can result in high development costs
- Risk = f(probability) – analogous to uncertainty.

This analysis links uncertainties in physical performance and cost forecasting to better understand the integrated dynamics between probability, risk, and economic viability.

The objective is to build a framework to determine the probability of reaching a given LCOE given a variety of uncertainties and future unknowns:

- Start with a representative EGS Project
- Vary uncertain physical and economic parameters over realistic ranges
- Develop distribution curves of the LCOE

Approach

- Representative EGS Project
  - Binary power plant
  - Plant performance varies as f(production temperature)

Parameter	Value	Parameter	Value
Depth	2500 m	**Target Power Sales**	25 MW
# of Production Wells (incl. confirmation wells)	10	Resource Temperature	180 C
# of Injection Wells	5	**Well Separation Distance**	500 m
# of Confirmation and Exploration Wells	3 ea.	**Screened Interval**	500 m
Production Well Cost	$9,295,048	**Pre-heater/Evaporator Pinch Point**	5 C
Injection Well Cost	$11,868,686	**Evaporator Pressure**	1 MPa
Confirmation Well Cost	$11,154,058	**Condenser Temperature**	40 C
Exploration Costs	$5,905,380	**Turbine Efficiency**	85%
Stimulation Cost / Inj. Well	$2,000,000	**Feedpump Efficiency**	75%
Total Brine Mass Flow Rate	~450.0 kg/s	**Project Lifetime**	30 yrs

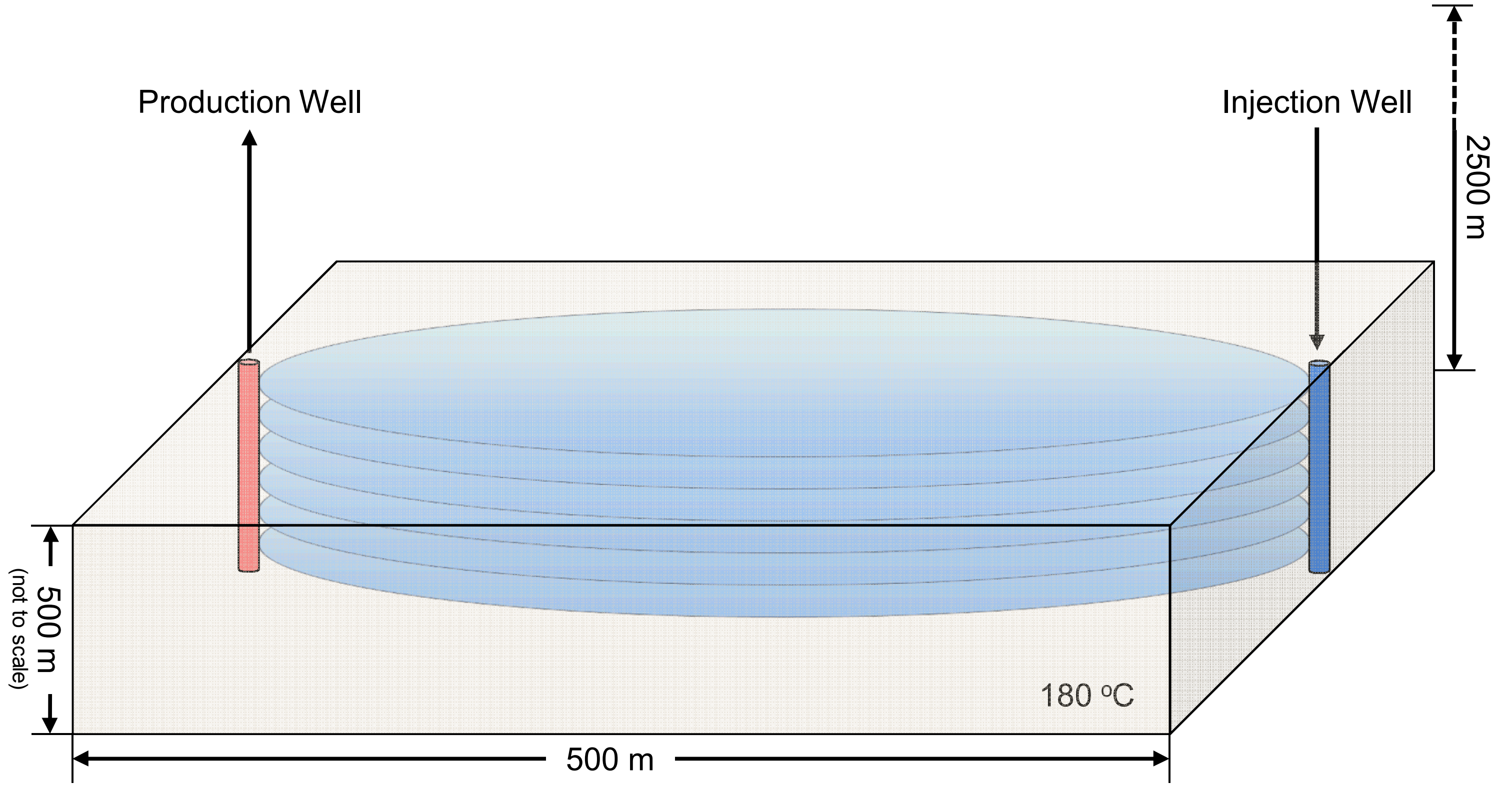
blue = power plant parameters

- Uncertainty
  - Physical
    - Reservoir width
    - # of fractures
    - Fracture aperture

    (Reservoir width and # of fractures: Reservoir Volume)
  - Economic
    - Well Costs
    - Plant Costs

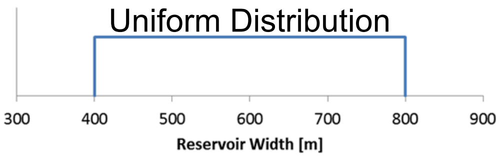
Uncertainty – Physical System

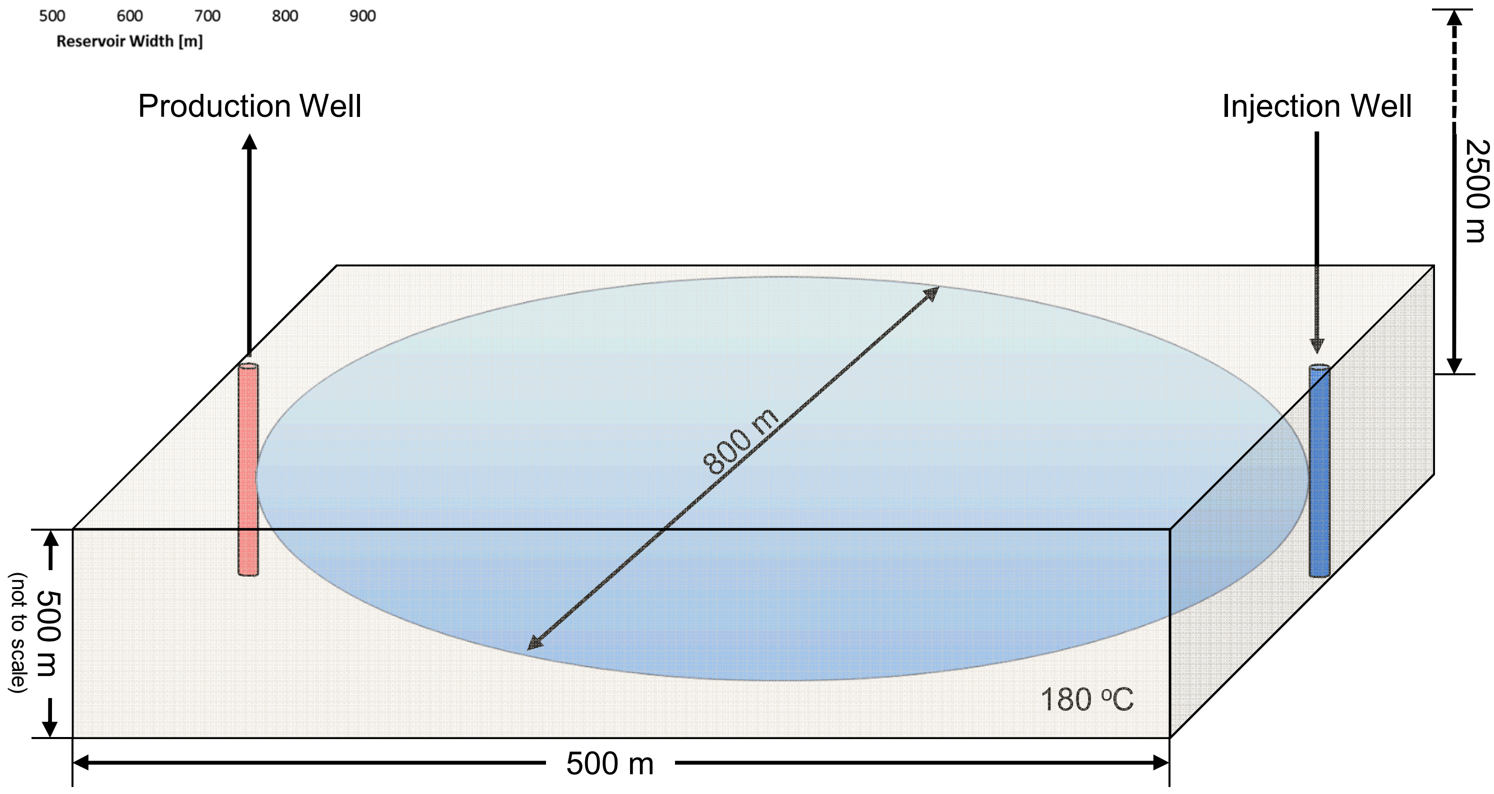
Reservoir Width   Number of Fractures   Aperture



Uncertainty – Physical System

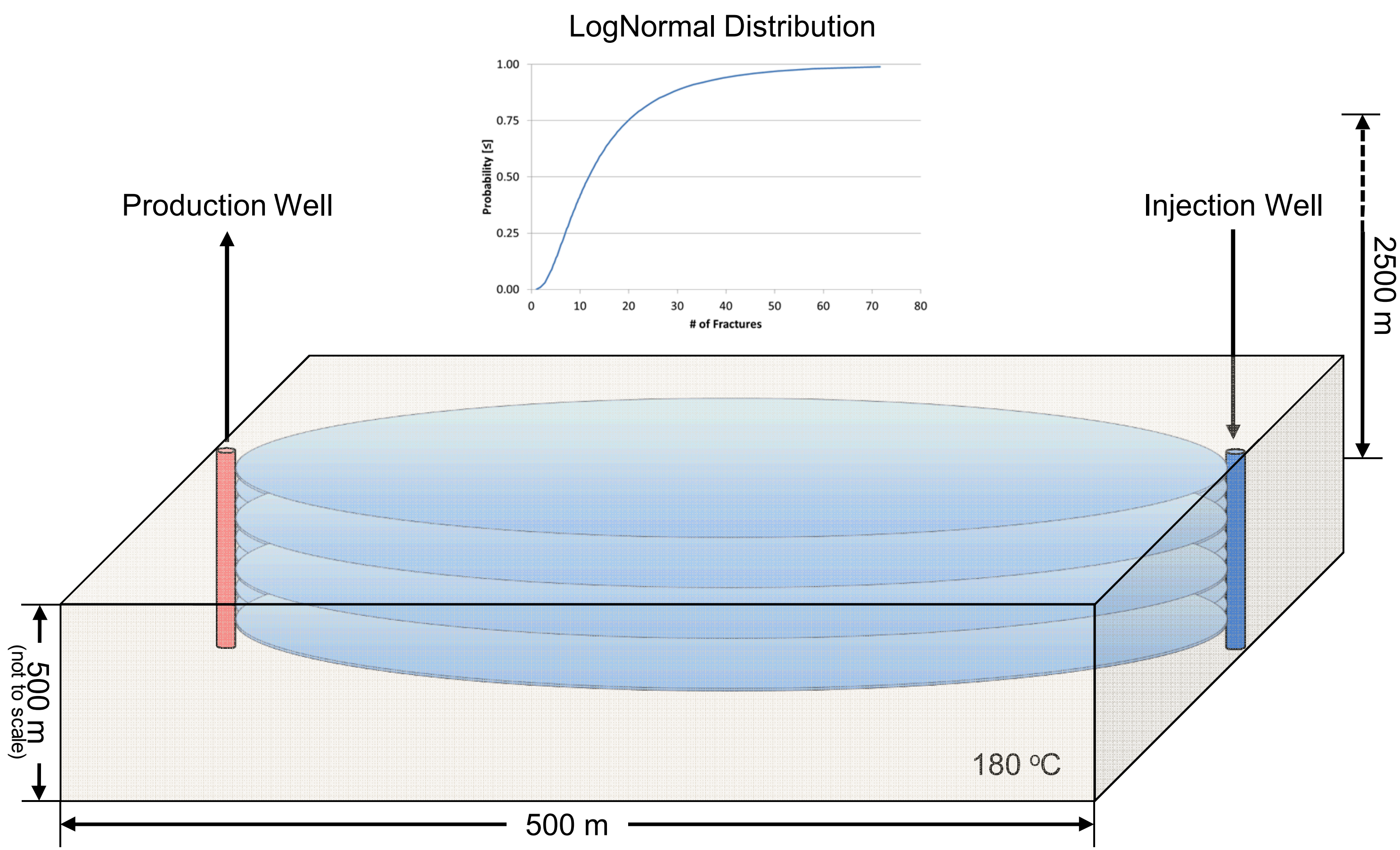
Reservoir Width   Number of Fractures   Aperture





Uncertainty – Physical System

Reservoir Width | Number of Fractures | Aperture

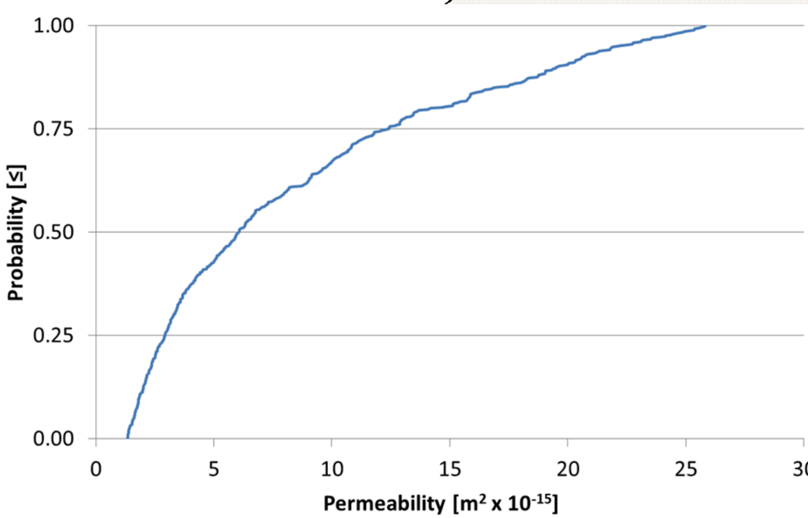


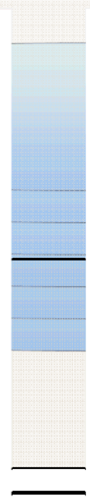
Uncertainty – Physical System

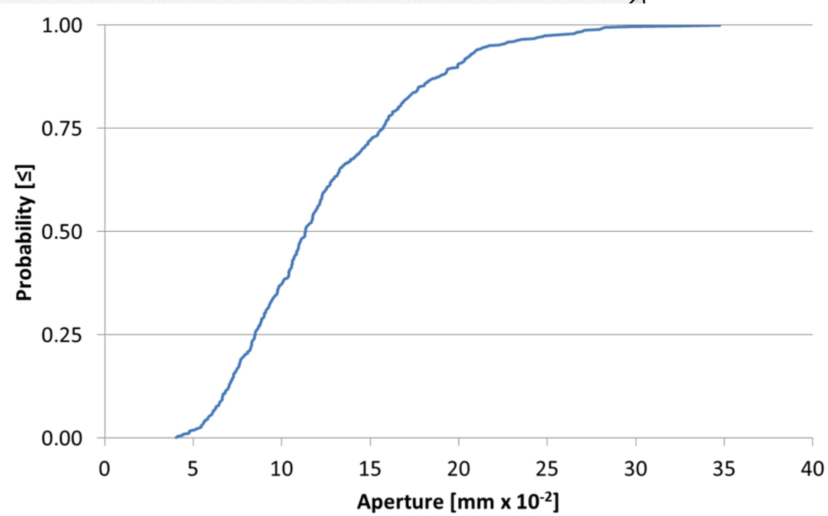
Reservoir Width Number of Fractures Aperture

- All cases are simulated at a target permeability: $k_{targ} = 5x10^{-15}$ m^2.
- $\ln(k_{targ})$ is randomized between 95-105%
- Permeability k = f(# of fractures, aperture) (Snow, 1968)
- Aperture is calculated as a function of k_{rand} & # of fractures (also random)

$$k_{rand} = \exp\left(\ln\left(k_{targ}\right) v_k\right) \qquad a = \sqrt[3]{\frac{6Hk_{rand}}{n_{frac}}}$$



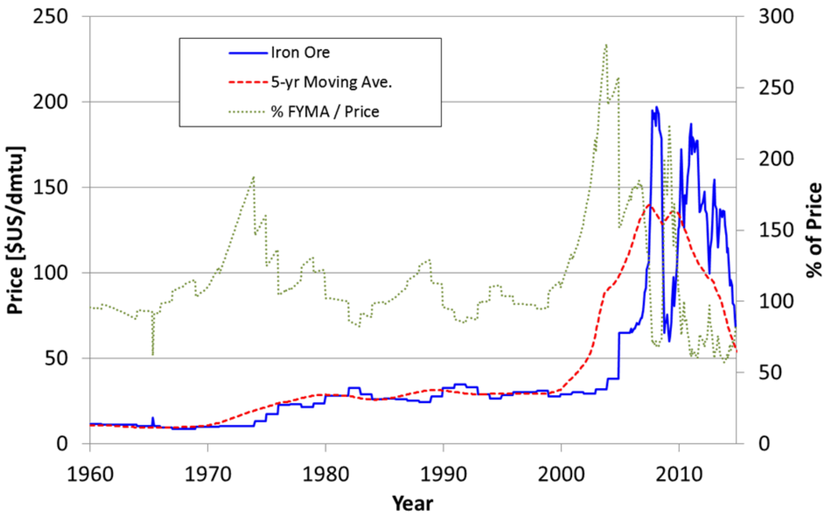


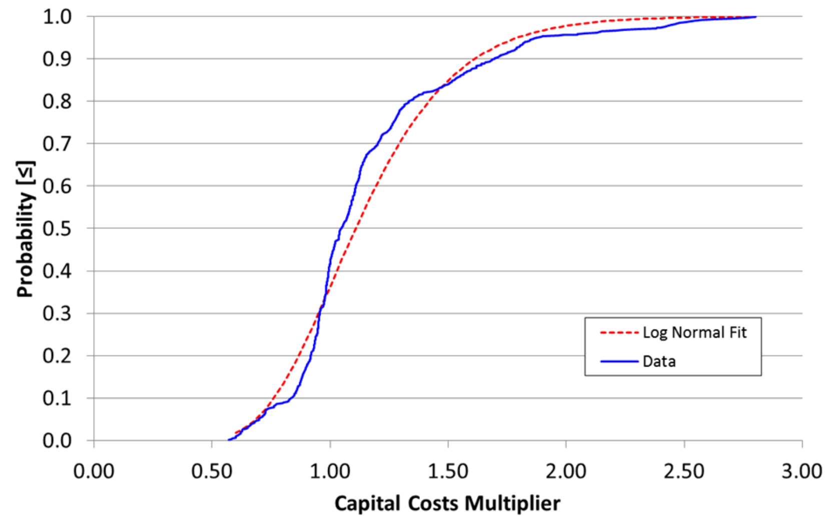


Snow, D.T.: Rock fracture spacings, openings, and porosities, *Journal of Soil Mechanics*, Foundations Division of the Am. Soc. Of Civil Engrs., **94**, 73-91.

Uncertainty - Economic

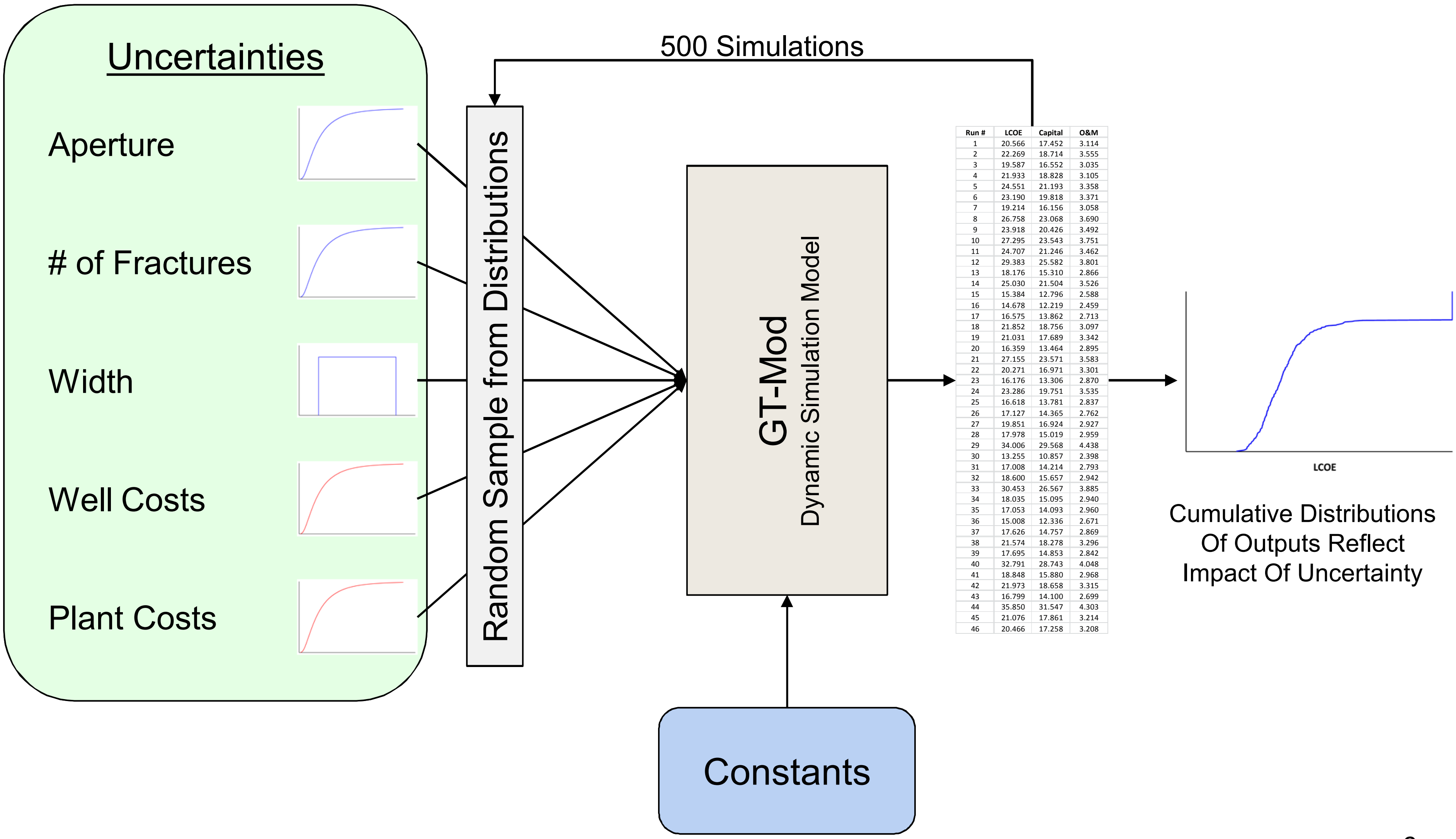
- Begin with default costs as calculated in GETEM
- Iron Ore Monthly Prices – World Bank Commodity Price Data*
- % 5-yr moving average (FYMA) to each months' price (1960 – 2014)





*databank.worldbank.org/data-catalog/commodity-price-data

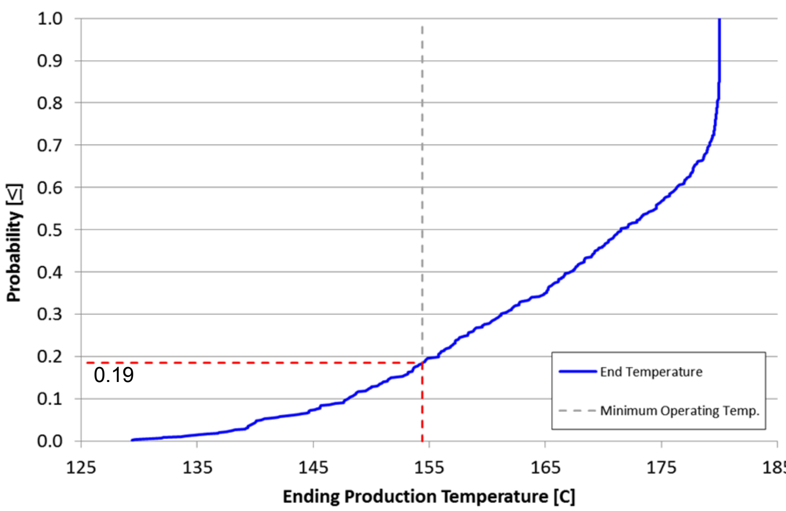
Probabilistic Modeling

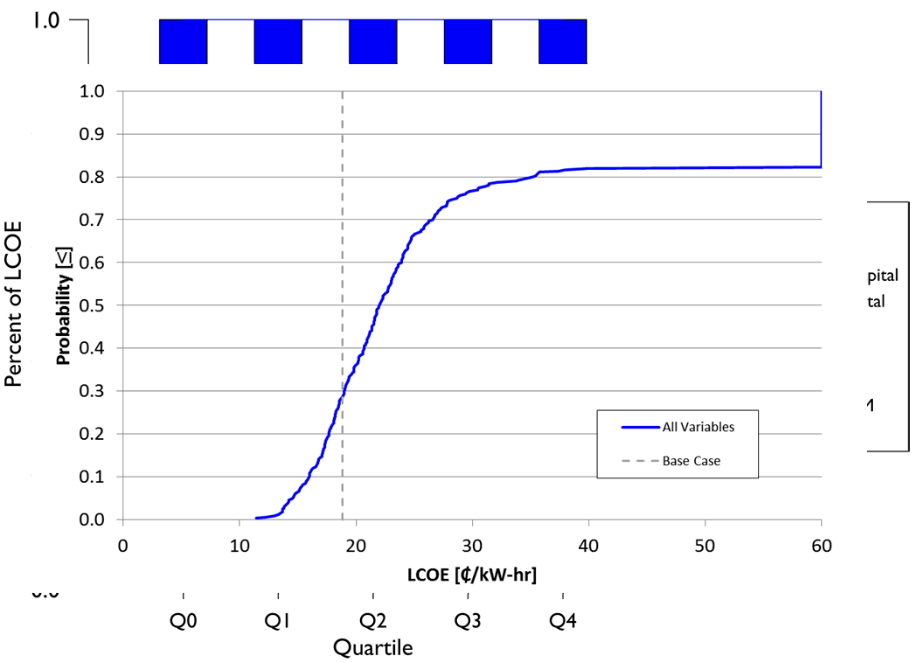


Run #	LCOE	Capital	O&M
1	20.566	17.452	3.114
2	22.269	18.714	3.555
3	19.587	16.552	3.035
4	21.933	18.828	3.105
5	24.551	21.193	3.358
6	23.190	19.818	3.371
7	19.214	16.156	3.058
8	26.758	23.068	3.690
9	23.918	20.426	3.492
10	27.295	23.543	3.751
11	24.707	21.246	3.462
12	29.383	25.582	3.801
13	18.176	15.310	2.866
14	25.030	21.504	3.526
15	15.384	12.796	2.588
16	14.678	12.219	2.459
17	16.575	13.862	2.713
18	21.852	18.756	3.097
19	21.031	17.689	3.342
20	16.359	13.464	2.895
21	27.155	23.571	3.583
22	20.271	16.971	3.301
23	16.176	13.306	2.870
24	23.286	19.751	3.535
25	16.618	13.781	2.837
26	17.127	14.365	2.762
27	19.851	16.924	2.927
28	17.978	15.019	2.959
29	34.006	29.568	4.438
30	13.255	10.857	2.398
31	17.008	14.214	2.793
32	18.600	15.657	2.942
33	30.453	26.567	3.885
34	18.035	15.095	2.940
35	17.053	14.093	2.960
36	15.008	12.336	2.671
37	17.626	14.757	2.869
38	21.574	18.278	3.296
39	17.695	14.853	2.842
40	32.791	28.743	4.048
41	18.848	15.880	2.968
42	21.973	18.658	3.315
43	16.799	14.100	2.699
44	35.850	31.547	4.303
45	21.076	17.861	3.214
46	20.466	17.258	3.208

Results

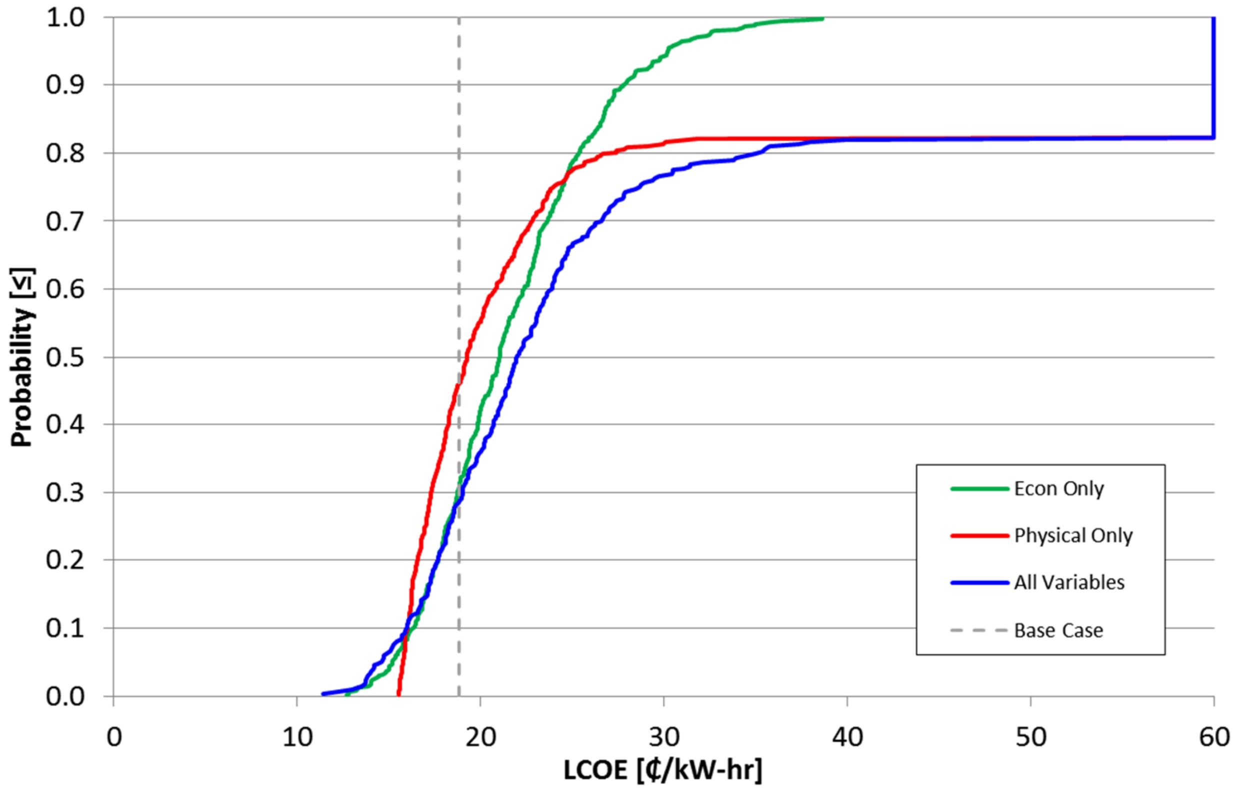
- 19% that ending production temperature < minimum
- 29 % LCOE < Base Case (default values, 18.831 ₵/kW-hr)
- Plant and well capital costs: 58% - 66% of LCOE





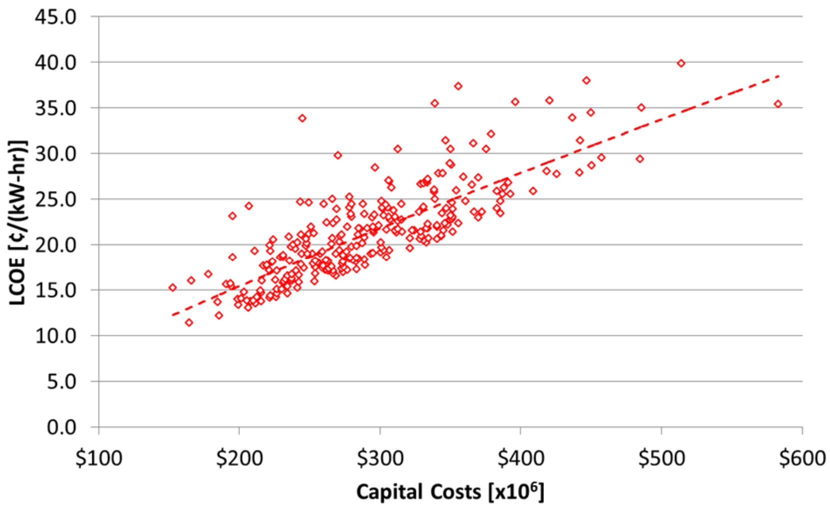
Comparing LCOE Components

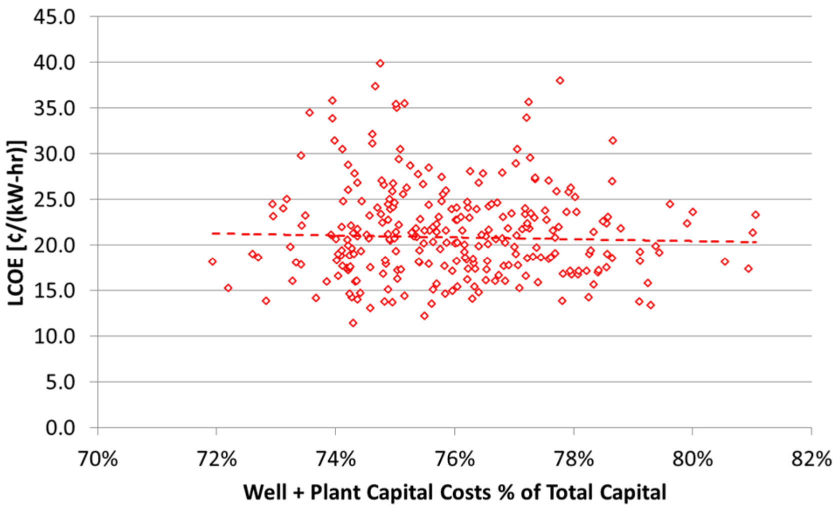
- Physical uncertainty contributes more to higher LCOE values
- Economic uncertainty contributes more to lower LCOE values



Priority Influencers

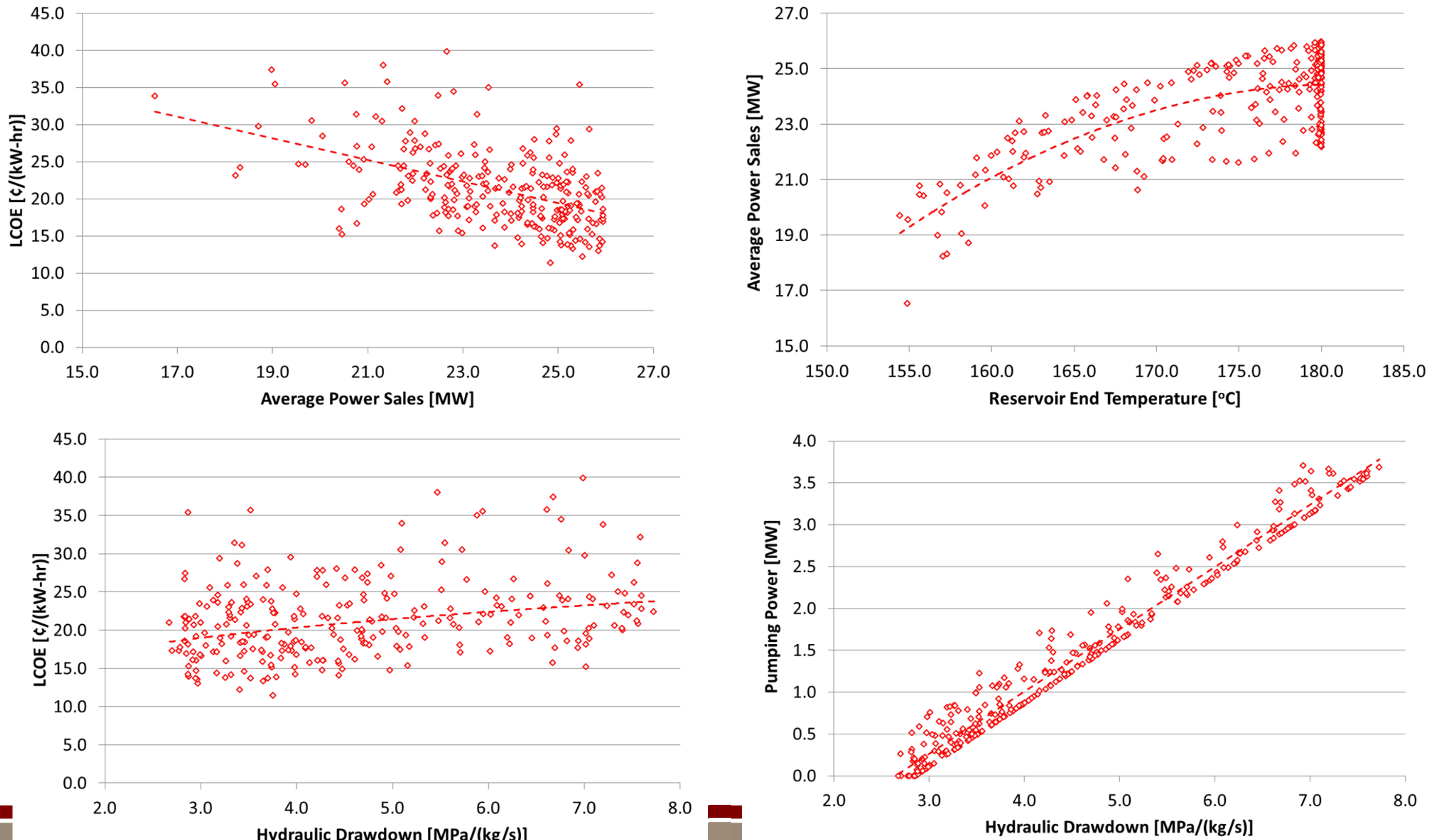
- Capital Costs have a strong influence on the LCOE
- Well and Plant costs are the largest % of Capital Costs





Priority Influencers

Reservoir End Temperature & Hydraulic Drawdown



Summary

- Objective: to build a framework to determine the probability of reaching a given LCOE given a variety of uncertainties and future unknowns
- Used probabilistic modeling to produce cumulative distributions of the LCOE as an integrated function of uncertainty
- The 3 physical uncertainties (number of fractures, aperture, and reservoir width) control thermal drawdown and pumping requirements
- The 2 physical uncertainties control capital costs (and by extension, O&M costs)

Summary

- Results show that the final LCOE distribution is skewed towards the high end: 71% probability of doing worse than the default values
  - Physical uncertainties contribute more to higher LCOE values – lower performance is bounded
  - Physical performance is non-linear
- Economic uncertainties contribute more to lower LCOE values
- Most important factors are capital costs and pumping requirements

Thank You