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Presented at the Stanford Geothermal Workshop, 1-3 February 2010, Stanford, California

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Pacific Gas & Electric/PIX 00059

DOE 2009 Geothermal Risk Analysis: Methodology and Results

February 1, 2010

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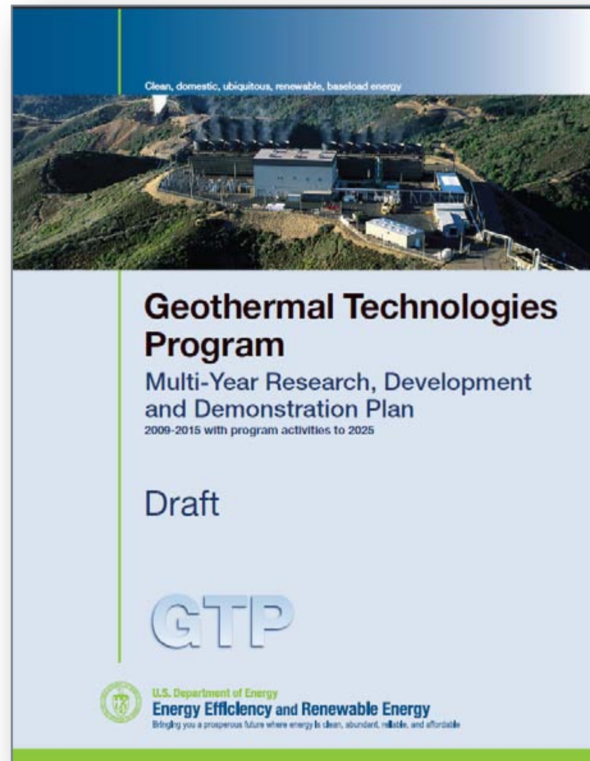
USES OF RISK ASSESSMENT

Standardized annual risk process for all EERE programs used to:

1. Meet the National Academy of Science's requirement to report uncertainty
2. Improve project, program, and portfolio design, performance, and likelihood of success
3. Clarify issues associated with accepting, managing, or rejecting risks
4. Link science research opportunities with applied energy RD&D
5. Increase decision-maker understanding of potential RD&D results
6. Obtain answers to key RD&D questions.

GTP uses risk information to:

1. Set technical goals
2. Provide input for the supply curve used in estimating benefits under the GPRA



Risk Analysis and Supply Curve Process

EXPERTS
Knowledge

EXPERTS
Estimate high, low, & median values for performance Parameters

ANALYSTS
Aggregate Estimates

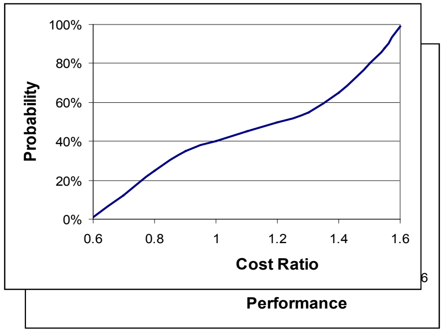
MODELERS
Cost and Performance Analysis

GETEM

PROGRAM DECISIONS

- Critical issue identification
- Redundant R&D
- Improved understanding of potential

SUPPLY CURVE



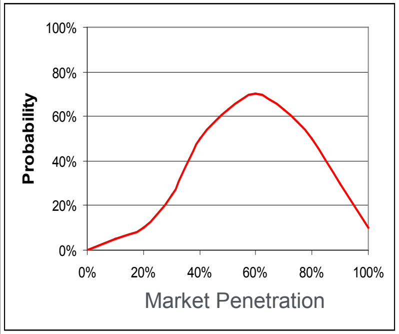
MODELERS
Market and Economic Analysis

SEDS

NEMS/MARKAL

ReEDS

MARKET PENETRATION



PROGRAM BENEFITS

- Environmental Benefits
- Economic Benefits
- Energy Security

Step 1: Select energy systems to evaluate and technical improvement opportunities (TIOs) to assess

1. Funding Levels
   a. No DOE funding
   b. Target DOE geothermal funding
   c. Over-Target DOE geothermal funding
2. Timeframes
   a. 2015
   b. 2025
3. Technologies

Addressing ubiquitous sources of EGS—beyond easily accessible resources—mandated by Program appropriators when Program restarted in FY2008

Geothermal Technology	2006 Risk Assessment	2009 Risk Assessment
Hydrothermal	2006 Risk: Flash & Binary	Exploration only
Low-Temperature/Co-Production	Not included	Not included
EGS, including: 1. Engineered Geothermal Systems 2. Enhanced Hydrothermal Systems	2006 Risk: Flash & Binary	Multiple TPMs
Direct Use (including Geothermal Heat Pumps)	Not included	Not included

Preparation

Step 1: Select energy systems to evaluate and technical improvement opportunities (TIOs) to assess

Reference Scenario

a. What parameters (e.g. resource temperature) needed to be assumed in order for experts to provide input on the requested TPMs?

b. What values (e.g. 200^{o}C) should be assumed for each parameter needed?

Goal: Produce one scenario—which all expert groups will use—that:

a. Has potential for significant market penetration

b. Is more advanced than the first-step EGS power plant

c. Is not so advanced as to be unreasonable.

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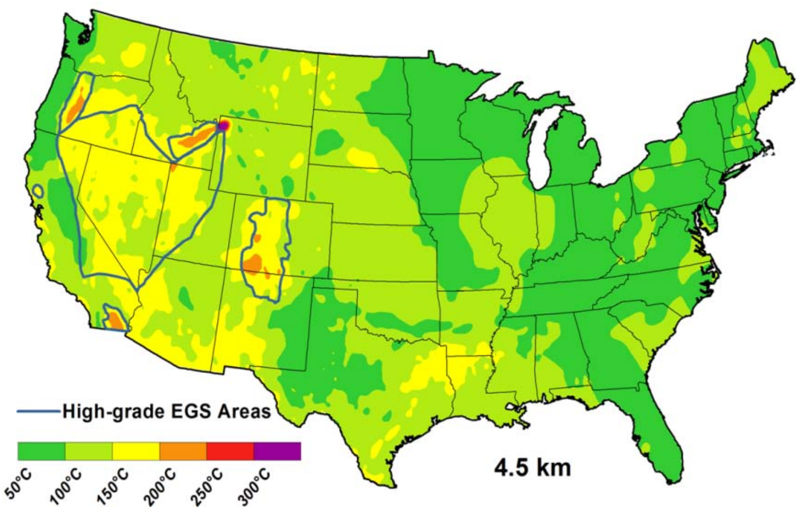
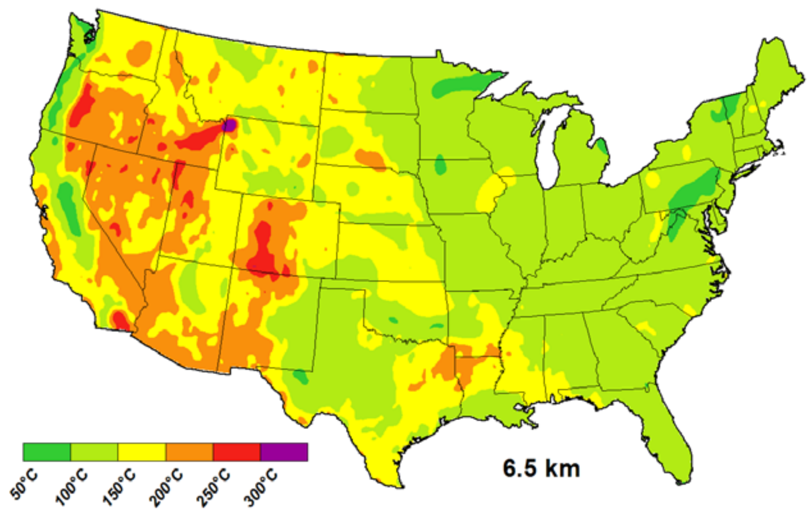
Step 1: Select energy systems to evaluate and technical improvement opportunities (TIOs) to assess





Map Source: SMU
NOTE: Maps do not include anomalous, high-temperature hydrothermal locations

2006 Risk Assessment

Reference Scenario: 4 km, 200° C

- Some of the best resources
- Not very geographically widespread

2009 Risk Assessment

Reference Scenario: 6 km, 200° C

- Good resource; more geographically widespread
- Technically able to drill that deep
- Same depth used by SNL in drilling assessment

Preparation

Step 1: Select energy systems to evaluate and technical improvement opportunities (TIOs) to assess

Reference Scenario

Parameter	Value		Parameter	Value		Parameter	Value	
Year of the $	Dec-08		Well Casing ID at TD	17.78 cm	7 in	Pump Depth Setting	1 km	3,281 ft
Geothermal Type	EGS		Deviated Ramp Length (at 45°)	500 m	1,641 ft	Total Dynamic Head (TDH)	1.2 km	4,000 ft
Resource Rock Temperature	225° C	437° F	Well Separation	650 m	2,133 ft	Injection Pumping	none/low to prevent water losses downhole	
Fluid Temp at Power Plant Inlet	200° C	392° F	Producer-Injector Well Ratio	2:1		Number of Fractured Intervals	2	
Ambient Temperature	15° C	59° F	Producer Flow Rate (per well)	60 kg/s		Pump horsepower	1065 HP	
Exploration	few to none O&G wells in area		Injection Temperature	80° C	176° F	Gross Capacity	30 MWe	
Easy Drilling (e.g., Sed overburden)	1,500 m	4,922 ft	Water Loss/Total Injected	0.02		Net Capacity	20 MWe	
Resource Rock Type	igneous		Thermal Drawdown (fluid)	0.3%/yr		Capacity Factor	0.95	
Drilling Coat Curve (in GETEM)	median cost curve		Geofluid Pump Efficiency	0.6		Energy Conversion	binary	
Resource Stress Regime	normal faulting transitional to strike-slip		Flasked Wireline Tool Service Time	10 hours		Cooling Technology	air-cooled	
Well Depth	6 km	19,686 ft	Permanent Tool Lifetime	6 years		Plant Lifetime	30 years	
Well Deviation from Vertical	0 degrees		Pump Lifetime (then replace)	3 years				

- Parameters selected by experts; values developed from extensive expert input
- Difficult to develop reference scenario because EGS is new technology. Some capabilities are unknown. (e.g. producer/injector ratio, producer flow rate, thermal drawdown)

Preparation

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Step 2: Define technology performance measures (TPMs) to assess and map to TIOs and associated R&D activities

Exploration (Hydrothermal & EGS)

1. Non-Well Exploration Costs
2. Exploration Well Success Rate

Well Construction

1. Well Drilling/Construction Cost/ft
2. Production Pump Cost
3. Downhole Pump Temperature
4. Pump Horsepower
5. Wireline Tool Temperature
6. Permanent Equip. Temperature
7. Zonal Isolation Pressure
8. Zonal Isolation Temperature

Reservoir Engineering

1. Well Stimulation Cost
2. Production Well Flow Rate
3. Thermal Drawdown Rate
4. Producer-Injector Ratio
5. Short-Circuit Mitigation Probability
6. Reservoir Creation Probability

Energy Conversion

1. Binary System Capital Cost
2. Binary System O&M Cost/Yr
3. Brine Effectiveness

*EGS Enabling Technologies

While we could not risk ALL metrics required for EGS, we tried to identify those:

a. that are **critical** to the development of EGS
b. where future improvements could have **significant** impact on project costs

Step 3: Recruit Experts

Expert Group	Expert Team	
	Attended	Responded
Exploration (well and non-well)	3 - DOE national laboratory 1 - USGS 3 - academia 3 - industry 10 TOTAL	3 - DOE national laboratory 1 - USGS 3 - academia 3 - industry 10 TOTAL
Wells (drilling, construction, tools, pumps)	3 - DOE national laboratory 1 - academia 5 - industry 9 TOTAL	3 - DOE national laboratory 1 - academia 5 - industry 9 TOTAL
Reservoir Engineering	1 - DOE national laboratory 1 - USGS 5 - academia 3 - industry 10 TOTAL	1 - DOE national laboratory 0 - USGS 4 - academia 1 - industry 6 TOTAL
Power Conversion	1 - DOE national laboratory 1 - academia 5 - industry 7 TOTAL	1 - DOE national laboratory 1 - academia 5 - industry 7 TOTAL

Preferences

- More reservoir engineering experts—these are key enabling technologies
- More reservoir engineering experts from industry—EGS experience

Next Analysis

- Recruit sooner
- Check availability
- Reserve time on schedule

Step 4: Expert Probability Assessment (2 weeks)

Green: Provided by Analyst
Yellow: Provided by Expert

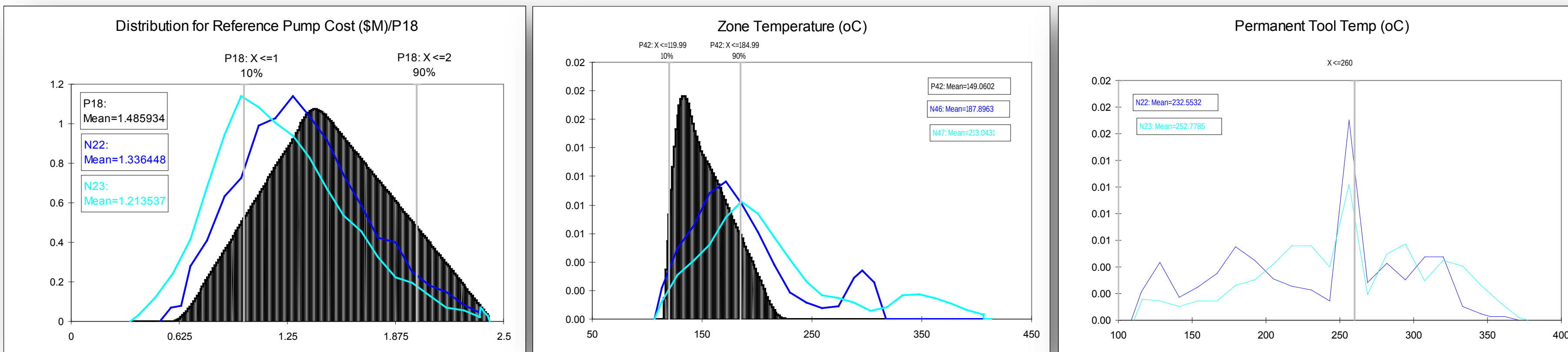
TPM INFORMATION:

2e. Assessor Self-rating:	A world expert (5)	(for this TPM)			
2f. Quantity (TPM):	Drilling Cost				
2g. Units and Description:	$/foot	2007 US dollars / vertical foot			
2h. Improvement:	Decreasing				
2i. Reference value:				Single Value	
	Reference Yr:	2008		7,000	
			Minimum:		Maximum:
2j. Extreme Future Limits:			500		7,500
2k. Learn by Doing:	Start Year:	2020	LBD Range: 6%	8%	15%

	Goal Years (a)	If no Advance Value = (b)	Probability of Advance (c)	DISTRIBUTION 10%ile (d)	DISTRIBUTION (mode) Most Likely (e)	DISTRIBUTION 90%ile (f)	Input Values **CHECK** (g)
2l. No DOE-Baseline R&D:	2015	7,000	100%	5,500	6,500	6,900	TRUE
	2025	6,500	100%	4,500	5,500	6,000	TRUE
2m. DOE Planned R&D:	2015	6,500	80%	4,700	5,800	6,200	TRUE
	2025	5,500	90%	2,800	3,500	5,000	TRUE
2n. DOE Expanded R&D:	2015	6,500	90%	3,000	3,750	4,500	TRUE
	2025	5,500	95%	2,000	2,250	3,500	TRUE

Step 5: Aggregate Expert Input & Review With Experts

Jim McVeigh (Sentech) completed all expert aggregation—this made it clear when experts' input did not make sense.



Round 1 draft improvement distributions for $30M funding level

Discussion among the experts revealed:

1. Sometimes calculated minimums fell below minimum specified—yet experts were adamant that both numbers were specified correctly—they did not feel triangular distributions best fit the distributions
2. Experts were accounting for potential failure of all manufactured products, so distributions showed metrics potentially getting worse. These would be adjusted by experts in Round 2.

RD&D Investment - Potential LCOE impacts

EGS Reference Scenario
Summary of 50th Percentile LCOE

Varied Metric (TPM)	Total Potential LCOE for EGS Reference Scenario					
	2015			2025		
ANNUAL FUNDING LEVEL:	No DOE Funding	DOE Planned	DOE Expanded	No DOE Funding	DOE Planned	DOE Expanded
Well Drilling/Construction Costs	25.3	24.3	23.3	23.9	22.2	21.0
Plant Capital Costs		25.2	24.5		23.6	23.0
Well Stimulation Costs		25.3	25.1		23.7	23.5
Plant O&M Costs		25.3	25.1		23.8	23.6
Pump Costs		25.3	25.3		23.8	23.8
Exploration Success Rate		25.3	25.3		23.9	23.8
Non-Well Exploration Costs		25.3	25.3		23.9	23.9

- Values for 50th percentile LCOE (in Year 2008 ¢/kWh) for EGS reference scenario for single TPM improvements under no budget, target budget ($30 million), and over-target budget ($60 million) levels
- For comparison: Current estimate of LCOE = 26.4 ¢/kWh. LCOE calculated for reference scenario binary EGS plant. Binary EGS plant reference scenario assumptions: reservoir temperature = 225° C, reservoir depth = 6,000 m, power plant design temperature = 200° C. EGS “enabling technologies” assumed constant: production well flow rate = 60 kg/s, thermal drawdown rate = 0.3%/year, and producer-injector ratio = 2:1.

GETEM Modeling

RD&D Investment - Potential LCOE impacts

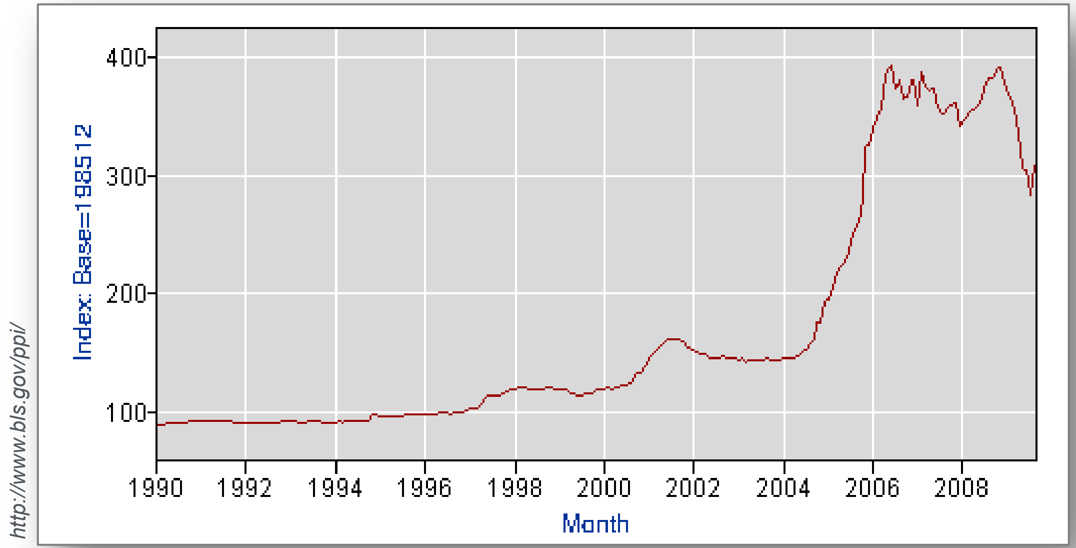
Hydrothermal Exploration Scenario
Summary of 50th Percentile LCOE

<table>
<tr><th rowspan="2">Varied Metric (TPM)</th><th colspan="6">Total Potential LCOE for EGS Reference Scenario</th></tr>
<tr><th colspan="3">2015</th><th colspan="3">2025</th></tr>
<tr><td>ANNUAL FUNDING LEVEL:</td><td>No DOE Funding</td><td>DOE Planned</td><td>DOE Expanded</td><td>No DOE Funding</td><td>DOE Planned</td><td>DOE Expanded</td></tr>
<tr><td>Exploration Success Rate</td><td rowspan="2">12.5</td><td>12.5</td><td>12.5</td><td rowspan="2">12.2</td><td>12.1</td><td>12.1</td></tr>
<tr><td>Non-Well Exploration Costs</td><td>12.5</td><td>12.5</td><td>12.2</td><td>12.2</td></tr>
</table>

- Values for 50th percentile LCOE (in Year 2008 ¢/kWh) for reference hydrothermal plant for single TPM improvements under no budget, target budget ($30 million) and over-target budget ($60 million) levels. Current estimate of LCOE is 12.8 ¢/kWh. LCOE calculated for reference scenario hydrothermal EGS plant (reservoir temperature = 175° C, reservoir depth = 1,524 m, power plant design temperature =175° C, production well flow rate = 44.2 kg/s, thermal drawdown rate of 0.3%/year, and producer-injector ratio of 3:1).

Metrics Affecting LCOE

Producer Price Index for "Drilling oil, gas, dry, or service wells"



- Recent rise in drilling costs partly responsible for the large role drilling costs play in overall EGS economics.
- At the time of the risk elicitations, drilling costs were near historic highs due to:
  - high rig rental rents caused by high crude oil and natural gas prices (which led to increased demand for oil and gas drilling)
  - the scarcity of steel and cement.

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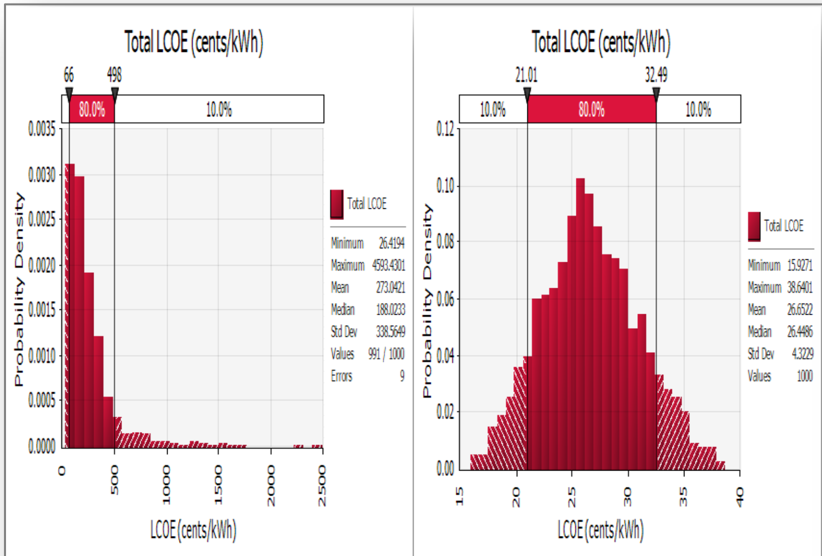
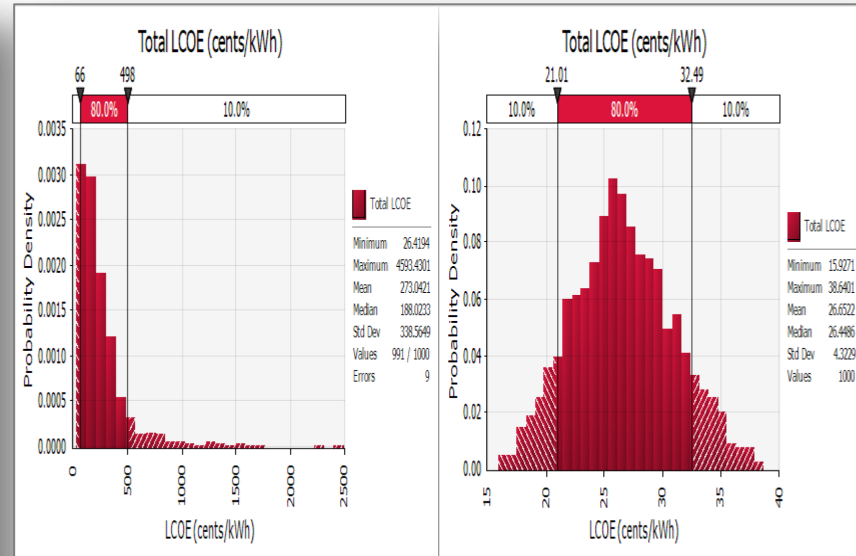
Aggregated Expert Distribution



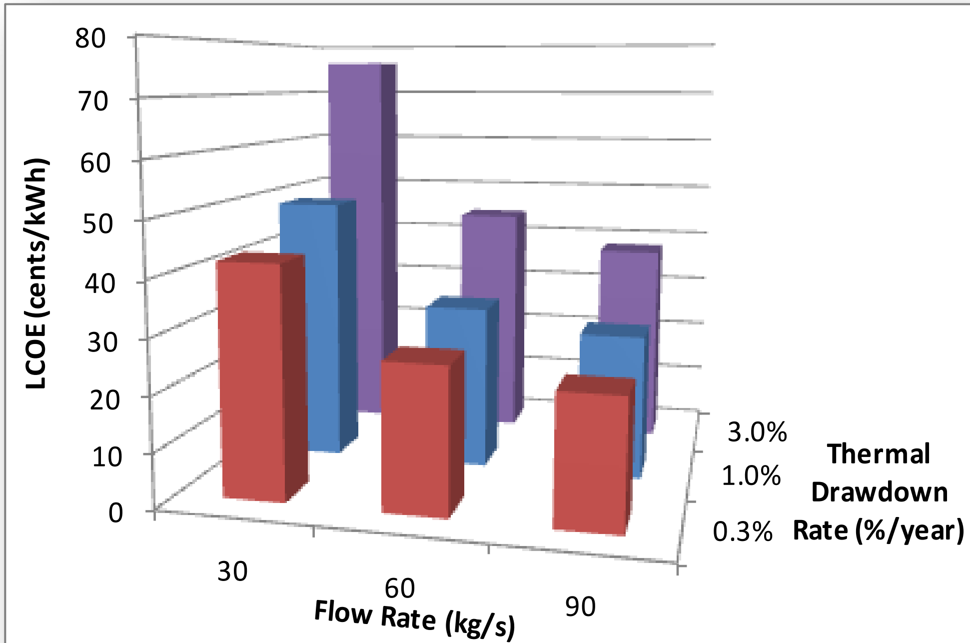
Distribution of LCOEs
for reference scenario EGS plant
assuming current costs
as provided by experts for all TPMs



Distribution of LCOEs with EGS
enabling-technology TPMs
fixed at constant values

production well flow rate:	60 kg/s
thermal drawdown rate:	0.3%/year
producer-injector ratio:	2:1

Metrics Affecting LCOE

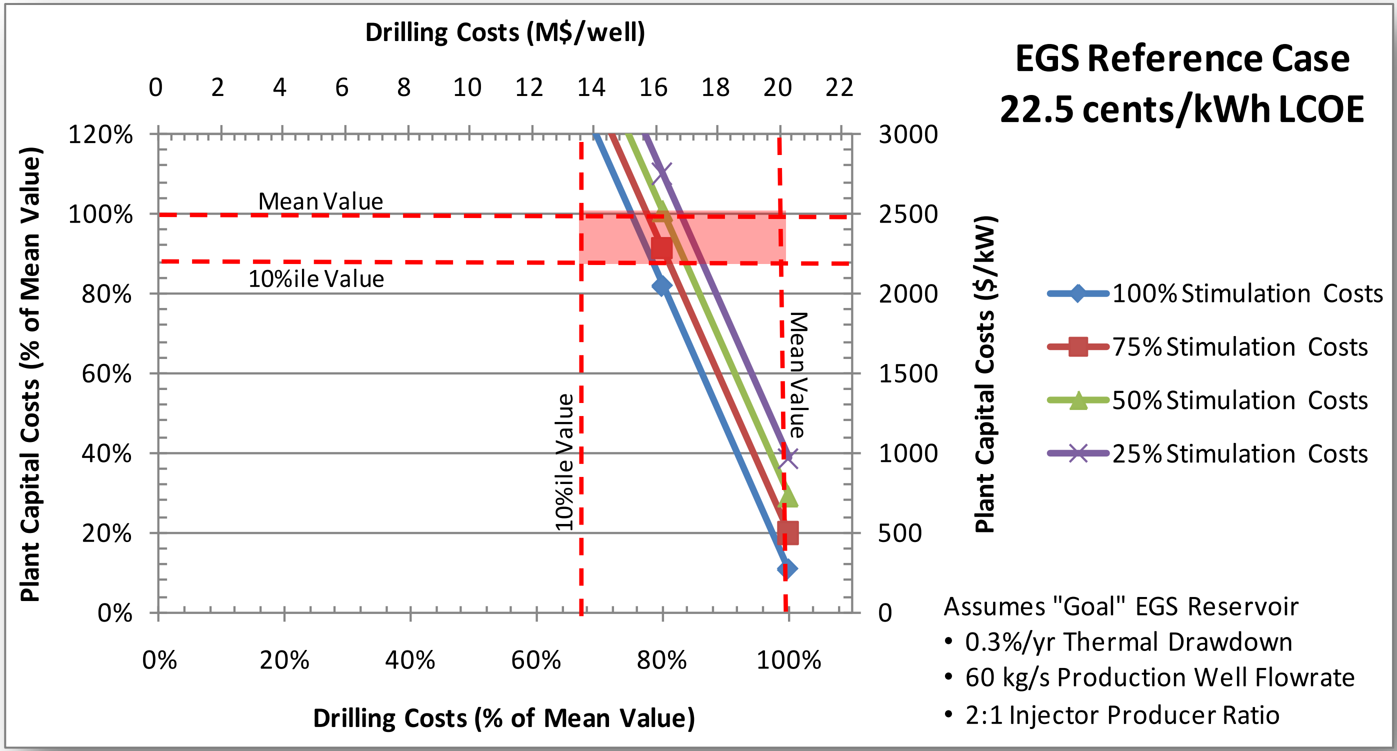


Summary of 50th Percentile LCOE for EGS reference scenario plant

Prod. Well Flow Rate:	30 kg/s	60 kg/s	90 kg/s
Thermal Drawdown	LCOE (2008 ¢/kWh)		
3.0%/yr	75.8	44.5	38.0
1.0%/yr	49.1	30.2	26.6
0.3%/yr	42.4	26.4	23.4

(assumes producer-injector ratio of 2:1)

Budget Adjustments - Potential LCOE impacts



- Drilling, power plant and stimulation cost scenarios that give 22.5 cents/kWh EGS reference case LCOE.
- Axes show plant and capital costs as both actual dollar values and as percentage of mean value from aggregated expert distributions.
- Dotted red lines indicate 100% of mean value and 10th percentile values from aggregated expert distributions.

Conclusions

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1. Considerable strides made in establishing a risk analysis protocol to be used by the GTP on an annual basis.
2. Greatest potential for reduction in levelized cost of EGS power:
   - reducing well drilling/construction costs
   - reducing power plant costs.
3. The near-historic high drilling costs is partly responsible for the large role it plays in overall EGS economics.
4. Reduce costs through RD&D investment in:
   - reducing well costs will lower the LCOE
   - reservoir engineering and plant performance to reduce the number of wells needed.
5. All experts believed that:
   - RD&D needs to first occur in enabling technologies for EGS
   - RD&D funding should not all be spent in only a few areas. The industry has the potential to benefit from investment in all four areas: exploration, wells/pumps/tools, reservoir engineering, and power conversion technologies.
6. Trade-off studies should be conducted to improve on the reference scenario design

Thank You

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