Recoverable EGS Resource Estimates

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Energy from the Earth’s Heat

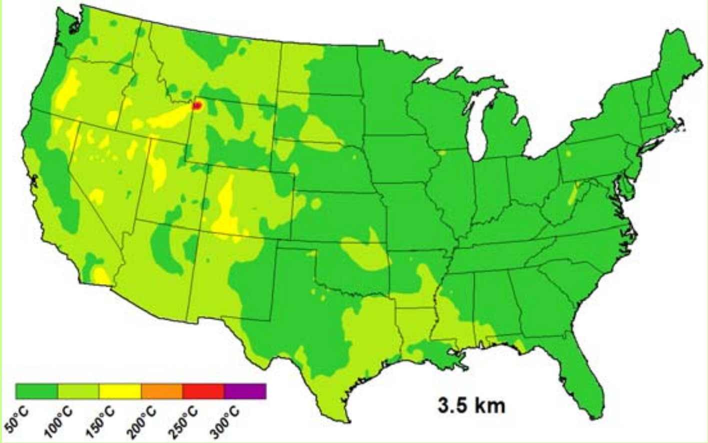
- ☐ Conductive heat energy
  - – Greater than 3 km
  - – Requires stimulation or other engineering to develop reservoir
- ☐ Convective heat energy
  - – Hydrothermal systems
  - – Impermeable or low permeability systems on the edges of hydrothermal systems
  - – Fractured, but may require stimulation or engineering to develop
- ☐ Hot water co-produced with oil and gas

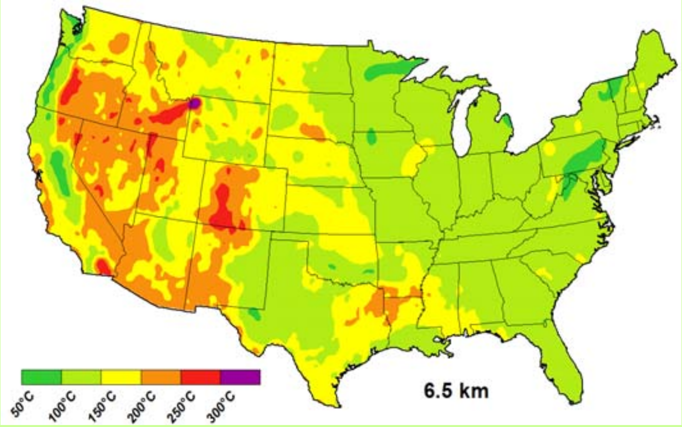
Conductive Resource - Base vs. Reserves

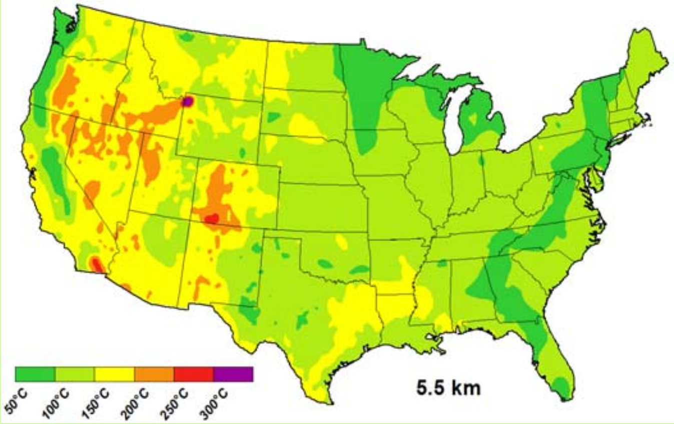
- ❑ Resource Base
  - Total heat in place
  - Between 3 km and 10 km
- ❑ Reserves
  - Economic today
  - Electric generation
  - Direct use of heat
  - EGS has no commercial projects as yet, so no reserves
- ❑ Recoverable Resource
  - Extractable
  - Conversion efficiency
  - Recoverable fraction
  - Accessible
  - Economics of recovery

Temperature at Depth

- Calculated by SMU
- Maps of temperature at depth at mid-point of 1km slices
- Area at each temperature in each depth slice
- Used to calculate heat in place







Abandonment Temperature

- Assume reservoir rock cooled 10°C
- Limit for conversion equipment at surface
- Leaves heat in place for future heat mining with different equipment
- Resource is sustainable due to enormous quantity of heat in place remaining, or available for recovery by heat mining, $Q_{available}$

$$Q_{total} - Q_{abandonment} = Q_{available}$$

Recovery Factor

- How much of the available heat can we recover?

$$F_r \equiv \frac{Q_{rec}}{Q_{total}} = f[V_{active}, V_{total}, C_\gamma, T_{r,i}, T_{r,a}, T_o]$$

$$F_r = \frac{\rho V_{active} C_\gamma (T_{r,i} - T_{r,a})}{\rho V_{total} C_\gamma (T_{r,i} - T_o)}$$

$$F_r = \phi_v \frac{(T_{r,i} - T_{r,a})}{(T_{r,i} - T_o)}$$

Q_{rec} = recoverable thermal energy content of the reservoir

ϕ_v = active reservoir volume/total reservoir volume

ρ = rock density (kg/m^3)

V_{total} = total reservoir volume (m^3)

V_{active} = active or effective reservoir volume (m^3)

C_γ = rock-specific heat (kJ/kg °C)

$T_{r,i}$ = mean initial reservoir rock temperature (°C)

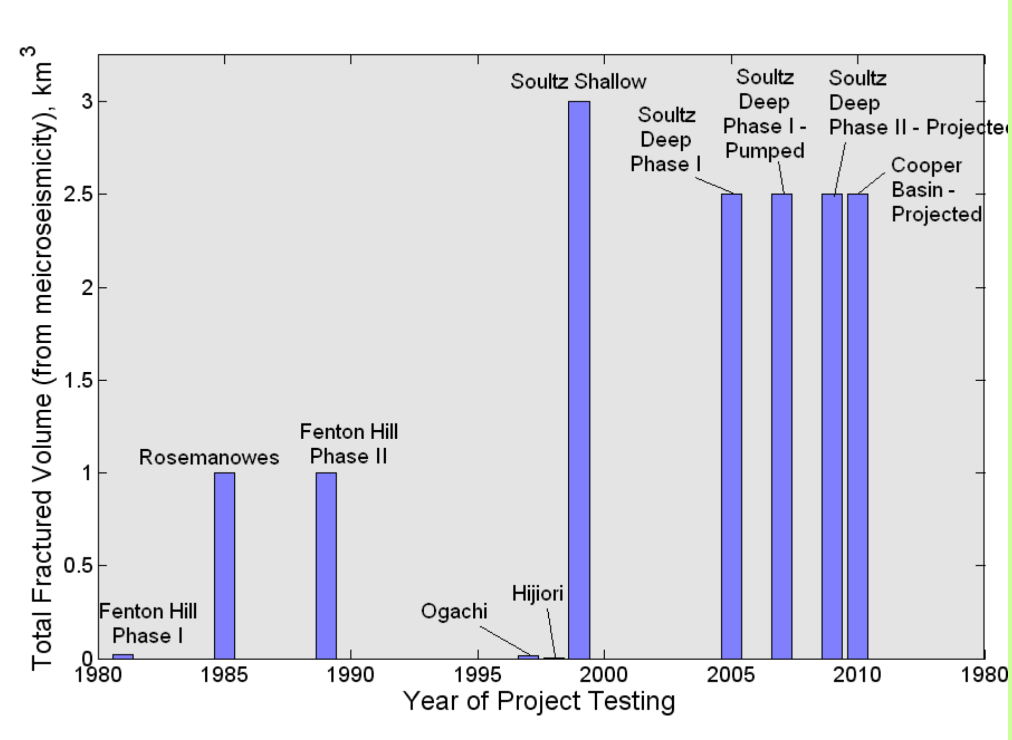
T_o = mean ambient surface or “dead-state” temperature (°C)

$T_{r,a}$ = mean rock temperature at which reservoir is abandoned (°C).

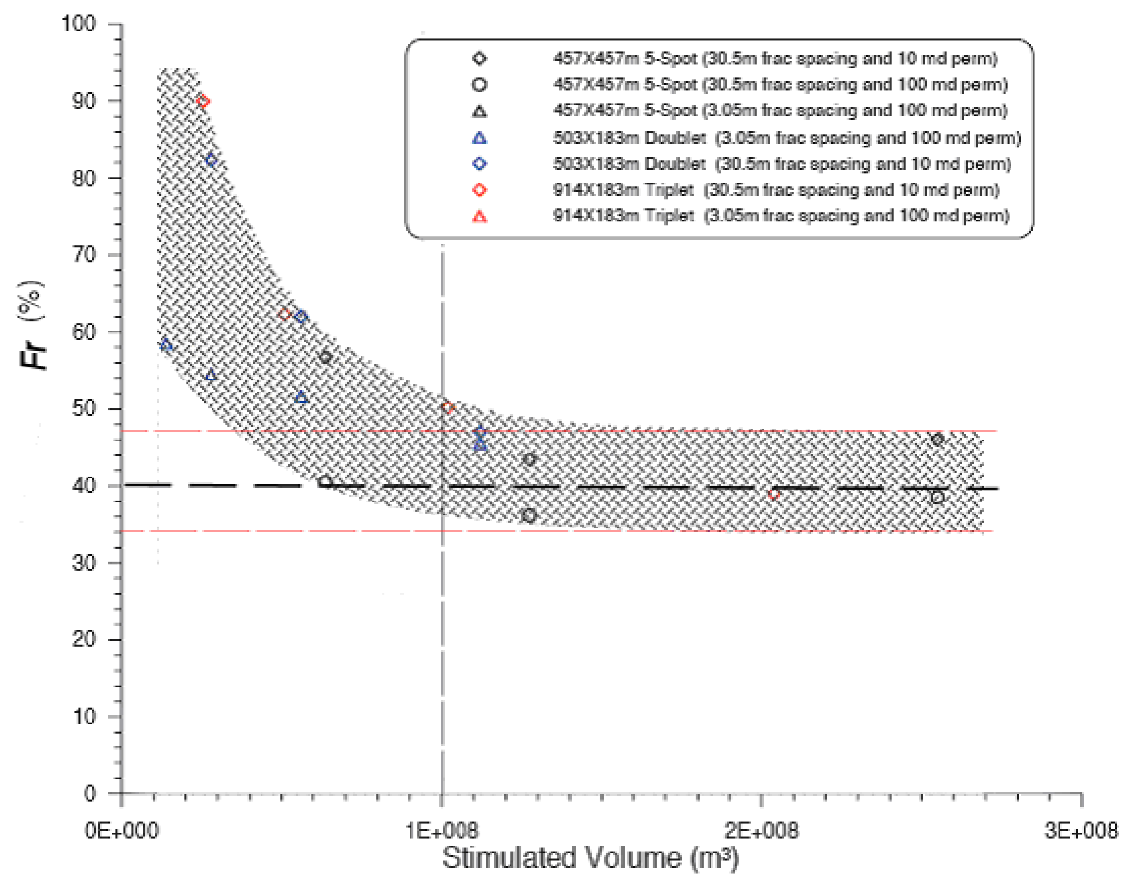
Fractured Volume

- Recovery of heat depends largely on fractured volume
  - Active heat exchange area
  - Fracture spacing
  - Path length between wells
  - Injector/producer pattern

Fractured Volume for EGS Projects



Recoverable Heat

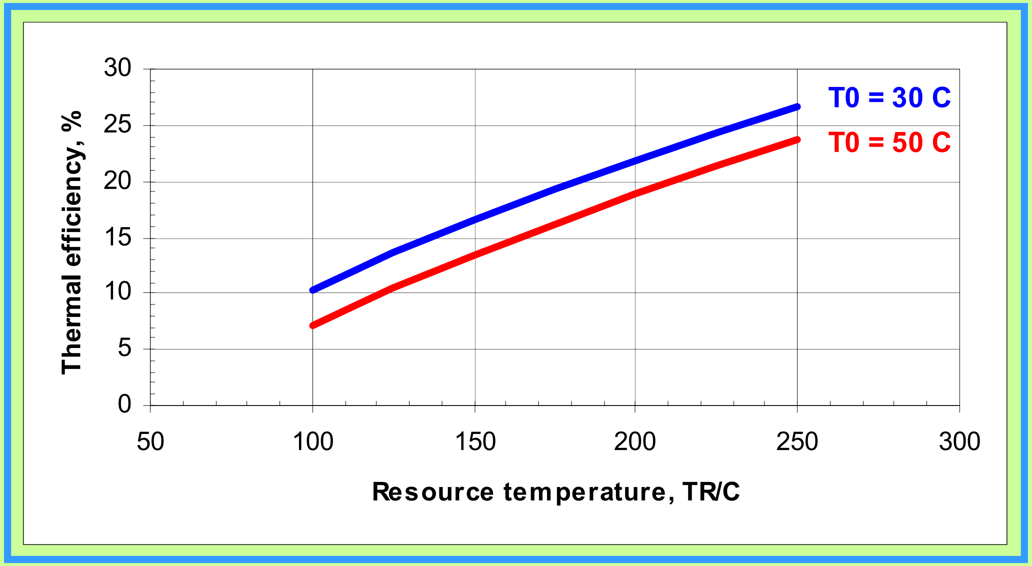


- ☐Sanyal and Butler, 2005.

Usable Energy – Converting Heat to Power

- Heat alone is beneficial.
- Conversion of heat to power better justifies well cost
- Heat in kilojoules = heat in kiloWatt-sec
- Convert heat to electric power
  - kW-sec/1000 kW/MW = MWt-sec
  - MWt-sec/(30 yrs in seconds)
  - Conversion efficiency MWt x ηth → MWe

Conversion to Electric Power - Cycle Efficiency



Temperature, ˚C	Cycle Thermal Efficiency η_{th}, %
150	11
200	14
250	16
300	18
350	22

Inaccessible Area

- ☐ Some areas are inaccessible for development:
  - Parks – State and National
  - Recreation Areas
  - National Monuments
  - Wilderness

Subtract inaccessible fraction

Total Recoverable Power

Total Recoverable Electric Power in Net MWe for 30 Years,

20% Recoverable Fraction of Thermal Energy from the Reservoir

Depth of Slice, km	Power available for slice, MWe	Amount at 150ºC, MWe	Amount at 200ºC, MWe	Amount at 250ºC, MWe	Amount at 300ºC, MWe	Amount at 350ºC, MWe
3 to 4	122,000	120,000	800	700	400	
4 to 5	719,000	678,000	39,000	900	1,200	
5 to 6	1,536,000	1,241,000	284,000	11,000	600	
6 to 7	2,340,000	1,391,000	832,000	114,000	2,800	
7 to 8	3,245,000	1,543,000	1,238,000	415,000	48,000	1,200
8 to 10	4,524,000	1,875,000	1,195,000	1,100,000	302,000	54,000
TOTAL	**12,486,000**					

Total Recoverable Power

Total Recoverable Energy in Net MWe for 30 Years

2% Recoverable Fraction of Thermal Energy from the Reservoir

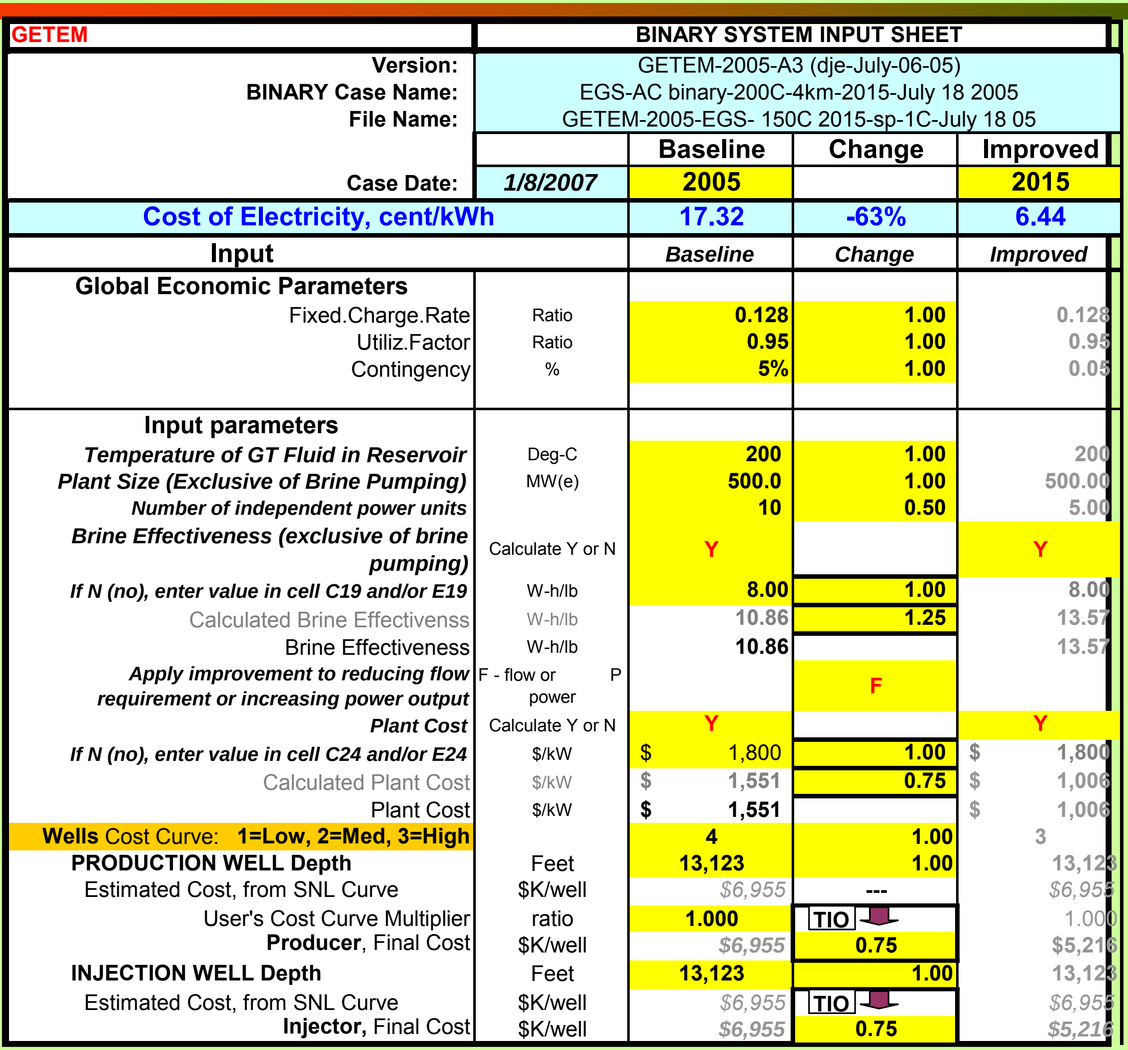
Depth of Slice, km	**Power available for slice, MWe**	**Amount at 150ºC, MWe**	**Amount at 200ºC, MWe**	**Amount at 250ºC, MWe**	**Amount at 300ºC, MWe**	**Amount at 350ºC, MWe**
3 to 4	12,000	12,000	80	70	40	
4 to 5	72,000	68,000	4,000	90	120	
5 to 6	154,000	124,000	28,000	1,100	60	
6 to 7	234,000	139,000	83,000	11,000	300	
7 to 8	324,000	154,000	124,000	41,000	5,000	120
8 to 10	452,000	187,000	119,000	110,000	30,000	5,000
TOTAL	**1,249,000**					

Economic Modeling

☐ Two models used:

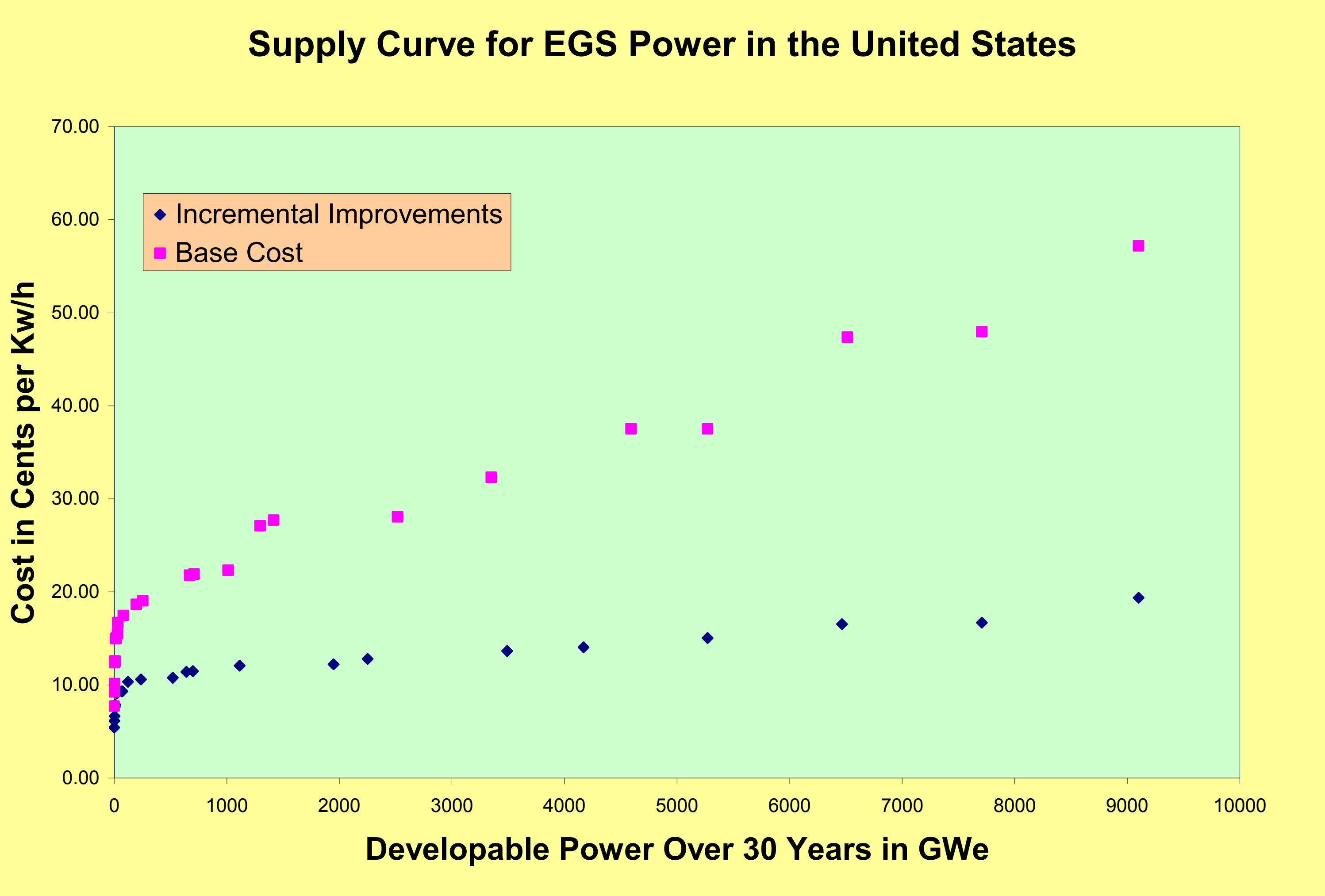
- GETEM – Geothermal Electricity Technology Evaluation Model
  - U.S. DOE developed new cost of power modeling tool
  - GETEM allows comparing cost of power with current technology to cost with improved technology.
- MIT EGS model
  - Updated for 2004 costs
  - Similar costs to GETEM for all but the highest cost resources
  - Can optimize costs for depth and temperature

Economic Modeling-GETEM

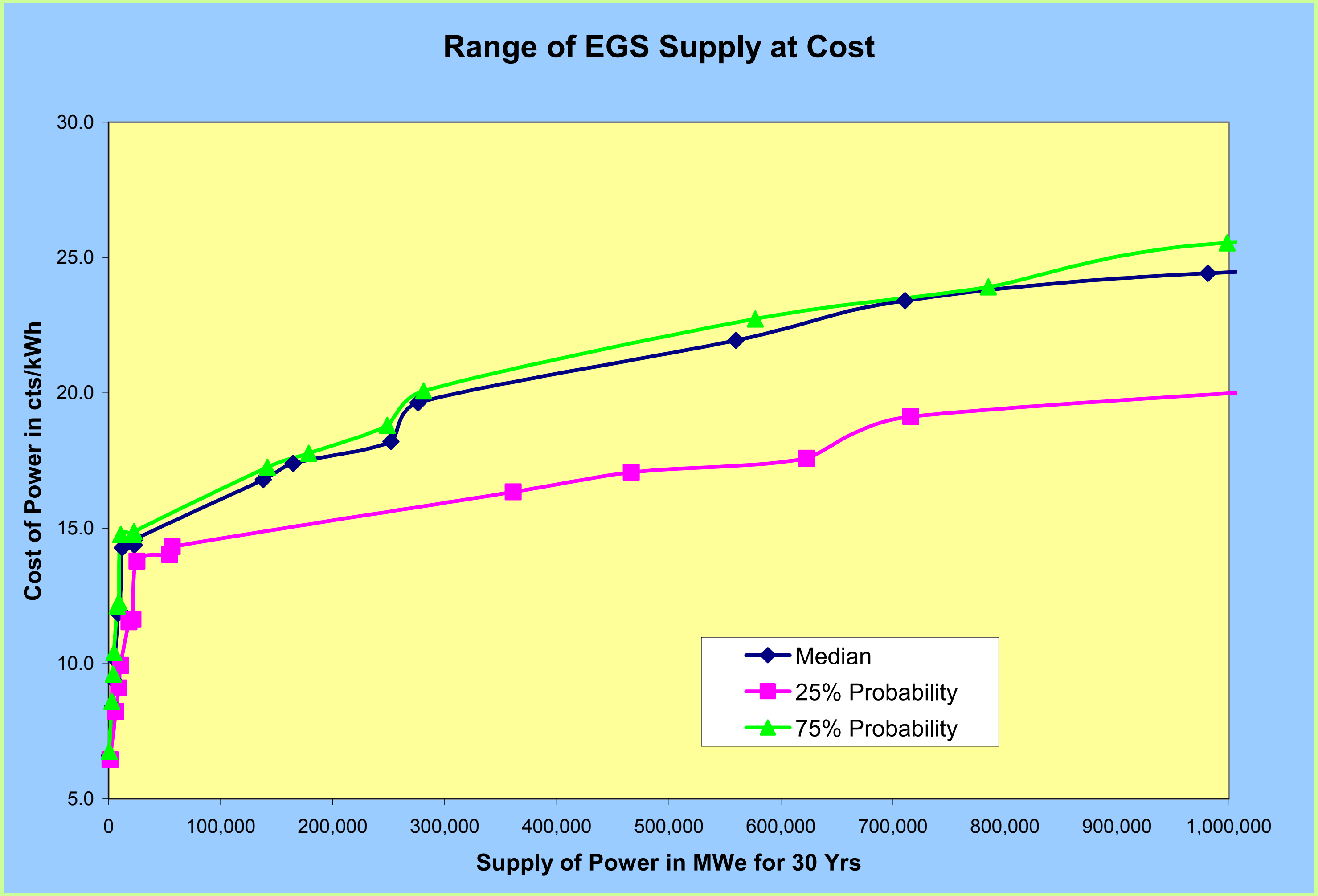


GETEM		BINARY SYSTEM INPUT SHEET		
Version:	GETEM-2005-A3 (dje-July-06-05)			
BINARY Case Name:	EGS-AC binary-200C-4km-2015-July 18 2005			
File Name:	GETEM-2005-EGS- 150C 2015-sp-1C-July 18 05			
		Baseline	**Change**	**Improved**
Case Date:	*1/8/2007*	**2005**		**2015**
Cost of Electricity, cent/kWh		**17.32**	**-63%**	**6.44**
Input		***Baseline***	***Change***	***Improved***
Global Economic Parameters				
Fixed.Charge.Rate	Ratio	**0.128**	**1.00**	**0.128**
Utiliz.Factor	Ratio	**0.95**	**1.00**	**0.95**
Contingency	%	**5%**	**1.00**	**0.05**
Input parameters				
Temperature of GT Fluid in Reservoir	Deg-C	**200**	**1.00**	**200**
Plant Size (Exclusive of Brine Pumping)	MW(e)	**500.0**	**1.00**	**500.00**
Number of independent power units		**10**	**0.50**	**5.00**
Brine Effectiveness (exclusive of brine pumping)	Calculate Y or N	**Y**		**Y**
If N (no), enter value in cell C19 and/or E19	W-h/lb	**8.00**	**1.00**	**8.00**
Calculated Brine Effectivenss	W-h/lb	**10.86**	**1.25**	**13.57**
Brine Effectiveness	W-h/lb	**10.86**		**13.57**
Apply improvement to reducing flow requirement or increasing power output	F - flow or P power		**F**	
Plant Cost	Calculate Y or N	**Y**		**Y**
If N (no), enter value in cell C24 and/or E24	$/kW	$ 1,800	**1.00**	**$ 1,800**
Calculated Plant Cost	$/kW	**$ 1,551**	**0.75**	**$ 1,006**
Plant Cost	$/kW	**$ 1,551**		**$ 1,006**
Wells Cost Curve: **1=Low, 2=Med, 3=High**		**4**	**1.00**	**3**
PRODUCTION WELL Depth	Feet	**13,123**	**1.00**	**13,123**
Estimated Cost, from SNL Curve	$K/well	*$6,955*	**---**	*$6,955*
User's Cost Curve Multiplier	ratio	**1.000**	TIO	1.000
Producer, Final Cost	$K/well	***$6,955***	**0.75**	**$5,216**
INJECTION WELL Depth	Feet	**13,123**	**1.00**	**13,123**
Estimated Cost, from SNL Curve	$K/well	*$6,955*	TIO	*$6,955*
Injector, Final Cost	$K/well	***$6,955***	**0.75**	***$5,216***

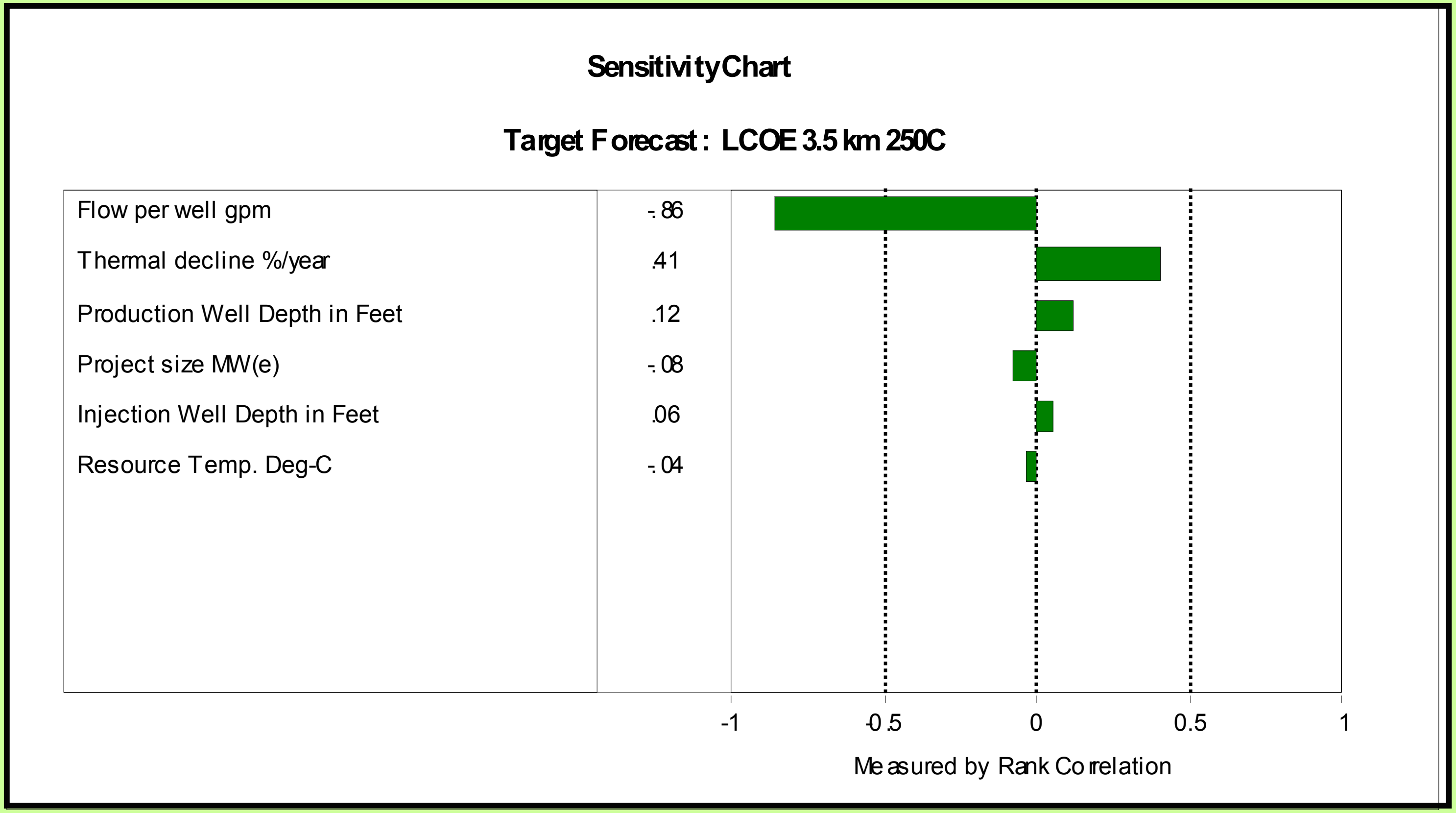
Supply Curve for U.S. Conductive EGS



Supply Curve for EGS Power



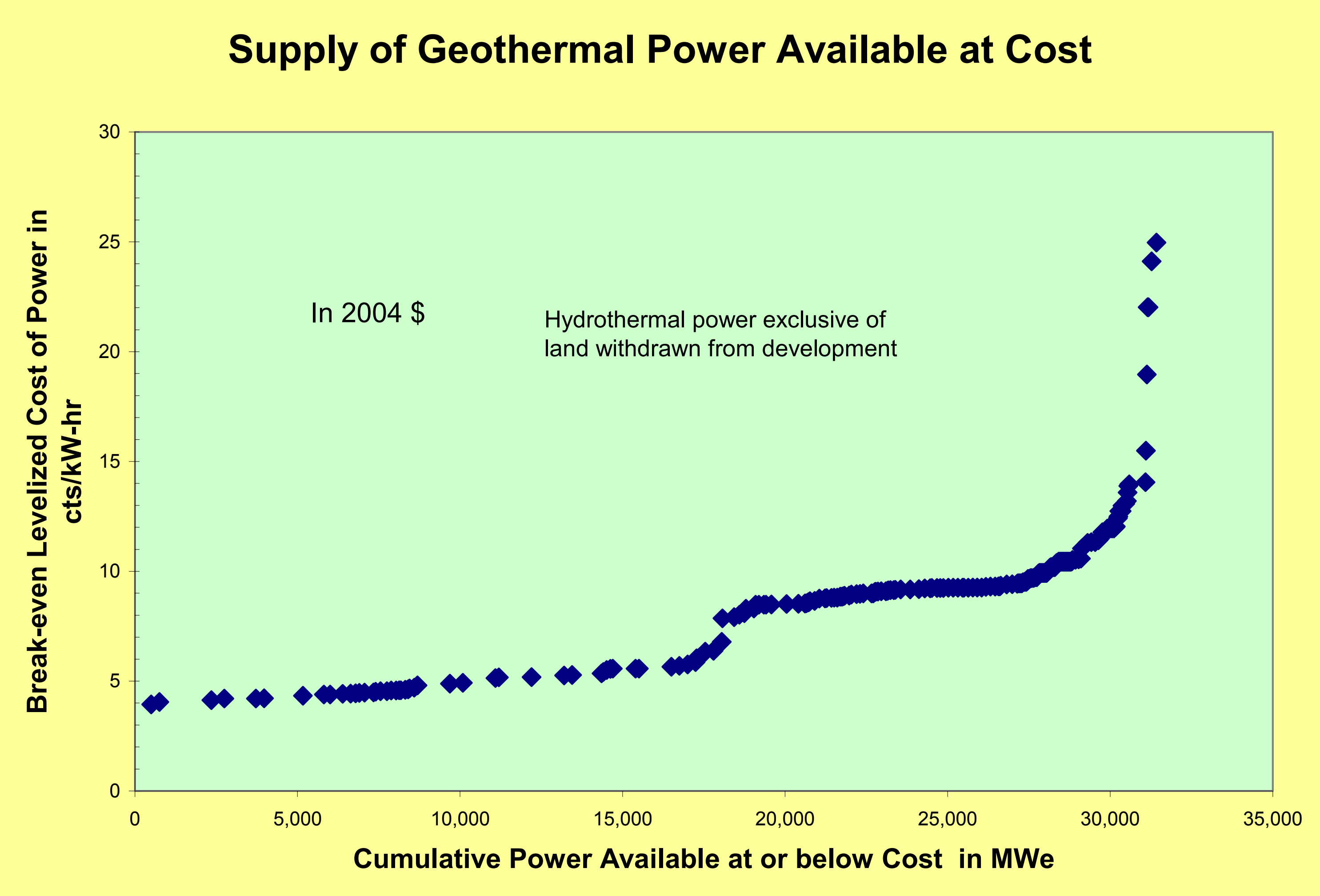
Cost - Sensitivity to Resource Variables



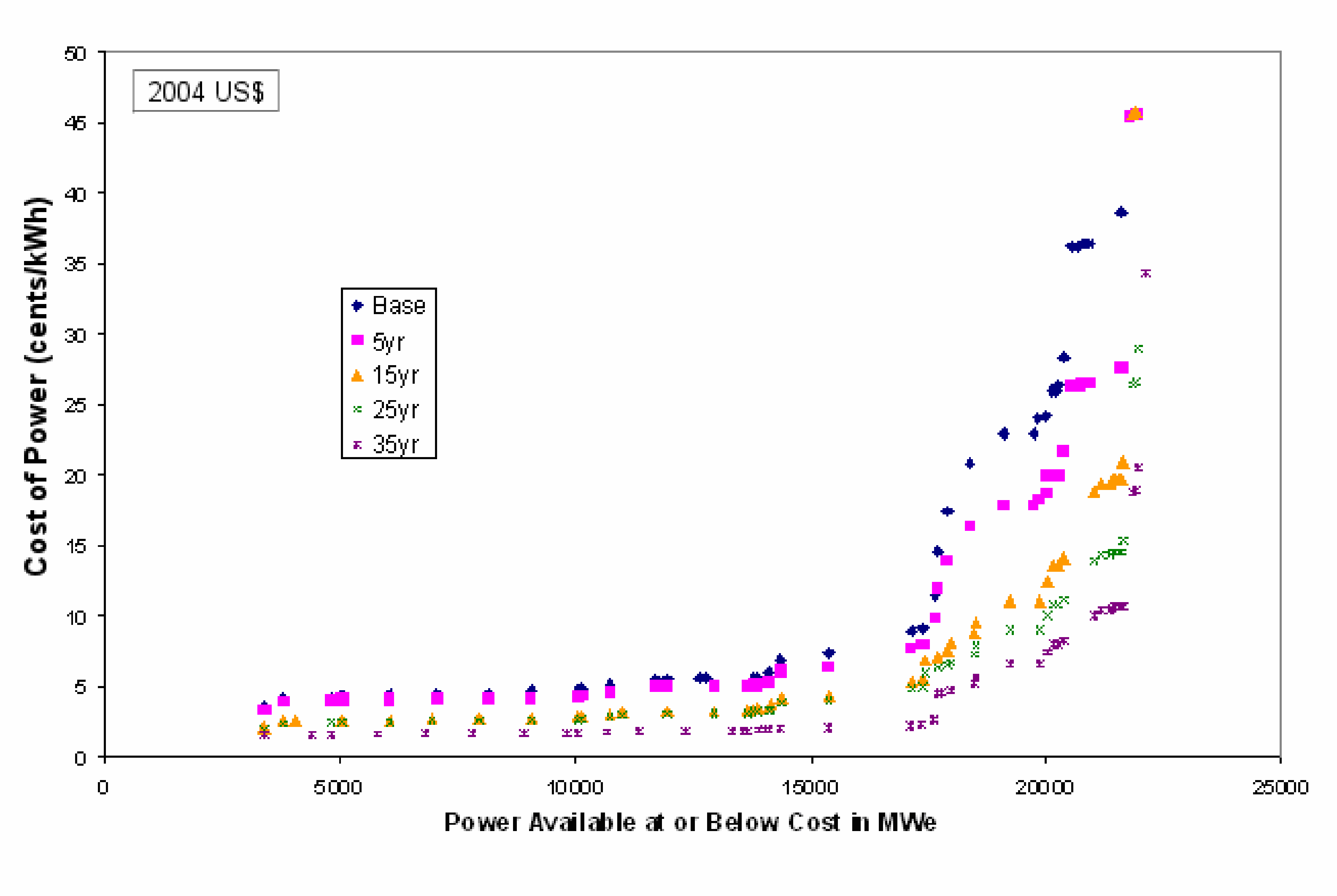
Convective vs. Conductive Resource

- Above 3 km
  - High temperature fluids
  - Permeability often controlled by faults and fractures
  - Rock heated by convection of hot water
- Hydrothermal resource – very high permeability
- Shallow EGS resource
  - On margins of hydrothermal systems
  - Volcanic heating

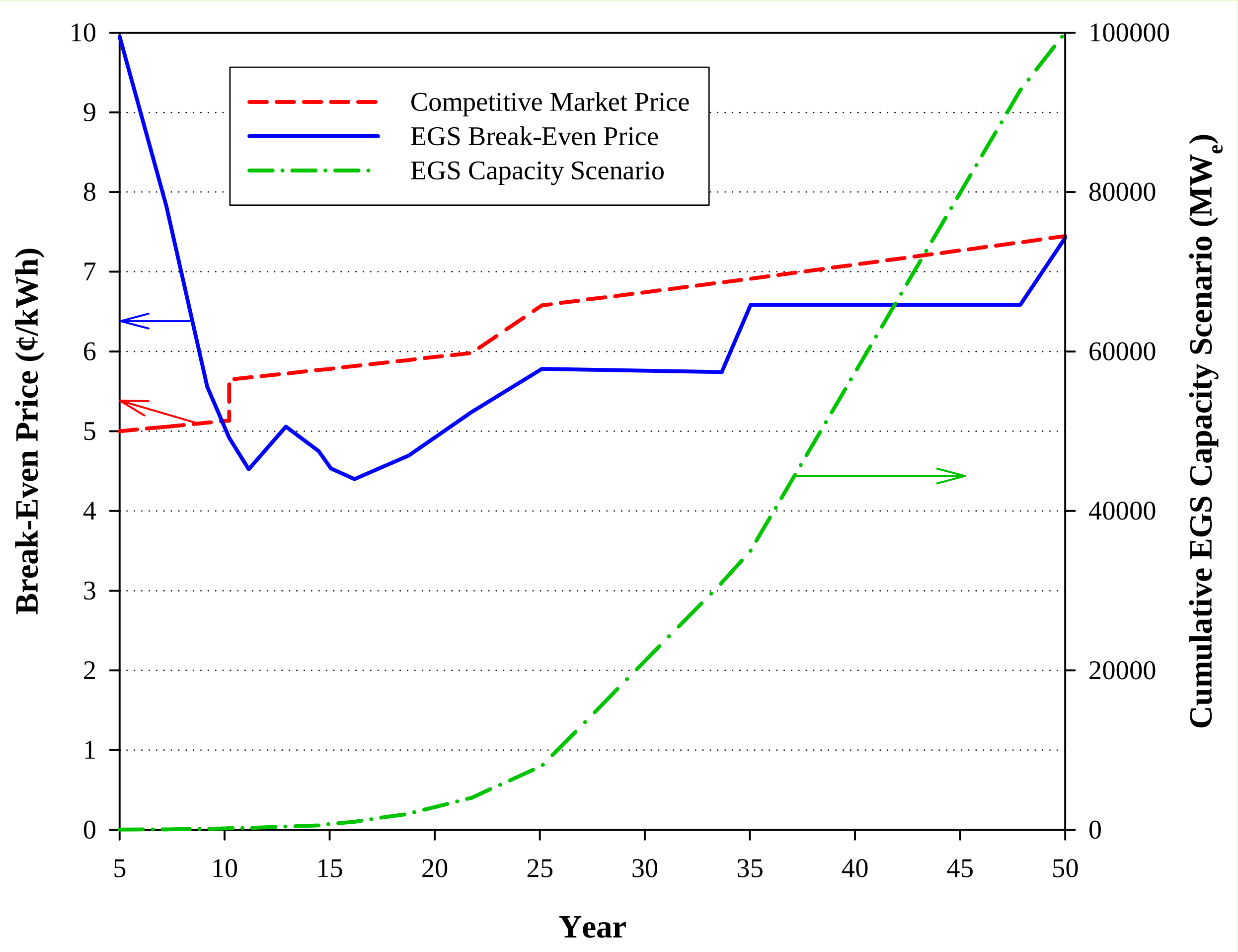
Hydrothermal and EGS Associated with Hydrothermal



Technology Improvement Impact on Cost of Power



Market Penetration of EGS Power



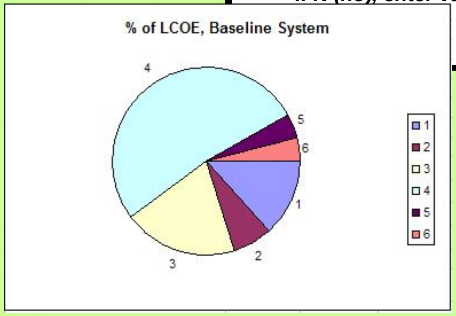
Assumes:

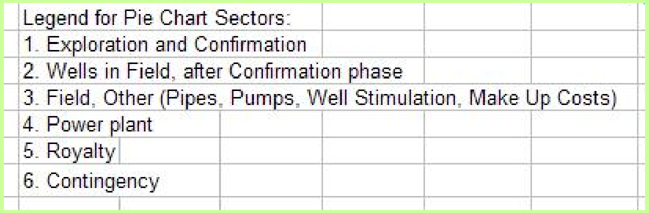
- Learning curves starting from 60 kg/s/prod.
- Technology improvement based on US Federal spending of $216 million.
- Uses MIT model and assumptions for learning curves

Cost of Power from Co-Produced Fluids

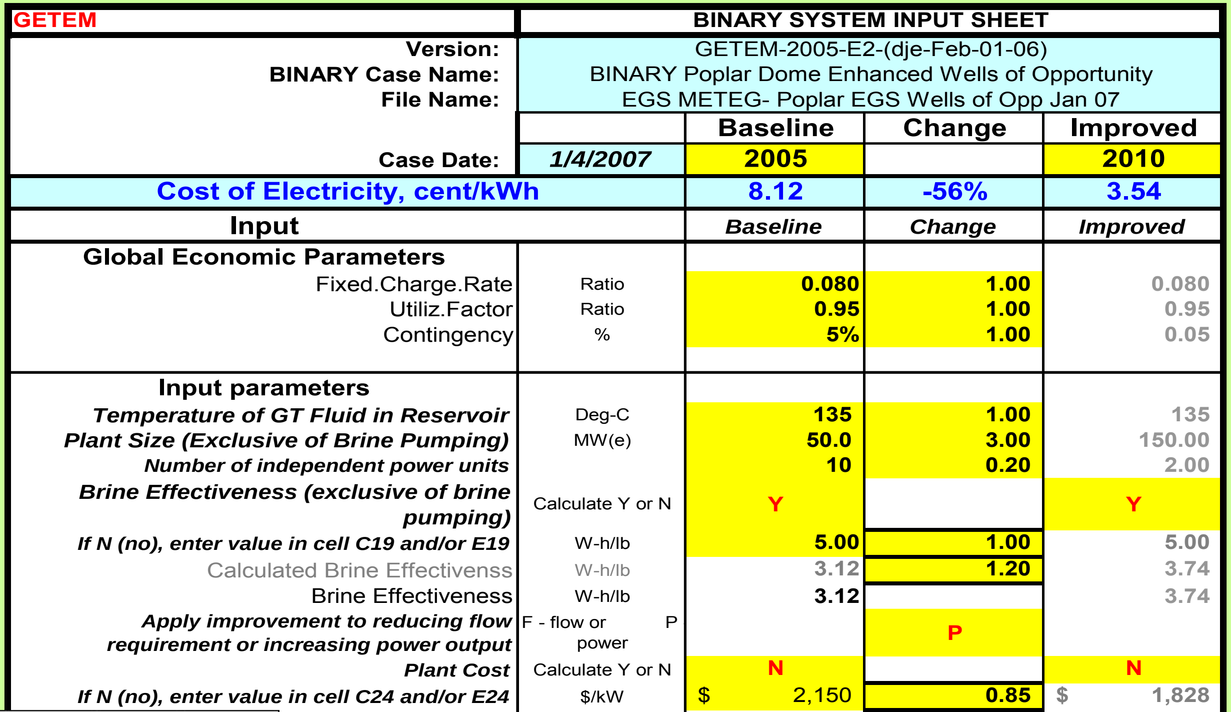
Wells of Opportunity

GETEM	BINARY SYSTEM INPUT SHEET			
Version:	GETEM-2005-E2-(dje-Feb-01-06)			
BINARY Case Name:	BINARY Poplar Dome Wells of Opportunity			
File Name:	EGS METEG- Poplar EGS Wells of Opp Jan 07			
		Baseline	**Change**	**Improved**
Case Date:	*1/4/2007*	**2005**		**2010**
Cost of Electricity, cent/kWh		**15.02**	**-61%**	**5.86**
Input		***Baseline***	***Change***	***Improved***
Global Economic Parameters				
Fixed.Charge.Rate	Ratio	**0.080**	**1.00**	0.080
Utiliz.Factor	Ratio	**0.95**	**1.00**	0.95
Contingency	%	**5%**	**1.00**	0.05
Input parameters				
Temperature of GT Fluid in Reservoir	Deg-C	**135**	**1.00**	135
Plant Size (Exclusive of Brine Pumping)	MW(e)	**5.0**	**2.00**	10.00
Number of independent power units		**10**	**0.20**	2.00
Brine Effectiveness (exclusive of brine pumping)	Calculate Y or N	**Y**		**Y**
If N (no), enter value in cell C19 and/or E19	W-h/lb	**5.00**	**1.00**	5.00
Calculated Brine Effectivenss	W-h/lb	3.12	**1.20**	3.74
Brine Effectiveness	W-h/lb	**3.12**		3.74
Apply improvement to reducing flow requirement or increasing power output	F - flow or P power		**P**	
Plant Cost	Calculate Y or N	**N**		**N**
If N (no), enter value in cell C24 and/or E24	$/kW	$ 2,150	**0.85**	$ 1,828
Calculated Plant Cost	$/kW	$ 5,038	**0.85**	$ 2,992
Plant Cost	$/kW	**$ 2,150**		$ 1,828




Legend for Pie Chart Sectors:
1. Exploration and Confirmation
2. Wells in Field, after Confirmation phase
3. Field, Other (Pipes, Pumps, Well Stimulation, Make Up Costs)
4. Power plant
5. Royalty
6. Contingency

Cost of Power from Co-Produced Fluids



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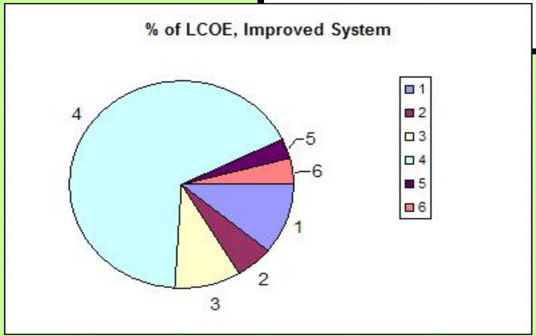
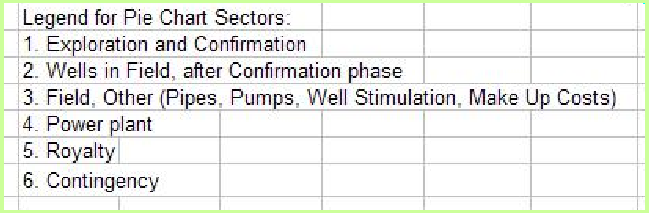
BINARY Case Name:	BINARY Poplar Dome Enhanced Wells of Opportunity			
File Name:	EGS METEG- Poplar EGS Wells of Opp Jan 07			
		Baseline	**Change**	**Improved**
Case Date:	*1/4/2007*	**2005**		**2010**
Cost of Electricity, cent/kWh		**8.12**	**-56%**	**3.54**
Input		***Baseline***	***Change***	***Improved***
Global Economic Parameters				
Fixed.Charge.Rate	Ratio	**0.080**	**1.00**	0.080
Utiliz.Factor	Ratio	**0.95**	**1.00**	0.95
Contingency	%	**5%**	**1.00**	0.05
Input parameters				
Temperature of GT Fluid in Reservoir	Deg-C	**135**	**1.00**	135
Plant Size (Exclusive of Brine Pumping)	MW(e)	**50.0**	**3.00**	150.00
Number of independent power units		**10**	**0.20**	2.00
Brine Effectiveness (exclusive of brine pumping)	Calculate Y or N	**Y**		**Y**
If N (no), enter value in cell C19 and/or E19	W-h/lb	**5.00**	**1.00**	5.00
Calculated Brine Effectivenss	W-h/lb	3.12	**1.20**	3.74
Brine Effectiveness	W-h/lb	**3.12**		3.74
Apply improvement to reducing flow requirement or increasing power output	F - flow or power P		**P**	
Plant Cost	Calculate Y or N	**N**		**N**
If N (no), enter value in cell C24 and/or E24	$/kW	$ 2,150	**0.85**	$ 1,828
Calculated Plant Cost	$/kW	$ 3,179	**0.84**	$ 1,866
Plant Cost	$/kW	**$ 2,150**		$ 1,828





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5. Royalty
6. Contingency

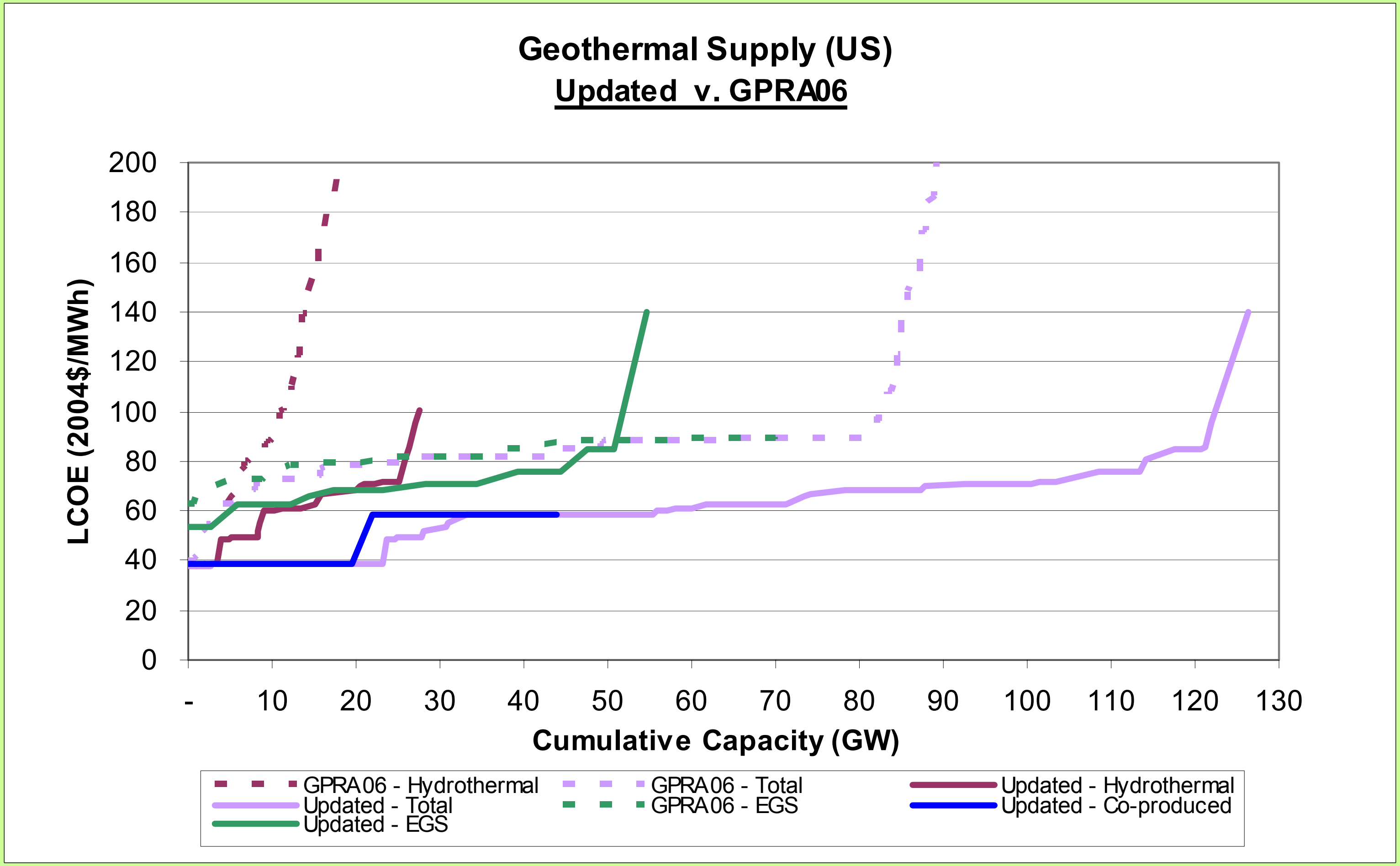
Geothermal Energy from Oilfields

- Heat included in conductive resource if deeper than 3 km.
  - Dissolved methane not calculated
  - Geopressured resource – kinetic energy not included
- Deep sedimentary basins
- Co-produced hot water with oil and gas
- Large amounts of available data
- Wells of opportunity

Modeling Geothermal Market Penetration

- ❑ Uses National Energy Modeling System – NEMS
- ❑ NEMS makes assumptions about technology learning curves, cost escalation.
- ❑ Demand based on projections from utilities in each of the federal regions.
- ❑ Each technology, ie, pulverized coal, solar thermal, PV, wind, geothermal, etc. has it’s own submodule to provide supply input and predict technology improvement

Supply Input for Geothermal Submodule of NEMS



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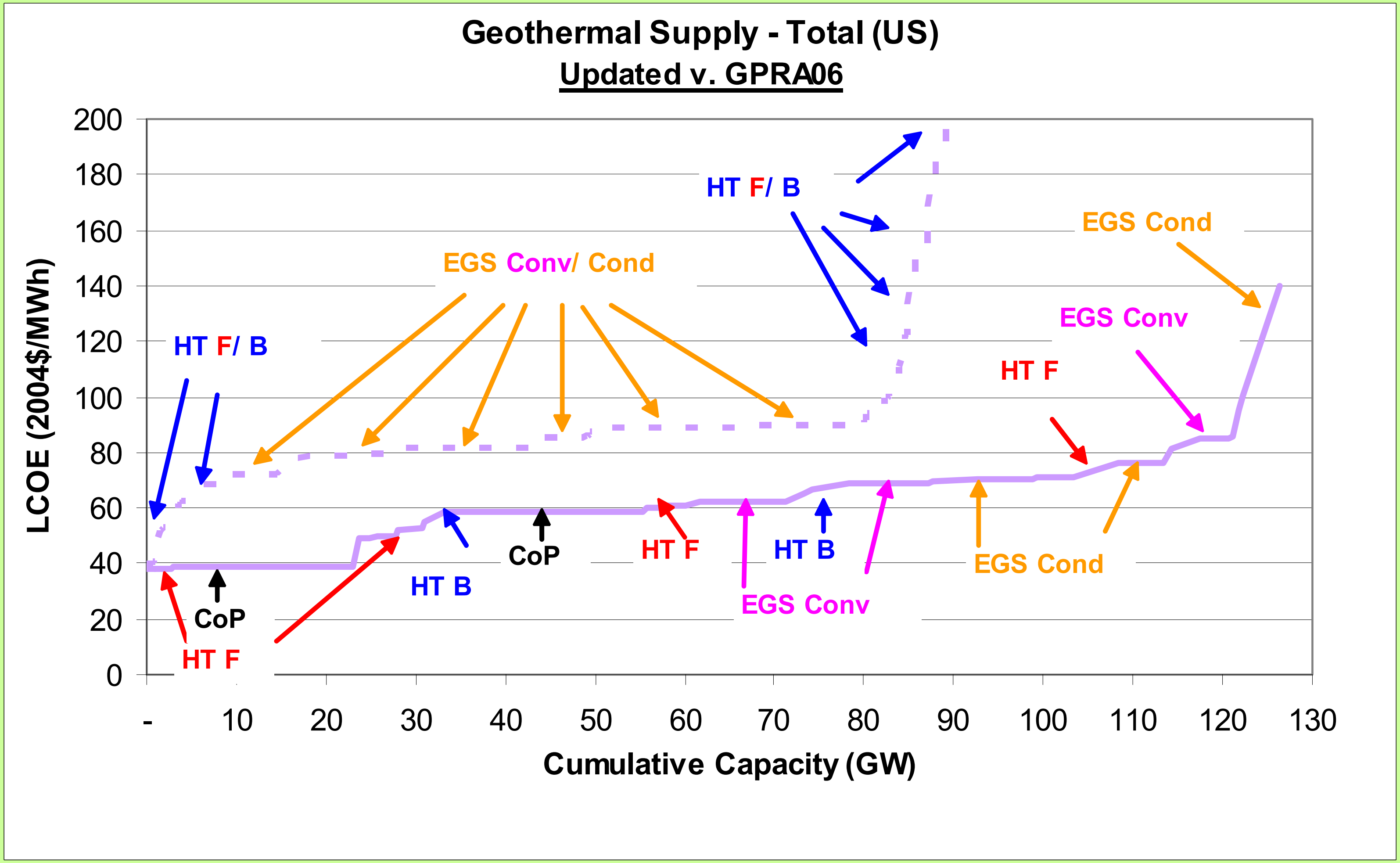

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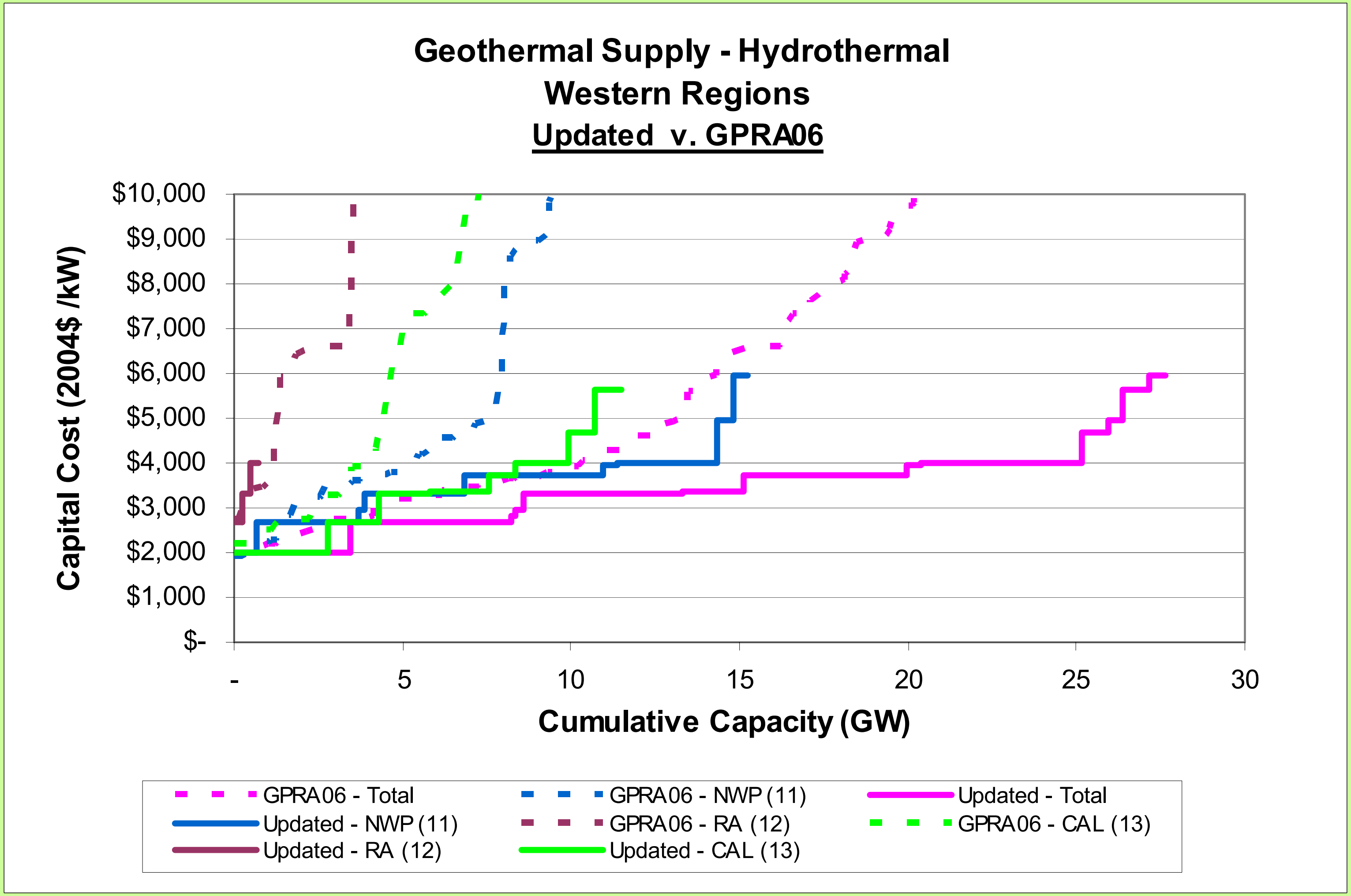

Forcast Geothermal Capacity from NEMS