AAPG/SPE/SEG HEDBERG CONFERENCE
"ENHANCED GEOTHERMAL SYSTEMS"
MARCH 14-18, 2011 – NAPA, CALIFORNIA

Managing EGS Play Portfolios – Assessing Geologic Uncertainties, Resource Distributions and Economic Adequacy

Barry Goldstein
Primary Industries & Resources, South Australia (PIRSA), Australia

A large number of distinctly different geologic settings are now being explored to define 'sweet-spots' where deep drilling can prove that all the conditions necessary for economically viable Enhanced (Engineered) Geothermal Systems are extensive in several locations worldwide.

The portion of these exploration drilling projects that prove that sufficiently hot rocks exist within reasonable drill depths will then (probably) progress to flow tests, to prove locally that geothermal plays are at least adequate to flow sufficiently hot fluids at significant rates, fulfilling the objective of that proof-of-concept phase on the path to commercializing geothermal resources. The portion of plays proved locally to have the capacity to flow at potentially economic rates can then move into a pre-competitive demonstration phase on the path to proving geothermal reserves, as a precedent to justify development. In particular, successful path-finder EGS projects are expected to stimulate competitive investment globally.

Given this as background, and based on the (estimated AUS$500+ million (US$490+ million) already invested in geothermal projects in Australia, the Australian Geothermal Energy Group (AGEG) forecasts:

- At least 10 successful research (exploration drilling) and proof-of-concept (heat energy is flowed) deep geothermal projects by 2014. This will be enabled with government grants and market frameworks that stimulate pre-competitive, 'learn-while-doing' investment to pull low emissions and renewable energy technologies through costs-curves, towards market-competitive energy supplies.
- Several geothermal power generation demonstration projects in distinctively different geologic settings in the coming years, and at least 3 by 2014, if governments provide sufficient 'pull' for pre-competitive, 'learn-while-doing' investment in the demonstration of hot sedimentary aquifer and hot rock (EGS) geothermal projects.
- Compelling success with geothermal power generation demonstration so the investment community is convinced hot rock EGS is real by 2014, again, if governments provide sufficient 'pull' and market incentives for pre-competitive, 'learn-while-doing' investment in the demonstration of low emissions and renewable energy technologies, and hot rock geothermal, in particular.
- Realising the vision of safe, secure, reliable, and the lowest-priced renewable and emissions-free base load power from geothermal energy for centuries to come, with at least 10% of Australia's base-load demand from hot rock power by 2050.

Standard investment management methods including the aggregation of risk-weighted (expected) net present values will inevitably be applied to steward funding for efficient and effective exploration, proof-of-concept and pre-competitive demonstration projects on the road to commercializing corporate and national portfolios of hot rock resources.

A coherent portfolio approach is posed to constructively influence corporate strategies and government policies (and programs) to commercialize vast geothermal plays efficiently, at maximum pace and minimum cost. In particular, the methodology posed enables consistent estimates of the costs and benefits of precompetitive learning-while-doing (learning curves) through research (drilling), proof-of-concept (flow testing) and demonstration (pre-competitive power generation) phases of EGS projects.

The method is presented as a hypothetical scenario of three distinct yet-to-be proven hot rock play-trends with potential to be economically viable EGS projects. The methods are as defined by Capen (1992) and Rose (1992) for dealing with exploration uncertainties and estimating the chance of economic success in petroleum exploration. These methods are well recognized as *world's best practice* for petroleum exploration, and have been proven to be effective in managing geologic uncertainties in very competitive oil and gas markets.

Additionally, uncertainty in resource size can be managed with a a probabilistic range, for example, assuming that a log normal distribution adequately describes the range of recovery of stored heat

The Method

Three key geologic factors need be <u>at least</u> adequate quality for the hot rock EGS plays to exist. These three factors are:

- sources of heat in the form of radiogenic, high heat-flow basement rocks (mostly granites);
- insulating strata to provide thermal traps; and
- permeable fabrics within insulating and basement rocks that are susceptible to fracture stimulation to create geothermal reservoirs.

Paraphrasing Rose (1992), experts can assess the likelihood of key geologic factors being at least adequate within a defined area, and estimate the chance that a hot rock play exists.

This calculation does not address the size of the resource, just the likelihood that all necessary conditions that are favorable for geothermal energy to accumulate in permeable rocks (or rocks susceptible to fracture stimulation) in a particular location.
In a situation where all wells have found a hot rock resource, and geothermal reservoirs have been developed, the likelihood of each of these factors being adequate in the drilled area can be assessed to be 100%, and the chance of encountering at least adequate geology is also 100%.

Where insufficient information is available to have such high certainty, the chance of geologic adequacy will be less than 100%, and can be estimated from the serial product of factor adequacy assignments. For hot rock EGS plays, the serial product of the chance for at least adequate quality for three key factors (heat source, heat trap and heat reservoir) is proposed as the chance for (an at least adequate) hot rock EGS play to exist over the area where the factor adequacy assignments apply.

As defined by Rose (1992), the serial product of key geologic factor adequacy is the chance for geologic success.

Further assessment of the likelihood of economic success can take into account the minimum necessary well flow rates required to underpin a break-even (threshold economic) net present value outcome based on all forecast (scenario) costs (CAPEX and OPEX) and revenues (pre- and post tax and depreciation) for research (including exploration drilling), proof-of-concept flow tests, pre-competitive demonstration of EGS, appraisal projects to convert geothermal resources to a proven reserve status, marketing, development, transmission, distribution and finally sales to end-users. Factors such as cost of capital and the extent of integration across the supply: demand chain will differ between companies.

On this basis, the estimated chance of attaining target heat flow rates (expressed as a threshold litres/second rate of flow to surface at a threshold initial temperature) is proposed as a fourth factor quality estimate that enables the quantification of the chance for at least a break-even economic result.

In summary, the product of the chance of geologic success and the chance for threshold economic heat flow rates is offered as an estimate of the chance for at least break-even (economic) success. This is the chance that all the factors that characterize a particular EGS play as favorable for both (1) geothermal energy to have accumulated in a particular location and (2) economic production rates.

Estimates of resource and reserve volumes to various levels of certainty for use in discounted (for time value) cash flow scenarios to express a mean (average) net present value come from other methods that are not addressed here, but will be addressed in future publications.

Taking this another step, net present values for an average or mean full-cycle EGS production scenario, and estimates of the chance of economic success for an EGS play-trend enable estimates of expected values and a portfolio approach to investment in EGS plays. This methodology is illustrated by way of a hypothetical example.

Say, for EGS *Play A*, the likelihood (expressed as a probability, P) for each of the four key hot rock EGS factors are as follow:

Hot Rock Play A EGS Factors	Descriptions
$P_{\text{heat source}}$ = 90%	Very certain radiogenic granites at depth, given ≥210ºC at target depth is assumed <u>minimum</u> adequacy for heat exchange efficiency.
$P_{\text{heat trap}}$ = 90%	Insulating strata at depth very certain
$P_{\text{heat reservoir}}$ = 50%	Prevailing stress regimes favor natural fractures, but no local well control. Critical uncertainty
$P_{\text{heat flow rate}}$ = 50%	Minimum threshold flow estimated to be 75 l/s at ≥200ºC at surface

In this example:
the chance for EGS play geologic success (*i.e.* the probability of geological success P_g)

= ($P_{heat\ source}$ x $P_{heat\ trap}$ x $P_{heat\ reservoir}$)
= 90% x 90% x 50%
= 40.5%

the chance of geologic inadequacy is the complement of P_g, that is,

= 100% - P_g
= 100% - 40.5%
= 59.5%.

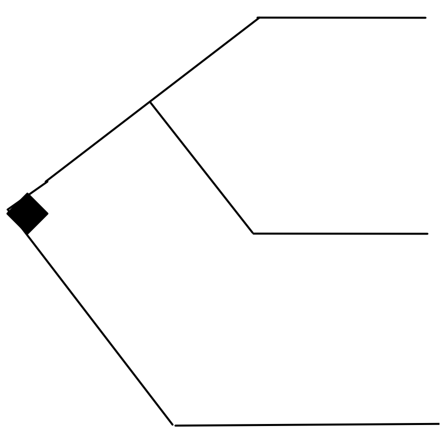
the chance of a technical success (*i.e.* a geologic success with inadequate flow rate) is thus,

= (1- $P_{heat\ flow\ rate}$) x P_g
= (100% – 50%) x 40.5%
= 20.25%

and the chance for an economic success (*i.e.* the probability of economic success P_s) is

= ($P_{heat\ source}$ x $P_{heat\ trap}$ x $P_{heat\ reservoir}$ x $P_{heat\ flow\ rate}$)
= = 90% x 90% x 50% x 50%)
= 20.25% = P_s

This may be illustrated using a decision-tree format as shown in figure 1.



Economic Adequacy = 20.25%
Say NPV of mean success case is $50 million for a single area within a play trend. The NPV for the mean success case for the entire play trend is $500 million

Geologic Adequacy but < Threshold Flow Rate = 20.25%
Say incremental cost of unsuccessful fracture stimulation is $2 million

Geologic Inadequacy = 59.5%. Say cost of failure is $10 million

Chance of economic failure = 20.25% + 59.5% = **79.75%**

Sum of probabilities = 100%

Figure 1. Decision-tree for hypothetical EGS Play A.

In this case (figure 1), the simplified pre-drill expected net present value to drill and fracture stimulate a well in EGS Play A is $0.56 million and calculated as follows:

= (P_s for Play A mean resource) – ((1- P_s) x NPV of well operations with post-frac flow tests)
= {20.25% x $50,000,000} - {$12,000,000 79.75%)
= $560,000 Expected Net Present Value

If the success scenario NPV of the entire play trend is much greater than $50 million, the expected value of the information to be gained by drilling to test EGS Play A will be commensurately greater.

Value of Information

Say the unrisked net present value for the entire play that can be addressed with the drilling of one deep well is $500 million, and if successful, the implication are for:

$P_{\text{heat reservoir}}$ to move from 50% to 75%; and

$P_{\text{heat flow rate}}$ to move from 50% to 75%.

In this example

the chance for EGS play geologic success (Pg)
= 90% x 90% x 75% = 60.75%

the chance of geologic inadequacy is the complement of 60.75% i.e. 39.25%.

the chance of EGS technical success
=P heat flow rate) x Pg = (100% – 75%) x 60.75% = 15.19%

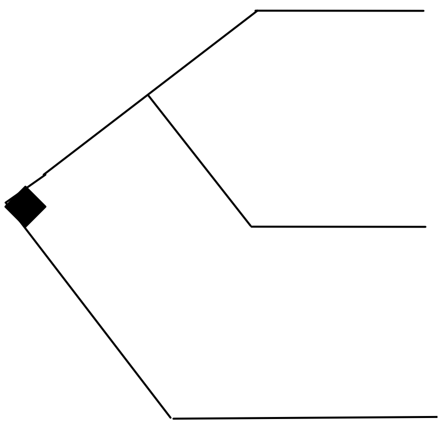
The chance for EGS economic success
= Pg (60.75%) x $P_{\text{heat flow rate}}$ (75%) = 45.56%

This is illustrated with in a decision-tree format in figure 2

In this particular case the value of the information gained from a successful exploration (research) and flow test (proof-of-concept) result in EGS Play A is the shift in expect value, which is illustrated in figure 2. The value of the information gained from a successful exploration and flow test result in a well that increases certainty in the prevalence of EGS Play A reservoirs is estimated as follows:

Pre-drill Expected NPV for Hypothetical EGS Play A
{20.25% x $500 million unrisked NPV for EGS Play A} - {$12 million x 79.75%) = $91.68 million

Post drill Expected NPV for Hypothetical EGS Play A
{45.56% x $500 million unrisked NPV for EGS Play A} - {$12 million x 54.44%) = $221.27 million
The value of this information is very large, and can be estimated to be the difference between the pre- and post-drill expected net present values expressed above.



Economic Adequacy after successful exploration and flow tests shifts from 20.25% to **45.56%**
Say the NPV for the mean success case for the entire play trend is $500 million

Geologic Adequacy but < Threshold Flow Rate after successful exploration and flow tests shifts from 20.25% to **15.19%**
Say incremental cost of unsuccessful fracture stimulation is $2 million

Geologic Inadequacy after successful exploration and flow tests shifts from 59.5% to **39.25%.** Say cost of failure is $10 million

After successful exploration and flow tests, the chance of failure shifts from {20.25% + 59.5%} = 79.75% to {15.19% + 39.25%) = 54.44%

Sum of probabilities = 100%

Figure 2. Decision-tree for value of information associated with a hypothetical EGS Play A.

Let us for a moment assume we have three independent EGS play-trends to explore with characteristic play-trend geologic factor adequacies as displayed below – then we can determine the chances that EGS plays will be at least geologically adequate, geologically inadequate, geologically adequate but short of threshold economic heat flow rates and economically successful.

Portfolio:	**Play A**		**Play B**		**Play C**	
Factors	Chance of Adequacy	Chance of Inadequacy	Chance of Adequacy	Chance of Inadequacy	Chance of Adequacy	Chance of Inadequacy
$P_{heat\ source}$	90%	10%	90%	10%	50%	50%
$P_{heat\ trap}$	90%	10%	90%	10%	90%	25%
$P_{heat\ reservoir}$	50%	50%	75%	25%	50%	50%
$P_{heat\ flow\ rate}$	50%	50%	25%	75%	25%	75%
	Play A		**Play B**		**Play C**	
$P_{geologic\ success} = P_g$	(90% x 90% x 50%) = **40.50%**		(90% x 90% x 75%) = **60.75%**		(50% x 90% x 50%) = **22.50%**	
$P_{geologic\ failure} = 1-P_g$	(1 - 40.50%) = **59.50%**		(1 - 60.75%) = **39.25%**		(1 - 22.50%) = **77.50%**	
$P_{technical\ success}$	40.50% x (1 - 50%) = **20.25%**		60.75% x (1 – 25%) = **45.56%**		22.50% x (1 – 25%) = **16.88%**	
$P_{technical\ failure}$	(1- 20.25%) = **79.75%**		(1- 45.56%) = **54.44%**		(1- 16..88%) = **84.22%**	
$P_{economic\ success} = P_s$	(40.50% x 50%) = **20.25%**		(60.75% x 25%) = **15.19%**		(22.50% x 25%) = **5.63%**	
$P_{economic\ failure} = P_f$	(1 – 20.25%) = **79.75%**		(1 – 15.19%) = **84.81%**		(1 – 5.63%) = **94.38%**	

First – if assignments are made in a consistent way – this provides a tool for ranking plays.
Second – if assignments are made in a consistent way - this enables estimates of the chance that exploring all three play trends will result in at least one geologically adequate EGS play being discovered as follows:

$$1 - \{\text{Probability}_{\text{geologic inadequacy for } \mathbf{A}} \times \text{Probability}_{\text{geologic inadequacy for } \mathbf{B}} \times \text{Probability}_{\text{geologic inadequacy for } \mathbf{C}}\}$$

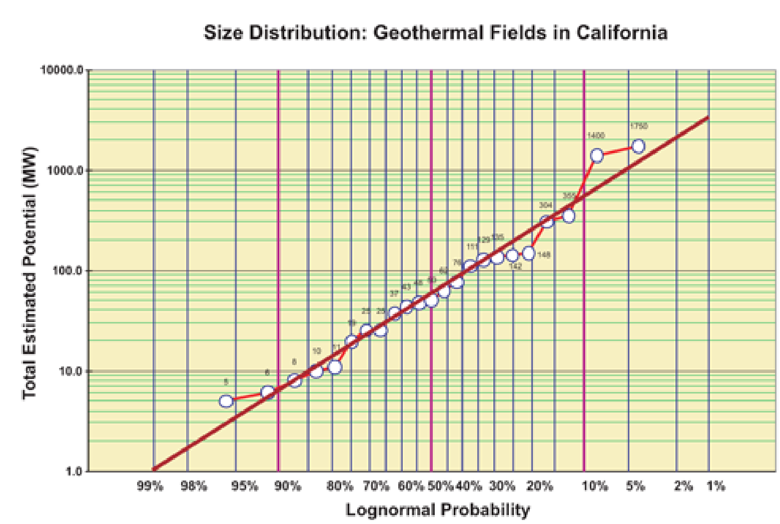
In this hypothetical example, the chance of finding at least one EGS play that will flow to economic expectations. is estimated as follows:

$$100\% - (79.75\% \times 84.81\% \times 94.38) = \mathbf{36\%}$$

Funding exploration through demonstration of an independent fourth EGS play trend would inevitably increase the chance of demonstrating at least one economically attractive resource.
The likelihoods for success in EGS can be integrated estimates of EGS resource sizes and corresponding estimates of net present value for EGS development scenarios to formulate a portfolio management system.

This form of logic can assist companies and governments in ascertaining appropriate multi-year budgets to support the exploration and demonstration phase of alternative EGS plays. This form of logic is routinely applied in managing portfolios of upstream petroleum ventures, and can assist companies and governments in their process for planning multi-year budgets for the exploration and proof-of-concept and demonstrations phases of several prospective hot rock plays in Australia.

Resource Size Assessments - Reality check for the Log normal Distribution of Geothermal Resources
Published data for geothermal fields in California have been assessed and appear to confirm a log-normal distribution as displayed in Figure 3



Data shown here comes from the Factsheet published by the California Geothermal Energy Collaboration and GeothermEx in 2006. To download that information, visit:

http://www.ucop.edu/ciee/geothermal/documents/FinalGeothermalFactSheetAndMap.pdf

California Field Data	
Minimum	5.0
P99	5.2
P90	8.4
P50	50.0
Swanson's Mean	126.0
P10	344.8
P1	1673.0
Maximum	1750.0
Mode	25.0

Fitted Line (Ln)	
Minimum	-
P99	1.0
P90	6.4
P50	59.3
Swanson's Mean	189.7
P10	546.7
P1	3380.6
Maximum	-
Mode	10.5

	California Geothermal Fields and Existing Power Plants	Total Potential MW Gross
1	Siskiyou Medicine Lake [Glass Mountain] Field	304
2	Modoc Lake City [Surprise Valle] Field	37
3	Lassen Honey Lake Field (1 Wineagle Plant & 1 Amedee Plant)	8
4	Lake Sulphur Bank [Clear Lake] Field	43
5	Sonoma & Lake The Geysers Field (21 Power Plants)	1400
6	Napa Calistoga Field	25
7	Mono Long Valley Field (2 Mammoth Pacific & 1 PLES Plant)	111
8	Ventura Sespe Hot Springs Field	5
9	Imperial Salton Sea Field (10 Plants - Salton Sea Units 1-5, CE Turbo, Vulcan, Hoch, Elmore & Leathers	1750
10	Imperial Niland Field	76
11	Imperial Truckhaven	25

	California Geothermal Fields and Existing Power Plants	Total Potential MW Gross
12	Imperial Westmoreland	50
13	Imperial Superstition Mountain Field	10
14	Imperial Mount Signal Field	19
15	Imperial Brawley - North Field	135
16	Imperial Brawley - East Field	129
17	Imperial Brawley - South Field	62
18	Imperial Glamis Field	6
19	Imperial Dunes Field	11
20	Imperial East Mesa Field (2 GEM Plants & 4 ORMESA Plants)	148
21	Imperial Heber Field (Heber 1 & 2 Power Plants & William Gould Plant)	142
	Totals in California	3784

Figure 7. Analysis illustrating a log-normal distribution for geothermal fields in California

With this observation, the assumption that log normal distribution could adequately describes the range of recovery of stored heat from a minimum of 0.5% at a 99% probability to a maximum of

40% of stored heat at a 1% probability. This implies: a low-side recovery of 1.34% of stored (90% probability); a mid-range recovery of 4.47% of stored heat (50% probability); a Swanson's mean[1] recovery of 6.68% of stored heat; and a high-side recovery of 14.95% of stored heat (10% probability). The following table provides preliminary global estimates for technically recoverable geothermal resources associated with this assumption.

Table. Range of technical recoverable heat energy from accessible geothermal resources	Probability	99%	90%	50%	Log-normal mean	10%	1%
	Recovery Factor	0.05%	1.34%	4.47%	7.00%	14.95%	40.00%
Accessible Stored Thermal Energy Estimates	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6
<10 km under continents (EPRI, 1978)	400	0.200	5.360	17.880	28.000	59.800	160.000
< 10 km under continents (Tester, et al 2005)	105	0.053	1.407	4.694	7.350	15.698	42.000
5-10km (by difference between above and below)	260	0.130	3.484	11.622	18.200	38.870	104.000
<5 km under continents (WEC 1994)	140	0.070	1.876	6.258	9.800	20.930	56.000
3 - 5 km (by difference between above and below)	98	0.049	1.313	4.381	6.860	14.651	39.200
< 5 km non-volcanic (Muffler and Guffanti, 1979)	65	0.033	0.871	2.906	4.550	9.718	26.000
From 15 degrees C to 3 km under continents (EPRI, 1978)	42	0.021	0.559	1.866	2.922	6.241	16.697
< 3 km non-volcanic (Muffler and Guffanti, 1979)	35	0.018	0.469	1.565	2.450	5.233	14.000

Over-all Conclusion

Several methods long used in the oil and gas industry can be usefully adapted to separate risk from uncertainty and to enable deliberate, internally consistent ranking with portfolios of geothermal plays and prospects

References

California Geothermal Energy Collaborative and GeothermEx, Inc., 2006, Factsheet - California Geothermal Fields and Existing Power Plants, Funded by the California Energy Commission PIER Program. Download from: http://www.ucop.edu/ciee/geothermal/documents/FinalGeothermalFactSheetAndMap.pdf

Capen, E, 1992, Dealing with exploration uncertainties, in Steinmetz, R (ed.), The Business of Petroleum Exploration: AAPG Treatise of Petroleum Geology, Chapter 5, p. 29-62.

EPRI (Electric Power Research Institute), 1978. Geothermal energy prospects for the next 50 years. ER-611-SR, Special Report for the World Energy Conference 1978.

Goldstein, B.A., Hill, A.J., Budd, A.R. and Malavazos, M., 2007, Hot Rocks in Australia – National Outlook, Geothermal Resource Council 31st Annual Meeting,

Muffler, L. J. and Guffanti, M. (1979), "Assessment of Geothermal Resources of the United States - 1978." Circular 790, Washington, D.C. U.S. Dept. of Interior, Geological Survey, http://www.geo-energy.org/aboutGE/ potentialUse.asp.

Rose, P. R, 1992, Chance of success and its use in petroleum exploration, in Steinmetz, R. (ed.), The Business of Petroleum Exploration, AAPG Treatise of Petroleum Geology Chapter 7, p. 71-86.

Tester, J.W., E.M. Drake, M.W. Golay, M.J. Driscoll, and W.A. Peters, 2005, Sustainable Energy – Choosing Among Options, MIT Press, Cambridge, MA, 850 pp.

WEC, 1994, New renewable energy resources: a guide to the future. Kogan Page Ltd., London, UK, 1994, 391 pp.

[1] Swanson's mean is the weighted approximation for a log-normal distribution equal to the summation of 30% of the 90% probability value, 30% of the 10% probability value, and 40% of the 50% probability value e.g. (P90 x 0.3) + (P10 x 0.3) + (P50 x 0.4) equals the Swanson's mean value