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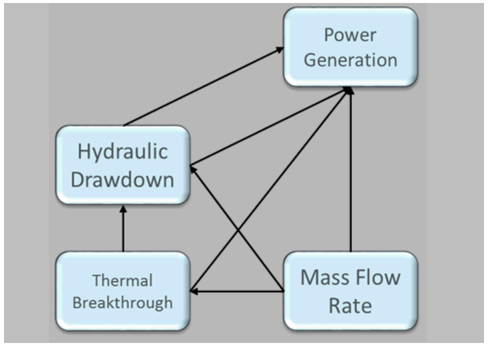

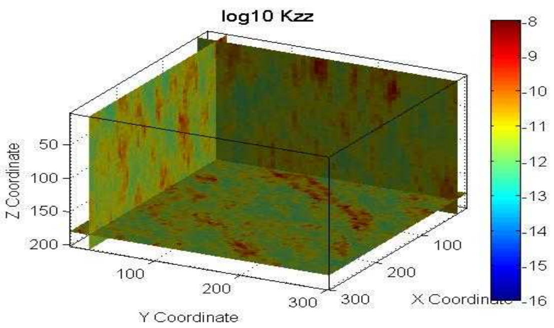

Reservoir Management and Development

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Reservoir M&D

- Looks at a project after reservoir exploration and confirmation are complete
- EGS and hydrothermal power generation
- Sedimentary and crystalline rock environments
- Investigate the technologies and practices that establish and affect the below-ground thermal, hydraulic, and economic performance of a geothermal system
  - Baseline
  - Future improvements
- Utilize
  - Literature
  - Subject Matter Expert’s
  - Modeling and Analysis

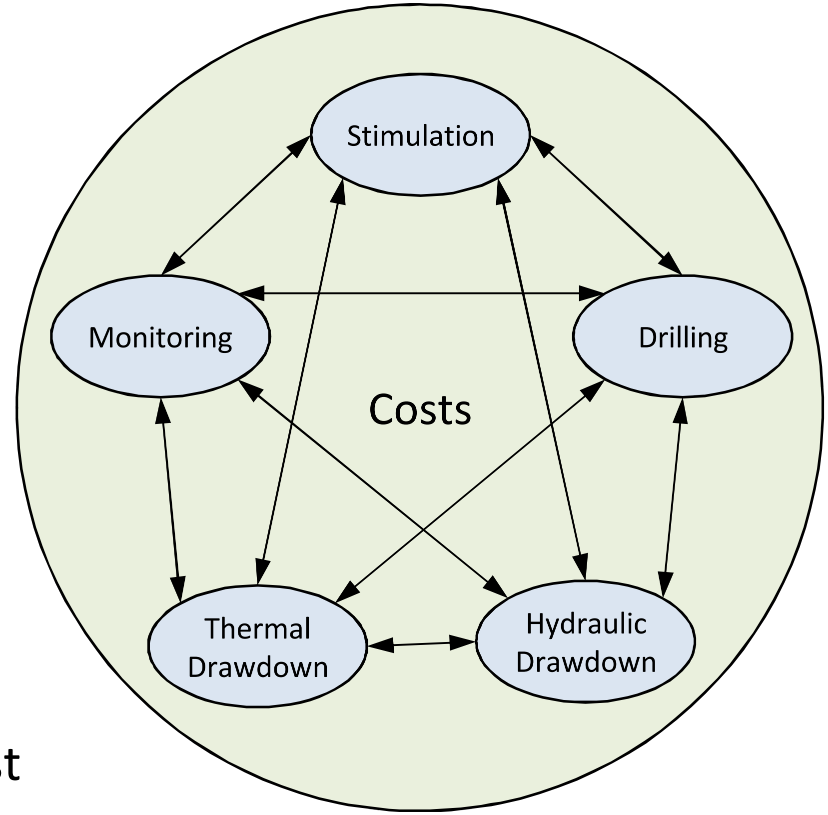
Reservoir M&D – Two Parts

- Support NREL – Potential to Penetration (P2P) task by providing RM&D related inputs to GETEM
  - Establish / Confirm GETEM default values
  - Anticipate cost reductions / performance improvements
- Investigate broader implications of RM&D that are not able to be addressed in the P2P task
  - THMC processes
  - Reservoir characterization
  - Long-term management

We welcome feedback and suggestions!

RM&D GETEM Inputs

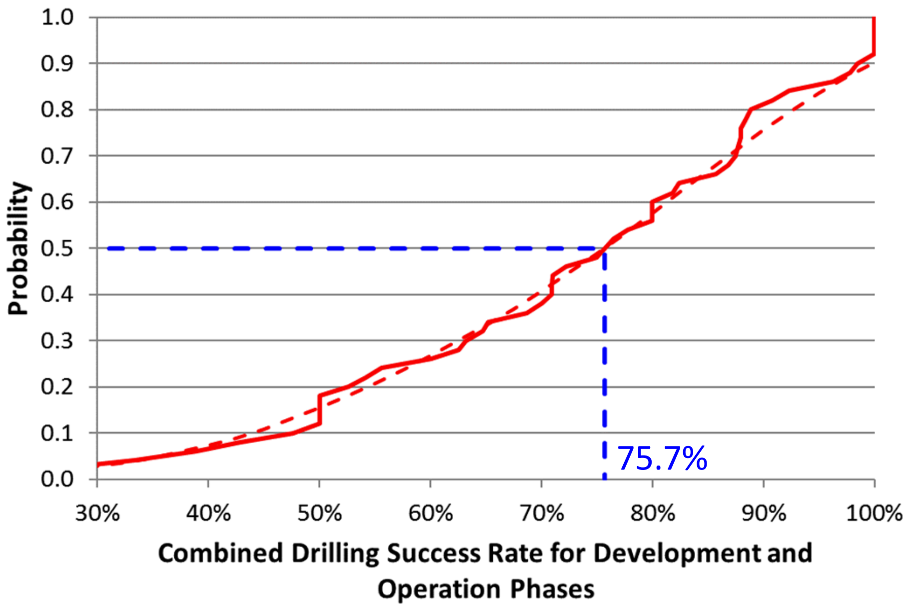
- Drilling
  - Success rate during development
  - Production / Injection well size
  - Stimulation costs (EGS)
  - Drilling costs
- Pumping
- Reservoir Performance
  - Production well flow rate
  - Productivity / Injectivity Index
  - Thermal drawdown
  - Water loss and makeup water cost
- All is Connected to All



Success Rate During Development

- GETEM Default: Hydro – 75%, EGS – 90%
  - Sanyal and Morrow (2012) – 2308 wells

Success Rate by Project Phase				
	Overall	Exploration	Development	Operation
Mean	78%	59%	74%	83%
Mode	50%	80%	100%	100%
Median	71%	60%	72%	88%



- Wells > 1500m & 150 °C
  - 76.7%

Suggested new value: 76% for both.

Sanyal, S.K., and J.W. Morrow. 2012. "Success and the Learning Curve Effect in Geothermal Well Drilling - a Worldwide Survey." Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford, CA, January 30 - February 1, 2012.

Stimulation Costs*

- GETEM Default: $2,500,000 (EGS Only)
  - Brown (1983) – "Typical hydraulic fracturing job"
    - $250k - $1250k
  - Tester and Herzog (1991) give stimulation costs per kWe as a function of reservoir temperature
    - $1500/kWe @ 180 ^{o}C to $350/kWe @ 250 ^{o}C
  - Sanyal et al (2007) – Experience at Soultz and Cooper Basin
    - $582k to $1164k
  - USEIA (2016) suggests 40% of total well costs are for completion, which includes stimulation. Assuming average completion costs of $4200k of which 75% are materials and time, stimulation is ~$1000k.
- Suggested new value: $1,250,000

Brown, G.L. 1983. "Geothermal Wells - the Cost Benefit of Fracture Stimulation Estimated by the Geocom Code". Sandia National Laboratories. Albuquerque, NM. SAND83-7440

Tester, J.W., and H.J. Herzog. 1991. "The Economics of Heat Mining: An Analysis of Design Options and Performance Requirements of Hot Dry Rock (Hdr) Geothermal Power Systems." Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford, CA, January 23-25.

Sanyal, S.K., J.W. Morrow, S.J. Butler, and A. Robertson-Tait. 2007. "Cost of Electricity from Enhanced Geothermal Systems." Thiry-Second Workshop on Geothermal Reservoir Engineering, Stanford, CA.

USEIA. 2016. "Trends in U.S. Oil and Natural Gas Upstream Costs". U.S. Energy Information Administration. Washington, DC.

*All values have been adjusted to 2016 dollars.

Productivity Index

- GETEM Default: 2500 lb/hr/psi for both Hydro and EGS
  - GEIE (2009) – Soultz
    - Pre-stimulation (10 – 20 lb/hr/psi)
    - Post-stimulation (200 – 220 lb/hr/psi)
  - Xie (2015): Injectivity based on maximum injection rates during stimulation at Soultz, Ogachi, Hijori, Basel, Rosema, Cooper Basin, & Fenton Hill ranging from 30 to 650 lb/hr/psi, median 110 lb/hr/psi
  - Benato et al. (2015): 940 lb/hr/psi @ Desert Peak
  - Other references*: 5 – 220 lb/hr/psi
- Suggested new value: 2500 lb/hr/psi – Hydro, 250 lb/hr/psi - EGS

GEIE. 2009. "Egs Pilot Plant, Publishable Final Activity, European Geothermal Project for the Construction of a Scientific Pilot Plant Soultz". GEIE Exploirtation Miniere de la Chaleur.

Xie, L., K.-B. Min, and Y. Song. 2015. "Observations of Hydraulic Stimulations in Seven Enhanced Geothermal System Projects." *Renewable Energy* 79:56-65. doi: http://dx.doi.org/10.1016/j.renene.2014.07.044

Benato, S., S. Hickman, N.C. Davatzes, J. Taron, P. Spielman, D. Elsworth, E.L. Majer, and K. Boyle. 2015. "Conceptual Model and Numerical Analysis of the Desert Peak Egs Project: Reservoir Response to the Shallow Medium Flow-Rate Hydraulic Stimulation Phase." *Geothermics*. doi: 10.1016/j.geothermics.2015.06.008.

*Albaric, J., V. Oye, N. Langet, M. Hasting, I. Lecomte, K. Iranpour, M. Messeiller, and P. Reid. 2014. "Monitoring of Induced Seismicity During the First Geothermal Reservoir Stimulation at Paralana, Australia." *Geothermics* 52:120-131. doi: 10.1016/j.geothermics.2013.10.013.

*Baisch, S., E. Rothert, H. Stang, R. Voeroes, C. Koch, and A. McMahon. 2015. "Continued Geothermal Reservoir Stimulation Experiments in the Cooper Basin (Australia)." *Bulletin of the Seismological Society of America* 105 (1):198-209. doi: 10.1785/0120140208.

*Calo, M., C. Dorbath, and M. Frogneux. 2014. "Injection Tests at the Egs Reservoir of Soultz-Sous-Forets. Seismic Response of the Gpk4 Stimulations." *Geothermics* 52:50-58. doi: 10.1016/j.geothermics.2013.10.007.

*Dempsey, D., S. Kelkar, N. Davatzes, S. Hickman, and D. Moos. 2015. "Numerical Modeling of Injection, Stress and Permeability Enhancement During Shear Stimulation at the Desert Peak Enhanced Geothermal System." *International Journal of Rock Mechanics and Mining Sciences* 78:190-206. doi: 10.1016/j.ijrmms.2015.06.003.

Drilling Costs

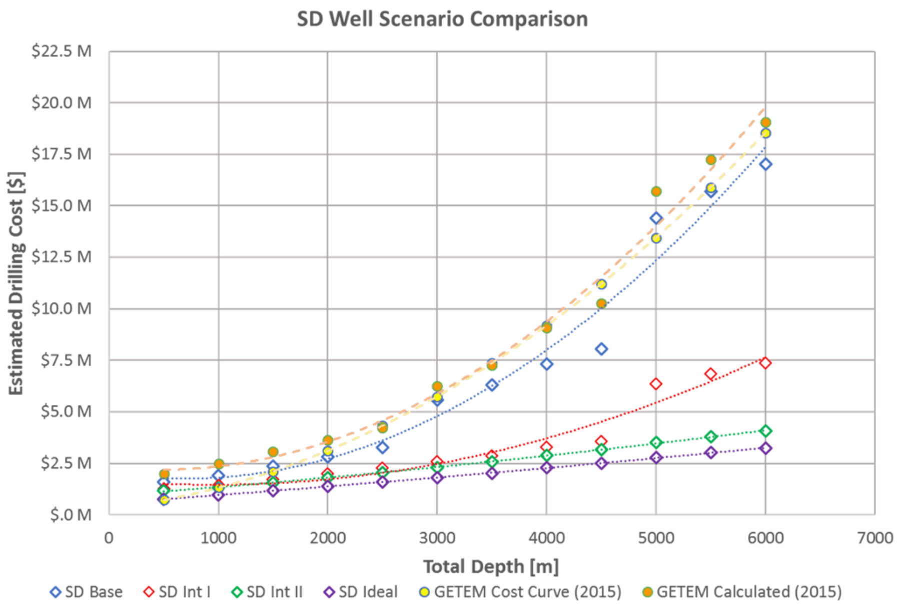
- Four Cost Categories
  - Drilling Time: Rotating on bottom, tripping drill pipe, bit and BHA costs, labor, etc.
  - Non-Drilling Time: Flat time, running casing, cementing, logging, etc.
  - Trouble Time: Costs that arise from adverse hole conditions and unexpected failures (e.g. lost circulation)
  - Additional Time: Site prep, mob-demob, wellhead equipment, etc.
- Base Assumptions – Use GETEM Design Defaults
  - Minimum # of intervals = 3
  - From 3 – 5 km = 4 intervals
  - > 5 km = 5 intervals
  - Surface casing & Production zone = 304.8 m (1000 ft)
- Well Cost Simplified

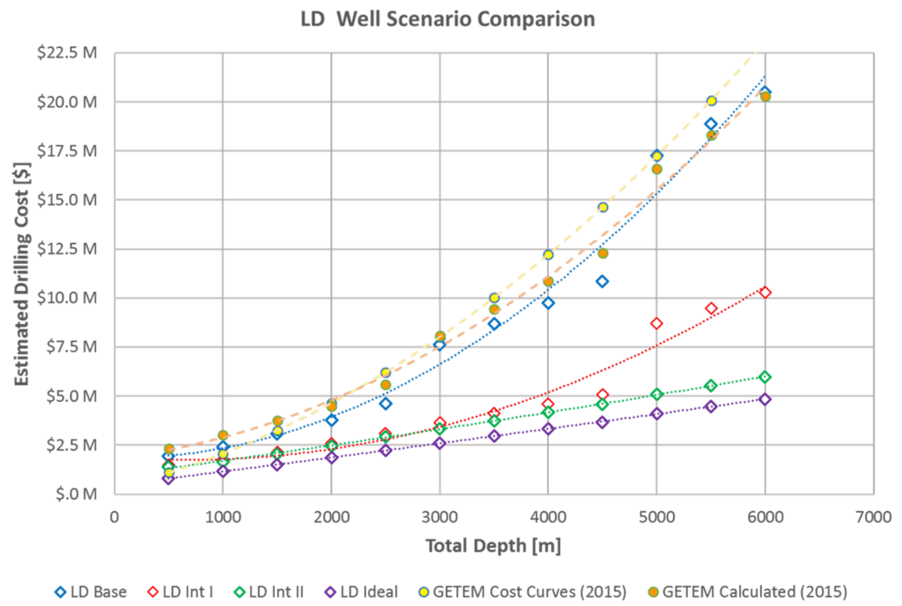
Drilling Cost Scenarios

- Base, Intermediate 1, Intermediate 2, and Ideal
  - 12 depths ranging from 500 – 6000 m
  - Two Production Zone Hole Diameters: Small (8.50”), Large (12.25”)

Category	Variable	Base	Int. 1	Int. 2	Ideal
Drilling Time	ROP [ft/hr]	25	50	75	100
	Bit Life [hr]	50	100	150	200
Non-Drilling Time	# Cased Intervals	3-5 Default	3-4	2-3	1
	Mud Costs	Standard	Half with air or water	Half with air or water	Full depth with air or water
	Logging	Wireline	Production interval only	Log while drilling	Log while drilling
Trouble Time	Contingency	25%	15%	0%	0%

Drilling Costs





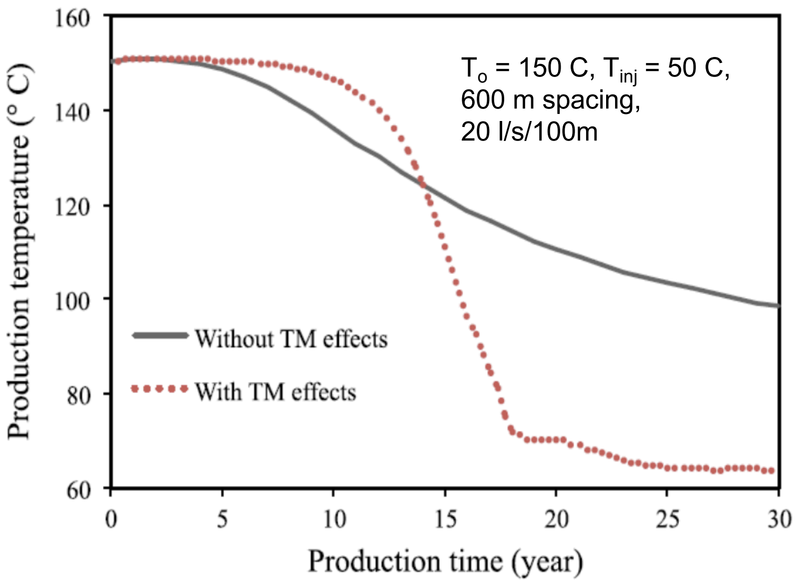
Depth [m]	Temp [C]	Base [¢/kW*hr]	Ideal [¢/kW*hr]	% Change
3000	175	19.07	11.63	39.0%
6000	225	33.00	14.32	56.6%

Based on 2016 GETEM defaults using new Base and Ideal drilling cost scenarios.

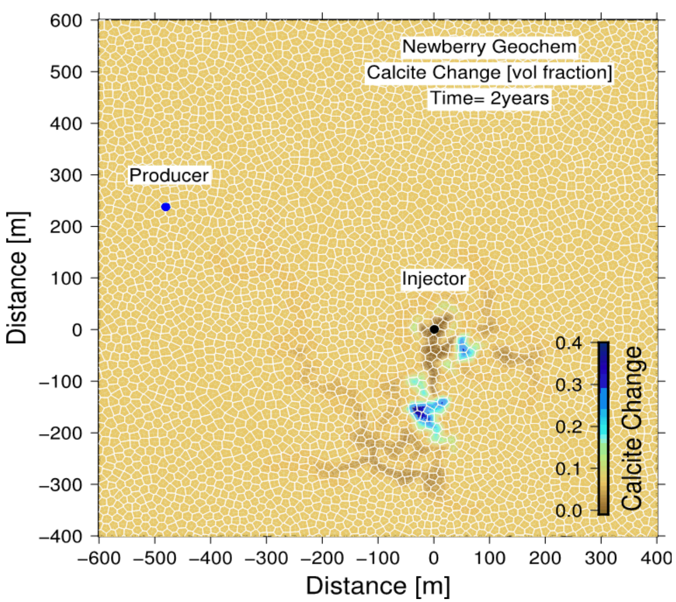
Broader Implications

- THMC
  - EGS requires finding and predicting high permeability zones that remain ‘sustainably permeable’ for decades

Thermo-Mechanical Processes



Geochemical Processes



Fu, P., Y. Hao, S.D.C. Walsh, and C.R. Carrigan. 2016. "Thermal Drawdown-Induced Flow Channeling in Fractured Geothermal Reservoirs." Rock Mechanics and Rock Engineering 49:1001-1024. doi: DOI 10.1007/s00603-015-0776-0

Sonnenthal et al., unpublished work from EGS Validation project

Next Steps

- Examine the Implications of THMC more closely
  - Predictive modeling
  - Zonal isolation
  - Etc.
- Tradeoff Analyses
  - Well design
  - Flow rate
  - Temperature
  - Costs
  - Etc.