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Analysis and Optimization of a Closed Loop Geothermal System in Hot Rock Reservoirs

Sandia National Laboratories

Yaro Vasyliv, Gabriela A. Bran-Anleu, Alec Kucala, Sam Subia, and Mario J. Martinez

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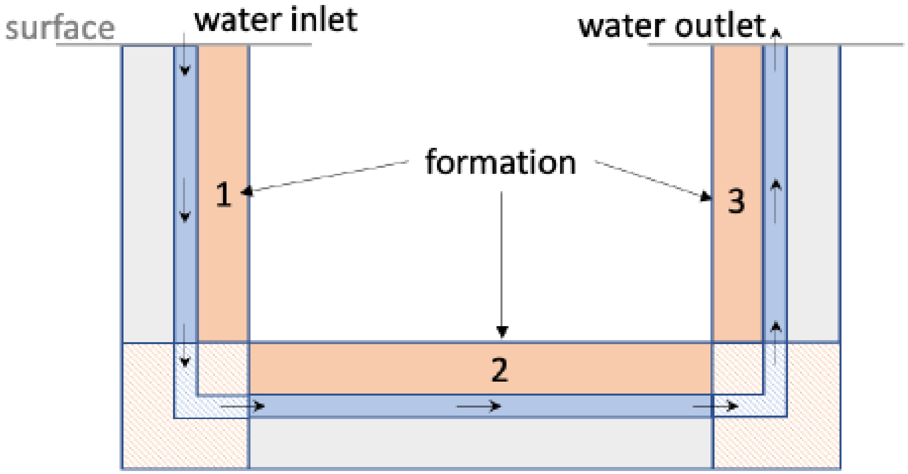
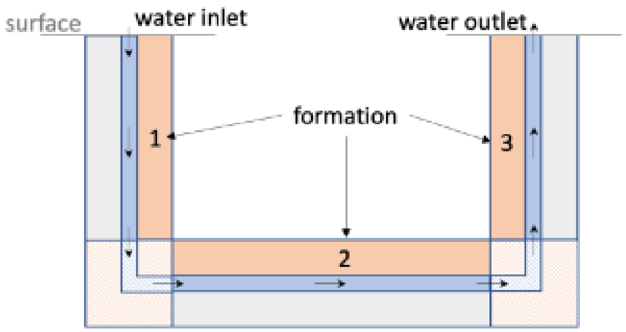
Motivation

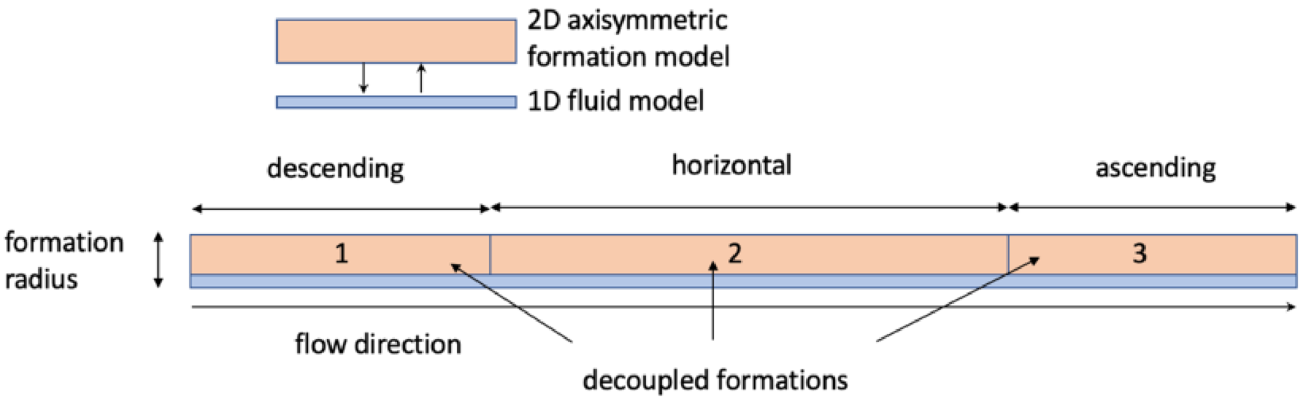
- Nearly all U.S. geothermal power production is from conventional hydrothermal plants in western states
  - High-grade hydrothermal fields (e.g., Geysers field) are the exception and not the norm, stagnate growth for geothermal since the 1980s (10,000 – 15000 GWhe)
  - Estimated 95% available geothermal energy is in hot-dry-rock (HDR) with average gradients 30 C/km
- Closed loop geothermal systems (CLGS) are an alternative to EGS
  - Different heat exchanger designs (e.g., u-tube, coaxial)
  - Working fluid is re-circulated in tubing and can target hot-dry-rock or wet-rock
  - How much thermal / mechanical power can be produced over 20-40 years operational period for optimal closed loop systems ?

Example u-tube heat exchanger



Methodology I

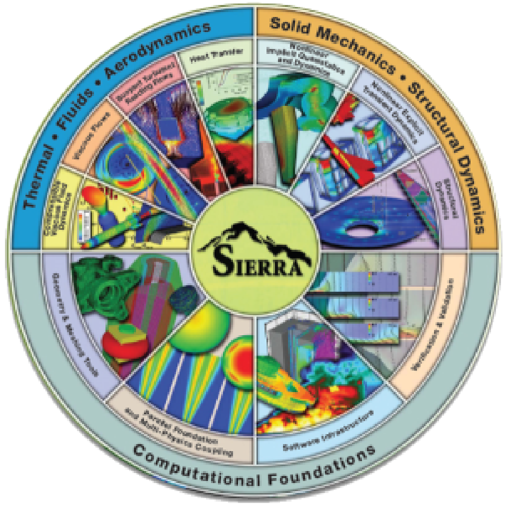




1. Heat transfer is through heat conduction (i.e., HDR)
2. Water is the working fluid
   - 1D area-averaged thermal energy balance
   - Coupled to formations through a convective boundary condition with Gnielinski heat transfer correlation
3. 2D axisymmetric formations
   - Heat transfer between Region 1 – 2 and Region 2 – 3 is ignored
   - Heat transfer in “elbow” regions is negligible
   - Region 2 has constant initial temperature
4. Pressure computation is decoupled
   - Incompressible fluid w/ properties as functions of temperature, evaluated at an average pressure
   - Steady momentum balance w/ Darcy-Weisbach friction factor used to model wall shear stress
5. Thin layer of insulation modeled as in series thermal resistance added to heat transfer coefficient

Methodology II

Multi-physics PDE solver



- Weak form of coupled PDEs is discretized using linear (1D fluid) and bilinear elements (formation)
- Meshed biased to resolve radial gradients
- SUPG stabilization
- Adaptive time stepping w/ predictor-corrector
- Nonlinear system of equation solved using Newton iterations w/ preconditioned GMRES for linear systems

Optimization / Uncertainty Quantification / Sensitivity Analysis

- Used to drive SIERRA
- Gradient-based optimization of the objective function w/ central differences

$$F_{\mathrm{mech}} = \int_0^T \left(\dot{m} \Delta h_{\mathrm{f}} \eta - \frac{1}{\eta_{\mathrm{p}}} \max\left(\dot{W}_{\mathrm{p}}, 0\right) \right) dt - \frac{CL}{C_{\mathrm{e}}}$$

- Parametric sweep of design space

Validation I

- Comparison to Song et al. (2018) and Stanford solution for u-tube placed in Xinji thermal reservoir w/ water as the working fluid

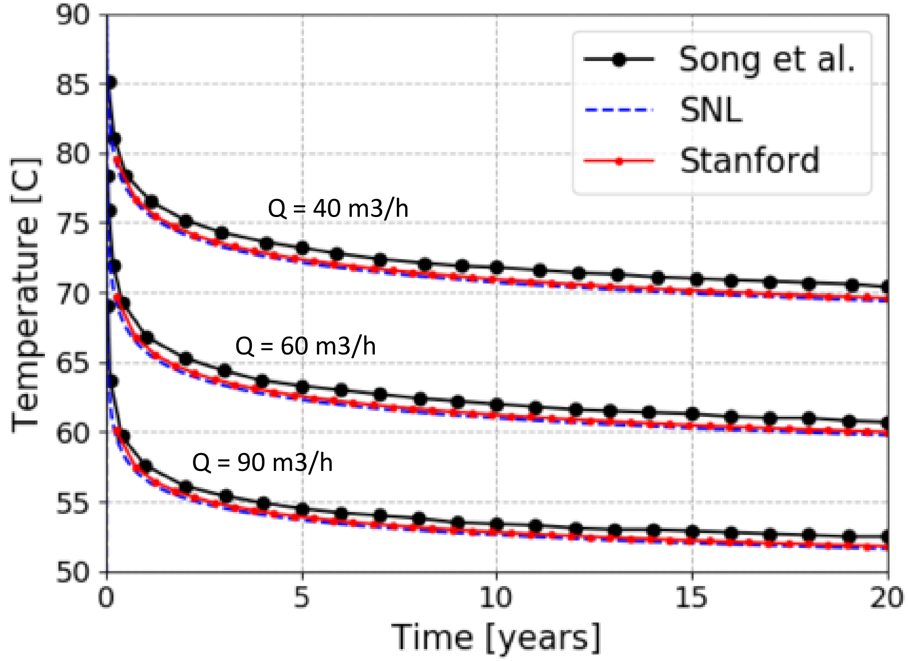
- Formation thermal characteristics

Rock density [kg/m3]	Rock specific heat [J/kg-K]	Rock thermal conductivity [W/K-m]	Surface temp [C]	Formation gradient [C/m]
2200	850	3.0	25	30

- Insulation is neglected in our model here (results in slight underprediction)

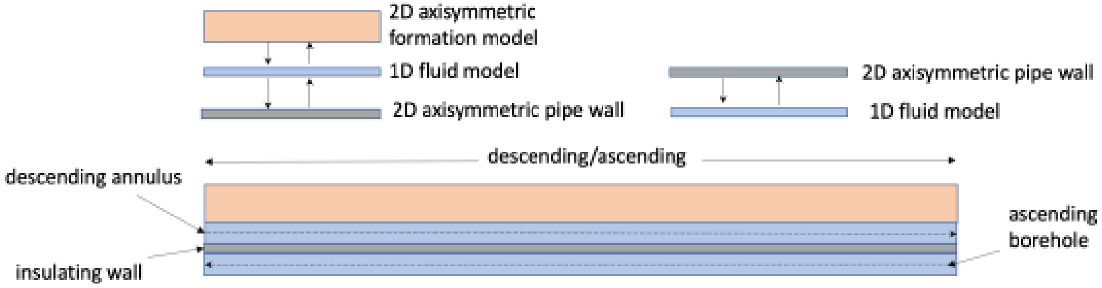
Flow rate [kg/s]	Formation gradient [C/m]	Depth [km]	Horizontal length [km]
varied	30	3.5	6

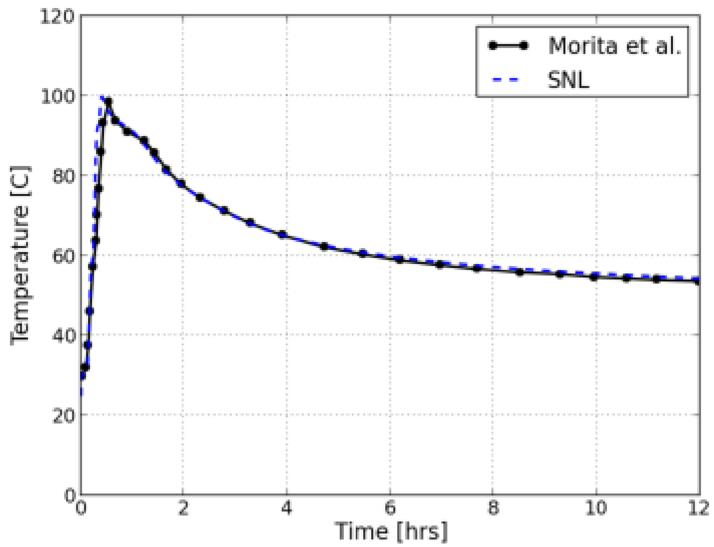
- Heat transfer coefficient is effectively infinite, any sufficiently large value will produce a similar solution



Validation II

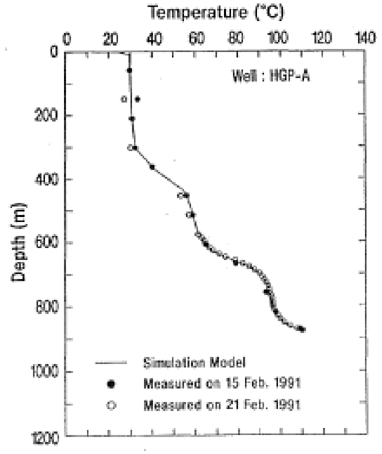
- Comparison to HGP-A Downhole Coaxial Heat Exchanger (DCHE) experiments in Hawaii (Morita et al. 1992)





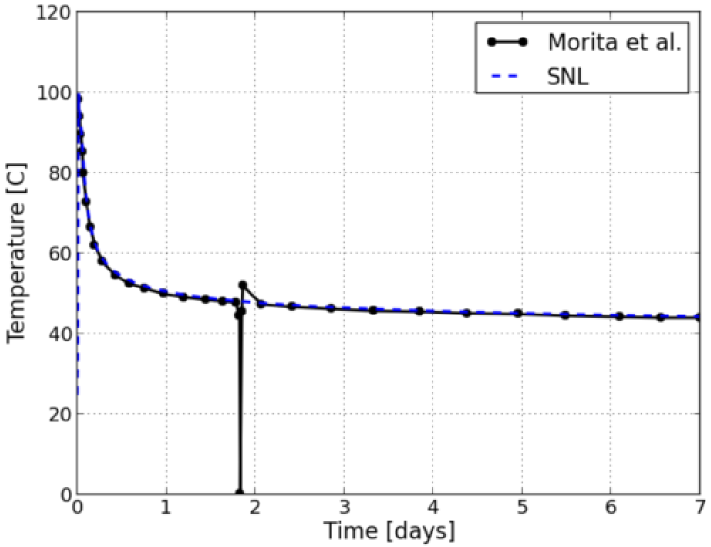
- Formation thermal characteristics

Rock density [kg/m3]	Rock specific heat [J/kg-K]	Rock thermal conductivity [W/K-m]
3050	870	1.6



- HGP-A DCHE params

Injection temp [C]	Flow rate [kg/s]	Well depth [m]	Insulation [W/K-m]
30	1.33	876.5	0.06



Results I

- FORGE site approx. thermal characteristics (225 C bottom borehole temp)

Rock density [kg/m3]	Rock specific heat [J/kg-K]	Rock thermal conductivity [W/K-m]	Surface temp [C]	Formation gradient [K/km]
2750	790	3.05	25	78.8

- Emplace 8.5" diameter u-tube heat exchanger w/ water as the working fluid

- Thin-layer of insulation 0.01 m thick w/ conductivity .025 W/K-m added to the ascending well bore

Injection temp [C]	Pipe Diameter [m]	Well depth [km]	Flow rate [kg/s]	Horizontal length [km]	Insulation length [km]
27	0.2159	2.5	Varied [1-60]	Varied [1-10]	Varied [0-2.5]

$$F_{\text{mech}} = \int_0^T \left(\dot{m}\Delta h_f \eta - \frac{1}{\eta_p} \max(\dot{W}_p, 0) \right) dt - \frac{CL}{C_e}$$

- Optimization

drilling cost $C = 1640$ \$/m

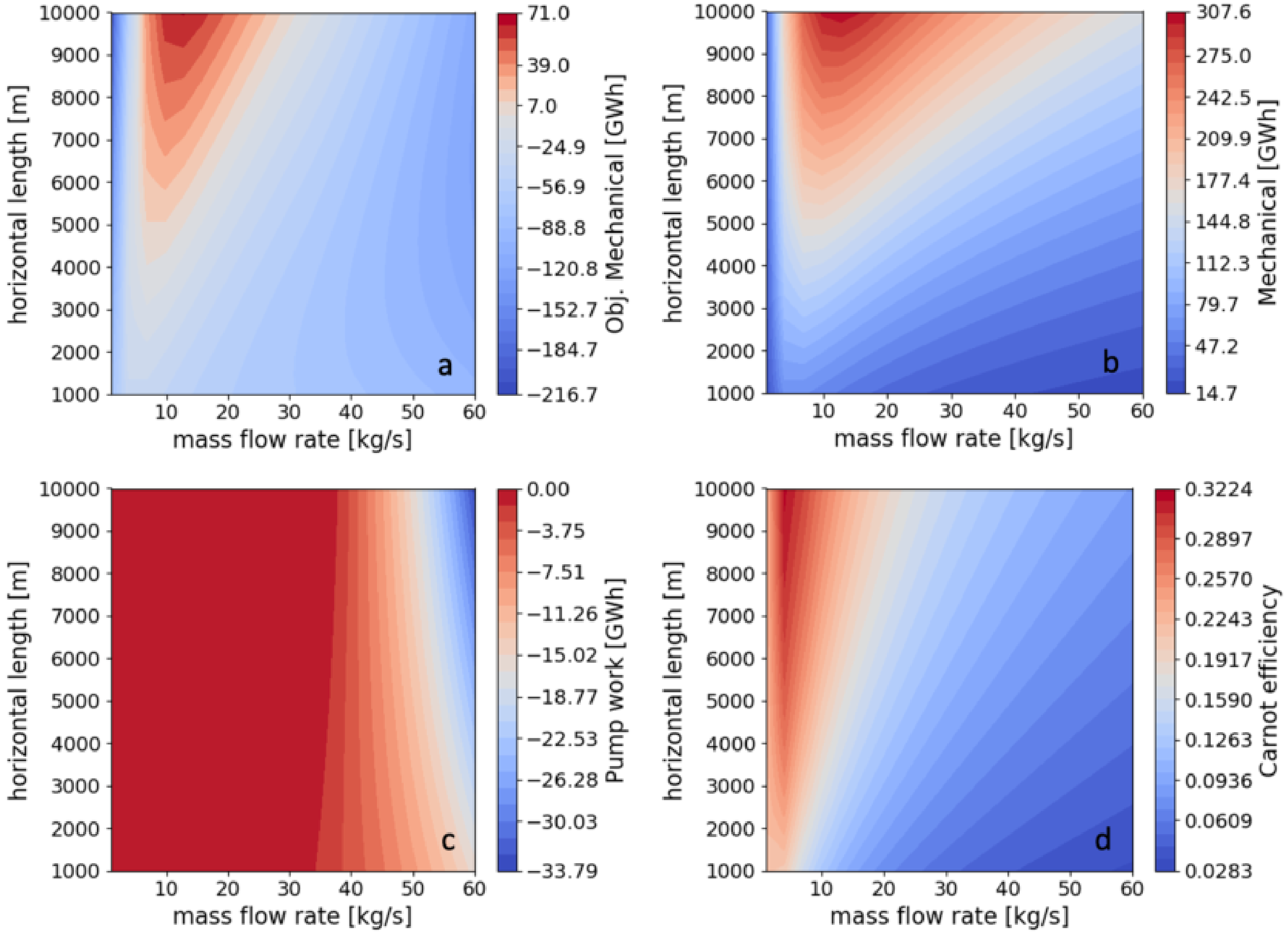
electricity price $C_e = 104500$ \$/GWhe

Flow rate [kg/s]	Horizontal length [km]	Insulation length [km]	Obj. function [GWhe]	Mechanical Output [GWhe]
10.8	10	1.4	88	324.6

Results II

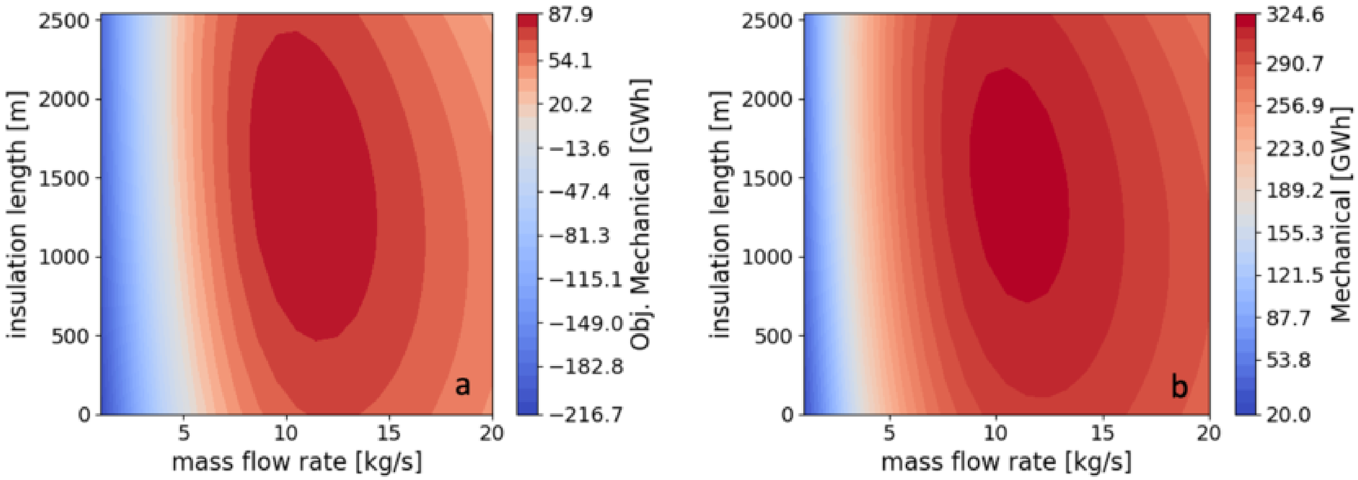
- Feasibility envelope is narrow, depends strongly on drilling costs (Fig. a)
- Optimal mass flow rate exist for each horizontal length, no true optima in 1-10km (i.e., increasing length still increases obj.) (Fig. b)
- 8.5” diameter pipe has wide thermosiphon envelope (Fig. c)
- Carnot efficiency peaks around narrow band, does not correspond to max output, chosen design corresponds to plant efficiency of 0.18 (Fig. d)

Mass flow rate – horizonal length plane (no insulation)



Results III

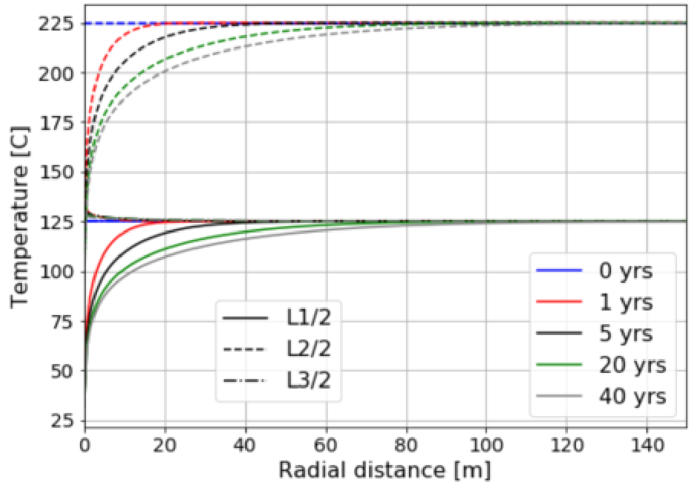
Mass flow rate – insulation length plane (max. horizontal length)



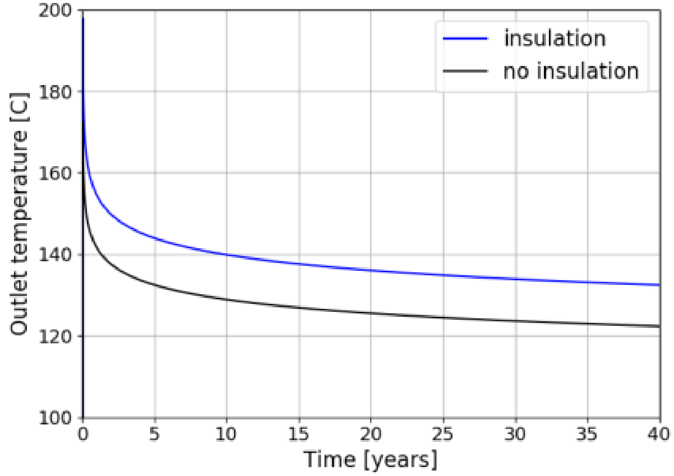
- Insulation increases mech. output by less than 6% at optimal conditions, increases outlet temp by about 10 C
- Thermal drawdown is contained to 100 m radius at 40 years
- Increasing diameter to 15” results in less than 10% increase (penalties on diameter not considered)

Flow rate [kg/s]	Horizontal length [km]	Insulation length [km]	Mechanical Output [GWhe]
12.26	10	1.38	355.1 GWhe

Thermal drawdown of HDR reservoir at optimal conditions



Insulation impact on outlet temperature at optimal conditions



Conclusions

- Optimal system for 8.5” diameter pipe produces ~325 GWhe over 40 years (< 1 MWe average) and operates as a thermosiphon, equates to less than 800 homes powered

Flow rate [kg/s]	Horizontal length [km]	Insulation length [km]	Obj. function [GWhe]	Mechanical Output [GWhe]
10.8	10	1.4	88	324.6

- Longer horizontal legs always better for (8.5” pipe w/ 1-10km horizontal leg)

- Each horizontal leg length has an optimal mass flow rate (i.e., there is balance in increasing residency time versus increasing enthalpy flux)

- Insulation length and diameter have modest impact on output at optimal mass flow rate / horizontal leg length

- Other mechanisms are needed to enhance heat transfer

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