

Deep Direct-Use Geothermal: A Probabilistic Systems Analysis Approach for Techno-Economic Analysis

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ABSTRACT

The Hawthorne Nevada, deep direct-use geothermal study is a two-year effort funded by the U.S. Department of Energy to determine the techno-economic feasibility of implementing a large-scale, direct-use facility for the Hawthorne Weapons Army Depot (HWAD) and facilities in the city of Hawthorne. The approach links a production side analysis (PSA) and demand side analysis (DSA) into a whole-system analysis (WSA) to provide an integrated assessment of the resource and the probability of delivering economically viable direct-use energy to Hawthorne.

Hawthorne, Nevada is in the western part of the Basin and Range province and has been the focus of geothermal investigations for over 40 years. Over the last 15 years, several studies completed by the U.S. Navy Geothermal Program Office (GPO) in conjunction with industry professionals quantified the existence of several low temperature geothermal prospects, the most promising of which is called Prospect A. The promise of Prospect A is based on drilling and flow testing by the researchers that produced ± 100 °C water at flow rates of up to 31 l/s. Measured productivity indexes range from 30-300 l/s/MPa, suggesting a warm and productive heat source.

Despite the promise of the resource, uncertainties in its spatial extent and long-term sustainability mean that techno-economic analyses must include probabilities of the sustainability of the resource under different operating scenarios. Here, the PSA is conducted by integrating a wide range of disparate data (Ayling et al., 2020) to estimate lognormal P90, P50, and P10 resource capacities. These capacities are used as input to a thermal-hydrologic (T-H) model to estimate thermal drawdown for each capacity estimate for a range of DSA scenarios. Using a systems-based approach, the WSA links the dynamic T-H simulations of the PSA/DSA combinations with the techno-economic model GEOPHIRES to account for both the temporal dynamics and uncertainties in the system to produce probabilistic distributions of several performance metrics including the levelized cost of heat (LCOH) and the risk to investment. This paper summarizes the work done in the PSA and DSA and details the process by which the WSA is created and executed.

1. INTRODUCTION

The town of Hawthorne, with a population of approximately 3,200, sits in western Nevada roughly 90 miles southeast of Reno and serves as the seat of Mineral County (Figure 1). Hawthorne houses a local hospital, a K-12 school system, the county courthouse, library, and the sheriff's office. In 1981 the Nevada Department of Energy commissioned a study to create a plan to develop geothermal energy for the town of Hawthorne (GDA, 1981). That study estimates the annual heat demand for space heating in the courthouse, hospital, library, and schools to be 3.2 GW-hr/yr (10.8×10^9 BTU/yr) with a peak demand of 2.6 MW (8.8×10^6 BTU/hr).

Hawthorne is also the location of the 60,000 ha (147,000 acre) Hawthorne Weapons Army Depot (HWAD). The HWAD currently uses two 373 kW (500-hp) diesel fired boilers that produce steam for district heating of the office buildings and the housing units from September 1st to May 31st each year (273 heating days) (Power Engineers, 2012).

Hawthorne lies in the 100-km wide (62 miles) Walker Lane tectonic belt, which has long been recognized as having geothermal resources that can support commercial grade power or large scale district heating (GDA, 1981, Trexler et al., 1981, Bohm and Jacobsen, 1977). The Walker Lane belt is a north-northwest trending geologic trough between the stable North American continent and the Sierra Nevada micro-plate (Oldow, 2003). It is characterized by northwest striking right-lateral strike-slip faults that run from the San Andreas fault in Southern California up to the eastern slope of the Sierra Nevada range. Walker Lane is the home to many geothermal energy prospects, some of which have been successfully developed (Faulds et al., 2006, Faulds and Hinz, 2015).

The geothermal resource in Hawthorne was recently characterized by the United States Navy Geothermal Program Office (GPO) as part of a focused exploration and development campaign (Lazaro et al., 2010, Meade et al., 2011) that resulted in drilling 3 moderate to deep wells along the eastern front of the Wassuk Range (Figure 2). Testing of the most promising well, HWAD-2A, revealed an extensively fractured horizon with a down-hole temperature of 115 °C (239 °F). A flow test performed on HWAD-2A demonstrated 96 °C (207 °F) fluid flowing at 12.4 l/s (196 gal/min) with a calculated productivity index (PI) of 82.36 l/s/MPa (9 gpm/psi). As part of the Navy work, a new 2-meter temperature survey, was completed in 2009 and 2010 (Kratt et al., 2010). The 2-meter temperature survey envelopes the area of a previous survey (Trexler et al., 1981) and extends coverage further to the

northeast and south. The newer results support the earlier work in the areas of overlap, while also identifying, two new thermal anomalies (Figure 2).

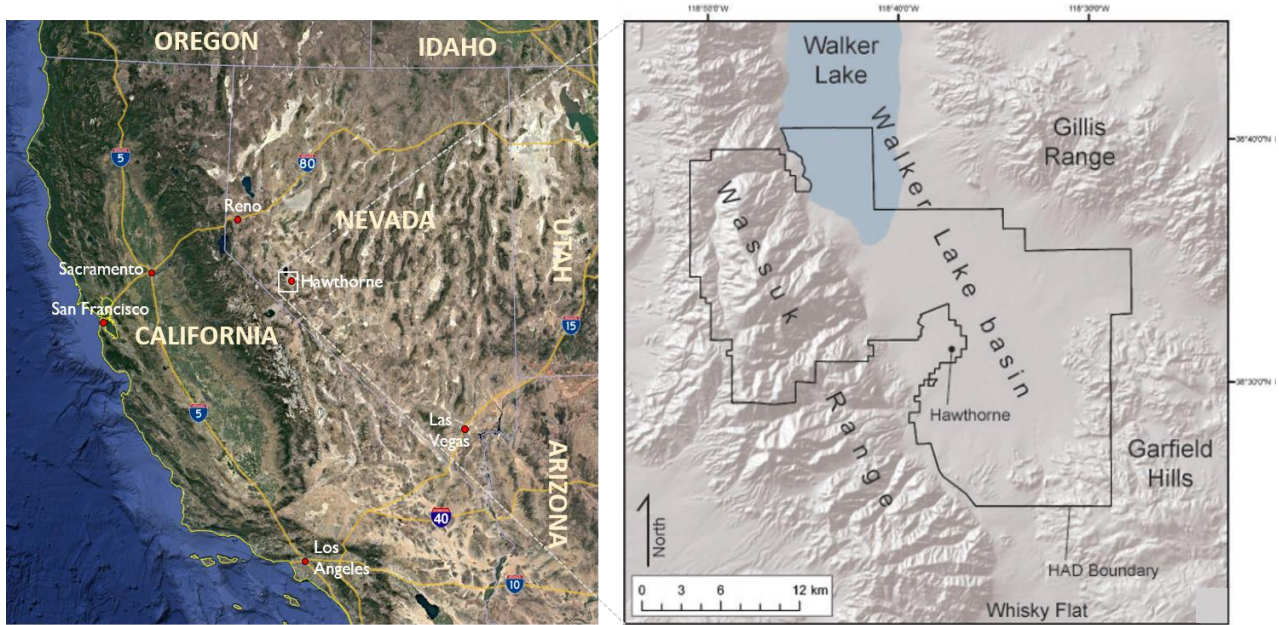


Figure 1: Left - The study area of Hawthorne, Nevada in relation to the western United States (left). Right – Closeup of the Hawthorne area showing the HWAD boundary and the placement of the City of Hawthorne.

As part of the GPO work, Power Engineers Inc. (PE) was commissioned by the Navy GPO to conduct a study (Power Engineers, 2012) to evaluate three direct-use heating options for the HWAD. A limiting factor of the PE study is that it does not include the entire geothermal resource, which extends onto the adjacent town and county land, nor did it include town or county facilities in its proposed direct-use applications. One source that was not included in the PE study that is relevant here is known as the El Capitan well (Figure 2), which was drilled in the early 1980's as a potential geothermal source for a planned resort. While the resort never panned out, flow tests revealed that the “El Cap” well can produce over 31.5 l/s (500 gpm) of 99 °C (210 °F) water with minimal drawdown. Another private well, the Maples well, west of the town near HWAD-2A produced elevated water temperatures of 93 °C (200 °F) (Trexler et al., 1981).

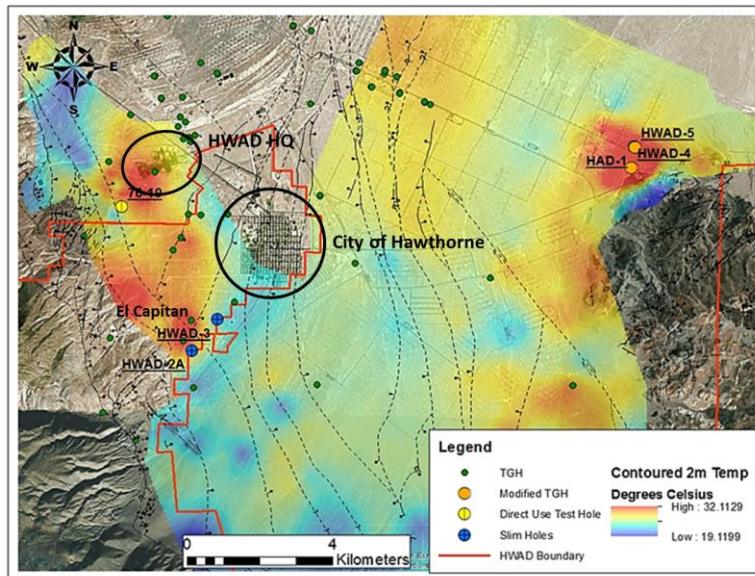


Figure 2 - Satellite image of the central HWAD and town of Hawthorne, NV, overlaid with 2m temperature contours. Red line shows portions of the HWAD northern and western boundaries. The three deep Navy “HWAD” wells (HAD-1, HWAD-2a, and HWAD-3) and the El Capitan well (green dot) are labeled, as are several shallow wells that show higher temperatures. The town of Hawthorne and the HWAD headquarters (HQ) area are circled. After Kratt et al., 2010.

The Navy GPO also supported the development of a 3D geologic model of the Hawthorne region to better understand the mechanism by which elevated water temperatures may occur (Moeck et al., 2010). The modeling combined geologic surface data and sets of geologic cross-sections based on well data to create a 3D stratigraphic representation of the geology (Figure 3). The

model clearly shows the releasing bend in the NNW-trending fault system (red box) along the Wassuk Range front that is thought to be the reason for the geothermal fluid flow.

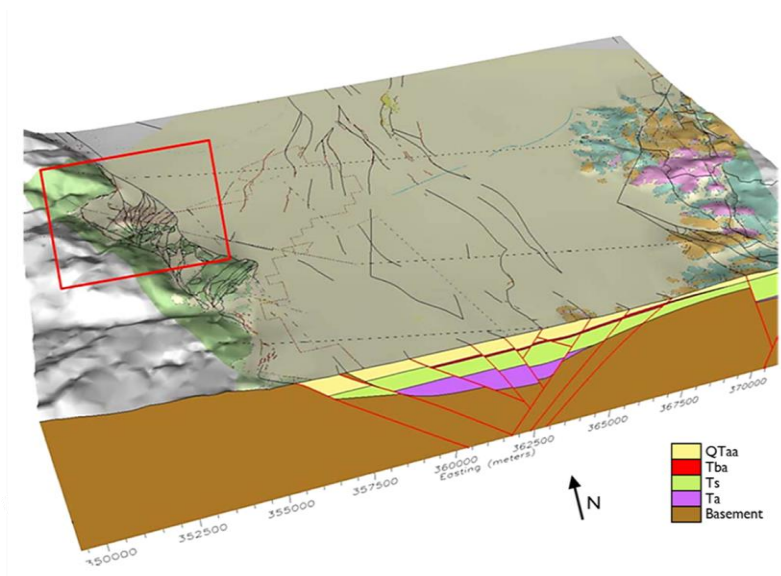


Figure 3 - 3D Geologic model of the Walker Lake Valley Region from Moeck et al. (2010). The City of Hawthorne is in the lower right-hand portion of the red square, which highlights the complex releasing bend along the Wassuk Range front. QTaa = Quaternary alluvial and lacustrine sediments, Tba = Late Tertiary basaltic andesitic lavas, Ts = Late Tertiary fluvial and lacustrine sediments, Ta = Late Tertiary andesite lavas, Basement = Mesozoic volcanics, sediments, and granite.

Despite the promising geothermal conditions, estimated enthalpy flow rates at the surface do not constitute a commercially viable, electricity producing resource. However, the potential for direct-use applications is high. This project evaluates the feasibility of the direct-use of this geothermal resource for the HWAD and adjacent town and county facilities with the ultimate objective of providing end users an inexpensive and more reliable and sustainable energy source for heating and cooling.

To accomplish this, we use a multi-disciplinary, three-tiered analysis approach that links a production side analysis (PSA) and a demand side analysis (DSA) into a whole-system analysis (WSA) to produce an integrated assessment of the resource and to determine its ability to provide economically viable direct-use energy to the Hawthorne area. The PSA leverages past work to inform a sub-surface flow and heat transport model to determine the long-term thermal performance as a function of flow rate. The DSA determines the cumulative heating and cooling loads for the town, county, and the HWAD facilities and the efficiencies and losses associated with their current systems. The WSA uses system dynamics theory to understand the integrated dynamic behavior and dependencies between the production and demand sides to determine the economic feasibility.

The study focuses on answering four high-level feasibility questions:

1. What is the sustainable, heating and cooling potential of the geothermal resource?
2. What are the heating and cooling demand loads of the service area?
3. What is the optimal direct-use configuration to exploit the resource?
4. What are the economics of that configuration?

By answering these questions and weighing the final answers against a suitable set of decision metrics, the feasibility of any configuration can be determined. However, despite the considerable amount of past work, there are gaps in the knowledge base that prevents us from answering them. The gaps mainly exist in the hydrogeologic characterization of the resource and its long-term dynamic response under different levels of exploitation. Thus, to answer the feasibility questions, the following scientific questions were considered:

1. What are the hydrogeologic characteristics of the resource?
2. What is the sustainable pumping capacity of the resource?
3. What are the dynamics between the rate of geothermal fluid extraction, temperature, and sustainability?
4. How does seasonality affect:
 - a. Plant and system efficiencies?
 - b. Heating and cooling demands?
5. How do system uncertainties influence the feasibility estimates?

The integrated three-tiered, PSA, DSA, and WSA approach developed for this project provides us with a systematic and efficient manner for which to address these questions. The key is in gaining a better understanding of the hydro-geothermal system and the dynamics between it and the district heating and cooling requirements.

The balance of this paper will start with (Section 2) a summary of the PSA where the conceptual model of the geothermal system is determined. Section 3 will present the numerical flow and heat-transport model, its setup and its results. The WSA and its linkages to the PSA and DSA are presented in Section 4 followed by the results in Section 5.

2. PRODUCTION SIDE ANALYSIS

The details of the production side analysis are being presented in a companion paper (Ayling et al., 2020) and thus the information presented here is a summary of their key findings. Production side analysis (PSA) focuses on creating a conceptual model of the geologic and hydrologic system that is consistent with our current level of understanding and that allows for the creation of a numerical flow and heat transport model of the system.

As part of the PSA, we conduct a detailed review of all existing geoscience data acquired at the site to date to develop a quantitative estimate of geothermal resource potential for one of the three Hawthorne geothermal prospects (Prospect A – along the southwest side of the basin over the releasing bend in Figure 3). This includes a review of substantial well data from water wells and geothermal exploration wells (downhole temperature logs, lithology, water chemistry, borehole televiewer, and alteration mineralogy), detailed geological and structural mapping information, geophysical data (gravity, magnetic, and seismic reflection), 2-m temperature data, and an existing 3D geological model of the basin.

We find that the thermal anomalies associated with Prospect A reflect the influence of two, related geothermal fluids in close proximity that are chemically-distinct, with different temperatures and spatial extent (lateral and vertical). One fluid represents a deeper resource, hosted in altered, fractured Mesozoic granitic basement along a segment of the Wassuk Range-front fault system, and characterized by mature, alkali-chloride fluids, with ~4000 ppm total dissolved solids (TDS) and a maximum measured temperature of ~115 °C at ~1,500 m depth. A second fluid is hosted in Neogene basinal sediments at <400 m depth, with maximum measured temperatures of ~100 °C, TDS of ~1000 ppm, and a sodium-sulfate fluid chemistry. The outflow of this shallow resource can be tracked down gradient (towards the NNE) into the basin using well temperature data, which map a vertically constrained plume that cools with distance from the inferred upflow location. The data suggest that the deeper resource is conductively transferring heat to the shallow resource, and structural and/or stratigraphic compartmentalization is preventing direct interaction and fluid mixing.

From the new conceptual model of Prospect A, we construct P10, P50, and P90 estimates of the resource capacity, where the P10 scenario exists as the 10th percentile between most optimistic and most pessimistic (Figure 4). Cross-sections of the temperature contours are shown in Figure 5 and Figure 6. The techno-economic analysis presented below focuses on the ‘shallow reservoir’ located in the Neogene basinal sediments due to lower drilling costs and ease of access, and the marginal gains that would come from going deeper.

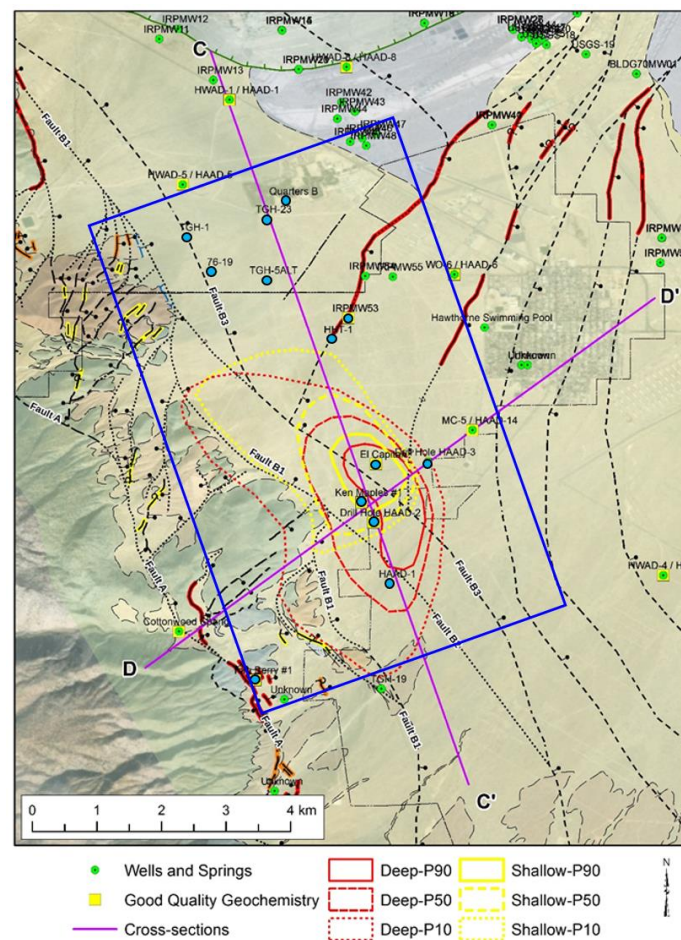


Figure 4 - Plan view of the limit for 90 °C water for the shallow and deep reservoir systems across the three capacity estimates (P10, P50, and P90). The blue dots indicate the wells used in the calibration of the numerical model. The blue box is the approximate extent of the numerical model. From Ayling et al., 2020.

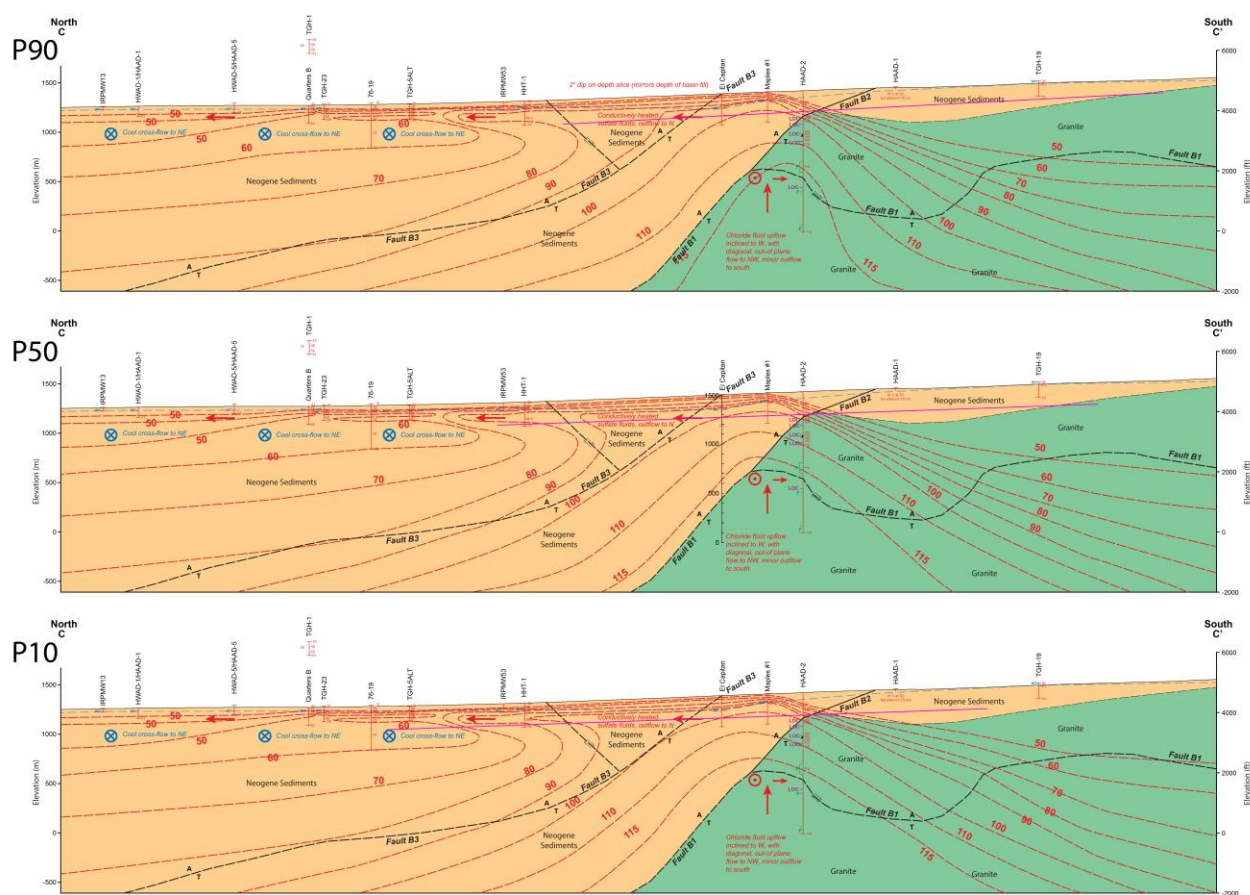


Figure 5 - Cross section along the C-C' line shown in Figure 4. Note how the plume of hot water is larger for the P10 capacity estimate than for the other estimates. The turnover of warmer water on top of cooler water is also evident in the contours to the north. From Ayling et al., 2020.

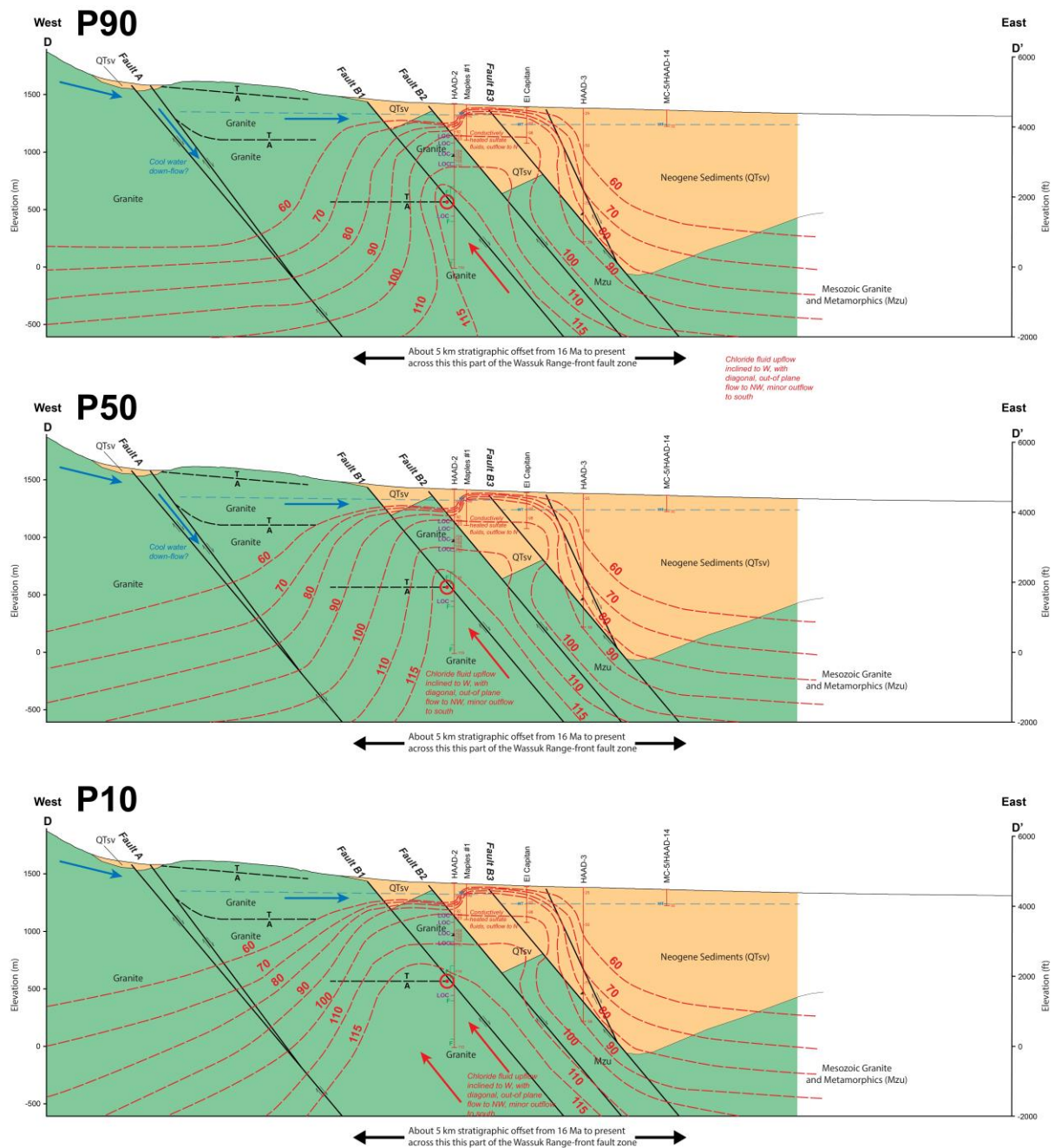


Figure 6 - Cross section along the D-D' line shown in Figure 4. Again, the more optimistic P10 estimate shows a wider plume of hot water than the other cases. From Ayling et al., 2020.

3. PRODUCTION SIDE NUMERICAL MODEL

The main purpose of the model is to better understand the sub-surface system and to estimate effective values of its geo- and hydrological characteristics such that the long-term thermal performance of the system can be estimated as a function of the extraction location and rate. The secondary purpose of the model is to place boundaries on the systems' thermal performance as a function of the uncertainties in the geo- and hydrological parameter estimates. This also has the side benefit of identifying sources of uncertainty that if better understood will narrow the feasibility estimates the most.

The model uses a simplified construct of the shallow reservoir by assuming a constant temperature bottom boundary condition that is constructed from the thermal cross-sections above. This is consistent with the conceptual model of there being little to no mixing between the shallow and deep waters and that the shallow system is heated through a convective process as opposed to upwelling and mixing. Three different bottom boundary conditions are used (Figure 7); one each for the P10, P50, and P90 capacity estimates.

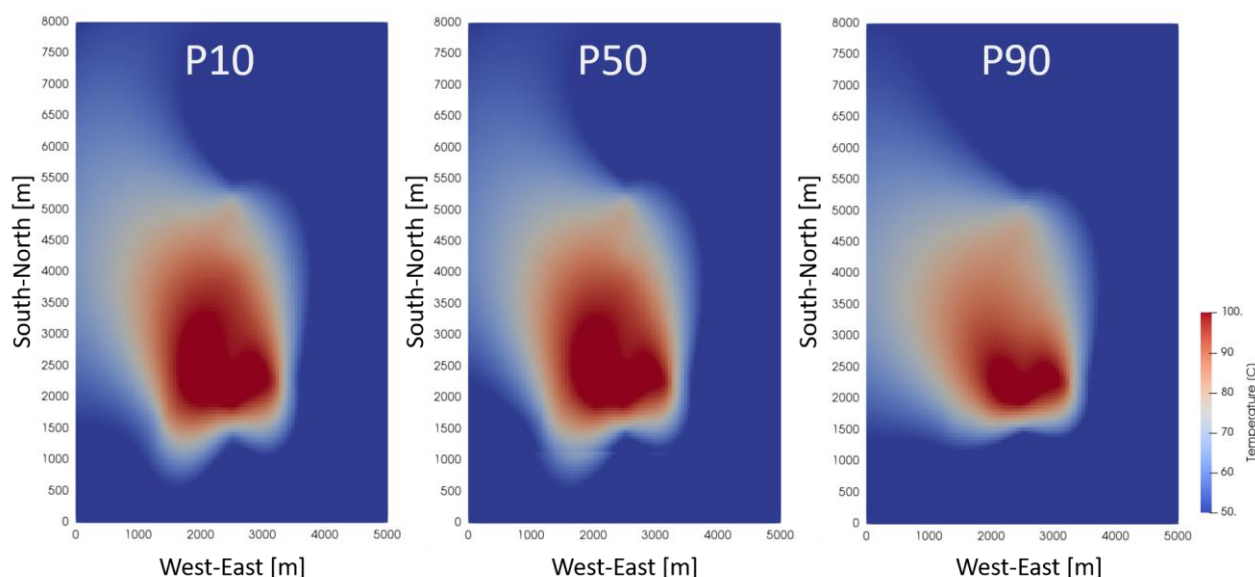


Figure 7 – Constant bottom boundary for the P10, P50, and P90 cases. The area of $> 90^{\circ}\text{C}$ is largest for the P10 case and smallest for the P90 case.

The model uses a structured grid that measures 5000 m (west to east: X-axis) by 8000 m (south to north: Y-axis) by 260 m thick (Z-axis), and uses a grid spacing of 50 m in the X and Y directions and 20 m in the Z direction (208,000 grid cells). The simulation is executed using PFLOTRAN (www.pflotran.org), which is an open source massively parallel subsurface flow and reactive transport code. Despite the relatively small grid, the ability to run the model on a parallel system was important for the calibration and the uncertainty analysis. The model is run in ‘TH’ (thermal-hydrological) mode, which assumes that the system is fully saturated and single phase.

Boundary conditions assume a no-flow, constant temperature along the bottom boundary, constant flux to represent recharge on the top boundary, constant pressure along the south and north boundaries and assume a regional flow from south to north, and no-flow along the east and west boundaries. The model is calibrated using the root mean squared error (RMSE) between the model simulation and the temperature profile data of existing wells (Figure 8), using Sandia’s ‘Design Analysis Kit for Optimization and Terascale Analysis’ (DAKOTA – dakota.sandia.gov). Calibration is done by systematically changing permeability, anisotropy, recharge rate, recharge temperature, and hydraulic gradient. The calibration simulations assume no pumping and run for 10,000 years to reach a steady-state condition from which to match the field data. Each capacity estimate is calibrated separately to better understand how the boundary conditions affect the calibrated values and determine the range of uncertainty in the final results. A cross-section of the pre-calibrated model for the P90 case is shown in Figure 9.

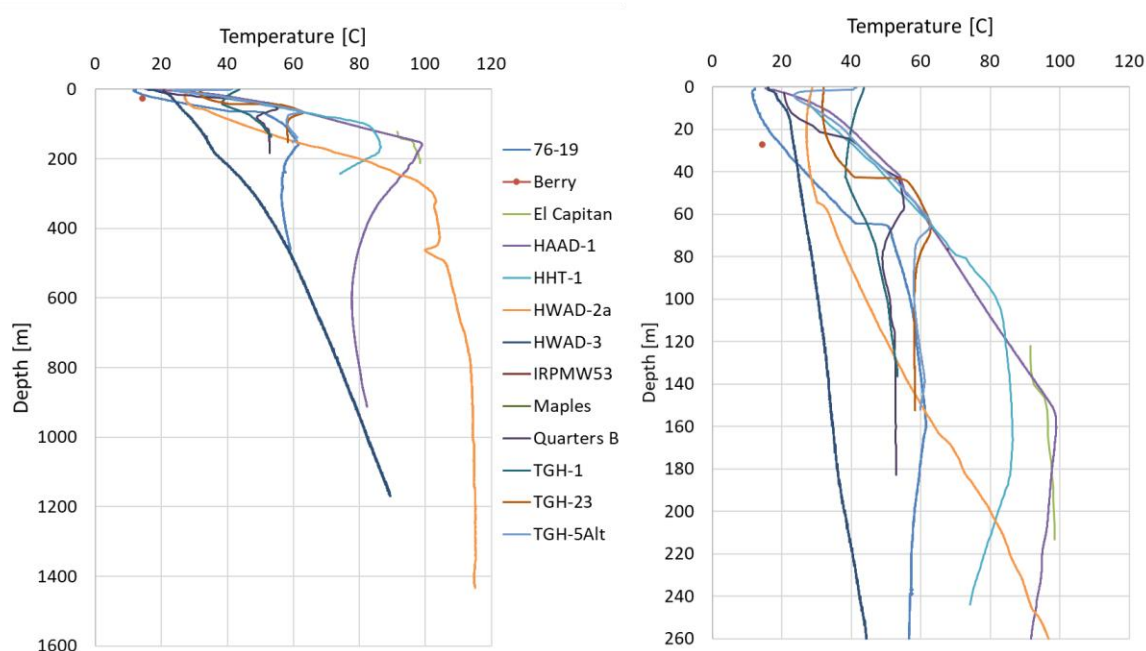


Figure 8 - Temperature profiles over the sampled depth (left) and the model domain (right). Well locations are shown in Figure 4.

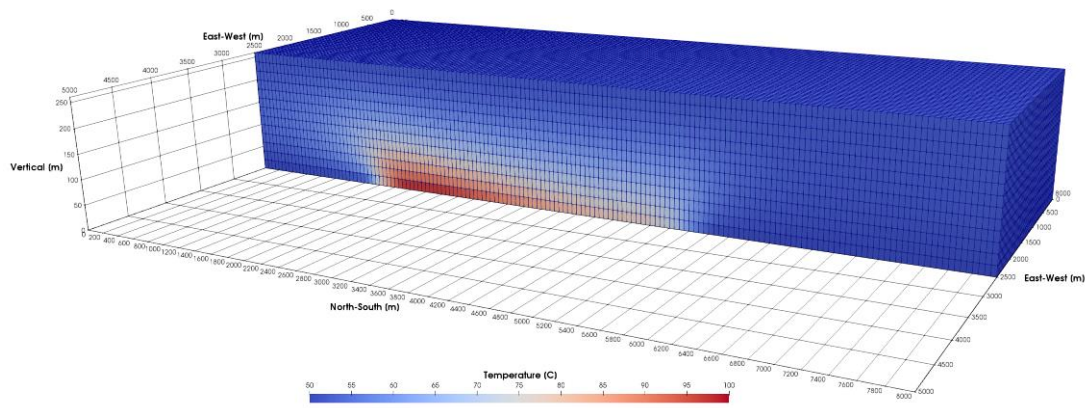


Figure 9 – Pre-calibrated model for the P90 case. North is to the right.

Once calibrated, the model is re-run to create the initial conditions for the pumping scenario runs. Three pumping scenarios are simulated (17.5 kg/s, 35 kg/s, and 70 kg/s - ~ 300 gal/min, 600 gal/min, and 1200 gal/min) assuming a single producer and a single injector. For the 35 kg/s and 70 kg/s pumping rates, additional scenarios assuming 2 producers and 2 injectors are also simulated. For this analysis, well placement for the single producer is set in the center of the >90 °C hotspots shown in (Figure 7) while for the two-producer case, the well placement is within the hotspot but spaced as to avoid interference. Future iterations will look at random placements within the hotspot and the sensitivity to well placement. The injection wells are placed down gradient beyond their range of influence with the production wells. The scenarios are listed in Table 1.

Table 1 - List of operating / configuration scenarios. Pxx refers to the different percentile cases (P10, P50, and P90).

Scenario #	Total Pumping Rate [kg/s]	# of Producers	# of Injectors
Pxx-01	17.5	1	1
Pxx-02a	35.0	1	1
Pxx-03a	70.0	1	1
Pxx-02b	35.0	2	2
Pxx-03b	70.0	2	2

4. WHOLE SYSTEMS ANALYSIS

Whole systems analysis (WSA) attempts to dynamically link the demand side and the production side to provide a clearer understanding of how the system responds under different operating scenarios (Figure 10). WSA is based on the performance assessment approach used to evaluate the effectiveness of nuclear repositories (e.g. Helton, 1993) but adds an economic component to link physical performance to economic performance. It also borrows from the world of system dynamics (Forrester, 1961) where a stronger emphasis is placed on temporal dynamics and feedback between systems rather than spatial dynamics within systems.

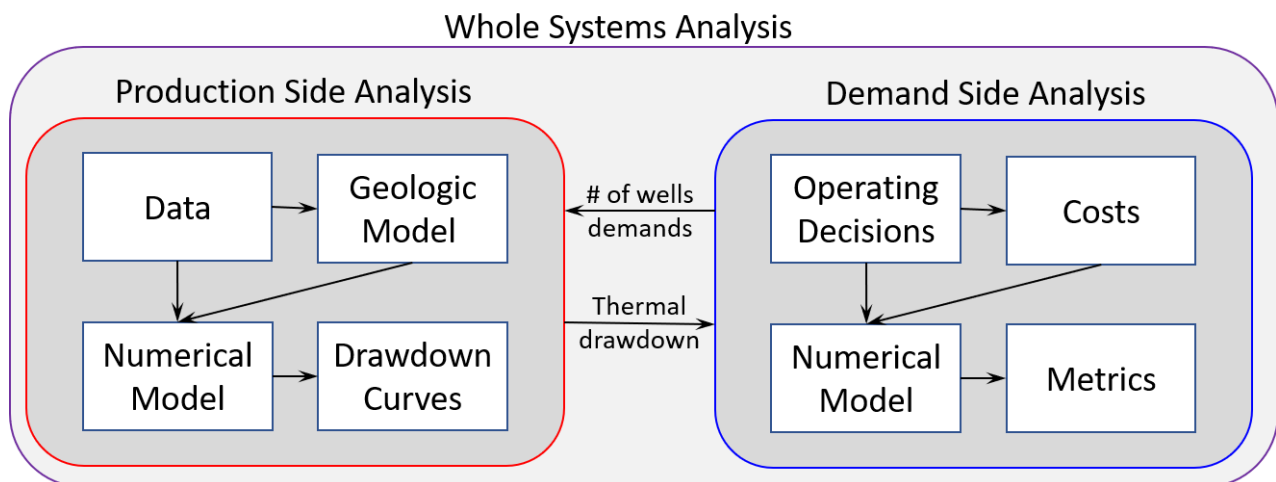


Figure 10 – Conceptualization of whole systems analysis as it pertains to deep direct-use geothermal energy. Feedback occurs when the thermal drawdown over time influences operations which in turn influence the thermal drawdown.

Geothermal energy is unique in that its economic performance and sustainability are tied to how heavily the system is stressed and how it is operated over the years. For deep direct-use systems, the key considerations are the capital costs, mainly drilling costs and costs for the heat exchanger(s), and the performance of the system over time. The latter point requires an understanding of how the system will perform under different operating decisions and whether the system is to be managed for the long or short term.

For the Hawthorne system, we set a 30-year performance horizon, which is standard for most energy production/use assessments. Thirty years is also about when the system infrastructure (e.g., heat exchangers, pipes, well casing, etc.) will need to be replaced, creating a ‘reset’ point with respect to the costs. For the analysis presented here, we focus only the production side by evaluating the system at each percentile case (P10, P50, and P90) over the different pumping scenarios and well configurations using the techno-economic model GEOPHIRES (Beckers, 2019).

5. RESULTS

This project is ongoing as of the time of this writing and thus results of the calibrated model are not yet available but will be completed for the conference presentation. However, Figure 11 shows an initial calibration result for the P10 capacity estimate. At this stage, the model is doing a good job of capturing the temperature profiles for wells down gradient (towards the north) of the hotspot (76-19, TGH-1, TGH-23, TGH-5alt, and Quarters B) but is underestimating the temperature for wells closer to and within the hotspot, especially for depths > 50m. Further work is needed to understand this dynamic and the reasons behind it.

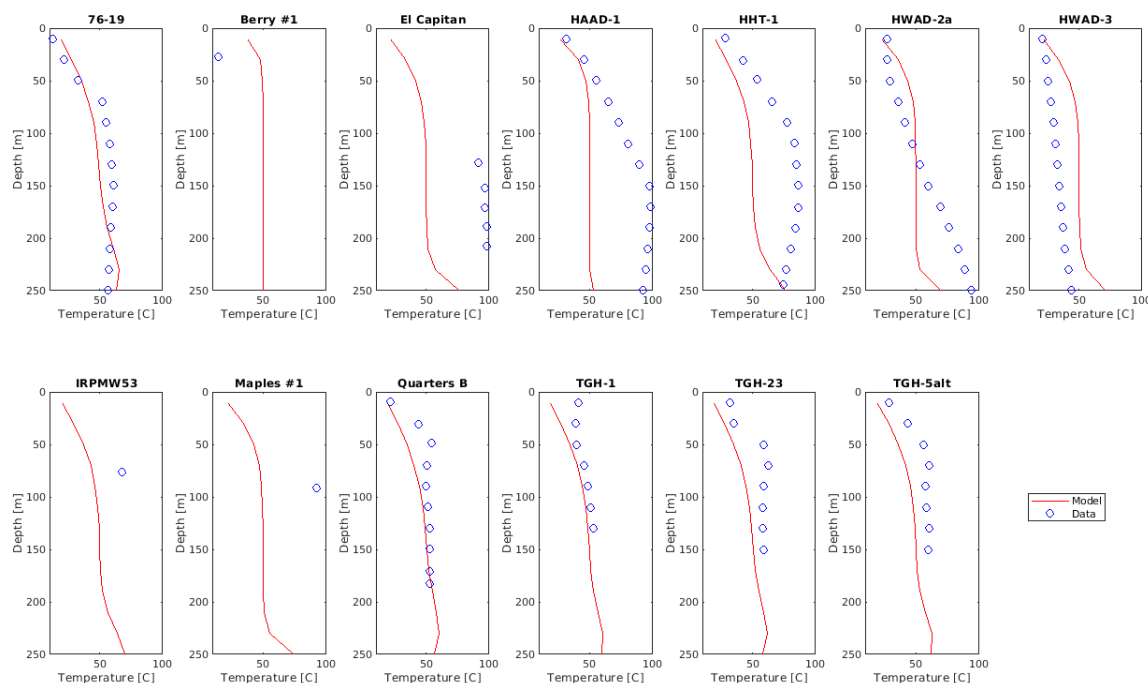


Figure 11 - First calibration effort for the P10 case. Results show better fits for the down gradient wells than for wells over the hotspot. See Figure 4 for well locations in relation to the model domain and hotspot.

Using an initial calibration result for the 02a scenario (single production and injection well pumping at 35 kg/s), we looked at the variability of the initial heat production and the annual average heat production as a function of the variability in the calibration parameters (Figure 11). The initial heat production across all parameters shows a small range when compared to the average annual heat production. This is to be expected since all cases are starting with the same initial conditions. However, the variability in the average annual heat production indicates that there is a large amount of parameter uncertainty within the model. This will be reduced once the calibration is complete but will still likely be significant. Examining the differences between the P10, P50, and P90 capacity estimates is inconclusive at this point, likely due to the relatively small sample size (~ 10 each) and the fact that the parameter sets were not filtered for realism.

Uncertainty in the thermal performance of the system over time is the dominating factor when determining the system configuration and operations. Once completed, the results will show how variability in pumping rate, well configuration, parameter uncertainty, and resource estimations influence the economic metrics and when taken together, will show how to minimize risk and increase system performance. These results will be presented at the conference.

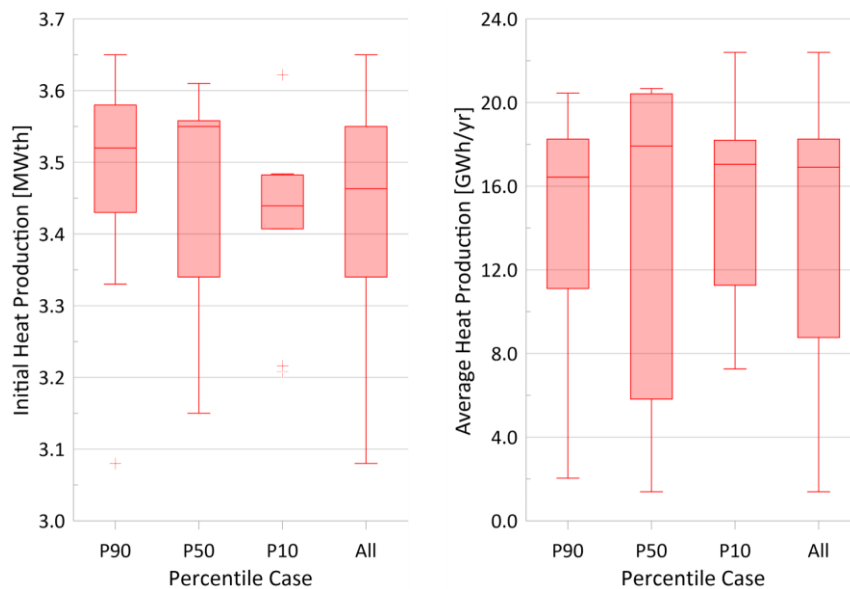


Figure 12 - Box and whisker plots showing the impact of parameter variability on the initial and average annual heat production.

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