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Feasibility of Development of Geothermal Deep Direct-Use District Heating and Cooling system at West Virginia University Campus-Morgantown, WV

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ABSTRACT

The Morgantown campus of West Virginia University (WVU) is uniquely positioned to host the first geothermal deep direct-use district heating and cooling (GDHC) system in the eastern United States. While much of the eastern United States does not have elevated heat flow, the Morgantown region of West Virginia is unique in exhibiting sufficient temperatures at the depth of a formation, the Tuscarora, which is expected to support a desirable flow rate of geofluid. Temperature and flow rate were identified in the 2006 MIT Future of Geothermal Energy Report to be the two most critical factors in minimizing the cost of geothermal energy. The WVU campus site offers surface demand coupled with the potential subsurface viability. Specifically, the existing district heating and cooling system that is in use year round will be leveraged. Absorption chilling systems are used to cool the campus in the summer and provide hot water circulating heat in the winter. Our overall project objectives are to 1) collect local information on these critical factors to understand the uncertainty and reduce the risk associated with developing the geothermal resource for use in a WVU campus GDHC system, and 2) complete an optimized design for the GDHC system by minimizing the delivered Levelized Cost of Heat (LCOH).

A Tuscarora geological model was built based on core analysis and permeability measurements using data from nearby wells. This geological model is then translated into a reservoir model. iTOUGH2/EOS1 is used to simulate the subsurface portion of a GDHC system using two well configurations: 1) a pair of vertical wells, and 2) a pair of horizontal wells. The performance of both configurations is evaluated based on achievable flow rates and production fluid temperatures; the recommended well configuration is selected based on the expected GDHC system performance. The thermal breakthrough and reservoir productivity increased for horizontal well configuration however, the well-head LCOH for vertical well horizontal well configuration is higher than vertical wells due to the additional cost of horizontal drilling.

To minimize the delivered LCOH, we perform an integrated surface-to-subsurface optimization of the full GDHC system. The economic and performance analysis of the GDHC system is evaluated for two cases: 1) using existing district heating and cooling facilities, and 2) by converting the current WVU campus steam infrastructure to a hot water system. The optimized GDHC system will be selected by minimizing the LCOH over these two possible configurations.

1. INTRODUCTION

In 2010, research completed by the Southern Methodist University (SMU) Geothermal Laboratory estimated that temperatures in the range that would be desirable for district heating could be achieved at reasonable drilling depths in the state of West Virginia (Blackwell et al., 2010; Frone and Blackwell, 2010). An area of particular interest with elevated heat flows was estimated to extend from north-central West Virginia (Monongalia County), to southeastern West Virginia (Greenbrier County), as shown in Figure 1 (Frone and Blackwell, 2010). Geothermal resource assessment completed using additional well data in the Appalachian Basin Geothermal Play Fairway Analysis also estimated a region of elevated heat flows in north-central West Virginia (Cornell University, 2017). The Morgantown campus of West Virginia University (WVU) is located within this region, and offers a desirable and unique combination of critical factors necessary to develop a deep direct-use geothermal system. In this paper, we evaluate the feasibility of a deep direct-use geothermal system for the WVU campus that can serve as a demonstration site for other areas in West Virginia that have similar geothermal resources.

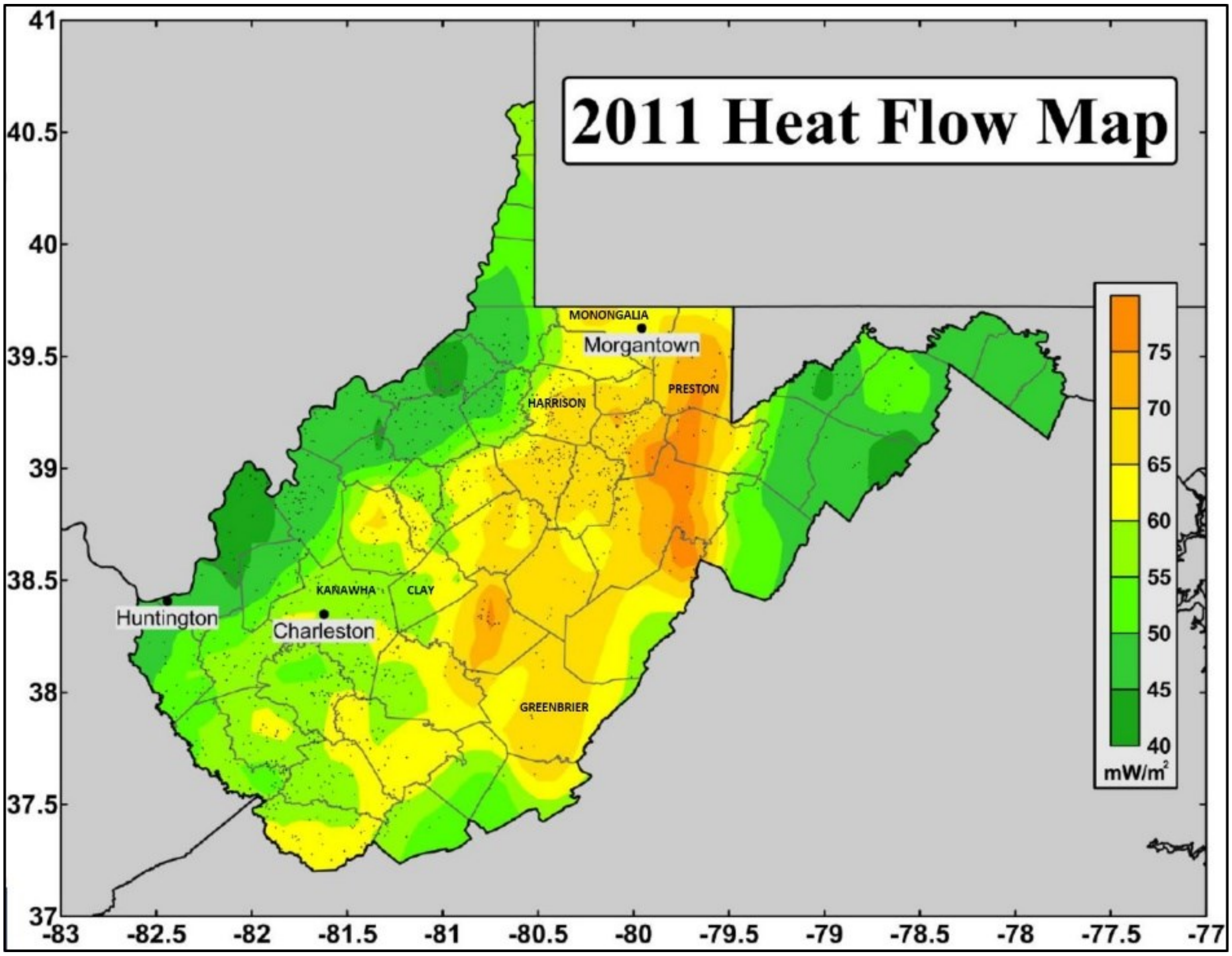

Figure 1: West Virginia geothermal heat flow map, illustrating a region with elevated heat flow that extends from north-central West Virginia (Monongalia County), to southeastern West Virginia (Greenbrier County) (Frone and Blackwell 2010). Small black circles indicate locations of wells for which the surface heat flow was estimated from bottom-hole temperatures.

The Lower Silurian Tuscarora Sandstone is chosen as the preliminary target formation for a geothermal reservoir for the WVU-Morgantown campus. This formation is approximately 100 m thick and encountered at a depth of about 10,000 ft (3048 m) in Morgantown. Local core data indicate a fracture-dominated reservoir with significant potential porosity and permeability. The thermal resource at our chosen geothermal site has been informed by an ongoing project, led by WVU and funded by the U.S. DOE Office of Fossil Energy, called the Marcellus Shale Energy and Environment Laboratory (MSEEL). This innovative project used downhole fiberoptic distributed temperature sensing (DTS) to provide new temperature-depth data near the proposed geothermal location (MSEEL, 2018).

The expected temperatures of the Tuscarora and expected high flow conductivity makes the WVU campus an ideal candidate for geothermal direct use. Temperature and flow conductivity were identified in the 2006 MIT Future of Geothermal Energy Report to be the two most critical factors in minimizing cost of geothermal energy. Direct-use geothermal development requires an additional critical factor for economic viability: available thermal demand and appropriate surface distribution infrastructure. The market for the geothermal resource in Morgantown will be the commercial and residential sectors of the West Virginia University campus, comprising 1,892 acres, 245 buildings and 30,000 faculty, staff, and students. The steam to the campus loop is currently provided by Morgantown Energy Associate (MEA), a coal-based power plant. As part of a U.S. DOE funded Geothermal Deep Direct Use project, research objectives for this site are to 1) decrease the uncertainty and risk associated with developing the geothermal resource for the WVU campus and 2) complete an optimized design for the geothermal system, minimizing the delivered Levelized Cost of Heat (LCOH).

In this paper, a 3-D conceptual model for the proposed geothermal site is developed using reservoir properties estimated from regional datasets. Two well configurations (vertical and horizontal) are compared based on reservoir performance and preliminary economic analysis of well head levelized cost of heat (LCOH). The surface demand is characterized by year-round steam consumption data for the WVU campus, and preliminary surface plant analysis for a hybrid geothermal-natural gas system to provide steam at the required conditions for campus infrastructure.

2. SUBSURFACE MODELING

2.1 3-D Geological Model

A 3-D geological model centered on the proposed well location on the West Virginia University (WVU) -Morgantown campus is shown in Figure 2. This model was constructed with the 3-D GeoModeller GMS (Aquaveo, LLC in Provo, Utah; 2013) and was informed from several studies including Patchen et. al. (2006) Appalachian Basin geologic play book, geologic cross sections from Ryder et. al., (2009), and a detailed 3-D geological study near Morgantown by McCleery et. al., (2018). The geological model includes 15 geoloigcal layers with horizontal extension of 40 km in each direction. The reservoir model used for geothermal simulations was derived from this geological model and only contains the target Tuscarora formation, as the two formations above and below are relatively impermeable. The heat exchange between the Tuscarora formation and the caprocks and base rocks are considered using a semi-analytical solution implemented in iTOUGH2 (Finsterle., 1999). Initial reservoir simulations using a 15 km x 15 km model domain with two vertical wells spaced 500 m apart with a flow rate of 15 kg/s indicated a pressure change of less than 0.2 MPa at 2.5 km away from the wells. Based on these simulations, the horizontal extension of the final reservoir model was selected as 5 km in each direction (Figure 2b). The vertical extension of the model is between -2600 and -2940 m, although the reservoir thickness is only about 100 m. This is due to the vertical depth variation of the target formation Tuscarora.

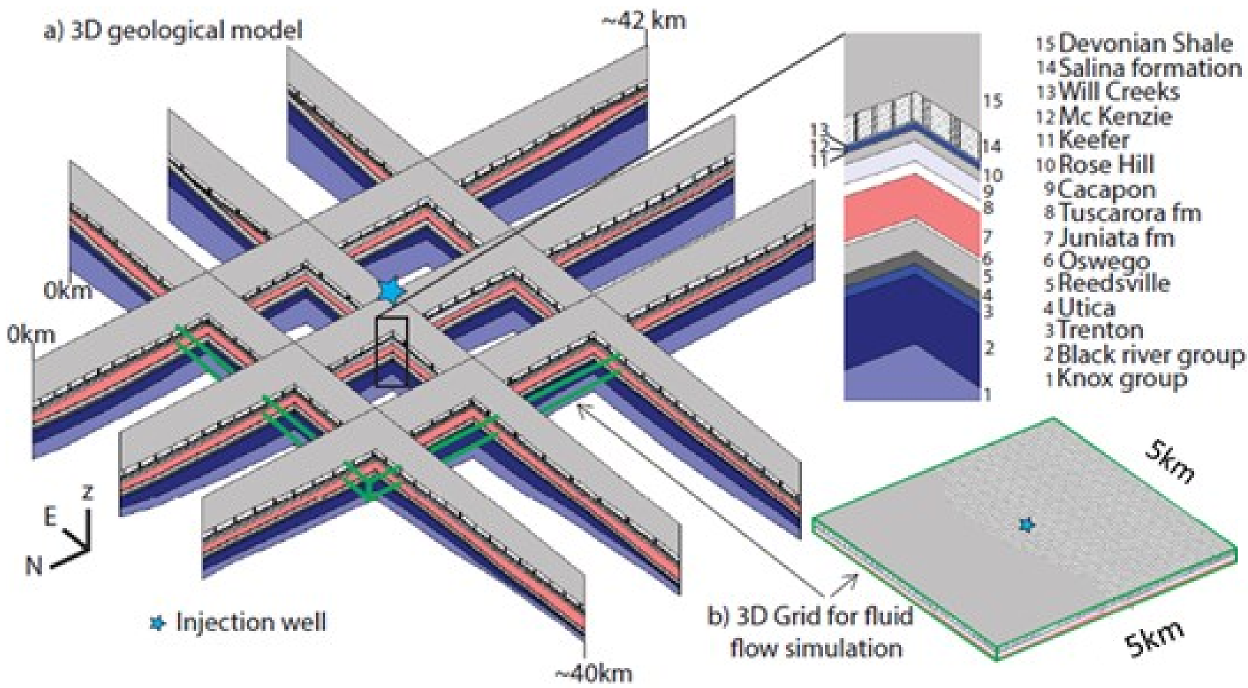

Figure 2: (a) the 3-D geological model, and (b) the 3-D grid used for numerical reservoir model simulations.

2.2 Temperature at the Tuscarora Reservoir Depth

The temperature at the depth of the Tuscarora sandstone in Morgantown was estimated using local corrected bottom-hole temperature (BHT) data (Cornell University, 2017; correction equations are described in Whealton, Stedinger and Horowitz, 2015) and a fiberoptic distributed temperature log taken within 5 km of the WVU campus (MSEEL, 2018). The temperature log likely represents thermal equilibrium conditions because it was taken after several months of well operation. The temperature log provides data to a depth of about 2.2 km in Morgantown. Prediction of temperatures at deeper depths is informed by local BHTs using the methods described in Smith (2016) (also in Cornell University, 2017). These methods are as follows: 1) the surface heat flow is predicted at each well location using a 1-D heat conduction model (Smith and Horowitz, 2017), and 2) the surface heat flow is predicted for Morgantown using kriging geostatistical interpolation of the well surface heat flows. Using the estimated surface heat flow mean and uncertainty for Morgantown, a Monte Carlo analysis of uncertain geologic properties (thermal conductivity, heat generation, formation thicknesses and depths) and surface heat flow were used in the 1-D heat conduction model to estimate temperatures at depth. The temperatures at 0.5 km depth increments in Morgantown based on 10,000 Monte Carlo replicates of these uncertain variables is provided in Figure 3. The top of the Tuscarora is expected to be approximately 3 km depth, which corresponds to a mean of 88 °C and 5% and 95% percentiles of [72.5, 104] °C. The initial temperature used in the reservoir model is calculated using a surface temperature of 13.4 °C and geothermal gradient of 26°C/km, resulting in the reservoir temperature in the range between 80~90°C over the reservoir thickness.

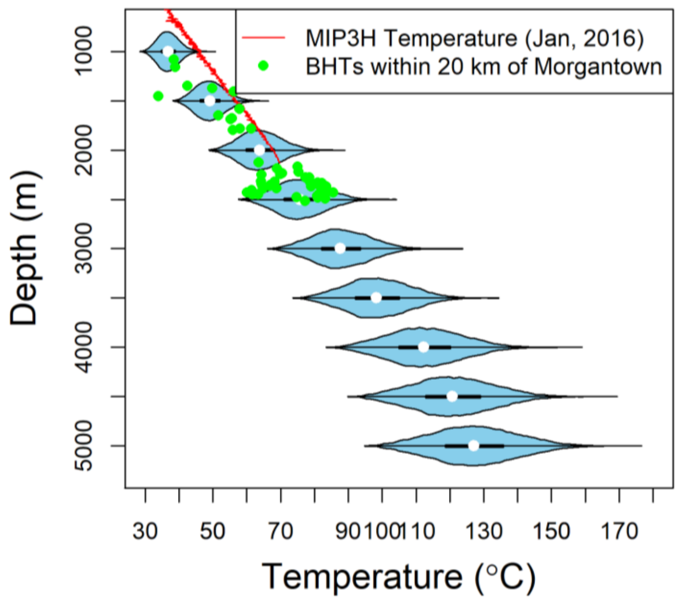

Figure 3: Predicted temperatures at depth in Morgantown in 0.5 km intervals with their uncertainty distributions shown as blue violin plots (kernel density plots). White circles are placed at the median predicted temperature at depth, and a black box in the center spans the 25th to the 75th percentile estimates. The temperature-depth measurements from wells within 20 km of Morgantown are overlain on this plot (green: bottom-hole temperatures, red: fiberoptic distributed temperature log).

2.3 Permeability

The permeability of the Tuscarora sandstone in Morgantown was estimated from 753 core measurements spanning a 273 ft (83 m) interval of the Preston-119 well located about 50 km SSE of Morgantown (McDowell, Lewis, and Daft, 2018). Measurements were taken using air and corrected to effective water permeability using a Klinkenberg correction (Jones, 1987). Measurements on fractures with horizontal or subhorizontal dip angles less than 20° were excluded because these fractures are likely to be closed at the depths of the Tuscarora. Permeability measurements were taken on several structural features. A histogram of the effective water permeability categorized by the type of feature is provided in Figure 4. Permeabilities less than 10 mD are found primarily in matrix rock. Permeable zones greater than 1 Darcy are found throughout the Tuscarora thickness in fractures (Figure 5). The shallower portion of the Tuscarora seems to have more frequent permeable zones than the deeper portion (Figure 5), so we model the upper 2/3^{rds} of the Tuscarora using higher fracture permeability (64 mD) than the lower 1/3rd of the Tuscarora (4 mD). Matrix permeability was assumed to be the same throughout the Tuscarora thickness, as observed in the core measurements (Figure 5).

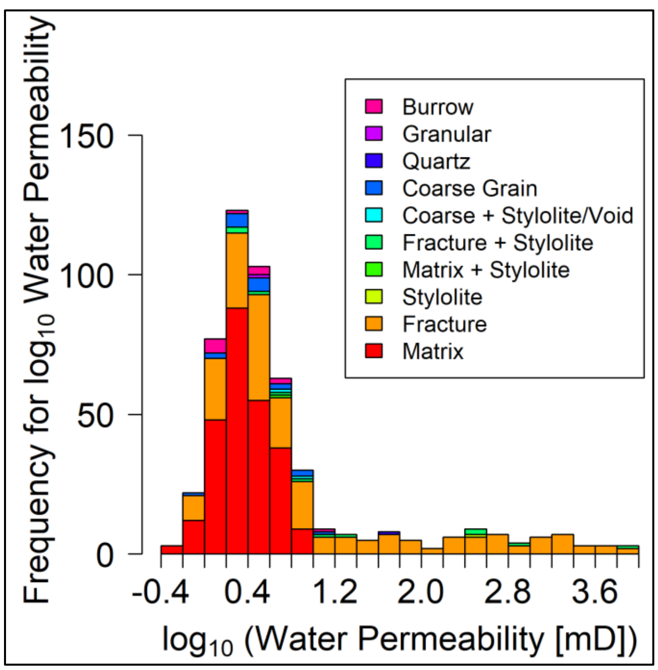

Figure 4: Stacked barplot showing the measured water permeability by the type of geologic feature measured in the Preston-119 well (~ 50 km SSE of Morgantown, WV). The aggregate distribution is the effective water permeability histogram for the measurements.

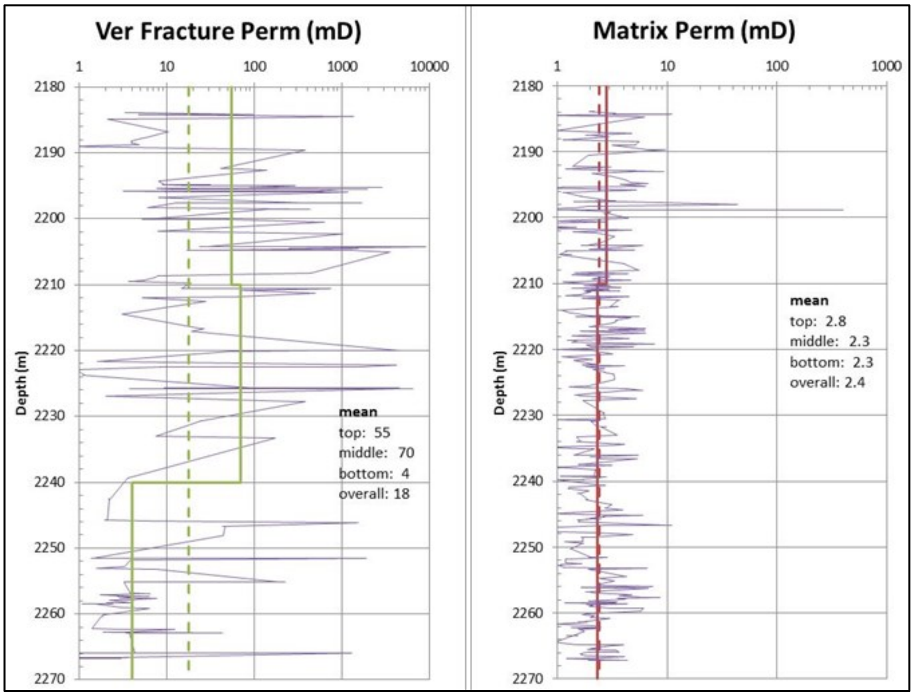

Figure 5: Vertical fracture permeability and matrix permeability at the depth of the Tuscarora Sandstone in the Preston-119 well (~ 50 km SSE of Morgantown, WV). The solid purple line connects individual measurements, and should not be used to suggest geologic trends. The thick dashed line indicates the average permeability over the thickness. Top, middle, and bottom refer to depths of 2180 – 2210 m, 2210 – 2240 m, and 2240 – 2270 m, respectively. The mean permeability in these depth ranges is shown on the plots.

2.4 Numerical Simulations

The numerical simulator iTOUGH2 (Finsterle, 1999), which is based on TOUGH2 (Pruess et al., 1999) was used for the numerical simulations, using the equation of state package EOS1, designed for multiphase flow of water (liquid, vapor) and heat. iTOUGH2 and TOUGH2 employ the integral-finite-difference method (Edwards, 1972; Narasimhan and Witherspoon, 1976) for spatial discretization, which is a flexible method that can create accurate grids with variable resolution, and also provides convenient means to represent dual-continua (i.e., fractured and matrix) media (Pruess and Narasimhan, 1982, 1985).

The fact that gas production has been successful from the unstimulated Tuscarora suggests that a connective fracture network exists. Initially it was not clear how a geothermal reservoir model that assumed fracture permeability would compare to a simpler porous-medium continuum model with equivalent permeability values. As a result, three reservoir models were compared: a single permeability (K) model and two dual K (fracture and matrix) models. The reservoir parameters for the single K model are listed in Table 1. For the two dual K models: The first model assumes that all fractures conduct flow, while the second model assumes only 10% of fractures conduct flow. For both models, a 2-D fracture network (i.e., only vertical fractures) is considered as the horizontal fractures are likely closed at the Tuscarora depth. The fracture properties are given in Table 2. Matrix permeability is 2.4×10^{-15} m^2 and porosity is 8%.

The boundary conditions for all of the simulations are no fluid flow in all directions and no heat flow in lateral directions, while heat exchange at the top and bottom of the reservoir is calculated based on semi-analytic conductive heat exchange (Pruess et al., 1999). Initial temperature follows the geothermal gradient, while pressure is based on hydrostatic equilibrium.

Table 1: Reservoir physical parameters for the single permeability continuum model.

Reservoir Parameter/Condition	Value
Thickness [m]	100
Porosity	0.08
Upper 2/3 reservoir permeability [m^2]	6.4×10^{-14}
Lower 1/3 reservoir permeability [m^2]	4.0×10^{-15}
Geothermal Gradient [°C/km]	26
Thermal conductivity [W/m/ °C]	2.00
Rock specific heat [J/kg/ °C]	1000
Rock grain density [kg/m^3]	2500
Pore Compressibility [Pa^{-1}]	3.2×10^{-10}
Temperature of Injected fluid [°C]	21

Table 2: Fracture specifications for Dual K models.

Fracture Model Name	Porosity	Upper Layer Permeability [m^2]	Lower Layer Permeability [m^2]	Fracture Spacing [m]	Fracture Volume Fraction
DK3	0.99	6.4×10^{-14}	4.0×10^{-15}	0.3	1.5×10^{-3}
DK4	0.99	6.4×10^{-14}	4.0×10^{-15}	3.0	1.5×10^{-4}

Geothermal reservoir production simulations were carried out for two different injection-production well configurations: 1) two vertical wells, and 2) two horizontal wells. The performance of both the configurations were compared based on production fluid temperatures, time to thermal breakthrough, and thermal drawdown. Based on the performance and cost, one well configuration will be selected for further uncertainty analysis.

2.5 Results

Vertical Well Configuration: Simulations with vertical injection and production wells on single K and dual K models are performed for different well spacing. The mesh around the injection well is locally radial with a wellbore radius of 0.1 m. Injection well flow rate is specified as 15 kg/s. The production well is specified using a deliverability model against a fixed bottom hole pressure (P_{wb}) of 18 MPa. The production fluid temperature with respect to time for all three permeability models described in Section 2.4 are shown in Figure 6. As well spacing increases, the time for thermal breakthrough increases decreases for all three permeability models. Simulated temperatures over time and the time to thermal breakthrough are similar for the permeability models evaluated (single K and both dual K models).

With a large volume of reservoir rock to be accessed by flow in fractures with relatively small spacing, the fluid residence time is long and the heat exchange between the fractures and matrix rocks is no longer dominated by the heat exchange area between fracture and matrix but depends on the amount of heat stored in reservoir volume (Zhou, et. al., 2019). With no known large discrete fracture, and given the interest is in the long-term thermal behavior, only the single continuum model is considered for further analysis.

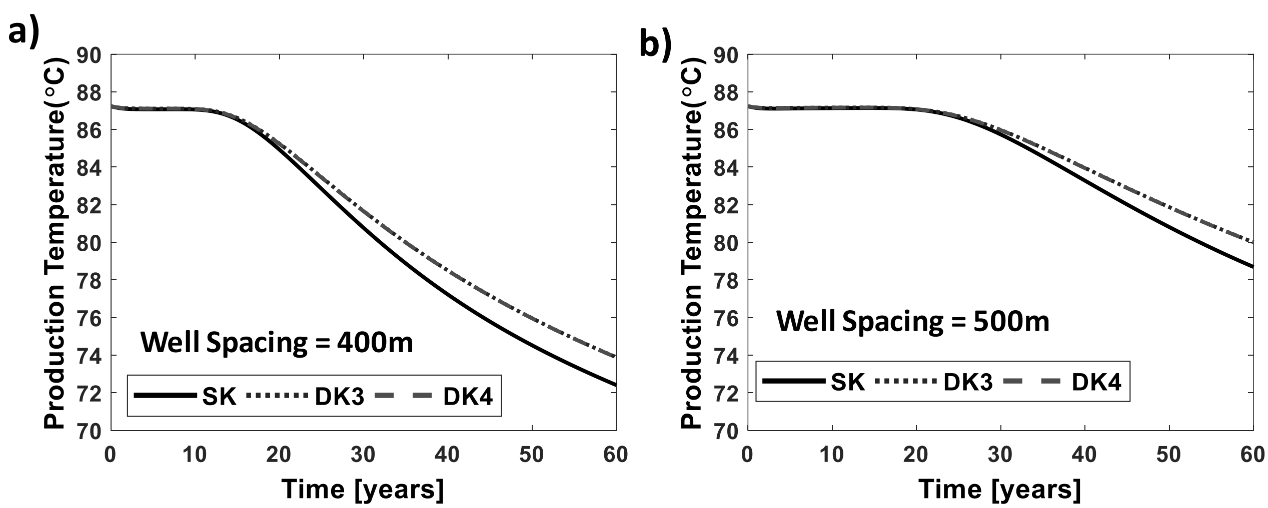

Figure 6: Produced fluid temperature at reservoir over time for well spacing of 400 m (a) and 500 m (b) for the three permeability models considered (single K and two dual K).

Horizontal Well Configuration: Simulations for horizontal well configurations (lateral length = 300 m and 500 m) in the single continuum model were completed for various well spacing. The injection and production wells are represented using locally radial meshes with a wellbore radius of 0.1 m. Injection flow rate is 15 kg/s, while the production well is modeled as a sink with a constant pressure of 26 MPa. The production fluid temperature and reservoir impedance (defined as (injection pressure minus production pressure), divided by production flow rate) are compared with results from vertical well configurations in Figures 7 and 8, respectively. With an increase in the horizontal lateral length, the time until thermal breakthrough increases, and the reservoir impedance decreases. For the well spacing evaluated, the reservoir impedance for horizontal wells is much less than for vertical wells.

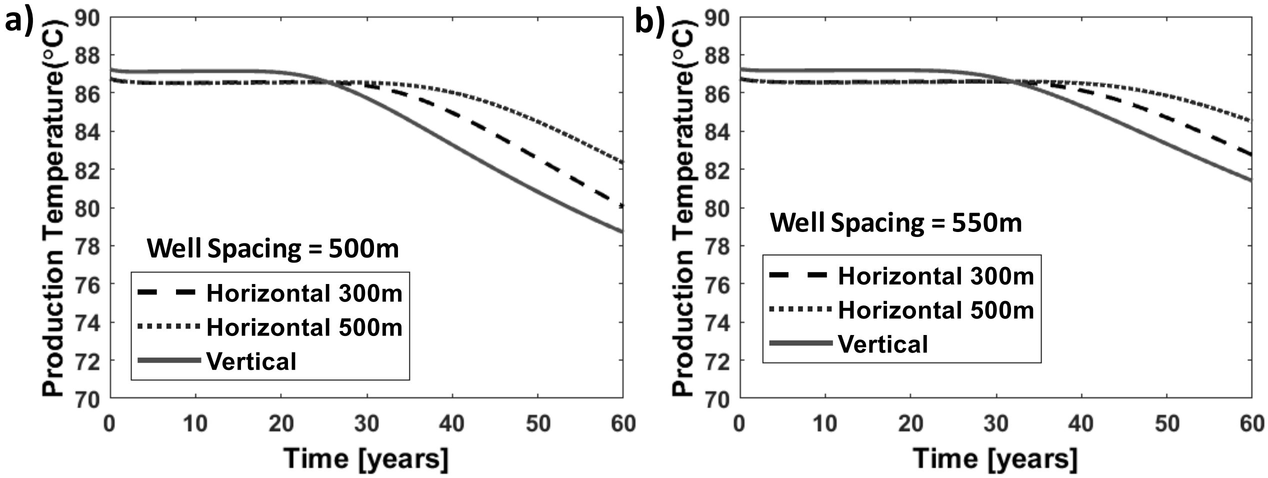

Figure 7: Produced fluid temperature over time for well spacing of 500 m (a) and 550 m (b) for vertical and horizontal well configurations.

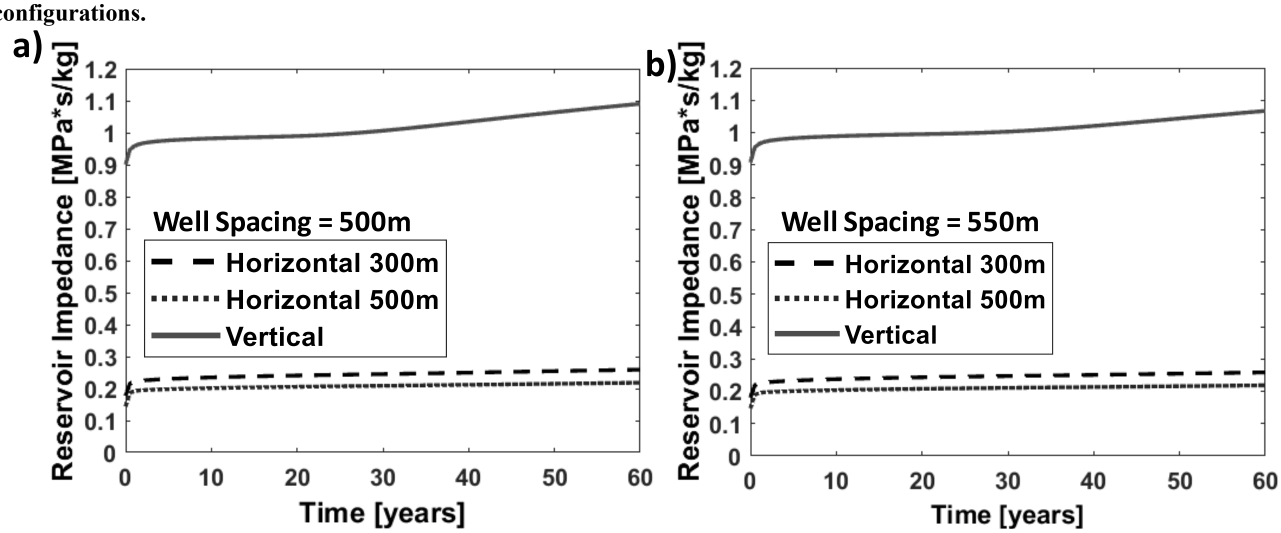

Figure 8: Reservoir Impedance over time for well spacing of 500 m (a) and 550 m (b) for vertical and horizontal well configurations.

3. ECONOMICS

Preliminary economic analysis of well-head levelized cost of heat (LCOH), i.e. the capital costs for drilling wells and pumping costs for production and injection of fluid for different well configurations, is performed using the software GEOPHIRES (GEOthermal energy for the Production of Heat and electricity Economically Simulated), developed at Cornell University and maintained on Github by Beckers and McCabe (2018) (Beckers et al., 2014; 2013). We calculated well-head LCOH for a well spacing of 500 m. Horizontal wells with lateral length of 500 m are considered, and to consider high costs for horizontal well drilling, a cost adjustment factor of 1.5 is used. The surface plant capital cost is considered to be zero because infrastructure already exists that could use for this system. The default values are used for financial parameters and built-in correlations are used for well-drilling and exploration costs to the depths of the Tuscarora reservoir. The technical parameters used are given in Table 3.

Table 3: GEOPHIRES input parameters to calculate well-head levelized cost for both vertical and horizontal well configurations.

Parameter	Vertical	Horizontal
Geothermal Fluid Flow Rate (kg/s)	16.5	17.0
Geothermal Gradient (°C/km)	26	26
Ambient Temperature (°C)	13.5	13.5
Well Depth (km)	2.9	2.9
Well Configuration (-)	Doublet	Doublet
Well Inner Diameter (inch)	8.0	8.0
Reservoir Impedance (GPa.s/m^3)	1.0	0.15
Production Wellbore Heat Transfer	Ramey's Model	Ramey's Model
Reinjection Temperature (°C)	20	20
Reservoir Model	Figure 6 Temperature Data	Figure 8 Temperature Data

Reservoir Water Loss Rate	0%	0%
Well drilling cost correlation	1 (vertical, small diameter)	1 (vertical, small diameter)
Well Drilling and Completion Capital Cost Adjustment Factor	1.0	1.5
Plant Lifetime (Years)	30	30
Economic Model	3 (Bicycle (Hardie,1981))	3 (Bicycle (Hardie,1981))
End-Use Option	2.0 (Direct-Use Heat)	2.0 (Direct-Use Heat)
Circulation Pump Efficiency	0.8	0.8
Utilization Factor	0.9	0.9
End-Use Efficiency Factor	0.9	0.9

The well-head LCOH for vertical and horizontal well configurations are \$16.78/MMBTU and \$19.91/MMBTU respectively. The high value of horizontal well configuration is due to higher drilling costs.

4. SURFACE MODELING

4.1 Characterize Energy Demand

The year-round energy consumption data of the WVU campus is investigated to characterize the energy demand. Five main energy distribution points across the campus are metered:

1. Medical Center: Health sciences campus and hospital
2. Towers: Residential area
3. Ag. Science: Engineering and Agriculture buildings
4. Life Sciences: Life Sciences building
5. Downtown: Majority of the campus buildings in downtown area.

Servers installed at these five meter points record steam temperature, pressure and flow rate, and return condensate temperature and flow rate. Steam temperature, pressure and flow rate for the Medical Center meter recorded for November is shown in Figure 9. The average steam temperature, pressure, and flow rate are 341°F (171.7°C), 91.14 PSIG (6.21 atm gauge), and 38,117 PPH (17,290 kg/h), respectively. The steam demand fluctuates based on the daily weather. The steam usage for the entire campus for 2017-2018 is shown in Figure 10. Most of steam usage comes from the main campuses i.e, Medical center, Evansdale and Downtown meter points. The peak usage is observed in the month of January and the minimum usage is in June.

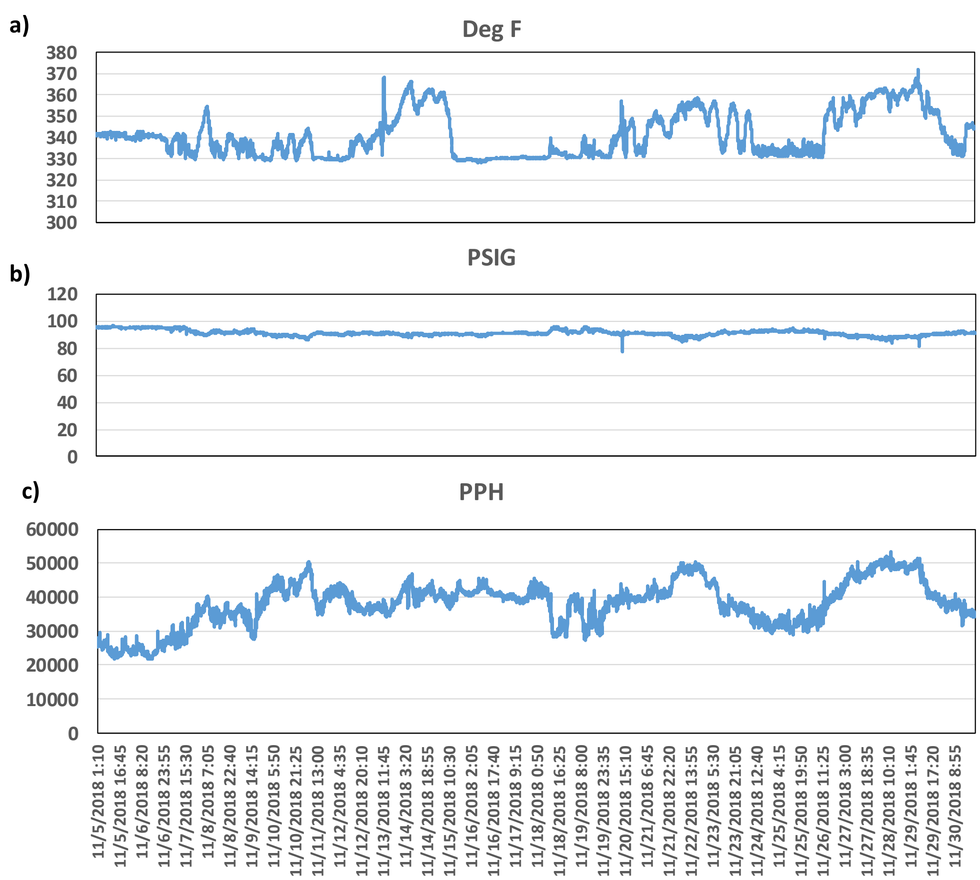

Figure 9: Steam temperature (a), pressure (b) and flow rate (c) from medical center meter point during month of November.

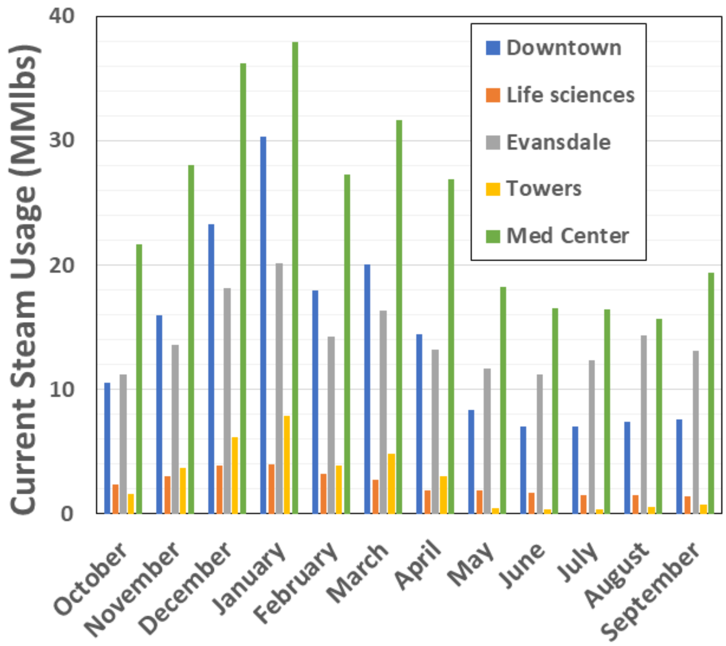

Figure 10: Annual WVU campus steam consumption data for 2017-2018.

4.2 Surface Plant Modeling

The current district heating and cooling system for the WVU campus is steam based, whereas the geothermal system would supply hot water. Conversion of this system from steam to hot water has been investigated, but could be uneconomical and complicated given the campus infrastructure (Rafferty, 1986). In this paper, we consider an alternative hybrid geothermal-natural gas system to provide steam to the campus. The surface plant developed for the hybrid system consists of standard district heating equipment: heat exchanger, natural gas boiler, storage tanks, and the pumping and pipeline units. We modeled this system using Aspen Plus. Figure 11 shows the closed loop configuration for the proposed hybrid district heating system at WVU. Based on the location of the proposed well and steam demand at the five meter points, two cases are considered: 1. supply steam to the entire WVU campus (all five meter points), and 2. supply steam to only the Medical Center, Evansdale, and Towers meter points.

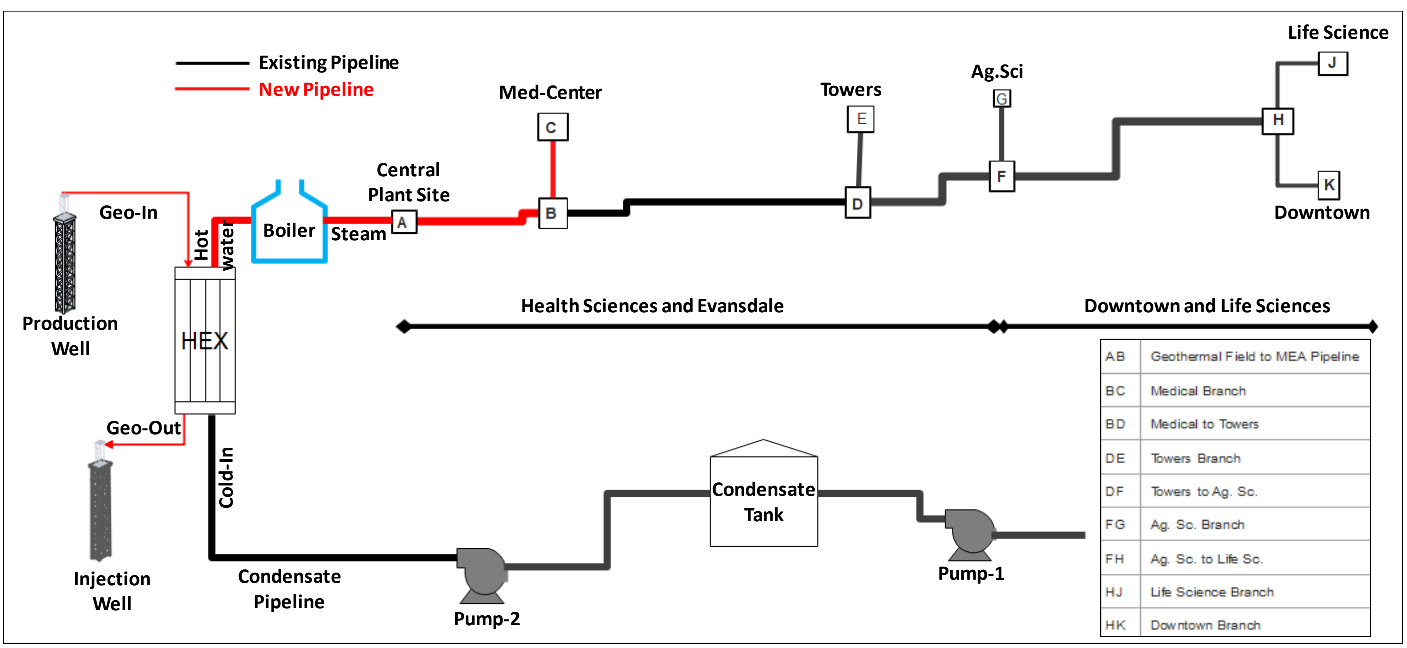

Figure 11: Schematic of the proposed hybrid geothermal-natural gas system to provide steam at required conditions for WVU campus.

Two design schemes are considered for case 1: 1-1. a centralized system, which provides high-pressure steam (250 psig and 500°F) to the main distribution center, and 1-2. a central geothermal heat exchanger where the condensate is preheated by geothermal fluid and is heated to saturated steam at 160 psig by the first boiler, and then it is split into two streams. One stream supplies steam at these conditions directly to Evansdale (Ag. Science and Towers meter points), and Health sciences (Med-center) campuses. The second stream is sent to a second boiler, where it is further heated to 250 psig and 500°F before supplying to downtown campus (Life Sciences and downtown meter points).

Similarly, the second case also has two design schemes: 2-1. a centralized system providing saturated steam at 160 psig to three meter points (Ag. Science, Towers, and Med-Center), and 2-2. a central geothermal heat exchanger with two boilers, one boiler to produce saturated steam at 160 psig for Ag. Science and Med-Center meter points and a second to produce saturated steam at 15 psig for Towers meter point. The secondary fluid flow rate is based on the monthly demand estimated in section 4.1 and the geothermal fluid flow rate is based on the peak demand in January. Other input parameters for the Aspen models are given in Table 4.

Table 4: Aspen Plus input parameters for geothermal heat exchanger

Variable	Case 1	Case 2
Geothermal Fluid Flow rate (kg/s)	15.2	15.2
Geothermal Fluid Inlet Temperature (°C)	90	90
Secondary Fluid Inlet Temperature (°C)	10	10
Secondary Fluid outlet Temperature (°C)	85	85

4.3 Results

The geothermal reinjection temperature and the geothermal contribution to the hybrid geothermal-natural gas system for all the cases considered are shown in Figure 12. Due to the high latent heat needed for conversion of hot water to steam, the geothermal contribution is low. Hence, in future work, another option will be considered to convert the steam-based heating and cooling to a hot water based system, where the campus hot water requirement will be supplied through the geothermal system and natural gas boilers will be used to supply steam that is needed for operation of absorption cooling towers, autoclaves, and other higher temperature demands.

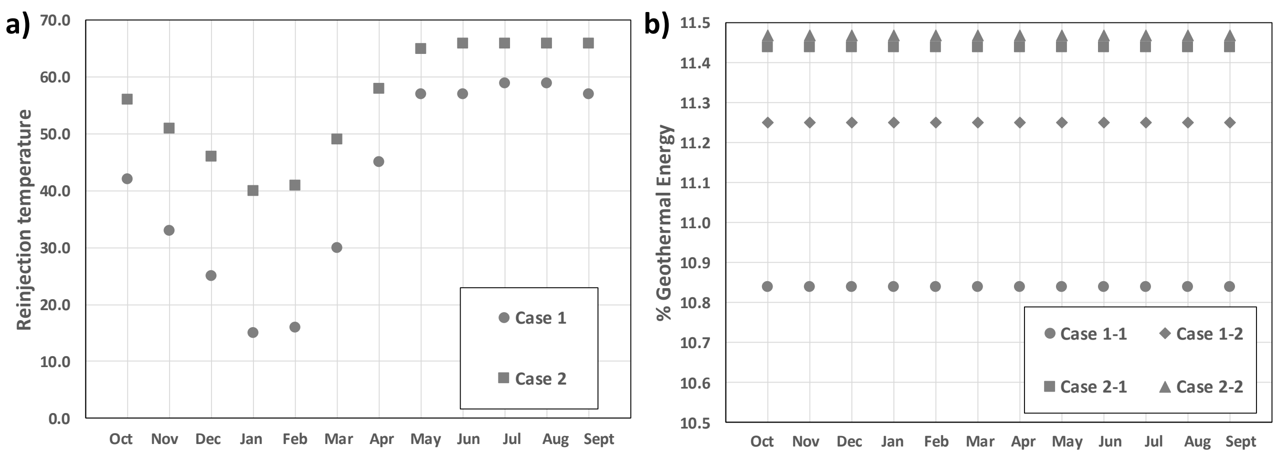

Figure 12: The geothermal reinjection temperature (a) and the geothermal contribution to the hybrid system (b) for both cases considered: 1. supply steam to entire WVU, and 2. supply steam only to Hospital, Health sciences (Med-center meter point) and Evansdale (Ag. Science and Tower meter points) campuses.

5. CONCLUSION AND FUTURE WORK

We presented a feasibility analysis for development of geothermal deep direct-use heating and cooling at the West Virginia University campus in Morgantown, WV. The Tuscarora Sandstone at a depth of 10,000 ft (~3000 m) was chosen as the preliminary target formation due to expected high flow conductivity and temperatures desirable for district heating. A 3-D conceptual model for the proposed geothermal site was developed using the estimated reservoir properties. Based on numerical reservoir modeling results, a dual K (fracture and matrix) permeability model results in temperature drawdown similar to a continuum media model, given the expected fracture spacing. Hence, a single K model is considered adequate for further analysis. The reservoir behavior using vertical and horizontal well configurations was analyzed and the thermal breakthrough and reservoir productivity increased with horizontal lateral length. However, the well-head LCOH for vertical well configuration is less than the horizontal well configuration due to the additional cost of horizontal drilling. The surface demand at the campus is characterized and a hybrid geothermal-natural gas system is considered for providing steam at the required conditions for campus infrastructure. The geothermal contribution to the hybrid system is low due to the high latent heat required for conversion of hot water to steam. Therefore, for future work, conversion of the existing steam-based system to a hot-water based system will be considered. Having arrived at a suitable reservoir model for the WVU campus, future work will consider sensitivity of the reservoir performance to the values assigned to subsurface variables.

SOFTWARE CREDITS

Some statistical analyses were completed using R version 3.5.0 (R Core Team, 2018) and the packages readxl (Wickham and Bryan, 2018), stringi (Gagolewski et al., 2018), stringr (Wickham, 2018), vioplot (Adler, 2005), and writexl (Ooms, 2018). Wellbore heat transfer and some economic calculations were completed using GEOPHIRES (Beckers and McCabe, 2018; Beckers, 2016)

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